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"Ennio De Giorgi"

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Ithaca
Viaggio nella Scienza

Neutrino: the Mutant Particle

Ithaca: Viaggio nella Scienza

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Introduction

On the first week of October 2015 the Royal Swedish Academy of Sciences announced that the Nobel Prize in Physics 2015 was assigned to Takaaki Kajita and Arthur B. McDonald for the discovery of neutrino oscillations, which shows that neutrinos have mass. This is the academic acknowledgement of a result which has deeply modified our understanding of fundamental physics. In about twenty years of exciting discoveries (and 80 from Pauli and Fermi ideas) neutrino physics has changed from a pioneering discovery activity into a mature precision science.

In this volume we collect a set of articles presenting modern issues of neutrino physics. These articles, with the exception of that of G. Mangano, were already published in Italian on *Ithaca*, an on-line journal devoted to present scientific issues to a public of non experts, high-school teachers, Physics students.

The traditional description of neutrino physics and of weak interaction, before the discovery of neutrino oscillations, is presented in the article written by Giampaolo Co'. The theoretical framework and the empirical evidences of neutrino oscillations are described in the article of Daniele Montanino.

The following contribution, written by Francesco Ronga, is the chronicle of the announcement of the discovery of neutrino oscillations in the summer of 1989 written by one of the protagonists of the discovery. Besides its historical interest, this article offers an insider view of the dynamics of scientific research and of the large international physics collaborations and experiments. Even though neutrino oscillation is now a widely accepted fact, the mysteries of neutrino structure are not fully clarified. One of main pending question was raised by Majorana: whether the neutrino is identical to its antiparticle, as it happens, for example, to the photon. This is discussed in the contribution by Francesco Vissani. Evidently, our knowledge about neutrinos is tightly related to the possibility of observing their interactions. Thus, the knowledge of their interaction with matter, discussed in article of Maria Barbaro, Omar Benhar and Carlotta Giusti, is essential. An overview of the situation of neutrino experiments planned in Europe and in the United States is given in the articles of Francesco Terranova and Camillo Mariani. The contribution of Vincenzo Flaminio describes present and future activities concerning neutrinos in astrophysics, while the article of Gianpiero Mangano deals with neutrinos and cosmology. Alessandro Mirizzi describes the role of neutrinos in supernovae explosions. Paolo Bernardini discusses the results of observations which could indicate the presence of new types of neutrinos, insensitive to ordinary weak interactions. Finally, Eligio Lisi indicates how the study of neutrinos helped and will help us to widen our scientific horizons, emphasizing the possibilities of investigating phenomena which go beyond our present understanding. We wish to stimulate the interest of the reader for neutrino physics, a lively branch of current scientific research, full of perspectives and expectations, and likely to surprise us again.

The Editors,
Elena Canovi, Giampaolo Co', Daniele Montanino, Francesco Vissani

Neutrinos and weak interaction

Giampaolo Co' *Dipartimento di Matematica e Fisica "Ennio De Giorgi" - Università del Salento*

This introductory article is addressed to those readers who do not have great familiarity with the neutrino physics and the weak interaction. I shall provide a short presentation of some well established facts that will be considered and discussed in the other articles of the present volume.

A little bit of history

It is common wisdom to choose the 1886 as the year of the discovery of the radioactivity. In this year, Henry Becquerel observed that some photosensitive slides, conserved in a drawer which was well sealed from the external light, had been impressed. The origin of this phenomenon was related to the presence of some material which, consequently, resulted to emit radiation.

In the first years of 1900 it was already evident that the radiation emitted from radioactive materials could be catalogued in only three different types, which were called α, β and γ following their penetration power in the matter. It was found later that the α rays, the least penetrating, are nuclei of ^{4}He, the γ rays the most penetrating ones, are high-energy photons, and the β rays, electrons.

The α and γ decays presented discrete spectra. This means that, for a specific radioactive material, the energies of the α or the γ rays were constant. This fact was immediately understood in terms of the energy conservation. In fact the value of the energies which were measured for the α or the γ rays coincided with the difference between the mass of the parent nucleus, the nucleus which undergoes to the radioactive decay, and that of the sum of the masses of the decay products.

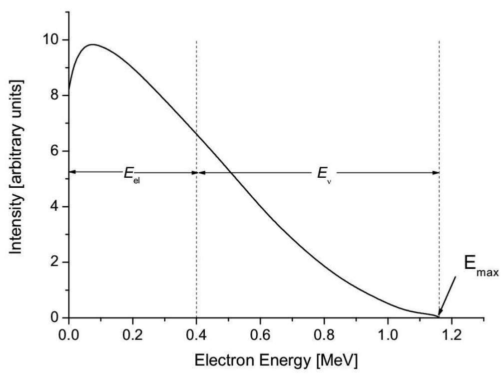

Figure 1: *Energy spectrum of the electron emitted in the β decay of the ^{210}Bi nucleus. The maximum energy $E_{\rm max}$, of 1.16 MeV, is given by the difference between the mass of the parent nucleus, ^{210}Bi, and that of the daughter nucleus, ^{210}Po. The vertical line indicates as, on the average, the available energy is divided between electron and antineutrino. The average energy of the electron is measured in calorimetric experiments.*

On the contrary, the energy spectrum of the electrons measured in the β decay, see Figure 1, was continuous for each material. Furthermore, calorimetric measures [1, 2] showed that, on the

The Pauli letter

Physics Institute of Politechnical School
Zürich

Zürich, Dec. 4th 1930
Gloriastrasse

Dear Radioactive Ladies and Gentlemen,
as the bearer of these lines, to whom I graciously ask you to listen, will explain to you in more detail, because of the "wrong" statistics of the N- and Li-6 nuclei and the continuous beta spectrum, I have hit upon a desperate remedy to save the "exchange theorem" of statistics[a] and the energy conservation law. It is the possibility that in the nuclei there could exist electrically neutral particles, which I will call neutrons, that have spin 1/2 and obey the exclusion principle and that further differ from light quanta in that they do not travel with the velocity of light. The mass of the neutrons should be of the same order of magnitude as the electron mass and in any event not larger than 0.01 proton mass. The continuous beta spectrum would then make sense with the assumption that in beta decay, in addition to the electron, a neutron is emitted such that the sum of the energies of neutron and electron is constant. Now it is also a question of which forces act upon neutrons. For me, the most likely model for the neutron seems to be, for wave-mechanical reasons (the bearer of these lines knows more), that the neutron at rest is a magnetic dipole with a certain moment μ. The experiments seem to require that the ionizing effect of such a neutron can not be bigger than the one of a gamma-ray, and then μ is probably not allowed to be larger than $e \times 10^{-13}$ cm.
But, so far, I do not dare to publish anything about this idea, and trustfully turn first to you, dear Radioactive people, with the question of how likely it is to find experimental evidence for such a neutron if it would have the same or perhaps a 10 times larger ability to get through matter than a gamma-ray. I admit that my remedy may seem almost improbable because one probably would have seen those neutrons, if they exist, for a long time. But nothing ventured, nothing gained, and the seriousness of the situation, due to the continuous structure of the beta spectrum, is illuminated by a remark of my honorable predecessor, Mr. Debye, who told me recently in Bruxelles: "Oh, It's better not to think about this at all, like new taxes". Therefore one should seriously discuss every way of rescue. Thus, dear radioactive people, scrutinize and judge. Unfortunately, I cannot personally appear in Tübingen since I am indispensable here in Zürich because of a ball on the night from December 6th to 7th. With my best regards to you, and also to Mr. Back.

Your humble servant
W. Pauli

[a] Pauli refers to the fact that the emission of a single fermion, the electron, violates the conservation of the spin statistics since it would transform a spin integer system in a state that, globally, would have semi-integer spin, or viceversa. (N.o.A.)

average, the electrons transported less than half of the available energy, obtained by the comparison between the masses of the parent and daughter nuclei. The hypotheses proposed to explain these observations raised many problems. It was even questioned wether in β decay processes the energy had to be conserved.

In the 1930, Wolfgang Pauli, in a nowadays very famous letter, see the box, proposed the idea of the existence of a particle without electric charge, therefore very difficult to detect, which would have been emitted together with the electron, in such a way that the sum of the energies of the two particles would be constant. Pauli named *neutron* this particle, which must be a fermion to satisfy the conservation of the statistics, see the note in the box.

In the 1932 Chadwick identified a neutral particle with the mass comparable with that of the proton, and called it *neutron*. Enrico Fermi immediately realised that this was not the particle predicted by Pauli, and differentiated the nomenclature of the two particles. As a good italian he called *neutron*, the big neutral one, the heavy particle identified by Chadwick, and *neutrino*, the small neutral one, that predicted by Pauli, much lighter than the neutron. Fermi developed in the 1934 the theory of the β decay where he predicted the emission of an electron and of an (anti)neutrino due to the action of a nuclear interaction different from that binding nucleons in nuclei.

The June 14th 1956, Frederick Reines and Clyde Cowan sent a telegram to Pauli with the following text " We are happy to inform you that we have definitely detected neutrinos from fission fragments by observing inverse beta decay of protons. Observed cross section agrees well with expected six times ten to the minus forty-four square centimetres. ". Pauli answered " Thanks for the message. Everything comes to him who knows how to wait. ".

The study of the weak interaction pointed out, in the middle '50s, that the parity (see the box) is not conserved in processes induced by this interaction [3]. The definition of the rate of the parity violation, and also of its sign, is an important page of the history of the fundamental physics of those years. The consequences of this fact on the neutrino characteristics are relevant. In all the processes we observe, the direction of the neutrino spin is opposite to that of its motion, while for the antineutrino they are parallel.

The idea that different types of neutrinos could exist was already wide spread when, in the 1962, the muon neutrino was identified [4].

All the phenomena induced by the weak interaction implied an exchange of the electric charge between the particles involved in the reaction. In the case of the β^- decay, for example, a nucleus is transformed in another nucleus which has a neutron less and a proton more. The positive electric charge acquired by the nuclear system is compensated by the creation of an electron, transporting negative electric charge. Globally, the electric charge is always conserved, and, up to now, phenomena violating the electric charge conservation have never been observed. The charge-exchange is referred to the fact that part of the electric charge is transferred from a system, in this case the parent nucleus, to another one, the daughter nucleus and the electron. Weak interaction processes where a lepton scatters from a target whitout charge-exchange have been predicted. In the 1973 [5] this type of reactions have been discovered by observing that muons and electrons interacted between them in scattering processes without that the respective electric charges were modified.

In the 1975 a new lepton was discovered [6], the τ, with a mass of 1777 MeV much larger than that of the electron and that of the muon. It was, then, predicted the existence of a new type of neutrino associated to this heavy lepton, and it was identified, in the 2001, by the DONUT experiment at the Fermi laboratory in the USA [7].

The W e Z^0 vector bosons mediating the weak interaction have been identified in the 1983 at the protons and antiprotons collider at the CERN of Genéve [8, 9, 10].

A wide experimental activity addressed to the study of the neutrino properties, has developed since the first years of the '90 of the past century. The other contributions of this book will give a general picture of the results obtained in these last years.

The standard model of fundamental particles and interactions

The present description of the basic components of the matter is summarised in Figure 2. There are two families of fermions of spin 1/2, quarks and leptons, each of them composed by six elements, characterised by various properties such as electric charge, mass, and another quantum number called flavour. These fermions interact by means of four fundamental interactions, gravitation, electromagnetic interaction and the two nuclear interactions, strong and weak. These four interactions are mediated by the exchange of other fundamental particles which have integer spin, therefore they are bosons.

The relative intensities of the four fundamental interactions can be estimated by using dimensionless quantities, see for example the Chapter 9.3 of Ref. [11]. By setting equal to 1 the intensity of the strong interaction, we find that that of the electromagnetic interaction is 10^{-2}, that of the weak interaction 10^{-5} and that of the gravitation 10^{-39}.

As indicated in Figure 2, gravity is not included in what is called *Standard Model*. Independently on the remarkable theoretical difficulties in the attempt to unify General Relativity and Quantum Mechanics, there are many empirical

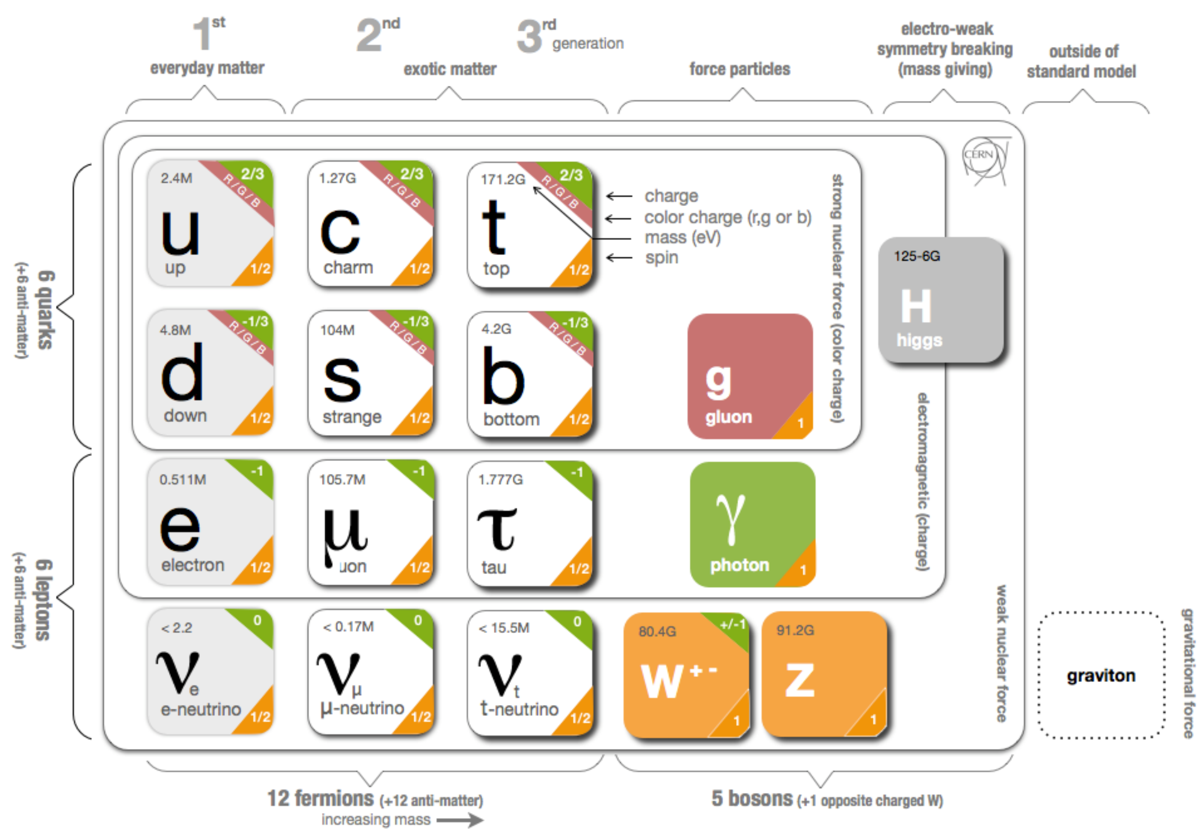

Figure 2: *Standard model.*

and observational problems which have not yet been solved. The boson which should mediate the gravitational interaction, the graviton, has never been identified. In any case, the role of the gravitation in the microscopic world, that concerned about atomic, nuclear and sub-nuclear phenomena, is irrelevant, because of its small intensity.

The strong interaction is active only between particles having color. This is the name that, historically, has been attributed to the quantum number which defines this characteristics. Color is present not only in the quarks but also in the bosons mediators of the strong interaction, the gluons. We never observed free quarks or gluons. We observe only particles composed by quarks and gluons which are called *hadrons*. Hadrons are named *barions* if they have half-integer spin, and *mesons* in case they have integer spin.

The electromagnetic and weak interactions act on both quarks and leptons. The photon mediates the electromagnetic interaction, while the bosons W, with mass of about 80 GeV and Z^0, with mass 91 GeV, mediate the weak interaction. It is common practice in nuclear and sub-nuclear physics to indicate the mass measured in the particle rest reference system. Furthermore, natural units, where velocity of light c and Plank constant $\hbar = h/2\pi$ are equal to unity. By using the well known Einstein expression $E = mc^2$ the masses can be expressed in energy units, electron volt units, 1 eV = 1.60×10^{-19} J.

Neutrinos are leptons without electric charge, therefore they are not sensitive to the strong interaction since they are leptons, and they are also not sensitive to the electromagnetic interaction, since they do not have electric charge. For this reason, neutrinos interact with matter only with the weak interaction. We can also state that every process involving neutrinos implies the presence of the weak interaction. Therefore weak interaction and neutrinos are strictly related and the understanding of the phenomena involving neutrinos implies the detailed knowledge of the weak interaction.

The Standard Model picture is completed by the Higgs boson discovered in 2013.

Neutrinos

The reactions induced by the weak interaction are called *leptonic* when only leptons are involved, *semi-leptonic* when both leptons and hadrons are involved, and *hadronic*, or *non leptonic*, when no leptons are presents.

The reaction of the muon decay is a typical leptonic process

$$\mu^- \to e^- + \nu_\mu + \overline{\nu}_e \quad . \tag{1}$$

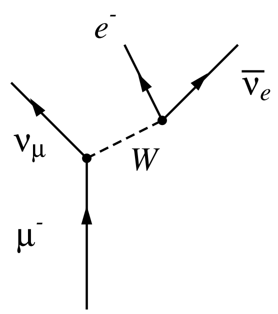

Figure 3: *Muon decay.*

Figure 3 presents the Feynman diagram describing the process of muon decay. Every element of this type of diagrams indicates a precise mathematical function and, by knowing the rules, it is possible the calculation of the transition amplitude directly related to observables quantities, for example the mean life in decay processes, or the cross section in scattering process.

In Figure 3 the time arrow goes from the lower part of the figure towards the upper part. The muon moves freely, its wave function is described by the Dirac equation in absence of any interaction. At a certain moment the muon μ decays by emitting a muon neutrino ν_μ and a W boson mediating the weak interaction. The W boson decays in an electron e^- and an electron antineutrino $\overline{\nu}_e$.

This manner of describing the process (1) has remarkable implications. The first one concerns the particle W which is virtual one. The conservation of energy and momentum is warranted only by the sum of the energies and momenta of the initial and final particles, respectively μ, ν_μ e^- and $\overline{\nu}_e$. The propagation of W does not conserve energy and momentum, this is the reason why this particle is called virtual. Remarkably, the existence of the W particle has been predicted in terms of virtual exchange in the description of weak process, such as the muon decay, well before the energy to produce real Ws, and also the technology to detect them, were available.

The negative charge is transferred by the W from the muon vertex to the electronic one, and is globally conserved. The other relevant fact is that the number of muon and electron leptons is separately conserved. It is common practice to analyse this fact by assigning a leptonic quantum number +1 to the leptonic particles and -1 to their antiparticles. Together with the conservation of other quantities, for example energy, momentum, angular momentum, electric charge, also the conservation of the leptonic number is a fundamental instrument to disentangle reactions and decays which can be observed, allowed, from those forbidden, never observed. Up to now a violation of the lepton number has never been observed, not only globally, but also separately for each type of the lepton family. The reaction (1), and the related diagram of Figure 3, indicate that the muon lepton number, +1, of the initial state is conserved by the presence the ν_μ in the final state. Since the electron lepton number in the initial state was zero, also the final state must have the same value. In effect, the existence of one electron and of an electron antineutrino in the final state generates an electron leptonic number of zero value.

The conservation of the leptonic number for each lepton family implies that the reaction

$$\mu^- \to e^- + \overline{\nu}_\mu + \nu_e \quad , \tag{2}$$

is prohibited. This reaction would conserve all the quantum numbers, and also the global lepton number, but it does not conserve the leptonic number separately for each family.

Another important weak decay is that of the free neutron

$$n \to p + e^- + \overline{\nu}_e \quad , \tag{3}$$

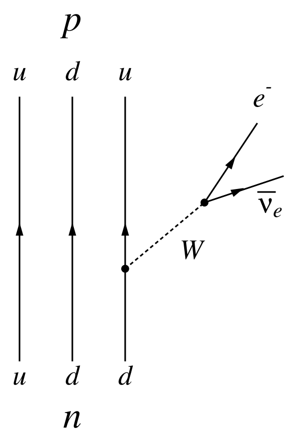

Figure 4: *Neutron decay.*

whose diagram is shown in Figure 4 in terms constituent quarks content of neutron and proton. In this picture one of the quarks of flavour d, with charge -1/3, is transformed in a u quark with charge +2/3. The electric charges are expressed in terms of charge unit corresponding, in modulus, to the electron charge.

The remarkable fact of this process is the change of the quarks flavour. **Only the weak interaction can modify the flavour of the quarks.** This characteristic of the weak interaction allowed its identification. The very short interaction range and the weak intensity would have hidden its presence if the weak interaction would not have some feature which generate phenomena that other interactions cannot produce.

Also in this case, we observe that the lepton number is separately conserved for each family. The two processes considered indicate a difference between neutrinos and antineutrinos. In effect, the antineutrinos produced by the reaction (3) can activate the reaction

$$\overline{\nu}_e + p \to n + e^+ \quad , \tag{4}$$

but not the reaction

$$\overline{\nu}_e + n \not\to \ p + e^- \quad , \tag{5}$$

where the symbol $\not\to$ indicates that this reaction has never been observed.

The weak interaction is mediated non only by the exchange of the charged $W^\pm$ bosons, but also by that of a neutral boson called Z^0, as, for example, in the process shown in Figure 5.

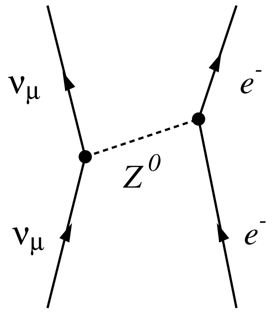

Figure 5: *Neutrino scattering with neutral interaction.*

A detailed investigation of various reactions which have been observed, and also those which have never been observed, indicates that the muon and tau neutrinos are different particles.

Weak interaction

The modern description of the phenomena induced by the weak interaction is based on the exchange of the $W^\pm$ and Z^0 bosons. In this picture the study of the interaction is related to the knowledge of the intensity and of the manner used to couple the two bosons with the interacting quarks and leptons. In other words, the key question is the quantitative description of the dots that in the various diagrams connect the lines indicating the exchange of W and Z^0 bosons.

Let's first consider the intensity of the weak interaction. The ideal phenomenon to be used for the evaluation of this quant ity is the muon decay represented by the diagram of Figure 3. This process involves leptons only, therefore it is not affected by the presence of other interactions, such as the strong one as in the case of the neutron decay. The contribution to the transition amplitude, whose square modulus is proportional to the muon decay rate, of the term describing the exchange of the W boson is given by the expression [12]

$$g \frac{1}{q^2 - \omega^2 + M_W^2} g \quad . \tag{6}$$

In this expression, q indicates the modulus of the momentum transferred by the muon to the decay products, and ω the transferred energy, given by the difference between the muon mass, 105 MeV, and that of the electron, 0.5 MeV. In this estimate I have considered that the neutrinos involved in the process are massless. The term M_W represents the W mass which is about 80 GeV. The factor g, which I have inserted twice to indicate that is associated to each vertex of the diagram, is a real constant representing the strength of the coupling between W and the other particles. This is the quantity which has to be determined and it is normally called *coupling constant*.

For many of the processes investigated, for example the case under study, we have that $q^2 - \omega^2 << M_W^2$ therefore it is reasonable to simplify the expression (6) by neglecting energy and momentum transferred

$$\frac{g^2}{q^2 - \omega^2 + M_W^2} \rightarrow \frac{g^2}{M_W^2} = \frac{\sqrt{2}}{\pi} \frac{1}{(\hbar c)^2} G_F \quad , \qquad (7)$$

where a new coupling constant G_F, called Fermi constant, has been defined. In the previous expression I have indicated for the first time the presence of two fundamental constants of the physics, $\hbar$, which is the Plank constant divided by 2π, and c, the speed of the light in vacuum.

The accurate measurement of the muon decay determines the value

$$\frac{G_F}{(\hbar c)^3} = 1.166 \times 10^{-5} \mathrm{GeV}^{-2} \quad . \qquad (8)$$

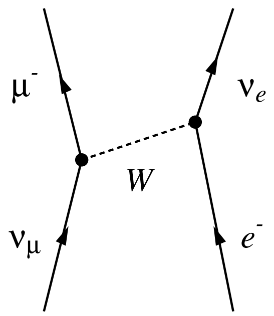

Figure 6: *Scattering of muon neutrinos with electrons.*

In order to appreciate the quantitative meaning of this value of the coupling constant, we consider the reaction presented in Figure 6, where a muon neutrino scatters, in a charged current process, from an electron. For the neutrino energies E_{ν_e} much smaller that the W mass, the expression of the cross section is given by [12]

$$\sigma = \frac{G_F^2}{\pi(\hbar c)^4} 2 m_e E_{\nu_e} \quad , \qquad (9)$$

where m_e=0.5 MeV is the electron mass. By substituting in the above expression the known values of the constants, we obtain

$$\sigma = 10^{-45} \, m_e^2 \, E_{\nu_e}(\mathrm{GeV}) \quad , \qquad (10)$$

where the electron mass and the neutrino energy must be expressed in GeV.

The extremely small value of this cross section can be understood if we calculate the mean free path of the neutrino in the matter. Let us consider a neutrino of 1 MeV energy propagating in iron where the electron number per m^3 is $\rho = 2.2 \times 10^{30}$. We can calculate the mean free path as

$$L = \frac{1}{\rho\sigma} = \left[1.7\,10^{-48}\,\mathrm{m}^2 \;\, 2.2\,10^{30}\,\mathrm{m}^{-3}\right]^{-1} \simeq 3.74\,10^{17}\mathrm{m} \quad .$$

By considering that one light year corresponds to about 10^{16} m, this results indicates that the mean free path of a 1 MeV neutrino in iron is of about 40 light years. These numbers clarify why neutrino detectors must have enormous masses.

The analysis of various phenomena related with the weak interaction indicates that the value of g, and consequently of G_F, is the same for each lepton involved in the process.

After having defined the intensity of the interaction, we consider the expression of the coupling between leptons and bosons W e Z^0. The starting point is the analogy with the electromagnetic interaction. In this latter case, the boson mediating the interaction is the photon which has spin 1. The type of coupling must describe correctly the sum of the angular momenta of the interacting particles. This type of coupling, because of the rotational symmetry, is analogous to that of a three-dimensional vector. For this reason, the coupling of particles with the photons is called of *vector* type.

Since also the mediators of the weak interaction have spin 1, also in this case a vector type coupling was considered at first. The discovery of the parity non conservation in weak interactions [3] generated doubts on this hypothesis. In

Parity

The parity of a physical quantity identifies its behaviour when the coordinate system is inverted in such a way that the vector indicating its position change sign. In mathematical terms, we can define a parity operator $\mathcal{P}$ that, when applied to the position operator, transforms $\mathbf{r}$ in $-\mathbf{r}$, i.e. $\mathcal{P}(\mathbf{r}) = -\mathbf{r}$. The eigenvalues of the parity operator can be only +1, positive parity, or -1, negative parity. The velocity, defined as the first derivative of the position with respect to the time, $\mathbf{v} = d\mathbf{r}/dt$, has negative parity $\mathcal{P}(\mathbf{v}) = d(-\mathbf{r})/dt = -\mathbf{v}$. All the vector quantities with negative parity are called *polar vectors* even though, trivially speaking, the adjective polar is often neglected. Also the momentum $\mathbf{p} = m\mathbf{v}$, where m is the mass of the considered particle, is a polar vector.
By using polar vectors it is possible to build other quantities having different properties under the action of the parity operator. For example, the scalar product of two vectors produces a *scalar* quantity with positive parity $A = \mathbf{r}_1 \cdot \mathbf{r}_2$, therefore $\mathcal{P}(A) = A$, since the sign of both vectors is modified. For the same reason, also the vector product of two polar vectors does not change sign under the action of the parity operator. This type of vectors are called *axial vectors* or *pseudo-vectors*. A typical axial vector is the angular momentum $\mathbf{L} = \mathbf{r} \times \mathbf{p}$. Also in this case the polar vectors defining $\mathbf{L}$ change sign therefore $\mathcal{P}(\mathbf{L}) = \mathbf{L}$. The scalar product between a polar and axial vector produces a scalar quantity with negative parity $\mathcal{P}(\mathbf{L}\cdot\mathbf{r}) = \mathbf{L}\cdot(-\mathbf{r})$. These quantities are named *axial*. The following table summarises the properties of the quantities presented above.

typology	parity
scalar	+1
polar vector	-1
axial, pseudo-scalar	-1
axial vector, pseudo-vector	+1

the box I summarise the parity properties of various physical entities. Here below I sketch the essential points of the motivations to exclude a coupling of pure vector type.

The diagrams I have presented in the figures show the transition amplitudes of the various processes which have been investigated. The transition probabilities are obtained by squaring these amplitudes. If the weak interaction would have only one type of coupling, either of vector or axial vector type, we would not observe parity violation. The application of the parity operator generates the change of an overall sign if the quantity has negative parity, or no change at all if the quantity has positive parity. In both cases, the application of the parity operator to the square of a quantity does not change its sign.

In the specific case under investigation, if the coupling would be only of vector type, V in jargon, the parity violation would not be observed. On the other hand, the algebraic structure related to the exchange of a spin 1 bosons allows a pseudo-vector, or axial vector, coupling, identified as A. However, if the coupling would be only of this type, again, we would not observe any parity violation effect. The violation of the parity happens only if both types of coupling are present in the transition amplitude. In this case, the vector term changes sign but not the axial one. By squaring a linear combination of the two terms, the interference term has a different sign when parity is modified. By using simple expressions to clarify the point we can write

$$|V + \alpha A|^2 = V^2 + \alpha^2 A^2 + 2\alpha V A \ , \qquad (11)$$

and applying the parity operator $\mathcal{P}$

$$\mathcal{P}(|V + \alpha A|^2) = (-V)^2 + \alpha^2 A^2 - 2\alpha V A \ . \quad (12)$$

The history of the definition of the value of the

α coefficient gives an example of how the modern science works. Wrong ideas on both absolute value and sign have been proposed, and also published, but the investigation has improved by continuously correcting these quantities until, at the end of the '60s of the past century, all the more refined measurements converged on the, nowadays accepted value, of $\alpha = -1$. For this reason, the weak interaction coupling is called of $V - A$ type.

This type of coupling, which implies the maximal parity violation, has important consequences for the neutrino physics. In order to clarify this point I introduce a new quantity called *helicity*, defined as

$$h = \frac{\boldsymbol{\sigma} \cdot \mathbf{p}}{|\mathbf{p}|} \quad . \tag{13}$$

Helicity is a pseudo-scalar quantity, see the box, and is equal to +1 when $\boldsymbol{\sigma}$, the particle spin, is aligned to the direction of the motion, indicated by the direction of the momentum $\mathbf{p}$, and -1 in the opposite case.

The $V - A$ coupling of the weak interaction implies that **all the neutrinos interacting with the matter have helicity -1, and all the antineutrinos have helicity +1.**

In reality, the quantity which is conserved in the processes induced by the weak interaction is not the helicity but another quantity, slightly different, called *chirality* which, contrary to helicity, remains constant independently of the reference system of the observer, and, for this reason, we say that is a relativistic invariant. The $V - A$ coupling implies that the weak interaction acts only on left-handed particles, i. e. with chirality -1, and right-handed antiparticles, i. e. with chirality +1.

For massless particles, chirality and helicity coincide. To be more precise, chirality and helicity have common eigenvalues and eigenvectors. Therefore to the left-handed chirality corresponds left-handed helicity, i.e. with -1 eigenvalue, and viceversa. From all of this, the previous statement about neutrinos, considered massless, becomes clear.

In case of particles with mass, chirality is conserved in weak interaction processes, and it can be described as linear combination of two eigenstates of the helicity. For massive particles, left-handed chirality can be described as a sum of left- and right-handed helicity states. The latter one is larger the larger is the particle mass, and, of course, it will be zero in case of massless particle.

The empirical consequences of this fact are numerous and remarkable. In my opinion, the more striking one is related to the pion decay. The charged pion π^- is a spinless meson with a mass of 140 MeV and a half-life of 2.6×10^{-8} seconds. The π^- decays as

$$\pi^- \to \mu^- + \overline{\nu}_\mu \quad , \tag{14}$$

with probability 99.9877 %. On the other hand, the decay

$$\pi^- \to e^- + \overline{\nu}_e \quad , \tag{15}$$

which is favoured from the energetic point of view and also because of the larger final states density, happens with probabilities of about 10^{-4}. This fact, totally anti-intuitive, is explained only in terms of chirality and $V - A$ coupling.

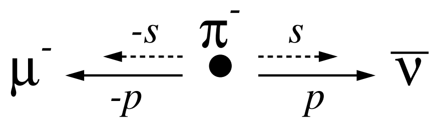

Figure 7: *The pion decay.*

Let's analyse the conservation of the spin by considering the decay of the pion in its rest reference system. The value of the helicity of the massless antineutrino is +1 and this implies that the antineutrino spin is aligned to the direction of motion. Since the pion is a spineless particle, the sum of the spins of all the particles in the final state must be zero. In the reference system of the decaying pion, the initial momentum is zero, therefore the sum of the momenta of the two final particles must be zero, this means that the charged lepton moves in the opposite direction with respect to that of the antineutrino, and, because of the spin conservation, also in this case spin and momentum must be aligned, i.e. the helicity value is +1. The $V - A$ coupling of the weak interaction forces the chirality of the particle to be -1. Because the charged leptons involved in the decay have a non zero mass, their chiral -1 states have a +1 helicity component proportional to the mass of the lepton. Since the μ^- mass is roughly 200 times larger than the electron mass, the component with helicity +1 is much larger for the muon than for the electron. This explains why the pion decays mainly in muons and its relative antineutrino. If muon and electrons would be massless, the pion could not decay by means of weak interaction processes.

Relevant ideas

In this article I presented some facts which I believe are important for the understanding of the physics of the neutrino and of the weak interaction. The knowledge of these phenomena, and their interpretation, are essential to understand the content of the other articles of this volume. I summarise here below the key concepts.

- Neutrinos are sensitive to the weak interaction only. In reality they are also sensitive to the gravitational force, but this interaction is negligible in the atomic, nuclear and subnuclear world.

- There are three types of neutrinos, each of them is associated to a charged lepton e^-, μ^- e τ^-. The leptonic number is conserved for each family, therefore, in charged-weak processes where it appears a certain type of lepton, a neutrino, or antineutrino, of the same family must appear. This implies that the various types of neutrinos can be distinguished by disentangling the reactions accessible from those prohibited. This kind of procedure allows us to distinguish also neutrinos from antineutrinos.

- The modern description of weak interaction phenomena is based on the exchange of two types of vector bosons, with spin 1. The W, electrically charged, with a mass of about 80 GeV, and the Z^0 boson, electrically neutral, with a mass of about 91 GeV.

- The weak interaction range is extremely short, of the order of one hundredth of fm, and its intensity very weak. The mean free path of a neutrino of 1 MeV in iron is of the order of some tens of light years.

- The weak interaction, because of its short range and small intensity, would not have been identified if would not produce specific phenomena. Only the weak interaction can modify the flavour of quarks and also that of the leptons. Furthermore, only in weak interaction processes the parity is not conserved.

- The way of coupling of the bosons mediating the interaction $V - A$, implies that only particle with left-handed chirality and anti-particles with right-handed chirality are sensitive to the weak interaction. Since for massless particles chirality and helicity coincide, massless neutrinos are identified only if their spin is anti-aligned to the direction of motion, they are left handed, and anti-neutrinos are right-handed.

At present, these facts are well consolidated but they do not exclude alternatives which can modify this picture. For example, the neutrino oscillation is now a commonly accepted fact, and this is explained, in the simplest manner, with the presence of a non zero neutrino mass. This implies that also neutrinos with +1 helicity can exist. What are the consequences? We cannot exclude the presence of neutrinos with helicity +1, but do they interact with matter by means of weak interaction, and how?

Despite of the detection difficulties, nowadays the neutrino physics has transformed in precision science. Its goal is not any more the discovery of a phenomenon, but rather the precise measurement of the quantities needed to describe, and understand, it. In the past the weak interaction, and in particular the neutrinos, have subverted many of our expectations, therefore let's wait for other surprises.

[1] C. D. Ellis, W. A. Wooster: "The average energy of disintegration of Radium E", *Proc. Roy. Soc. A* **117** (1927) 109.

[2] L. Meitner, W. Z. Orthmann: "Über eine absolute Bestimmung der Energie der primären β-Stralen von Radium E", *Z. Phys.* **60** (1930) 143.

[3] C. S. Wu, E. Ambler, R. W. Hayward, D. D. Hoppes, R. P. Hudson: " Experimental Test of Parity Conservation in Beta Decay", *Phys. Rev.* **105** (1957) 1413 - 1414.

[4] G. Danby, J.-M. Gaillard, K. Goulianos, L. M. Lederman, N. B. Mistry, M. Schwartz, J. Steinberger: "Observation of High-Energy Neutrino Reactions and the Existence of Two Kinds of Neutrinos ", *Phys. Rev. Lett.* **9** (1962) 36-44.

[5] F. J. Hasert et al.: "Search for elastic muon-neutrino electron scattering", *Phys. Lett. B* **46** (1973) 121-124.

[6] M. L. Perl et al.: "Evidence for Anomalous Lepton Production in $e^+ e^-$ Annihilation", *Phys. Rev. Lett.* **35** (1975) 1489.

[7] K. Kodama et al.: "Observation of τ neutrino interactions", *Phys. Lett. B* **504** (2001) 218.

[8] G. Arnison et al.: "Experimental observation of isolated large transverse energy electrons with associated missing energy at $\sqrt{s}$= 540 GeV", *Phys. Lett. B* **122** (1983) 103-116.

[9] M. Banner et al.: "Observation of single isolated electrons of high transverse momentum in events with missing transverse energy at the CERN $\overline{p}p$ collider", *Phys. Lett. B* **122** (1983) 476-486.

[10] G. Arnison et al.: "Experimental observation of lepton pairs of invariant mass around 95 GeV/c^2 at the CERN SPS collider", *Phys. Lett. B* **126** (1983) 398-410.

[11] K. S. Krane: *Introductory Nuclear Physics.* John Wiley and Sons, New York (1988).

[12] B. Povh, K. Rith, C. Scholz, F. Zetsche, W. Rodejohann: *Particles and nuclei. An introduction to the Physical Concepts.* Springer, Berlin (1993).

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Neutrino oscillations

There are two possible outcomes: if the result confirms the hypothesis, then you've made a measurement. If the result is contrary to the hypothesis, then you've made a discovery.

Enrico Fermi

Daniele Montanino *Dipartimento di Matematica & Fisica "Ennio De Giorgi" - Università del Salento*

Neutrino Oscillations are a macroscopic quantum phenomenon in which neutrinos can transform their flavor "on the fly". This phenomenon was suggested for the first time by Bruno Pontecorvo in the 50's of the previous century, has been subsequently confirmed and is now one indispensable tool both for the investigation of neutrino properties (in particular, neutrino masses) and for giving an explanation to some astrophysical anomalies.

Neutrino masses

Since it was conjectured by Pauli, neutrino has been a challenge for physicists owing to its elusive nature. In particular, scientists immediately realized that neutrinos must have a mass considerably lower with respect to the other known particles (except, perhaps, the photon), possibly also a null mass. Although the Standard Model of the electroweak forces in its "minimal" formulation provides a vanishing mass for neutrinos, physicists wondered if they could have a small mass. For example, due to the high number of relic neutrinos produced in the early phases of the Big Bang, a neutrino mass of few eV could provide a simple explanation for the existence of Dark Matter (although there are other reasons that exclude light neutrinos as the principal component of Dark Matter). It is worthwhile to remark that the electronVolt (abbreviated, eV) is a measure of energy corresponding to about 1.60×10^{-19} J. However, owing to the renowned mass-energy relation $E = mc^2$ it can be also considered as a measure of mass, corresponding to about 1.78×10^{-36} Kg. For example an electron has a mass $m_e = 0.511$ millions of eV, or MeV.

How can we measure the mass of the elusive neutrino? Of course we cannot put a number of them on a weighing scale (and anyway this kind of measure cannot be done for almost all the particles except atoms). We need to rely on indirect methods, the most popular are: 1) Precise measurements of the kinetic energy of the electrons emitted in β decays in which also invisible neutrinos are emitted (in this case if neutrinos are massive, electrons cannot take away all the available energy in the decay); 2) indirect effects of relic neutrinos on the evolution of the Universe after the Big Bang (in particular, on the formation of large scale structures); 3) very rare decays named *neutrinoless double β decays*. The last kind of measurement is possible only if neutrino is a *Majorana particle*, namely if it is equal to its own anti-particle. This possibility is contemplated in many extensions of the Standard Model.

Anyway, the previous methods have failed to measure the mass of neutrinos, setting only upper limits to few eV. Nevertheless, physicists are pretty sure that neutrinos have mass. How is this possible? To explain this we must stick to the realm of quantum mechanics.

Flavor eigenstates and mass eigenstates

We must keep in mind that the word *neutrino* does not refer to a single particle. Of course we all know the electron but perhaps not all know that this particle has two heavier "brothers ": the *muon* (μ) and the *tau* (τ). These two particles have the same quantum number of the electron (electric charge -1, spin $1/2$ etc.) except for the mass ($m_\mu = 105.7$ MeV and $m_\tau = 1777$ MeV). Muon and tau are unstable particles and once they are produced they quickly decay into lighter particles (including neutrinos), for this reason they are far from our common experience. These three particles are named *charged leptons* from Greek $\lambda\varepsilon\pi\tau o\zeta$, light, in contrast to *barions*).

Each charged lepton has in turn the corresponding neutral particle: precisely the neutrino. Therefore there are three different neutrinos, the *electron neutrino* (ν_e), *muon neutrino* (ν_μ), and *tau neutrino* (ν_τ). We assert that neutrinos are *flavored* and the three states ν_e, ν_μ and ν_τ are named in the quantum mechanical jargon *flavor eigenstates*. Charged leptons and neutrinos are generically named *Leptons*. Nowadays, we do not know further lepton families beyond the previous three. Moreover from LEP (Large Electron Positron) collider results on the Z^0 decay we know that, if they exist, such particles must be extremely heavy (including neutrinos), at least half of the mass of the Z^0 (i.e. about 42 GeV).

A neutrino of a family can be distinguished from another of a different family because in a weak interaction (specifically in a "charge current" interaction) a neutrino with a specific flavor transforms exclusively in its corresponding charged lepton. At the same time each lepton is always produced in pair with its corresponding anti-lepton. To be more specific, for example in the pion decay process

$$\pi^+ \to \mu^+ + \nu_\mu \quad , \tag{1}$$

the neutrino must be exclusively a muon neutrino. If this neutrino hits for example a proton it will be transformed into a muon (and not into another lepton)

$$\nu_\mu + n \to \mu^- + p \quad . \tag{2}$$

(Notice that the proton and the neutron in the previous reaction are in general embedded in a nucleus). This was exactly the experiment performed by Lederman, Schwartz e Steinberger [1]. They showed that electrons and muon neutrinos are different particles (and they won the Nobel Prize in 1988 for this discovery). We must remark however (and this will be important for the following) that in this experiment the distance between the decay of the pion and absorption of neutrinos was relatively small (about 30 m). We will see that with longer distances the situation is more involved.

The previous phenomenon can be encoded in the following way: each lepton carries a quantum number, named *family quantum number*, that we suppose to be conserved. This quantum number is conventionally positive for particles and negative for antiparticles. For example, in the case of pion decay in Eq. (1) we have

$$\begin{array}{ccccc} \pi^+ & \to & \mu^+ & + & \nu_\mu \\ 0 & = & (-1) & + & (+1) \end{array} \quad . \tag{3}$$

With this conservation law some processes are prohibited. For example, although the decay $\mu \to e\gamma$ is allowed from the point of view of kinematics, it is not observed because it would violate both muonic and electronic quantum number. Conversely, the process

$$\mu^- \to e^- + \nu_\mu + \bar{\nu}_e \tag{4}$$

(notice that the symbol $\bar{\nu}$ indicates antineutrinos) is allowed. The reader can easily verify that the quantum number of each family is conserved.

Let us now suppose that neutrinos are massive. Common sense would require that a neutrino of each flavor has a definite mass, that is, that we can measure the mass of ν_e, ν_μ or ν_τ. Actually, the situation is more complicated since it could happen (and indeed it is exactly what happens!) that neutrinos with definite mass (the so-called *mass eigenstates* do not coincide with flavor eigenstates. This fact may look bizzarre to people unfamiliar

Mixing matrix 3×3

In the general case the mixing matrix can be represented by the product of elementary mixing matrices. For example, the 3×3 matrix can be written as

$$\mathbf{U} = \begin{pmatrix} 1 & 0 & 0 \\ 0 & \cos\theta_{23} & \sin\theta_{23} \\ 0 & -\sin\theta_{23} & \cos\theta_{23} \end{pmatrix} \times \begin{pmatrix} \cos\theta_{13} & 0 & \sin\theta_{13}e^{i\delta} \\ 0 & 1 & 0 \\ -\sin\theta_{13}e^{-i\delta} & 0 & \cos\theta_{13} \end{pmatrix} \times \begin{pmatrix} \cos\theta_{12} & \sin\theta_{12} & 0 \\ -\sin\theta_{12} & \cos\theta_{12} & 0 \\ 0 & 0 & 1 \end{pmatrix}$$

In this case the mixing matrix depends on three mixing angles θ_{ij}, on a complex phase δ which accounts for *CP violations* in the leptonic sector (see the dedicated box). For antineutrinos $\delta \to -\delta$.

Oscillation formula in vacuum

Let us suppose, for example, that a muonic neutrino with energy E is produced at $x = 0$ (of course, this argument is valid for all initial flavors). At time $t = 0$ it will be thus in flavor eigenstate

$$|\nu(0)\rangle \equiv |\nu_\mu\rangle = -\sin\theta|\nu_1\rangle + \cos\theta|\nu_2\rangle \, .$$

Since the states $|\nu_i\rangle$ have definite mass and energy (and thus also definite momentum), they propagate as plane waves

$$|\nu(x,t)\rangle = -e^{-\frac{i}{\hbar}(Et-p_1x)}\sin\theta|\nu_1\rangle + e^{-\frac{i}{\hbar}(Et-p_2x)}\cos\theta|\nu_2\rangle \, .$$

Following the rules of quantum mechanics, the probability that at distance L from the production point the neutrino is observed in the state $|\nu_e\rangle$ is

$$\begin{aligned} P_{\nu_\mu\to\nu_e}(L) = |\langle\nu_e|\nu(L,t)\rangle|^2 &= |(\cos\theta\langle\nu_1| + \sin\theta\langle\nu_2|)\,|\nu(L,t)\rangle|^2 \\ &= \left|-\cos\theta\sin\theta e^{-\frac{i}{\hbar}(Et-p_1L)} + \cos\theta\sin\theta e^{-\frac{i}{\hbar}(Et-p_2L)}\right|^2 . \end{aligned}$$

If $E \gg m_i$ we can write $p_i c = \sqrt{E^2 - m_i^2} \simeq E - \frac{m_i^2}{2E}$; after straightforward calculations we obtain Eq. (7).

with quantum mechanics: There are complementary variables such as position and momentum of a particle that cannot be measured simultaneously. In a sense this is the equivalent of the Heisenberg uncertainty principle: if we know the flavor of a neutrino we cannot measure its mass and vice-versa.

Mass eigenstates are conventionally indicated with ν_i, with $i = 1, 2, 3$. Mass eigenstates and flavor eigenstates are related by a linear relation by means of an unitary matrix 3×3:

$$\begin{pmatrix} \nu_e \\ \nu_\mu \\ \nu_\tau \end{pmatrix} = \mathbf{U} \cdot \begin{pmatrix} \nu_1 \\ \nu_2 \\ \nu_3 \end{pmatrix} . \tag{5}$$

The matrix $\mathbf{U}$ is called *mixing matrix* or Pontecorvo-Maki-Nakagawa-Sakata matrix. The relation is easy to understand if we consider only two families of neutrinos (e.g. ν_e e ν_μ). In this case we have

$$\begin{aligned} \nu_e &= \cos\theta\,\nu_1 + \sin\theta\,\nu_2 \\ \nu_\mu &= -\sin\theta\,\nu_1 + \cos\theta\,\nu_2 \end{aligned} \tag{6}$$

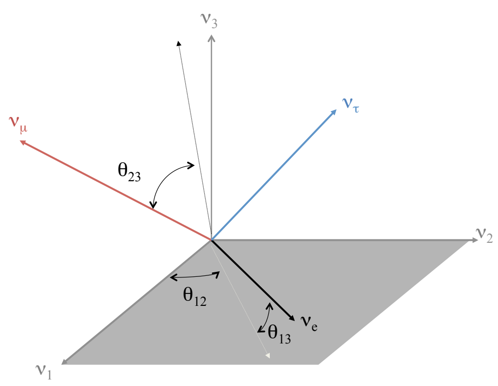

Figure 1: *A geometrical representation of the relation between mass and flavor eigenstates*

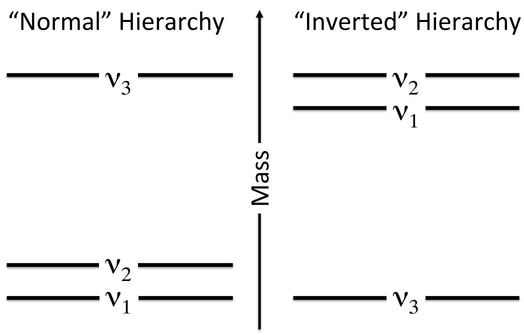

Figure 2: *Mass hierarchies of neutrinos*

namely a "rotation" in the space of states. The angle θ is called merely *mixing angle*. In the 3×3 case the mixing matrix can be written as the product of elementary mixing matrices, as illustrated in the box. In Fig. 1 there is a graphical representation of the mixing angles θ_{ij} in which mass and flavor eigenstates are represented as vectors.

For what concerns the masses, we will see from experimental results that two states have a mass difference lower than the difference with the third. Conventionally the closer states are named ν_1 and ν_2 with masses $m_1 < m_2$ respectively, while the "lone" state is conventionally named ν_3 with mass m_3. At the moment it is still unknown whether $m_3 > m_{1,2}$ or $m_3 < m_{1,2}$. This ambiguity is called "hierarchy". In the first case the hierarchy is called " normal", in the second "inverted". Notice that there is no reason to believe that normal hierarchy is more…normal than the inverted one. This denomination is purely conventional.

Flavor oscillations

Flavor oscillations in vacuum

Flavor oscillations can be explained in a naïve way. For simplicity let us consider a simplified system with only two flavors (e.g. ν_e and ν_μ), but the generalization to three flavors is straightforward. Let us suppose that a neutrino is produced in a given interaction (for example in a decay as in Eq. (1)). This state is initially in a flavor eigenstate that we can suppose with a well defined energy E. As we have already seen, this state is a superposition of mass eigenstates. Owing to particle-wave duality each mass eigenstate will evolve as a wave with wavelength $\lambda_i = \hbar/p_i$, where p_i is the momentum of the i-th state given by the relativistic relation $p_i^2 = (E^2 + m_i^2)/c^2$ (here and thereafter we will assume that masses are measured in eV). This means that the two waves propagate with different velocities. Thus, an interference between the two waves in which sometimes the waves add up in phase and sometimes in phase opposition occurs. This phenomenon is similar to the acoustic phenomenon of "beats" (a sort of vibrato) that can be heard in proximity of organ pipes.

The final consequence is that the neutrino is a superposition of mass eigenstates different from the initial one. There is in general a non-zero probability that the neutrino lies in the "orthogonal" state with respect to the initial one, that is, has changed its flavor. This phenomenon manifestly violates the family lepton number, although the total leptonic number is conserved.

In the simplified scenario with only two flavor states the conversion probability at a given distance L from the source of neutrinos is

$$P_{\nu_\mu \to \nu_e}(L) = \sin^2 2\theta \sin^2 \left(\frac{\Delta m^2}{4\hbar c E} L \right) , \quad (7)$$

where θ is the mixing angle, $\Delta m^2 = m_2^2 - m_1^2$. For those people who are familiar with quantum mechanics, a derivation of this formula is in the dedicated box. Of course, for unitarity $P_{\nu_\mu \to \nu_\mu} = 1 - P_{\nu_\mu \to \nu_e}$. We notice that oscillations are insensitive to absolute masses: for this reason from oscillation measurements we are sure

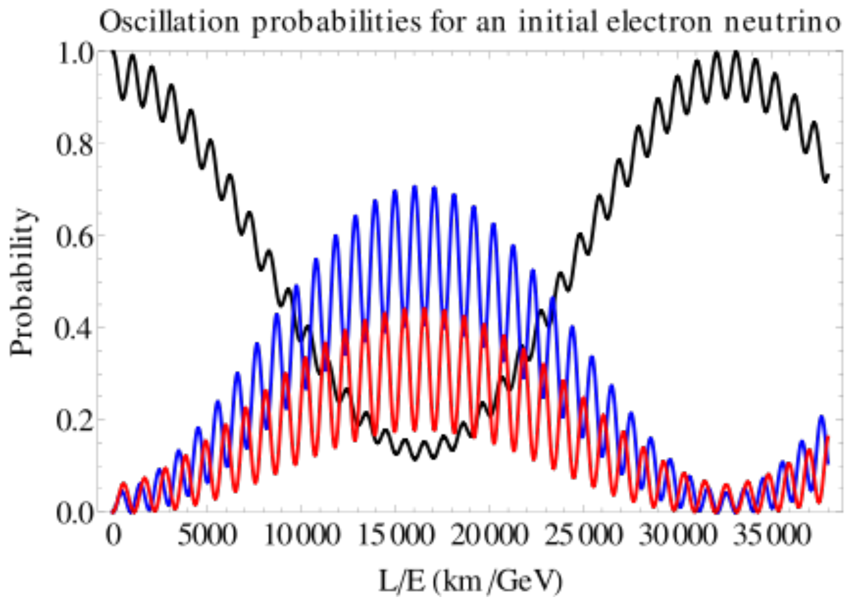

Figure 3: *Oscillation probability for an initial flavor ν_e. In black: ν_e, in blue: ν_μ, in red: ν_τ. Parameters used for the figure:* $\sin^2 2\theta_{13} = 0.10$, $\sin^2 2\theta_{23} = 0.97$, $\sin^2 2\theta_{12} = 0.86$, $\Delta m^2_{13} = 2.32 \times 10^{-3}$ *eV*^{2}, $\Delta m^2_{12} = 7.59 \times 10^{-5}$ *eV*^{2}, $\delta = 0$ *and normal hierarchy.*

that neutrinos have mass but do not know their values. We notice also that for $\theta = 0$ or $\pi/2$ the oscillation probability vanishes. This is not a surprise because in that case mass and flavor eigenstates overlap (see Eq. (6)).

Oscillation wavelength (in meters) is given by

$$\lambda_\nu \simeq 2.47 \text{ m} \times \frac{E}{\text{MeV}} \times \frac{\text{eV}^2}{\Delta m^2} , \qquad (8)$$

where the energy E is expressed in MeV and the mass square difference Δm^2 in eV^2. Notice that if θ is small and/or $L \ll \lambda_\nu$ the conversion probability is very small. In the experiment of Lederman, Schwartz e Steinberger the distance from source to detector was too small (30 meters, while for neutrinos with energy $E \geq 300$ MeV the oscillation wavelength is about 300 Km). For this reason in that experiment no $\nu_\mu \to \nu_e, \nu_\tau$ oscillations were detected.

A little technical remark is in order. The above derivation of Eq. (7) done in the box is simplistic owing to the assumption that neutrinos have a definite energy. With this assumption we have used plane waves (infinitely extended in space and in time). However this is unrealistic from a quantum point of view because in this case the particle is completely unlocalized (or, in technical words, the wave function is not normalizable). The solution is that states with definite energy and momentum are excluded in quantum mechanics. Indeed, owing to Heisenberg uncertainty principle, this implies that the experiment would last for an infinite time. However, more sophisticate derivations using localized wave packets lead to results very similar to Eq. (7) apart from small corrections, negligible for almost all practical purposes.

In the full three generation case of course the oscillation formula is more complex (we do not give here a explicit formula) and entails two oscillation wavelengths, one depending to the smallest mass square difference $\Delta m^2_{12} = m^2_2 - m^2_1$, and the other depending to the largest mass square difference $\Delta m^2_{13} = m^2_3 - m^2_1$. The sign of Δm^2_{13} defines the mass hierarchy: positive (negative) for normal (inverted) hierarchy. In Fig. 3 the oscillation probability for an initial ν_e is shown. We notice the presence of a short wave determined by Δm^2_{13} overlapped to a long-wave determined by Δm^2_{12}. It follows that the distance between source and detector is crucial for the measurement of the mass square difference that we want to investigate.

A further peculiarity of the full three generation case is the possibility to observe CP violations with neutrino oscillations (see the dedicated box for a brief explanation of the CP symmetry). This opens the door to the study of CP violations in the *leptonic sector*, that is in interactions involving only leptons and neutrinos. Notice that the substitution of a neutrino with its own antineutrino is in practice a CP transformation (and not merely C). Indeed, neutrinos are *chiral* particles, namely the orientation of the

Discrete symmetries and CP violations

Often symmetries are studied in physics, namely the property of natural phenomena to be invariant under certain kinds of transformations. An example are the *discrete* transformations. The most famous is the *parity* transformation, i.e., the reflection of the spatial coordinates (like in the "mirror world" in the novel *Alice's Adventures in Wonderland* written by Lewis Carrol). It is well known that electromagnetism, gravity, and nuclear strong interactions are invariant under parity (or under P operator), while weak interactions are not. This was shown for the first time in 1957 in a renowned experiment performed by madame Wu. In this experiment it was shown that in the nuclear decay ^{60}Co$\rightarrow$^{60}Ni$+e^- + \bar{\nu}_e$ the electron is emitted preferably in the opposite direction of the nuclear spin. This explicitly violates parity since under P the electron momentum does reverse the sign while the spin does not, and thus the electron would be emitted preferably in the direction of spin. In the novel, Alice could distinguish the real world from the mirror one by observing weak decays.
Furthermore, in particle physics there is a second kind of symmetry called *charge conjugation* or C in which particles are replaced with their antiparticles. Again, electromagnetic, gravitational and strong interactions are invariant under C but there are weak interactions that violate C, namely the process is different if we replace all the particles with their antiparticles.
For long time it was believed that the combination CP (namely with a simultaneous replacement of particles with antiparticles and inversion of the spatial coordinates) is an exact symmetry. For example, if in the experiment of madame Wu we ideally replace ^{60}Co nuclei with their anti-nuclei the positron will be emitted in the direction of nuclear spin, as required by P symmetry. An "anti- Alice" in the mirror world would not be able to distinguish the anti-mirror world from the real merely observing the nuclear decays. However, also this conjecture turned out to be false. Indeed, certain meson decays violate CP (for example the decay $K^0_L \rightarrow \pi^- e^+ \nu_e$ is slightly preferred respect to the decay $K^0_L \rightarrow \pi^+ e^- \bar{\nu}_e$, where K^0_L is a CP invariant combination of K^0 and $\bar{K}^0$; If CP were an exact symmetry the channels would be equivalent). This implies that CP is violated at least in the *adronic sector* (that is, when quarks are involved in the process). CP violations can have a significant role in the matter-antimatter asymmetry in the Universe.

spin is essentially opposite to the momentum (we say that they are *left-handed*) while for antineutrinos the spin is essentially aligned with the momentum (*right handed*). This means that $P_{\nu_\alpha \rightarrow \nu_\beta} \neq P_{\bar{\nu}_\alpha \rightarrow \bar{\nu}_\beta}$ (with $\alpha \neq \beta$) is a signal of CP violation. In practice, the oscillation probability for antineutrinos is similar to those for neutrinos but with substituting **U** whit its conjugate. Clearly, with only two generations the mixing matrix is real and no CP violations are allowed. With three generations we have in general CP violations (except the case $\delta = 0, \pi$) and this is equivalent to revert the sign of the phase δ in the 3ν oscillation probability formula. At the moment the value of δ is still uncertain (see below). The measure of δ and the search for CP violations in the leptonic sector will be one of the next goals of the neutrino physics.

It is worthwhile to remark that there is a further symmetry transformation named *time inversion* or T in which the temporal evolution of a system is reversed. A general theorem states that CPT must be an exact symmetry for all forces of nature (except, perhaps, for gravity). Therefore T violations are expected as a consequence of CP violations. This means that in general we can expect also that $P_{\nu_\alpha \rightarrow \nu_\beta} \neq P_{\nu_\beta \rightarrow \nu_\alpha}$, while always we must have$P_{\nu_\alpha \rightarrow \nu_\beta} = P_{\bar{\nu}_\beta \rightarrow \bar{\nu}_\alpha}$.

Neutrino oscillations in matter

Oscillation probability can be modified if neutrinos cross ordinary matter. Indeed, a neutrino during its evolution can always be decomposed in its flavor components. In ordinary matter the ν_e component has a different coupling with electrons of the medium with respect to the other components. Neutrinos with all flavors can interact with electrons and quarks in the medium by means of the exchange of a virtual Z^0 boson (*neutral current interaction*), while electron neutrinos can also interact with electrons through the exchange of a virtual W boson (*charge current interaction*) like in Fig. 4.

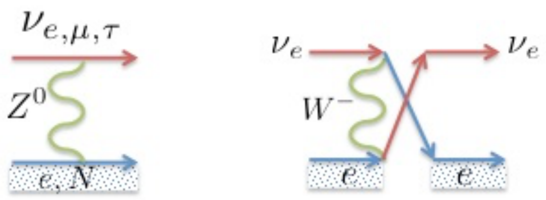

Figure 4: *Neutrino interactions in matter*

The first diagram gives an equal contribution for all flavors and thus can be neglected. The second diagram yields an additional "effective" square mass to the electron component given by

$$A = \pm 2\sqrt{2}(\hbar c)^3 G_F N_e E \quad (9)$$

where G_F is the Fermi constant and N_e is the electron density of matter and the sign $+$ $(-)$ for neutrinos (antineutrinos) holds. As a consequence the evolution equation for the flavor is modified (see the box). This is known as *Mikheyev–Smirnov–Wolfenstein* (MSW) effect [2, 3]. If neutrinos cross a slide of matter with constant density the oscillation probability can be rewritten as

$$P^M_{\nu_e \to \nu_e} = 1 - \sin^2 2\theta^M \sin^2\left(\frac{4\pi L}{\lambda^M_\nu}\right), \quad (10)$$

where θ^M and λ^M_ν are respectively the "effective" mixing angle and the oscillation wavelength in matter

$$\sin 2\theta^M = \frac{\sin 2\theta}{\sqrt{(A/\Delta m^2 - c_{2\theta})^2 + s^2_{2\theta}}}, \quad (11)$$

$$\lambda^M_\nu = \frac{\lambda_\nu}{\sqrt{(A/\Delta m^2 - c_{2\theta})^2 + s^2_{2\theta}}}. \quad (12)$$

From previous equations we see that when the condition $A = \Delta m^2 \cos 2\theta$ is fulfilled we can have an effective maximal mixing in matter ($\theta^M = \pi/4$) and thus a strong amplification of the oscillations, also for small θ. This phenomenon is known as *resonance*. In general, neutrinos cross slabs of matter with varying density (as in the case of solar neutrinos) and pass through the resonant layer. This can result in an amplification of the oscillation probability. We will not go into details of this technical topic.

It could be surprising that matter effects are important on oscillations while the scattering cross section for neutrinos is so small (light years in lead). However, this happens because the matter effect is *coherent*. Although the interaction amplitude for each electron is small, the effect adds up in each interaction. This effect is similar to photons crossing a birefringent crystal in which the index of refraction depends on the direction. Despite the transparency of the crystal the polarization plane is rotated.

Evidences of neutrino oscillation

Solar neutrinos

Sun is an intense source of electron neutrinos (about $6 \times 10^{10}/\text{cm}^2$ per second on the Earth!) because of the fusion nuclear reactions in its interior. In Fig. 5 the main nuclear reactions in the Sun are outlined. In particular, some reactions produce neutrinos with energy ranging from a fraction of MeV to 15 MeV. The first pioneering experiment aimed at detecting solar neutrinos was done by R. Davis in the Homestake mine in the 60's of the previous century. This experiment made use of the reaction $\nu_e + ^{37}\text{Cl} \to e^- + ^{37}\text{Ar}$ (for an historical review see the book by J. Bahcall [4]). It was clear that the observed neutrino flux was about 1/3 of that expected by solar models. Davis wondered if the oscillation mechanism described previously could explain this anomaly (we remark that solar neutrinos have typical energies of few MeV's, not enough to create μ or τ; this means that we can observe only a disappearance of the initial ν_e's but not the appearance of other flavors). However, this result was initially accepted with skepticism due the intrinsic difficulties of the experiment and the uncertainties in the solar models. This skepticism was overcame by new experimental results coming from the experiments Kamiokande in the 80's, and SuperKamiokande, GALLEX/GNO and SAGE in the 90's. In 2002 R. Davies earned the Nobel Prize

MSW equation

When neutrinos cross matter, the evolution equation is modified. In a simplified 2ν system the evolution equation becomes

$$i\frac{\partial}{\partial x}\begin{pmatrix}\nu_e\\ \nu_a\end{pmatrix}=\frac{1}{2\hbar cE}\left[\frac{\Delta m^2}{2}\begin{pmatrix}-\cos 2\theta & \sin 2\theta\\ \sin 2\theta & \cos 2\theta\end{pmatrix}+\begin{pmatrix}A(x) & 0\\ 0 & 0\end{pmatrix}\right]\begin{pmatrix}\nu_e\\ \nu_a\end{pmatrix},$$

where ν_a can be the ν_μ or ν_τ or a combination of the two and A is given by Eq. (9).
The matrix in the second member can be diagonalized through a unitary matrix $\mathbf{U}(\theta^M)$, with θ^M given by Eq. (11). States defined by the rotation $\boldsymbol{\nu}^M = \mathbf{U}^\dagger(\theta^M)\cdot\boldsymbol{\nu}^f$, where $\boldsymbol{\nu}^f$ are the flavor eigenstates, are the instantaneous eigenstates of matter mass (whose masses are the eigenvalues of the matrix in the second member of the MSW equation). Under certain conditions the instantaneous eigenstates propagate almost unchanged (namely, the conversion probability $P(\nu_i^M \to \nu_j^M)$ is very small). In this case the propagation is called *adiabatic*. For adiabatic evolution it can be shown that for an initial ν_e produced in matter at high density (as in the case of solar neutrinos) and observed in vacuum, the survival probability is given with good approximation by

$$P_{\nu_e\to\nu_e}\simeq\frac{1}{2}\left(1+\cos\theta\cos\theta_0^M\right),$$

where θ_0^M is the mixing angle at the production point. If neutrinos cross the resonance slab, this probability can be modified.

Cěrenkov Effect

Sometimes a charged particle moves in a medium faster than the light in the same medium ($v > c/n$ where n is the refraction index in the medium). In that case the particle loses energy by emission of a light cone (usually blue or UV) analogue to the shock wave behind a supersonic jet. This is known as *Cěrenkov* effect.

for the discovery of the solar neutrino anomaly.

The Kamiokande experiment, located in the Kamioka mine in Japan, started operations in 1982. It was a big tank of water containing 3000 tons of ultra-purified water surrounded by about 1000 photomultipliers. Neutrinos from Sun sometimes hits electrons in water. Since the scattered electrons are faster than light in water they emit light through the Cěrenkov effect (see the box). The Cěrenkov light is detected by photomultipliers and in principle it is possible to gain information on the neutrino energy and the direction of the incident neutrino. In principle, neutrinos with all flavors can scatter electrons but the ν_e has a cross section ~ 6 times greater than ν_μ, ν_τ. For this reason, if a conversion mechanism is working we expect a decrease in the scattering rate. The Kamiokande experiment was superseded by SuperKamiokande [5] which started operation in 1998. This experiment is similar to the previous but contains 50000 tons of water and is surrounded by 11000 photomultipliers in order to increase the sensitivity of the apparatus of a factor ~ 10.

GALLEX/GNO and SAGE are two (now terminated) experiments, the first located in the Gran Sasso National Laboratory (LNGS) in Italy and the second in the Baksan mine in the Caucasus. In these experiments the radiochemical technique used by Davis was used for a different nuclide, the ^{71}Ga: $\nu_e + ^{71}\text{Ga} \to e^- + ^{71}\text{Ge}$. The advantage of this nuclide is a higher cross section and a lower detection energy threshold.

The result of all these experiments was that the solar neutrino flux observed was lower than expected (although a different suppression was observed in different experiments) and this fact was hard to be explained with the uncertainties in the solar models. At this point, although an

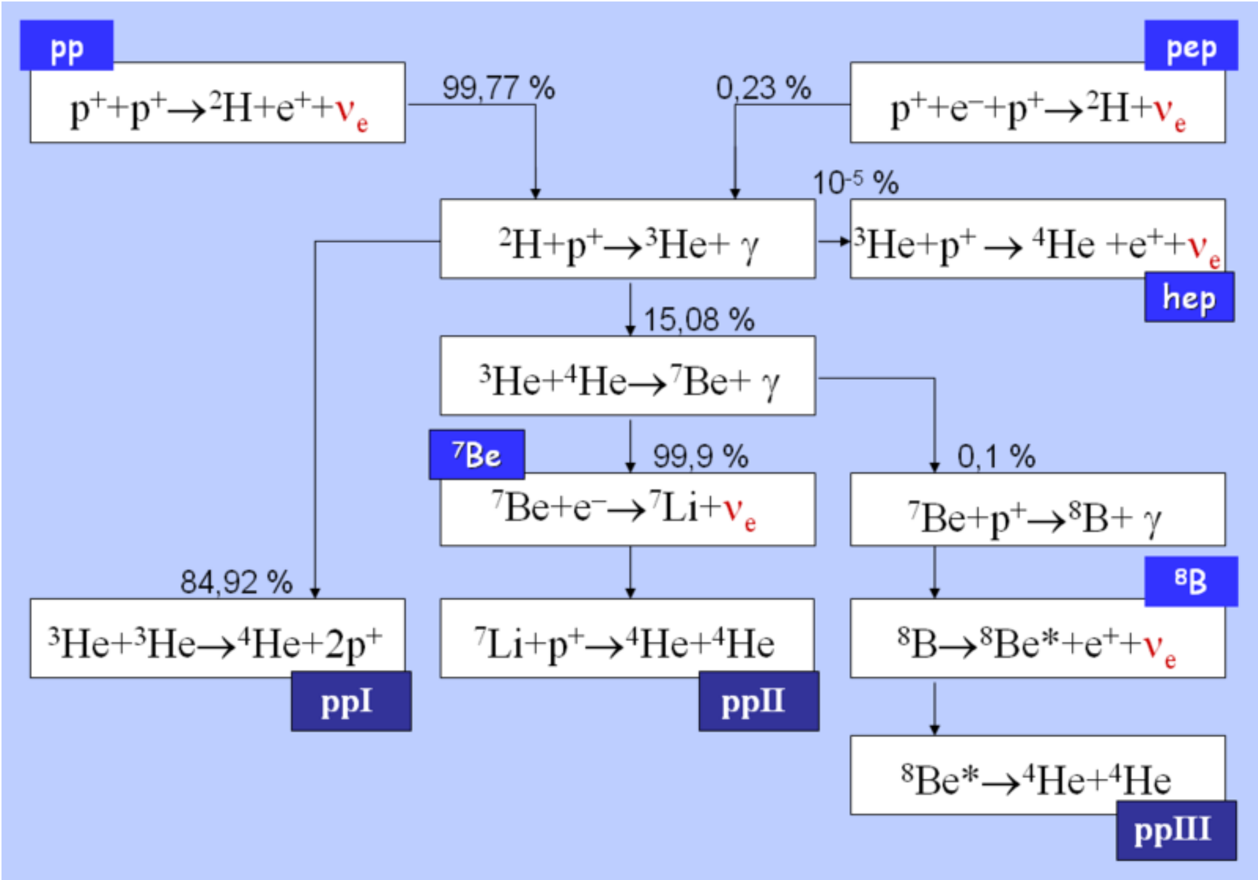

Figure 5: *Nuclear reaction in the Sun*

"astrophysical" solution to the problem related to possible unknown flaws in the solar models were in principle always possible, the oscillatory solution became more and more plausible. The differences in the flux observed in the various experiments could be explained for example with the energy dependence of the oscillation probability, since the experiments cover different energy ranges.

To untie this knot a new experiment was proposed: The Subdury Neutrino Observatory (SNO) [6]. This experiment (now ended) located in the Subdury mine in Canada, was conceivably similar to Kamiokande and SuperKamiokande but with a substantial difference: it used 1000 Tons of heavy water which consists of D_2O molecules in which hydrogen atoms are replaced with deuterium atoms (D$\equiv^2$H in which the nucleus contains a proton and a neutron). This allows two other kinds of reaction (besides the electron scattering) named *charge current* (CC) and *neutral current* (NC)

$$\begin{aligned} \nu_e + {}^2\mathrm{H} &\rightarrow p + p + e^- \quad (\mathrm{CC}) \\ \nu_x + {}^2\mathrm{H} &\rightarrow p + n + \nu_x \quad (\mathrm{NC})\,. \end{aligned}$$

Naïvely, in the first case an electron neutrino transforms a neutron into a proton and an electron that can be detected by the Cĕrenkov technique. In the second case neutrinos of all flavors just break the nucleus in a proton and a neutron. In this case the neutron can be absorbed by a nucleus releasing gamma rays that can be easily detected. The first reaction measures the flux of the electron neutrino component coming from the Sun. The second reaction has the same cross section for all flavors, thus measures the total solar neutrino flux.

The result was that the total neutrino flux coming from the Sun is perfectly consistent to that expected from the Bahcall Standard Solar Model (SSM) while the ν_e component is consistent with the $1/3$ suppression observed in other experiments. This was the first direct proof that a con-

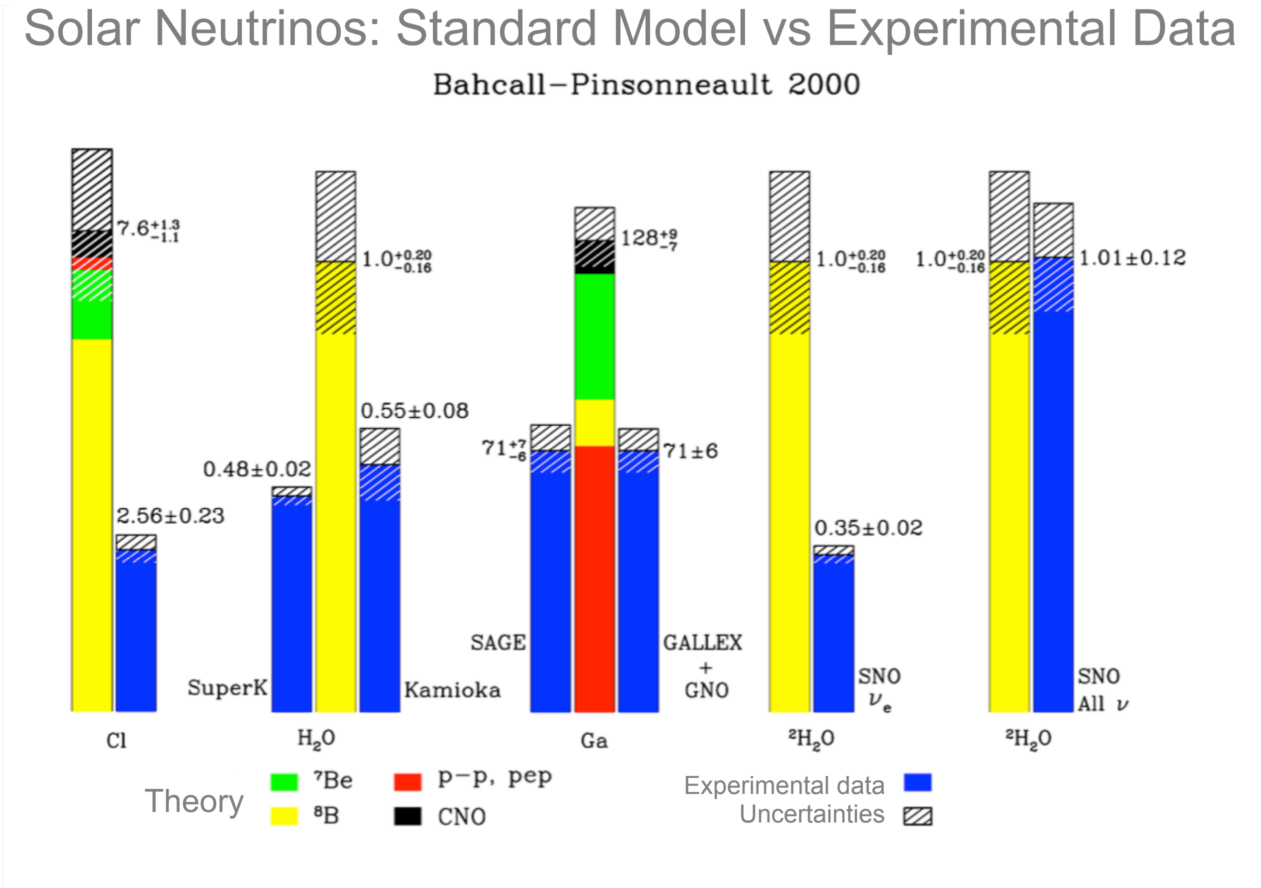

Figure 6: *Flux of neutrinos expected for each experiment with the contribution of the different sources compared with experimental results (in blue). Theoretical and experimental uncertainties are also shown*

version process $\nu_e \to \nu_a$ is working in the Sun. For this result the Chairman of the SNO experiment, Art McDonald gained the Nobel prize in 2015.

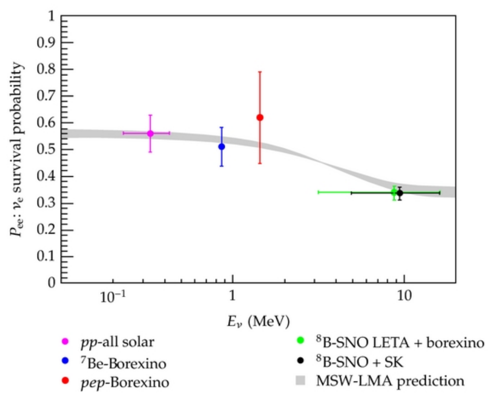

Figure 7: *$P_{\nu_e \to \nu_e}$ as function of the energy for solar neutrinos observed on the Earth*

A further confirmation that this conversion process is due to oscillations has come recently from the Borexino experiment [7]. This detector, located in the Gran Sasso laboratory is similar to Kamiokande but uses liquid scintillator (a substance which emits a flash of light when is crossed by a charged particle) instead of water. This allows to lower the threshold (scattered electrons do not need to be faster than light in the medium) and to detect neutrinos of low energy, namely "^{7}Be" e "pp" (see Fig. 5). The probability $P_{\nu_e \to \nu_e}$ can be reconstructed from low to high energies and confronted with the theoretical calculations. The result is in Fig. 7. In grey the oscillation probability calculated with the adiabatic formula is compared with the experimental results. Notice that in this case we do not observe the typical oscillatory behavior expected in Eq. (10) because the fast oscillations are "mediated away" by the integration on the production zone of neutrinos and on the finite energy resolution of the experiments. This was the ultimate spectacular confirmation of solar neutrino oscillations.

The KamLand Experiment

Despite the extraordinary evidence of solar neutrino oscillations, a "terrestrial" experiment under controlled conditions was in order. Indeed, although SNO confirmed the existence of a $\nu_e \rightarrow \nu_{\mu,\tau}$ conversion mechanism in the Sun, some alternative explanations were still possible (for example exotic flavor changing interactions in matter). Moreover, despite the extraordinary outcome of the Standard Solar Model, uncertainties on some astrophysical parameters (initial chemical composition, some nuclear cross sections, etc.) in the model reflect in uncertainties on the initial neutrino fluxes and thus on the measure of the oscillation parameters. A stand-alone experiment in combination with the results of solar neutrino detector would greatly improve the knowledge of the oscillation parameters.

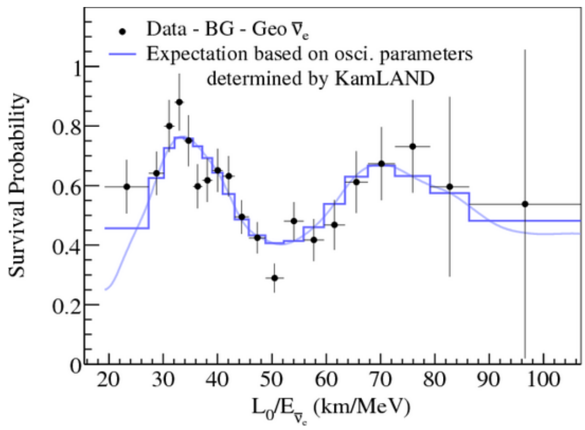

Figure 8: *Oscillation probability in KamLand*

To this purpose the KamLand detector was build in the Kamioka mine in Japan [8]. This experiment, similar to Borexino, was designed to observe the antineutrinos produced in the nuclear reactor of the Japan (which is the country with the higher number of running nuclear plants). Electron antineutrinos are detected through the inverse-β reaction $\bar{\nu}_e + p \rightarrow e^+ + n$. The detection in coincidence of a "prompt" positron and a "delayed" neutron is a reliable signal of the detection of a $\bar{\nu}_e$, helping to reject the background (this technique is the same used by Cowan and Reines in their first experiment of neutrino detection).

Also in this case we had a spectacular confirmation of the oscillation mechanism. In Fig. 8 the survival probability (actually, the ratio measured/expected number of events) is shown as function of L_0/E (notice that according to Eq. (7) the oscillation probability depends on L/E) where L_0 is the average distance of reactors from detector (of the order of some hundreds of kilometers). From this figure we easily recognize the typical oscillatory pattern expected from Eq. (7) (notice that in this case matter effects are negligible).

> **Neutrinos from nuclear reactors**
>
> Nuclear reactors are an intense source of $\bar{\nu}_e$. Indeed, after each fission radionuclides with a neutron excess are created. These nuclides decay more or less quickly through the β process producing antineutrinos. On average, we have $6\bar{\nu}_e$ and a yield of ~300 MeV per fission. This allows to calculate the flux of antineutrinos for a nuclear plant: $1.9 \times 10^{20} P_{\rm GW} \bar{\nu}_e/{\rm s}$, where $P_{\rm GW}$ is the thermal power of the plant in GigaWatt.

Combined analysis of KamLand + solar neutrinos

At this point we need to invert the experimental data to obtain the neutrino oscillation parameters (mass square differences, mixings). This can be done only by sophisticated statistical techniques. In principle, solar neutrinos are sensitive to all oscillation parameters except for the mixing angle θ_{23} and the phase δ. However, in the hypothesis of hierarchy ($|\Delta m^2_{13}| \gg \Delta m^2_{12}$) solar neutrinos have a very little dependence on the higher mass scale Δm^2_{13}. Since, as we will see, θ_{13} is small ν_e is nearly a combination of the states ν_1 and ν_2 (see the figure 1). In this situation, neutrino oscillations mainly depend on Δm^2_{12} and θ_{12} with only a tiny dependence on θ_{13}. In a sense, solar and KamLand neutrinos are sensitive to the "long waves" in Fig. 3.

The result of the analysis are "compatibility zones" at a certain confidence level (i.e., the probability that the true parameters lie in that area) in the parameter space. One example can be seen in Fig. 9 taken from [9] in the hypothesis $\theta_{13} = 0$. In particular we notice that $\Delta m^2_{12} \sim 7 \times 10^{-5}$ eV^2. We will come back later on the global analysis of all parameters.

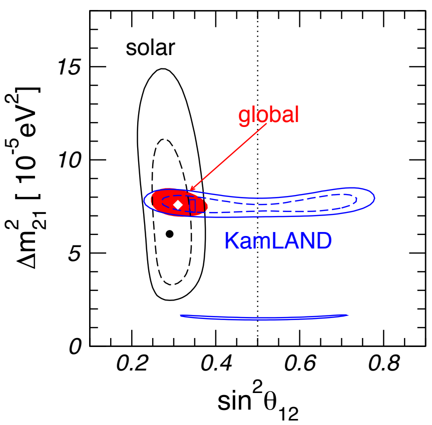

Figure 9: *Parameter area in the plane ($\Delta m^2_{12} - \theta_{12}$) allowed by the analysis of solar neutrino data and KamLand [9]. Dashed (solid): 90% (99.73%) Confidence Level. Colored area: combined analysis at 99.73% CL*

Atmospheric neutrinos

Earth atmosphere is itself a source of neutrinos due to high-energy cosmic-ray interactions with atoms. When a primary cosmic ray hits a nucleus in the stratosphere it can start a shower of secondary particles that are generally unstable. The majority of them are both positive and negative pions which mostly decay as in Eq. (1). Muons in turn decay as in Eq. (4). Consequently, two muon (anti)neutrinos are produced for each electron (anti)neutrino, whilst tau (anti)neutrinos are very rare. Atmospheric neutrino energies range from $\sim$ 100 MeV to PeV.

Several experiments have been devoted to the study of atmospheric neutrinos although the most important is Superkamiokande. Unlike solar neutrinos, muon neutrinos can in general be identified because the reaction $\nu_\mu + N \to \mu + N'$ (where N and N' are nuclei) is possible for neutrinos with energy $E \simeq 100$ MeV. Muons are relatively long lived and leave a clear Cěrenkov track in water. Although for $E \geq 1800$ MeV the reaction $\nu_\tau + N \to \tau + N'$ is also possible, the identification of ν_τ's is very challenging because of the very short life of the τ. Tau particle quickly decay into a shower of particles and are easily confused with the background.

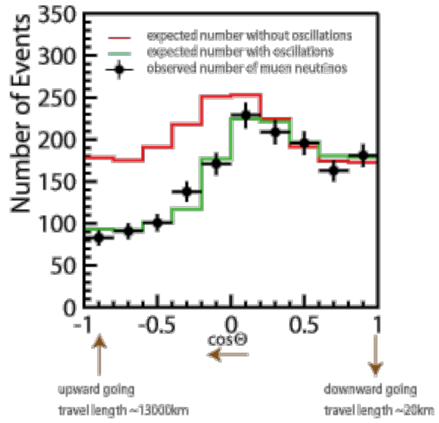

Figure 10: *Angular dependence of the muonic neutrino flux observed in SuperKamiokande. In red: Expected number of events in absence of oscillations; In black: Experimental data; In green: Expected number of events with oscillations*

Also in this case an anomaly arose. While the flux of electron neutrinos coming from all directions was consistent with that expected from the models, muon neutrinos were partly missing and the "disappearance" depended on the direction of sight. In Fig. 10 the muon neutrino flux as function of the zenith angle Θ is shown, being $\cos\Theta = 1$ the zenith direction (neutrinos coming from above) and $\cos\Theta = -1$ the nadir direction (neutrinos coming from below). We observe that for $\cos\Theta = 1$ the flux is almost consistent with the expected one but the flux decreases with decreasing $\cos\Theta$. This is a clear indication that the disappearance is a function of the travelled distance since downward going neutrinos are produced at few tens of kilometers from the detector while upward neutrinos have crossed all the Earth ($\sim$ 13000 Km) before detection. Again this could be a signal of oscillations. In this case we expect $\nu_\mu \to \nu_\tau$ conversion since there is not a clear appearance in the ν_e channel and tau neutrinos are very difficult to detect. An analysis performed by SuperKamiokande showed an oscillatory pattern similar to those expected in KamLand but with a different energy scale. For this discovery, the Chairman of SuperKamiokande, Takaaki Kajita, gained the Nobel Prize in 2015.

In order to have an independent confirmation of the oscillation mechanism under controlled conditions several "long baseline" experiments have been performed, in particular K2K [10] (terminated) and T2K [11] in Japan, MINOS [12] in

US and OPERA [13] in Italy. In these experiments a beam of muon neutrinos is "shot" toward a detector placed at few hundreds of Kilometers. In T2K and K2K the detector was SuperKamiokande, while in the first case the beam was sent from the J-PARC facility (250 Km far away from SK) and the second is sent from the KEK facility in Tsukuba (295 Km far away). In MINOS the detector is built in the Soudan mine while the beam is sent from Fermilab, 743 Km away.

The OPERA experiment, built in the Gran Sasso Laboratory, deserves a special mention. In this case the beam is delivered from CERN on a baseline of 730 Km. This experiment has been designed for the detection of the tau neutrinos. The detection makes use of a sophisticated technique in which the tracks left on a photographic emulsion are analyzed by an automatic equipment in order to distinguish signals of tau production (and decay) from other backgrounds. Till now in the experiment five ν_τ have been identified in the beam coming from CERN, more or less those expected in five years of data taking with the hypothesis of neutrino oscillations.

We do not intend here to discuss the details of the experiments described above. We just mention that all these experiments have confirmed neutrino oscillations as the right explanation of the atmospheric neutrino anomaly. These oscillations are different from those of solar neutrinos, not only because they involve $\nu_\mu \leftrightarrow \nu_\tau$ but also because they are sensitive to the largest mass square difference (Δm^2_{13}) and to the angle θ_{23}. A marginal sensitivity to the angle θ_{13} is still possible because a small evidence of oscillations of $\nu_\mu \to \nu_e$ both for atmospheric neutrinos and in MINOS and T2K was found. We come back in the next section to the measure of θ_{13}. Assuming for now $\theta_{13} = 0$, we can obtain compatibility zones similar to those obtained for solar neutrinos, but in the plane ($\Delta m^2_{13} - \theta_{23}$). In Fig. 11 an example taken from [9] is shown (but only MINOS is included in the analysis). We notice that Δm^2_{31} is of the order of 2×10^{-3} eV^2, that is a factor ~ 30 times greater than Δm^2_{12}, in agreement with the hierarchical hypothesis.

We stress also that in the unfortunate case that the lightest neutrino were massless, the mass of the heaviest would be $\sqrt{\Delta m^2_{31}} \sim 5 \times 10^{-2}$ eV.

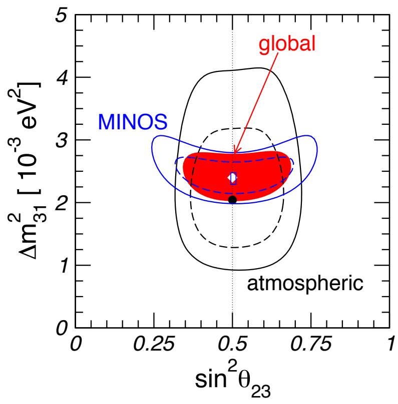

Figure 11: *Parameter area in the plane $\Delta m^2_{13} - \theta_{23}$ allowed by the analysis of atmospheric neutrino data and MINOS [9]. Dashed (solid): 90% (99.73%) Confidence Level. Colored area: combined analysis at 99.73% CL*

This can explain why direct searches of neutrino masses have been unsuccessful. The sensitivity of the present experiments (and apart from cosmology), of the next future experiments does not suffice to prove such a small mass. We hope we are not in this unlucky situation.

The measure of θ_{13}

Let us come back to Fig. 3. As we already noticed $P_{\nu_e \to \nu_e}$ has the structure of a "long wave" with a superimposed "short wave". The amplitude of the short wave is proportional to $\cos^4\theta_{13}\sin^2 2\theta_{12}$. Since, as we will see, the angle θ_{13} is small, the contribution of $\cos^4\theta_{13}$ is very small. The amplitude of short waves conversely is proportional to $\sin^2 2\theta_{13}$. KamLand experiment is essentially insensitive to short waves (due to energy resolution) and thus has a very small sensitivity to θ_{13}. In order to measure this parameter we need to shorten the distance from the source ($\sim$ Km) or increase the energy ($\sim$ GeV).

For reactor experiments only the first option is feasible. To this purpose three "short baseline" reactor experiments have been built, that is Daya Bay [14] in China, RENO [15] in South Korea and Double Chooz [16] in France. All these detectors (similar to KamLand) have confirmed the existence of short baseline oscillations, yielding a measure of θ_{13}. Moreover, we have already mentioned that also the high-energy long-baseline experiments can measure θ_{13} since both experiments have seen an excess of ν_e in the ν_μ beam with respect to those expected by the background, signal of $\nu_\mu \to \nu_e$ oscillations. The last measure is important because for long baseline experiments there is a sort of "degeneracy" between θ_{13} and the phase δ. A simultaneous measure of θ_{13} from the reactor and long baseline experiments can shed light on the phase δ.

In Fig. 12 the survival probability $P_{\nu_e \to \nu_e}$ (taken from [17]) in Daya Bay is shown. Also in this case the evidence of the oscillatory pattern is incontrovertible. A similar figure has been shown by the RENO experiment. In Fig. 13, taken from [18], the allowed zone in the parameter space $\theta_{13} - \delta$ are shown. We see that the combined analysis starts to constrain (at list at 2σ) the value of δ.

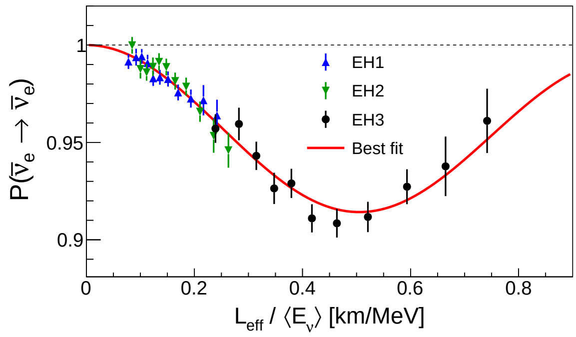

Figure 12: *Evidence of oscillations in Daya Bay [17]*

Combined analysis

In the box the present state-of-the-art oscillation parameters are shown [18] with the best fit value of each parameter and the range at three standard deviations. It is interesting to notice that, apart from δ, all the parameters are known with a precision of a few percent. This is an outstanding result for a sector that was considered pioneering less than twenty years ago and now has entered an era of precision measurements!

Sterile neutrinos?

Neutrino seems to deserve further surprises. There are several controversial measures that cannot be framed in the present oscillation scheme. In fact, there are two experiments that show an evidence of $\nu_\mu \to \nu_e$ but with a mass square scale difference which is not compatible with the values of the parameters shown in the table. They are LSND (terminated) and MiniBooNE [19]. Such anomaly is controversial because it involves the lower part of the energy spectrum (about 100 MeV) where the neutrino-nucleus cross section is poorly known (see Fig. 14).

More recently new calculations of neutrino fluxes from reactors would suggest a $\sim$3% "disappearance" of $\bar{\nu}_e$'s [20] in all reactor experiments (also in those where the distance between the reactor and the detector is very small and cannot be justified by θ_{13}-driven oscillations). Also in this case in principle there could be flaws in the calculations due to unknown effects in nuclear physics.

If we accept the oscillatory explanation we need of a new shorter scale of oscillation with respect to those shown in Fig. 3. This implies a value of Δm^2 of the order of a fraction of eV^2. Moreover, we need to introduce a new exotic state because, as we already said, there are only three light standard neutrinos. This new particle should not have the typical interactions expected in the Standard Model, in particular must not be coupled with Z^0 to evade the LEP measure. For this reason this neutrino is named *sterile*.

However, this hypothesis has several problems. For example there is an incompatibility between the results of LSND/MiniBooNE and the reactor anomaly (see Fig. 15 taken from [21]). A second sterile neutrino would be needful to accomodate all anomalies. We remark, however, that the mixing with sterile states must be small and this explains why the oscillations into sterile is not observed in solar and atmospheric neutrinos. However MINOS is able to measure the total neutrino flux through neutral current interactions.

Review of the oscillation parameters [18]

Parameter	Best fit	3σ range
$\Delta m^2_{12}/10^{-5}$ eV^2	7.54	6.99 – 8.18
$\sin^2\theta_{12}/10^{-1}$	3.08	2.59 – 3.59
$\Delta m^2_{13}/10^{-3}$ eV^2 (NH)	2.43	2.23 – 2.61
$\Delta m^2_{13}/10^{-3}$ eV^2 (IH)	2.38	2.19 – 2.56
$\sin^2\theta_{13}/10^{-2}$ (NH)	2.34	1.76 – 2.95
$\sin^2\theta_{13}/10^{-2}$ (IH)	2.40	1.78 – 2.98
$\sin^2\theta_{23}/10^{-1}$ (NH)	4.37	3.74 – 6.26
$\sin^2\theta_{23}/10^{-1}$ (IH)	4.55	3.80 – 6.41
δ/π (NH)	1.39	—
δ/π (IH)	1.31	—

Note: NH (IH) = Normal (Inverted) hierarchy

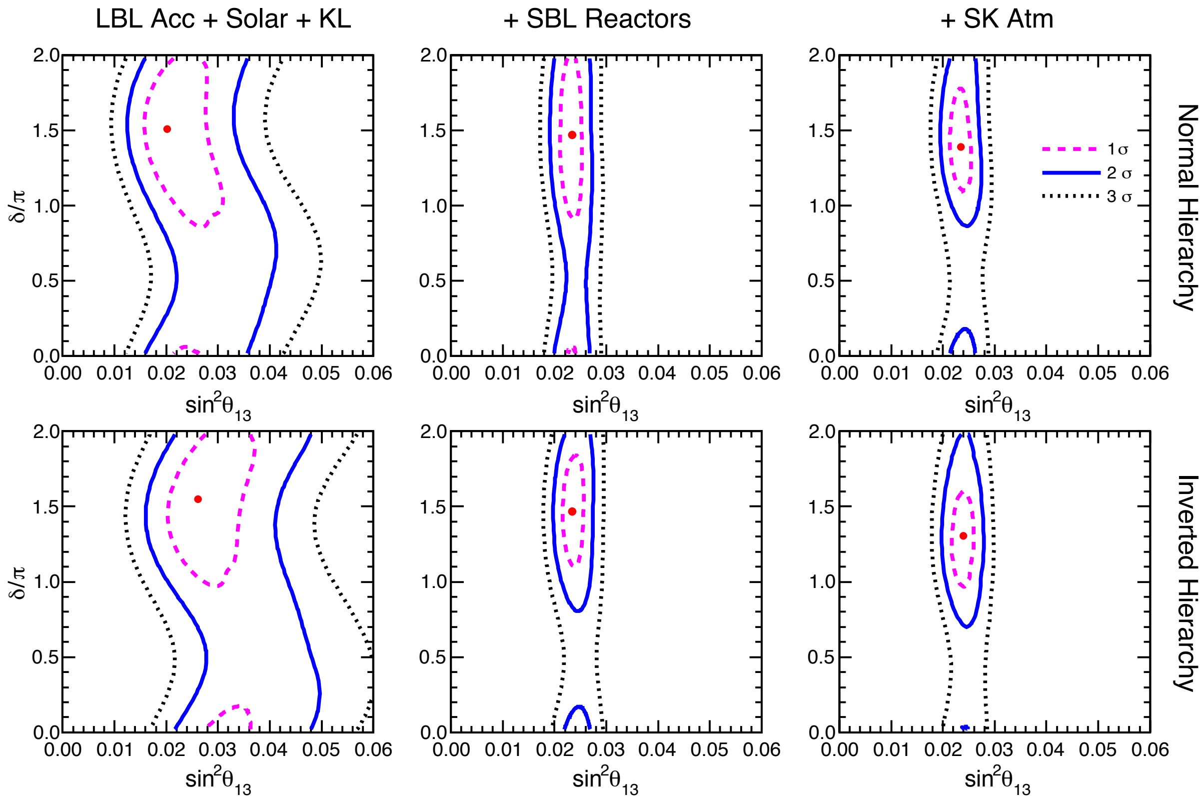

Figure 13: *Allowed zones in the plane $\theta_{13} - \delta$ [18]*

Oscillations into sterile neutrinos would result in disappearance of the total flux in MINOS. This disappearance has not been observed. Moreover a high value of Δm^2 is in clash with cosmological limits on neutrino masses. This makes this model extremely controversial. It is questionable whether sterile neutrinos are a sort of "medieval epicycles" and the true explanation should be sought elsewhere.

To solve this mystery, several experiments have been proposed. Among the others, we mention SOX [22] and ICARUS/NESSie [23]. In the first experiment an intense radioactive source of neutrinos will be placed close the Borexino experiment. In the second, under construction at CERN, a neutrino beam with energy ~GeV is sent to a liquid argon detector (similar to ICARUS experiment at Gran Sasso) at a distance of about 1 Km. Both experiments will be able to cover the parameter zone required to explain reactor and LSND/MiniBooNE anomalies and decide for or against sterile neutrinos.

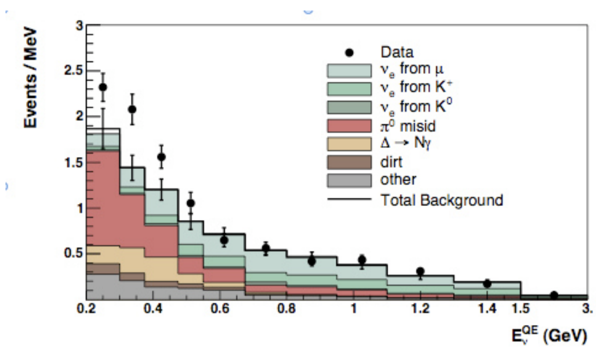

Figure 14: *The MiniBooNE anomaly: see the discrepancy between experimental data and the expected flux in the low energy bins*

The future

Besides sterile neutrinos, one of the next goals of neutrino oscillation physics will be to establish the true neutrino hierarchy. In fact, the knowledge of the hierarchy is crucial for the direct mass measurements. If the mass hierarchy is inverted next generation experiments of neutri-

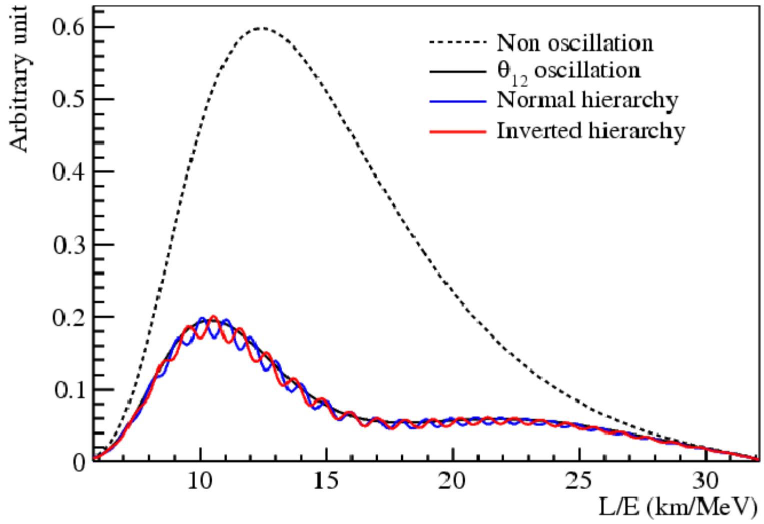

Figure 16: *Neutrino spectrum expected for JUNO*

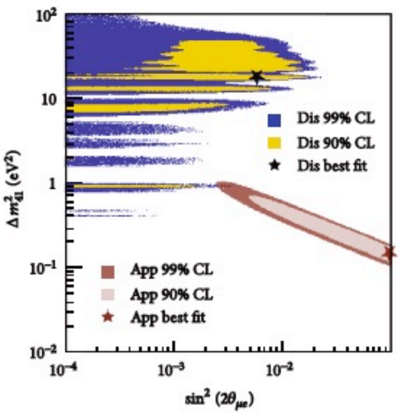

Figure 15: *Allowed zones in a "3+1" scheme for the evidences of LSND/MiniBooNE (in brown) and the reactor anomaly (in yellow/blu) [21]*

noless double-β decay must be able to confirm or disprove the Majorana nature of neutrinos. On the contrary, in the unlucky scenario of normal hierarchy and very light $\nu_{1,2}$ states it could be impossible with present and next generation experiments to decide on the nature of neutrino.

Unfortunately the measurementof the mass hierarchy is extremely difficult because we need to measure both oscillation scales with a single experiment. For example we can build a detector with an intermediate distance between short baseline and KamLand experiments (of the order of $\sim$ 100 Km). One proposal in this direction is the JUNO experiment [24], under construction in China with a detector at a distance of 70 Km from the Taishan Nuclear Power Plant. In order to understand the difficulty of this experiment in Fig. 16 the expected spectrum in the case of normal and inverted hierarchy is shown. The experiment must be able to distinguish between the two spectra with high precision!

An alternative proposal is the PINGU experiment [25]. In this case a deep portion of the IceCUBE experiment, a detector built at South Pole for the detection of neutrinos with very high energy ($\geq 10^{15}$ GeV), will be optimized for the observation of neutrinos with lower energy, in particular atmospheric neutrinos. In this case the MSW effect would amplify the effect of the differences of conversion probability for different hierarchies.

The next step will be the measurement of the phase δ. In the next future the NOvA experiment [26] experiment, intended as the successor of MINOS, will work both with muon neutrino and antineutrino beams, searching for $\nu_\mu \to \nu_e$ and $\bar{\nu}_\mu \to \bar{\nu}_e$ conversions. From the difference of the conversion probabilities it will be possible to extract the phase δ and to measure the other parameters (mainly θ_{13}) with higher precision.

Conclusions

Until little more than twenty years ago the idea that neutrinos are massive particles was accepted with a lot of skepticism. Nevertheless in few years that weird idea has become a precision science. Now we recognize that neutrinos are massive and we have measured the majority of parameters with great accuracy. At the same time we have solved a big astrophysical puzzle, the solar neutrino problem.

We stress that the measurement of neutrino masses and mixings is not just a theoretical curiosity. Indeed, the fact that neutrino mass is so small is a puzzle in the framework of Standard Model (at least in its non-minimal extensions). Neutrino masses could be generated through a sort of *see-saw* mechanism in some extensions of the Standard Model in which neutrinos are coupled with very heavy states. We refer to Eligio Lisi's article for the explanation of this mechanism. These models are in general predictive on the neutrino parameters. The measurement of the small neutrino masses paradoxically could open the door on very high energy scales, well beyond the reach of current accelerator experiments.

In this brief review I have not mentioned many other applications of neutrino oscillations, ranging from supernova neutrinos (in which the neutrino density is so high that non linear "self interaction" effects appear) or during Big Bang, or the role of oscillations in very high energy neutrinos, or on neutrinos produced in the Earth (the *geoneutrinos*), recently observed by KamLand and Borexino, that can shed light on the production mechanism of heat inside our planet.

In spite of these successes, some anomalies could open new perspectives (such as new sterile states). Fermi's aphorism mentioned at the beginning of this paper is still a reminder for scientists. Let us wait and see!

[1] G. Danby, J. M. Gaillard, K. A. Goulianos, L. M. Lederman, N. B. Mistry, M. Schwartz and J. Steinberger: "Observation of High-Energy Neutrino Reactions and the Existence of Two Kinds of Neutrinos", *Phys. Rev. Lett.* **9** (1962) 36.

[2] L. Wolfenstein: "Neutrino Oscillations in Matter", *Phys. Rev. D* **17** (1978) 2369.

[3] S. P. Mikheyev and A. Y. Smirnov: "Resonant neutrino oscillations in matter", *Prog. Part. Nucl. Phys.* **23** (1989) 41.

[4] J. N. Bahcall: *Neutrino Astrophysics.* Cambridge University Press (1989).

[5] SuperKamiokande web site: www-sk.icrr.u-tokyo.ac.jp/sk/index-e.html

[6] SNO web site: www.sno.phy.queensu.ca

[7] Borexino web site: borex.lngs.infn.it

[8] KamLand web site: kamland.lbl.gov

[9] T. Schwetz, M. A. Tortola and J. W. F. Valle: "Three-flavour neutrino oscillation update", *New J. Phys.* **10** (2008) 113011.

[10] K2K web site: neutrino.kek.jp

[11] T2K web site: t2k-experiment.org

[12] MINOS web site: www-numi.fnal.gov

[13] OPERA web site: operaweb.lngs.infn.it

[14] Daya Bay web site: dayabay.ihep.ac.cn

[15] RENO web site: hcpl.knu.ac.kr/neutrino/neutrino.html

[16] Double Chooz web site: doublechooz.in2p3.fr

[17] F. P. An *et al.* [Daya Bay Collaboration]: "New Measurement of Antineutrino Oscillation with the Full Detector Configuration at Daya Bay", *Phys. Rev. Lett.* **115** (2015) 111802.

[18] F. Capozzi, G. L. Fogli, E. Lisi, A. Marrone, D. Montanino and A. Palazzo: "Status of three-neutrino oscillation parameters, circa 2013", *Phys. Rev. D* **89** (2014) 093018.

[19] MiniBooNe web site: www-boone.fnal.gov

[20] G. Mention, M. Fechner, T. Lasserre, T. A. Mueller, D. Lhuillier, M. Cribier and A. Letourneau: "The Reactor Antineutrino Anomaly", *Phys. Rev. D* **83** (2011) 073006.

[21] J. M. Conrad, C. M. Ignarra, G. Karagiorgi, M. H. Shaevitz and J. Spitz: "Sterile Neutrino Fits to Short Baseline Neutrino Oscillation Measurements", *Adv. High Energy Phys.* **2013** (2013) 163897.

[22] SOX web site: web.ge.infn.it/sox/

[23] NESSie web site: web2.infn.it/NESSiE/

[24] JUNO web site: english.ihep.cas.cn/rs/fs/juno0815/

[25] M. G. Aartsen *et al.* [IceCube PINGU Collaboration]: *Letter of Intent: The Precision IceCube Next Generation Upgrade (PINGU).* arXiv:1401.2046 (2014).

[26] NOvA web site: https://www-nova.fnal.gov

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A story of neutrino oscillations

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Introduction

1998 is commonly considered the year of the discovery of the neutrino oscillations. Indeed, the story is rather more involved and lasted for about 30 years. In those years, a hot debate had developed about the lack of electron neutrinos coming from the Sun as well as the lack of muon neutrinos originating in the cosmic ray showers. However, this debate was restricted among the researchers directly involved in the experiments. In 1998, the evidence was so clear to cancel all the doubts and the results was accepted by the whole scientific community. Due to the fact that this complex story had many protagonists, the Nobel prize has been awarded only in October of 2015, after 17 years, to Arthur McDonald for the oscillations from Sun neutrinos and to Tataaki Kajita for the oscillations to atmospheric neutrinos. This award follows that assigned in 2002 to Raymond Davis jr. and Masatoshi Koshiba, which had as official motivation the first detection of astrophysical neutrinos from the Sun and from the 1987 supernova. This short history is focused to the period up to June 1998, when the evidence of neutrino oscillations became clear.

An extended version of this article can be found at the address www.lnf.infn.it /sis/preprint /pdf/getfile.php?filename=INFN-15-08-LNF.pdf

Neutrinos from the Sun

The 7th of March 2003 in a conference at the *Accademia dei Lincei*, organised by Milla Baldo Ceolin, Arthur McDonald, spokesperson of the Sudbury Neutrino Observatory (to become a Nobel laureate in 2015), pointed out that the deficit of Sun neutrinos (neutrinos of electron type) was known since 1968, the date of the first experimental work on the Sun neutrinos flux with the chlorine experiment of the Nobel laureate R. Davis jr. [1].

The deficit was large, about 30%, and it became statistically very significant. Already in the '70 it would have been possible to think at oscillations as a cause, and an experimental program for a more precise study could have started then. Nicola Cabibbo asked why this did not happen and why 30 years were needed to accept the neutrino oscillation phenomenon, which was already predicted by Bruno Pontecorvo in 1957. I remember McDonald to reply that it was a problem of scientific sociology.

Until the early fifties of the past century, particle physics had developed via the study of the cosmic rays. Then, there was the a quick development of the accelerators, and all the energies of the researchers were addressed to the research with accelerators. In a short time, the achievements became enormous and, immediately, people though that particle physics could be studied only with accelerators. The idea that one could do particle physics without accelerators at that time was proposed by a minority of researchers and mainly discussed in cosmic rays conferences.

Furthermore, the refined radio-chemical techniques used by Davis and collaborators where often not understood by the experimental physicists of that times, and the complex theoretical estimation of the Sun neutrino flux of John Bachall was suspiciously considered. All this incomprehension lead, in the USA, to non approving a second generation radio-chemical experiment on the solar neutrinos with Gallium. Experiments with Gallium were only approved in the second half of the 80's, and in Europe, at the Gran Sasso laboratories (Gallex) and in Russia (Sage).

In addition to these experimental prejudices, there was also a theoretical prejudice. In analogy with similar phenomena for the quarks, it was assumed that neutrinos oscillations would be too small to produce the observed large reduction of flux. In 1978 the influence of propagation through matter on the neutrino oscillations (matter effect) was studied by Mikheev, Smirnov and Wolfenstein [2, 3], This effect could produce an amplification of the oscillations. Therefore, a solution of the problem of solar neutrino oscillations, which saved the theoretical prejudice, was formulated: the original oscillation amplitude was small, but it was amplified by the matter effect.

A few theoreticians [4] indicated that, given the possibility of solar neutrinos oscillation, there was a solution in terms of small oscillation amplitudes and mass differences of about 10 eV. In this case neutrinos would have a relevant role in cosmology and they could explain the dark matter problem. On the base of these considerations, two experiments, CHORUS e NOMAD, were approved at CERN, aiming at the search for muon neutrino oscillations on the distances of the order of km.

Anyhow, I want to recall the presence of a small group of theoreticians not aligned to that dominant way of thinking. After the first confirmations of the deficit of solar neutrinos, and the beginning of the anomaly of the atmospheric neutrinos, G.L. Fogli started to work on the problem, and, in the 1994, the group of theorists from Bari, (G.L. Fogli, E. Lisi e D. Montanino) published a work [5] about a global analysis of the neutrino oscillations in solar and atmospheric neutrinos. This is the first of a set of papers which continues nowadays.

Atmospheric neutrinos and neutrino beam from CERN to Gran Sasso

The story of the deficit of muon neutrinos coming from showers, produced by the interaction of cosmic rays with the atmosphere, is even more complicated than that of solar neutrinos. In addition to the above outlined prejudices, a further problem arose because the various experiments were giving different results: today, these should be considered as due to statistical fluctuations and also to wrong data analyses.

In the '80s the theoreticians of the great unification (GUT) predicted that the proton could be unstable with a half-life value which should produce visible effects in 1000 tons detectors. Two different techniques were proposed: detection by means of the Cherenkov effect in water (IMB in the USA and Kamiokande in Japan) and detection by a calorimeter with iron plates separated by tracing detector (Frejus in France, Nusex in Italy, under the mont Blanc and Soudan in USA). The search for proton decay was limited by atmospheric neutrinos which could produce events similar to those expected from proton decay.

Early on, in 1986, the IMB experiment [7] observed the first atmospheric neutrinos and it turned out that the number of the detected muon neutrinos was smaller than expected, while the number of electron neutrinos was compatible with the predictions. This provoked a great excitment, as it was immediately clear that a possible cause for this effect was the oscillations of the muon neutrinos. The result of IMB, and then of Kamiokande, was not confirmed by Frejus nor, with smaller statistical evidence, by Nusex. Many people though that the effect was due to the differences between neutrino interactions in iron and in water.

The situation was further complicated in 1992, when the IMB collaboration published an analysis bases on muon produced by muon neutrinos and stopped inside the detector ("stopping muons") [8]. In this paper it was stated that there was no evidence for oscillations. Based on this analysis, they excluded wide regions of the values of two important parameters of the oscillations, the amplitude and the mass squared differences. In particular, they excluded just the values of the parameters which we have now well measured .

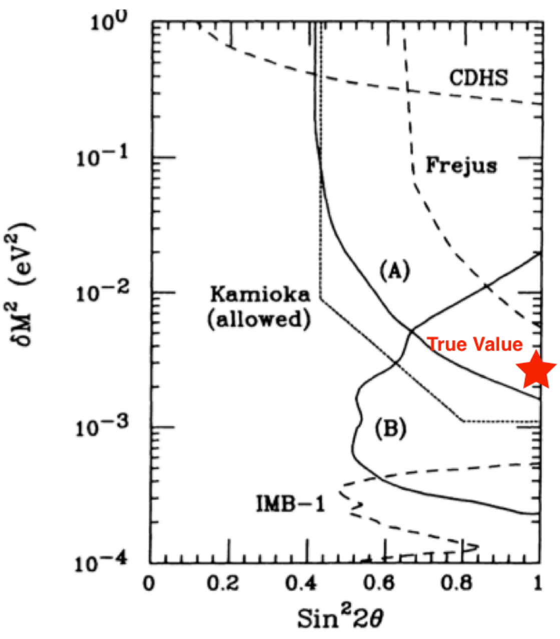

Figure 1: *Figure analogous to that of the IMB paper published on Physics Review Letters in 1992 [8]. All the curves include excluded regions, except that of Kamiokande, which defines the allowed region. One should notice that the curve B of IMB completely excludes the red star that represents the presently accepted oscillation values. This wrong result generated great confusion and slowed down the claim of the discovery.*

We show in figure 1 a plot similar to that published on the prestigious journal Physics Review Letters. This result seemed to be a definitive proof that the muon neutrino deficit was an instrumental issue. Other indications, confirming this result, were coming from that category of events called "upward muons" in the IMB, BAKSAN and Kamiokande itself: they seemed to exclude a muon deficit.

Despite all this, and in a restricted circle, the community was convinced that something should be there. I remember that in 1979, A. Zichichi, then chair of INFN (National Institute for Nuclear Physics), started the project of the underground laboratory under the Gran Sasso mountain. Since the beginning of the project, the possibility of oscillation experiments on a path of 732 km from CERN to the Gran Sasso was considered [9].

Around 1992, the Nobel laureate Carlo Rubbia, CERN director from 1989 to 1992, began to be interested in the issue [10]. Rubbia reconsidered the old idea of the beam from CERN to Gran Sasso and pushed for project of neutrino beam. With that beam one could test, in a controlled manner, the atmospheric neutrino anomalies.

However, the beam was never seriously considered, on the basis of the dominant prejudices. Even after 1998, the community of the European experimental physicists was divided, and the CERN - Gran Sasso neutrino beam was approved by INFN only in december 1999, during the INFN chair of E. Iarocci. At that time the competing projects of MINOS in the USA and K2K, T2K in Japan were already in an advanced state of development. As an example of the difficulties encountered, we can mention that some of the European countries refused to participate to the project, even though it was almost completely financed by Italy. For the approval of the CERN - Gran Sasso beam it was decisive the fact the Director General of CERN was Luciano Maiani.

MACRO and the atmospheric neutrinos

At this point I must insert some personal recollections, due to the fact that, in 1989 the MACRO experiment at the Gran Sasso lab began partially operative. The principal goal of MACRO was the search for magnetic monopoles predicted by Grand Unification theories. But the same apparatus could also reveal atmospheric muon neutrinos. The detection was based on the observation of upward muons produced in the rocks below the detector by the muon neutrinos. The muon direction was identified by measuring the times of the scintillator counters. The search for neutrino oscillations was one of the goals of MACRO since the beginning. The Figure 2, contained in the 1984 proposal [11] shows the region of the oscillation parameters accessible to MACRO. This region included the oscillation parameter values as we know them nowadays.

My involvement in the analysis of the neutri-

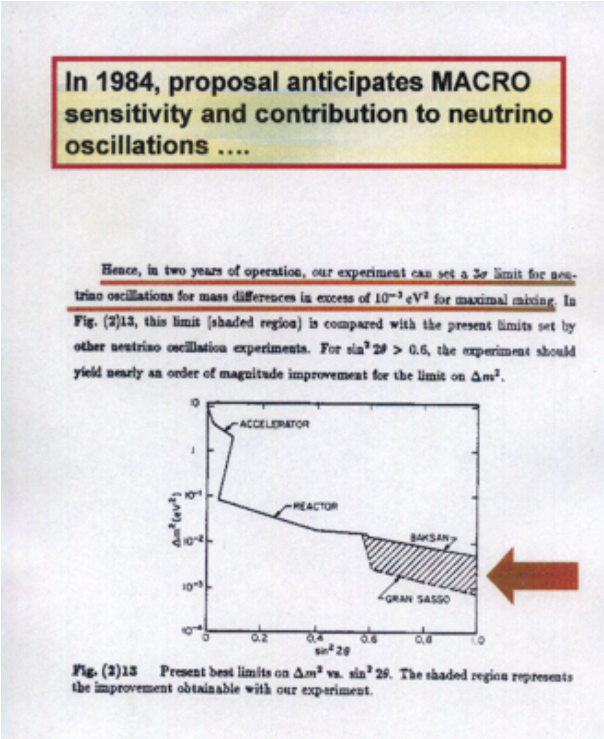

Figure 2: *Page of the proposal of MACRO of 1984 shown by B. Barish in the last MACRO meeting of January 21rst 2010 at the Gran Sasso Lab. The dashed region represented the result of the analysis of MACRO sensitivity in 1984. The oscillation signal was later found in this region.*

nos was partially accidental, since the Italian spokesman at that time, Enzo Iarocci, wanted to know if the third layer of scintillators, which was not yet built, was really needed in this type of analysis. Iarocci asked me to study this problem since he knew of my experience about time of flight in previous experiments.

Since MACRO was still under construction, data were taken in unstable conditions, and therefore great care was taken in formulating statements about the neutrino flux. However, already at that time, the deficit of events was clearly identified. This was particularly concentrated on the vertical direction. Many of us believed that this could be an instrumental fact due the unstable data acquisition, or that could be due to the presence of underground lakes or caverns, fact that was proved wrong. Preliminary results, based on 45 events on the neutrino astronomy were presented at the fifth conference "Neutrino Telescope" of Venice in march 1993 [12].

In MACRO, a group of people was formed to perform this specific analysis. The historical group constituted by Paolo Bernardini, Doug Michael, Antonio Surdo, Teresa Montaruli and Maurizio Spurio was then complemented, in various times, by Ed Diehl, Bob Nolty, Colin Okada, Eugenio Scapparone. This group had theoretical support by Paolo Lipari and Stanislav Mikheev. It was this small group of people that, usually, presented the results of MACRO at various conferences. These presentations were often left to us since there was a skeptical attitude about these results, even from the other members of the collaborations. Many people were convinced that the observed effects were due to uncontrolled efficiencies.

A more stable data acquisition, although limited to the lowest part of the apparatus, was available only in 1993 and preliminary results with the limited statistics of 74 events were published in 1995 [13]. We observed 73% of the expected events and the deficit in the vertical direction was confirmed. However, because of the limited statistics and of the negative results of IMB shown in fig. 1 we were very, perhaps too much, cautious in our conclusions. The abstract said: *At the 90% confidence level, the data are consistent with no neutrino oscillations or some possible oscillation hypotheses with the parameters suggested by the Kamiokande contained- event analysis.* The phrase was diplomatic since, as already mentioned, this result was in contrast with what reported not only in IMB but also BAKSAN and Kamiokande. I remember that Kamiokande gave contradictory results between events contained inside the detector and events not contained.

The project of the CERN-Gran Sasso beam was not making progress. The then director of the Gran-Sasso lab, Piero Monacelli, tried to stimulate, with scarce success, the CERN and the INFN adminitrations. Piero Monacelli also invited proposals for experiments with a possible CNGS beam.

In 1998, we published on Astroparticle Physics [14] an important experimental result which had been refused by Physics Review D in 1997. The topic of the article concerned the observation of upwards charged particles produced by muons in underground detectors. In our opinion this article was very important since we had discovered a background source in the search of upwards muon neutrinos that had not been considered by IMB or BASKAN. This background was dependent on the intensity of the cosmic rays, and this intensity in IMB and BASKAN was much larger than in MACRO because of the smaller shielding depth. This background, in our opinion, raised doubts on the IMB and BAKSAN results and in particularl on that reported in Fig. 1. This very strong, but correct statement was perhaps the reason of the rejection by Physics Review D, and, consequently, of our following submission to the European journal Astroparticle Physics.

So we arrive at the year 1998. The author of this note had been designated, already in 1997, to speak for the MACRO experiment at the XVIII neutrino conference in Takayama, scheduled on the 4th -9th of June 1998. Furthermore, Paolo Bernardini was designated to present at the Vulcano workshop of the 25th - 30th May 1998, which would have taken place just few days before the Takayama conference.

During 1997 and 1998 the MACRO statistics had increased, the analysis had improved, and we had carried out three parallel analyses and verified the compatibility of the results. One of these analyses used an alternate electronics for the measurement of the times (the circuit PHRASE developed in Pisa for the time measurement). We had also answered to a set of questions asked by Barry Barish to test the apparatus efficiency, questions also raised by Giorgio Giacomelli co-spokenman for the italian group. We found the reason why IMB and BAKSAN gave results we considered wrong. We were then ready to make stronger and explicit statements in support of the neutrino oscillations. We had only one perplexity, the region preferred by the MACRO data did not correspond to that proposed by Kamiokande (later on, other analyses of Kamiokande moved the preferred region).

With this attitude we gathered at the yearly MACRO meeting in USA where, in particular, we had to discuss about the presentations at the summer conferences. The first two were the Vulcano workshop and the " neutrino 1998" in Japan. The collaboration meeting was held on April 18th-20th in Boston, in coincidence with the famous maratone. The discussion on the presentation of the results was very hot. We have to consider that in the American group there were people who had taken part in IMB and people members of the Super-Kamiokande experiment. Furthermore, negative results of CHOOZ, a reactor experiment aimed at testing the Kamiokande results, assuming that there were disappearance oscillations of electronic anti-neutrinos, were about to be published. CHOOZ, which had among its members a group of scientists of MACRO, excluded one of the oscillation possibilities, but could not make any statement on the other possibility (muon neutrino in tau neutrino). This contributed to generate a skeptical atmosphere about oscillations.

For all these reasons, in spite of the efforts and of the opposition of the Italian part of the neutrino group, the majority decided that no statement should be made about neutrino oscillations. In particular, the figure of the allowed parameter region should not been shown.

Honestly speaking, I do not know what our presentations would have been like, in the wake of the negative decision of the MACRO group. Probably, I would have presented the same talk that I did, but with different spirit. However, the discussion had taken place in the absence of Barry Barish which was sick. By the way, this is the only time, to my knowledge, that Barry Barish was indisposed. Fortunately, the day after, Barish was again well, came to the meeting and asked what had happened. Later on, respecting the agreements taken when he had asked to test the efficiencies, he acted with his resolute behaviour and convinced the American group to change their mind.

The Takayama neutrino conference of June 1998

The conference started on Monday, June 4th. Immediately, people rumored that there was going to be a great announcement by Super-Kamiokande: there was therefore a great expectation. On the first day, there was a session dedicated to the solar neutrinos. In succession: the experiments in Homestake (the experiment of Davis with Chlorine), then Gallex, Sage and Super-Kamiokande.

It is impressive to observe how the deficit of the revealed neutrino flux was observed, in different manners, by all the experiments: the radiochemical ones as well as those in water. Furthemore, Super-Kamiokande had thousands of events where it was possible to begin studying small effects such as those due to the variation of the Sun-Earth distance. In his afternoon talk about the flux predicted by calculations J. Bachall pointed out that at this point the deficit was an effect of about 20 standard deviations. Many people expected the great announcement already on Monday, but that was not the case.

It became evident that there would have been more important results from Super-Kamiokande in the atmospheric neutrino sector. The morning of June the 5th was dedicated to this topic.

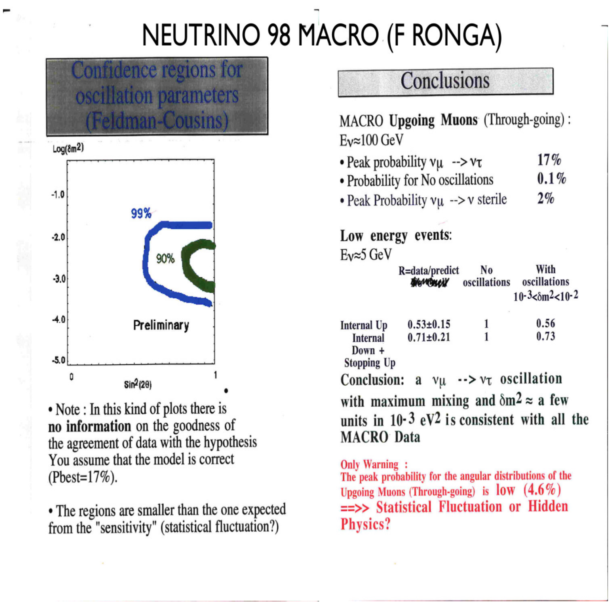

Figure 3: *Slides of the MACRO presentation at "neutrino 1998". The slides are still on the conference link http://www-sk.icrr.u-tokyo.ac.jp/nu98/scan/index.html. Similar slides had already been shown by Paolo Bernardini six days earlier at the Vulcano workshop 1998*

The schedule had in the successive order the talks of E. Peterson (Soudan2), F. Ronga (MACRO) and of the 2015 Nobel laureate T. Kajita (Kamiokande and Super-Kamiokande). This schedule worried me since I knew that Super-Kamiokande was an experiment of much higher quality than MACRO and therefore it was possible that, in case of discrepancy, the data of Super-Kamiokande would have received more consideration. Furthermore, we knew that the Kamiokande contained events favoured oscillations with mass differences much larger that those we observed, and we believed that this could be confirmed in the presentation of Kajita. For this reasons I waited with anxiety for the conclusions of Kajita.

After the conference, somebody thought that the presentation of MACRO was "adjusted" by knowing what Kajita was going to present. This is not true, since the guidelines of the presentation had been decided in the April Boston meeting, and the presentation was similar to that of Paolo Bernardini at the Vulcano workshop in the afternoon of the May 29th 1998. This latter workshop had a participation smaller that of *Neutrino 1998* therefore the echo had not reached the large public. We could therefore state that the first announcement of the neutrino oscillation was given in May the 29th 1998 at the Vulcano workshop by MACRO and not at Takayama.

The presentation of SOUDAN2 confirmed the deficit of muon neutrinos and solved, finally, the discrepancy iron-water, but did not draw any conclusion about oscillation parameters.

I show in Fig. 3 two of the most significant slides of the MACRO presentation. The first one is the plot of the confidence region which shows that, in 1998, MACRO had and effect larger than 99% confidence level in favour of oscillations from muon to tau neutrinos. The allowed region was not much different that that of Super-Kamiokande of Fig. 4. The second slide of MACRO shows, in the conclusions, that the sterile neutrino was disfavoured (there was a factor 8 between the probabilities in tau neutrino and sterile neutrinos).

This analysis had been possible thanks to the work of Paolo Lipari which had been working on the matter effect for some time. These results were published in the conference proceedings and, even earlier, submitted on June 29th 1998 at Phys. Lett. B [15].

I show in Fig.4 two slides, among the most significant ones, of the Super-Kamiokande presentations. The first one regards the analysis done to exclude the sterile neutrino with a study of the topology of the events. The second slide is the conclusive one, with the famous plot which is nowadays remembered all over the world. The strength of the Super-Kamiokande result laid on

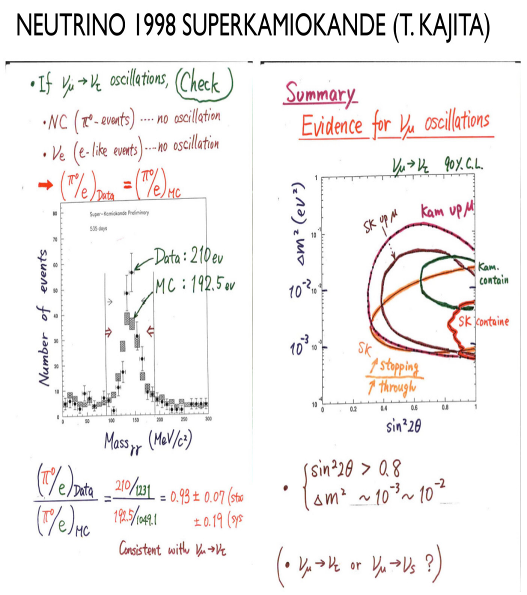

Figure 4: *Slides of the Super-Kamiokande presentation at neutrino 1998.*

the fact that the analyses carried out with different kind of events agreed in the result. The orange line (stopping/through) disproved completely the IMB result of Fig. 1. These results were immediately published and they are among the most quoted in particle physics [16]. We have to observe that the Super-Kamiokande results also contradicted, in part, the Kamiokande result (green curve) and were in total agreement with the MACRO result of Fig. 3.

The Japanese organised a press conference to advertise these results all over the world. The news spread with great success even with the general public. The result of MACRO disappeared however in the press releases, and the INFN was surprised about that, despite the efforts of G. Giacomelli. This happened, in part, because of the doubts and the perplexities mentioned above.

To confirm that MACRO collaboration acknowledged the role of Super-Kamiokande but that it had a relevant impact in the discovery, I want to stress that the preprint arXiv number of MACRO paper[15] is 9807005, while that of Super-Kamiokande[16] is 9807003. The MACRO paper was ready before that of Super-Kamiokande, but Giorgio Giacomelli (co-spokesperson of the collaboration) waited for the green light from his colleague and friend Koshiba to submit to the arXiv the paper soon after that of Super-Kamiokande.

The conference continued in minor tone after this historical event.

I just want to recall the signal, possibly due to sterile neutrinos, of the LSND experiment, since it had a great relevance in the European and Italian debate and in the approval of the CERN - Gran Sasso beam. There was a proposal for a neutrino beam on the short distance at CERN to test the LSND results, but the proposal was not approved. The LSND effect is not yet explained despite dedicated experiments at Fermilab in USA.

A negative effect of this debate was a further delay in the approval of the CNGS beam. There were also different proposal such as that of a beam from the CERN to the mountains of the Jura with distances of about 17 km. Many physicist were reluctant to work at the Gran Sasso lab, in an environment certainly more difficult than that of a large laboratory such as CERN.

Perhaps these considerations of social type, in addition to the financing problem, hindered the construction at CERN of a near detector. This detector would have widened the possibilities of the beam by comparing near and far measures. However there was perhaps the worry that the near detector would absorb great part of the interest. Eventually, the beam was approved in the December of 1999 with the scientific program of the appearance of tau neutrinos with he ICARUS and OPERA experiments. In this research the near detector is not needed.

Conclusions

The year 1998 was a turning point since the community of elementary particle physicists convinced itself of the neutrino oscillations after 30 years from the first indications. Later, many experiments have been proposed, approved and built.

In 2002 the Sudbury Neutrino Observatory collaboration published the paper on the direct evidence for neutrino flavor transformation from neutral-current interactions putting down another milestone in the solar neutrino oscillations[17]. This was the motivation for awarding the Nobel prize for solar neutrinos to

Arthur B. McDonald.

We are now with the third generation of experiments on the neutrino oscillations and all the terms of the the oscillation matrix have been measured, but one parameter. I have some personal regrets as an Italian and European, the unsufficient appreciation of the MACRO results, the division of the neutrino physicists community in Europe about scientific programs and the hostility of part of the community of particle physicists. As an example of these problems I recall that when financial restrictions on the construction of LHC appeared, one of the actions taken was to close the very small group of the CERN working on the OPERA experiment. This was certainly a signal psychologically very negative for the OPERA collaboration and for the European community.

The behaviour of the Japanese was completely different. They approved with determination the first beam of neutrinos on a long-distance (K2K) well before 1998, believing since the beginning in this type of physics, despite all the doubts exposed in this note. For these reasons the recent 2015 Nobel was well deserved.

After the end of the data acquisition of the CNGS, today the neutrino physics with particle beams is no longer present in Europe, neither for short nor for long distance. Perhaps, this is appropriate from the point of view of the division of tasks at world level, but it leaves a bitter taste. Fortunately, in Italy, at the Gran Sasso lab, the neutrino physics without accelerators is still present with the BOREX (neutrinos from the Sun and from a source), CUORE e GERDA (neutrino mass, and Majorana neutrinos).

[1] R. Davis, Jr., D. S. Harmer and K. C. Hoffman: "Search for neutrinos from the Sun", *Phys. Rev. Lett.* **20** (1968) 1205.

[2] L. Wolfenstein: "Neutrino Oscillations in Matter", *Phys. Rev. D* **17** (1978) 2369.

[3] S. P. Mikheev and A. Y. Smirnov: "Resonance Amplification of Oscillations in Matter and Spectroscopy of Solar Neutrinos", *Sov. J. Nucl. Phys.* **42** (1985) 913. [Yad. Fiz. **42**, 1441 (1985)].

[4] J. R. Ellis, J. L. Lopez and D. V. Nanopoulos: "The Prospects for CHORUS and NOMAD in the light of COBE and GALLEX", *Phys. Lett. B* **292** (1992) 189. [hep-ph/9207237].

[5] G. L. Fogli, E. Lisi and D. Montanino: "A comprehensive analysis of solar, atmospheric, accelerator and reactor neutrino experiments in a hierarchical three generation scheme", *Phys. Rev. D* **49** (1994) 3626.

[6] H. H. Chen, W. R. Kropp, H. W. Sobel and F. Reines: "Muons produced by atmospheric neutrinos: Analysis", *Phys. Rev. D* **4** (1971) 99.

[7] T. J. Haines *et al.*: "Calculation of Atmospheric Neutrino Induced Backgrounds in a Nucleon Decay Search", *Phys. Rev. Lett.* **57** (1986) 1986.

[8] R. Becker-Szendy *et al.*: "A Search for muon-neutrino oscillations with the IMB detector", *Phys. Rev. Lett.* **69** (1992) 1010.

[9] A. Zichichi "The Gran Sasso Project", in G. Ciapetti, F. Masas and S. Stipcich eds. *Physics and astrophysics with a multi kiloton modular detector undergound track detector* GUD workshop Rome 29-31 October 1981, A. Zichichi "Perspective of underground Physics the Gran Sasso project" CERN EP 88-28

[10] C. Rubbia, "The Renaissance of experimental neutrino physics", In *Madrid 1992, Proceedings, Perspectives on high energy physics and cosmology* 20-89, and CERN Geneva - CERN-PPE-93-008 (93/01,rec.Mar.) 36 p

[11] "Proposal for a large area detector dedicated to monopole search, astrophysics and cosmic ray physics at the Gran Sasso Laboratory", Bari Bologna Caltech CERN Drextel Frascati Indiana Michigan Pisa Roma Texas AM Torino Virginia Tech. Collaboration Caltech-Frascati 1984.

[12] F. Ronga [MACRO Collaboration], "High-energy neutrinos in the MACRO experiment", In *Venice 1993, Neutrino telescopes*, 285-297

[13] S. P. Ahlen *et al.* [MACRO Collaboration]: "Atmospheric neutrino flux measurement using upgoing muons", *Phys. Lett. B* **357** (1995) 481.

[14] M. Ambrosio *et al.* [MACRO Collaboration]: "The Observation of upgoing charged particles produced by high-energy muons in underground detectors", *Astropart. Phys.* **9** (1998) 105. [hep-ex/9807032].

[15] P. Bernardini [MACRO Collaboration], "Measurement of the atmospheric neutrino induced muon flux with the MACRO detector", hep-ex/9809003. F. Ronga *et al.* [MACRO Collaboration], "Atmospheric neutrino induced muons in the MACRO detector" *Nucl. Phys. Proc. Suppl.* **77** (1999) 117. [hep-ex/9810008]. M. Ambrosio *et al.* [MACRO Collaboration], "Measurement of the atmospheric neutrino induced upgoing muon flux using MACRO", *Phys. Lett. B* **434** (1998) 451. [hep-ex/9807005].

[16] T. Kajita [Super-Kamiokande and Kamiokande Collaborations], "Atmospheric neutrino results from Super-Kamiokande and Kamiokande: Evidence for neutrino(mu) oscillations", *Nucl. Phys. Proc. Suppl.* **77** (1999) 123. [hep-ex/9810001]. Y. Fukuda *et al.* [Super-Kamiokande Collaboration], "Evidence for oscillation of atmospheric neutrinos", *Phys. Rev. Lett.* **81** (1998) 1562. [hep-ex/9807003].

[17] Q. R. Ahmad *et al.* [SNO Collaboration], "Direct evidence for neutrino flavor transformation from neutral current interactions in the Sudbury Neutrino Observatory," Phys. Rev. Lett. **89**, 011301 (2002)

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Majorana's conundrum

Francesco Vissani *Gran Sasso Science Institute and Gran Sasso National Laboratories - INFN, L'Aquila*

The study of elementary particles has been a continuous source of excitement, and this is particularly true for neutrinos. The only experimental evidence we have of the existence of new and not yet fully understood physics is the fact that neutrinos have mass. Nonetheless, some of the oldest questions about these particles remain open, as the one put forward by Ettore Majorana about the nature of the mass of neutrinos. In this essay, we examine the meaning of this question. We will give a summary of the partial results attained so far and an outlook of the current developments, attempting an assessment of how far we are from the answer.

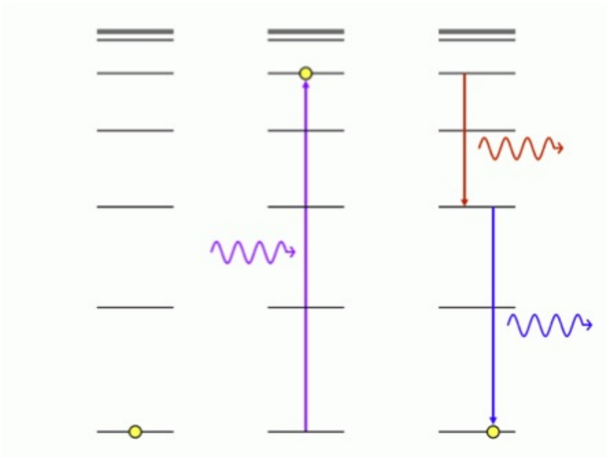

Figure 1: *An atomic electron absorbs a photon with energy E (purple wavy line) and becomes excited. Then the electron goes back to the initial state by emitting two photons with energies $E_1 + E_2 = E$. In other words, the energy is conserved but the number of photons can vary.*

Electrons, positrons, photons

We begin this essay recalling the scientific landscape of the time of Ettore Majorana, emphasizing those aspects which offered him inspiration.

The central problem was the understanding of the atom and of its constituents. Electrons, particles with negative charge and small mass, bind to the heavy (but small) nuclei with positive charge as understood by Rutherford and Bohr. This hypothesis explains the structure of the atom, its behavior and chemical transformations. Furthermore, as shown by Einstein, also light is composed of elementary particles, known as photons.

The study of the atom and of its components culminates into the formulation of *quantum electrodynamics*, a theory founded on the principles of relativity and quantum mechanics, and able to describe with astonishing accuracy the interactions between light and matter.

The first important observation is that the number of photons *is not* subject to a conservation law. For example, in an atomic transition it can change, as shown in Fig. 1.

For electrons, this is different. In any chemical transformations their number is fixed. When we consider a reaction with energies much larger that the electron mass, as in Fig. 2, energy can be converted to matter. It is then possible to produce new electrons, but always in association with

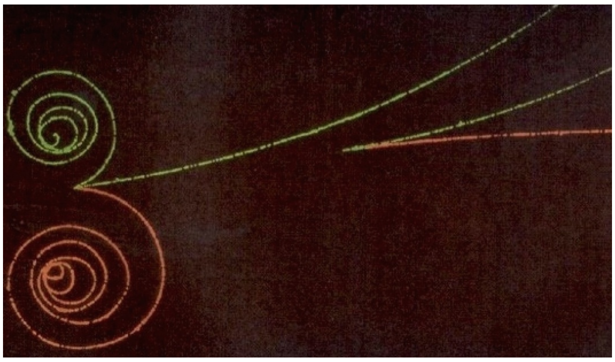

Figure 2: *Tracks left in a bubble chamber by electrons (highlighted in green) and positrons (in red). The presence of a magnetic field allows to measure the electric charge. The photons responsible of the reactions arrive from the left, but since they have no electric charge they do not leave any trace.*

Reactions involving elementary particles

In Fig. 2 we show two reactions in which an electron-positron pair is generated. In the first reaction, an atomic electron collides with a photon, as described in the formula

$$\gamma + e^- \to e^- + e^- + e^+ \ .$$

In the second reaction, the collision involves a photon emitted by the nucleus of the atom, γ^*:

$$\gamma + \gamma^* \to e^- + e^+ \ .$$

From the point of view of the conservation of electric charge, whose elementary value is -1, these reactions correspond to the algebraic identities $0 - 1 = -1 - 1 + 1$ e $0 + 0 = -1 + 1$, which show that electric charge is conserved.

positrons (that is, anti-electrons), which have opposite charge. In this manner, electric charge is conserved, and, consequently, the net number of electrons is left unchanged. This algebraic fact is summarized in the yellow box. For the interested Reader, we will describe in the rest of this section a few aspects of the formalism adopted.

In quantum electrodynamics, the charge-conservation law corresponds to an invariance principle. The possibility for the particle number to change is described by introducing the concept of quantized field. In Dirac's theory of electron, there is one field for the electron and one for the photon, usually indicated with $\mathbf{\Psi}$ and $\mathbf{A}_\mu$. These two fields differ in many respects, including the fact that the former is intrinsically complex, while the latter is real.[1] This means that $\mathbf{\Psi}$ describes a transition in which an electron disappears or an antielectron appears. The photon field is on the contrary neutral, meaning that there is nothing distinguishing the photon from the antiphoton: They are the same particle.

The law of conservation of the electric charge stems from a principle that states that: the physical transformations have to be invariant under the transformation $\mathbf{\Psi}' = e^{i\alpha Q}\mathbf{\Psi}$, where $Q = -1$ is the elementary electron charge and α is a real parameter. For this reason, the theory does not allow a new electron to appear (or disappear) alone, but requires that it to be associated with a positron. The net number of electrons is constrained by the invariance principle, which does not, on the other hand, affect the number of photons. Indeed, the photon field does not transform at all, or, in more mathematical terms, it transforms with $Q = 0$, precisely because $\mathbf{A}_\mu$ is real. Photons can appear (or disappear) alone (when this possibility is allowed by the law of energy conservation).

[1] This corresponds to well-known formal facts: in quantum mechanics the Schrödinger wave function is complex, while in Maxwell's thoery the electric and magnetic fields are real.

Other neutral particles

Since the early '30 of the last century, the study of the atomic nucleus and of high-energy reactions allowed to discover new particles. Two among these turned out to be neutral, meaning that they do not carry electrical charge. The first is the neutron, which weighs slightly more than the proton and together with it constitutes the atomic nuclei. The second is neutrino, which was discovered in a rather peculiar way.

Some nuclear transformations involve the emission of electrons, that in this context are called β rays according to Rutherford terminology. Such transformations were thought to be described by,

$$(A, Z) \overset{?}{\to} (A, Z+1) + e^- \ ,$$

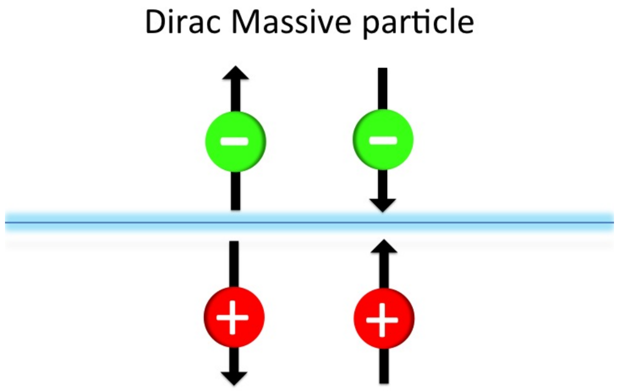

Figure 3: *A Dirac particle in its rest frame. Associated with it, there exists its antiparticle, which by definition has opposite charge, as recalled by the + sign upon the particle and by the different color. A typical case is the electron; note the two spin states.*

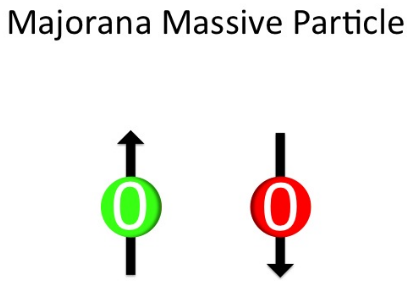

Figure 4: *A Majorana particle in its rest frame. It has two spin states as a Dirac particle, but it coincides with its antiparticle and therefore has no electric charge, just as the photon. A particle of this type could be the neutrino; for the meaning of the different color, see next figure.*

since the nuclear charge must increase of one unity to leave the charge unchanged. Physicists expected that the emitted electron's kinetic energy T was determined by the masses of the initial and final atoms, according to the expression, $T = (M_{\text{iniziale}} - M_{\text{finale}})c^2$. But, since '20, it was known that the previous prediction corresponds to *the maximum* value of T indicated by the experiments, which in reality takes all the values down to zero.

Pauli speculated that, the emission of a "β particle" was always accompanied by the emission of a neutral particle, that carries away some amount of energy. This was precisely the neutrino, which, as argued by Pauli, had only negligible interactions with ordinary matter (we will discuss later on the difference between neutrinos and antineutrinos). Three years later, thanks to Fermi, the interactions of these particles were quantified and in 1956 it was finally possible to observe them in laboratory.

Majorana's conundrum

The existence of neutral particles raises a question about their nature. Should they be considered akin to the photon, i.e. a particle which is not only electrically neutral, but even identical to its antiparticle, or, on the contrary, should they be assimilated to the electron, so that neutrino and antineutrino are distinguishable due to some hypothetical 'charge'? In short, are neutrinos identical to antineutrinos or not?

For the sake of clarity, we show in Fig. 3 a particle described by Dirac's theory. To pictorially represent electrons, we use spinning tops as it is customary in elementary chemistry courses. A Majorana particle is somewhat simpler: it coincides with its antiparticle, as shown in Fig. 4. We note that in both cases, Dirac and Majorana, particles at rest are considered.

We can call matter particles the electrons and the nuclei since they form the atoms. However, we can include in the same class also the neutron, that is part of the nuclei, and also the neutrino, in view of the existence of the β decay process. This is the common usage of particle physicists, and we shall follow it in this essay. We shall denote collectively as *matter particles* electron, proton, neutron, quarks and also the neutrinos. A common aspect of matter particles is that they all obey the Fermi-Dirac statistics (a generalization of the exclusion principle, obeyed by electrons and discovered by Pauli) and for these reason they are also called collectively fermions.

In formal terms, and taking into account the previous discussion, Majorana's conundrum is nothing but

> a hypothesis on the nature of the mass of neutral matter particles.

Majorana proposed his hypothesis in very gen-

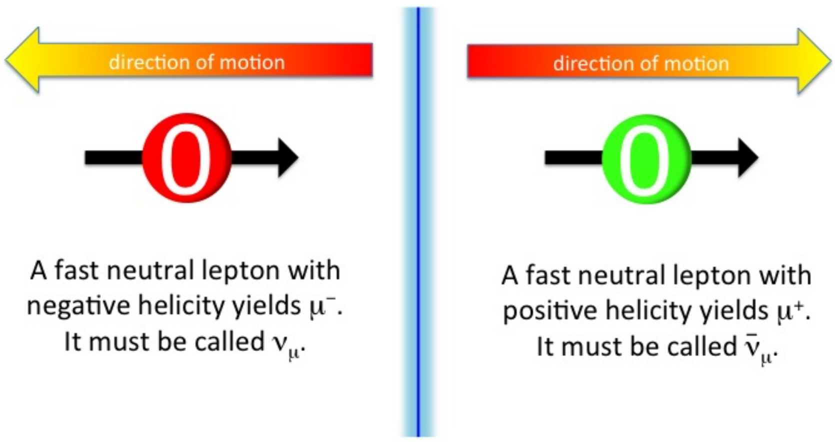

Figure 5: *When the kinetic energies of neutral leptons (neutrinos or antineutrinos alike) are much larger than their masses, they are more easily observable. In this regime, experiments show that states with antiparallel or parallel spin with respect to the direction of motion interact differently and produce negative or positive leptons respectively. This allows to define, in this regime, what is a neutrino and what is an antineutrino.*

eral terms: just as every complex number can be written as a combination of real and imaginary part, every matter field. (Formally, it is correct to say that the Majorana field is real, as the photon field).

But the most interesting case in when one Majorana field alone describes fully a particle. Since this is possible only for neutral particles, the original speculations involved both neutron and neutrino. But, as noticed by Racah, neutron has a non zero magnetic moment; this requires that it be described by Dirac's theory, at least in a first approximation. [2] For this reason, the main matter particle candidate to satisfy Majorana's hypothesis is precisely the elusive neutrino.

It should be noticed that we assumed neutrinos to be massive particles, since we introduced the concepts of Dirac and Majorana particle making specific use of the particles' rest reference frame. As we recall in the next section, this hypothesis is, indeed, satisfied.

What we know about neutrinos

Since the discovery of neutrinos, the meaning of Majorana's question has been progressively clarified. To understand how, let us start recalling the main things we learned about neutrinos. We will discuss some peculiarities of their interactions and the convincing clues that these particles are massive.

The three types of neutrinos We know for sure that three different types of neutrinos exist in Nature. They correspond to one of the three electrically *charged leptons* e, μ, τ, either particles or antiparticles. Each of them is produced together with the corresponding neutrino in decay processes, or is associated to them in interactions. For this reason, neutrinos and antineutrinos are often called *neutral leptons* and are indicated with the symbols ν_e, ν_μ, ν_τ.

As an example, consider the neutron decay process,

$$n \to p + e + \bar{\nu}_e$$

or another typical decay such as that of pions, that are particles from which neutrino beams are produced in the accelerators,

$$\pi^+ \to \nu_\mu + \mu^+ \ .$$

The experiments show that the first decay gives always and only neutral leptons ν_e, the second always and only neutral leptons ν_μ. We refer the Reader to the next section for more information about the distinction between neutrinos and antineutrinos.

[2] A Majorana state has zero magnetic moment. But it is not impossible that neutrons and antineutrons are Dirac particles but mix slightly among each other. In this case the mass eigenstates would be described by Majorana's theory.

Peculiar interactions and their consequences Let us focus on neutrino interactions. A first property, known since the times of Fermi, is that the larger their energy, the more neutrinos interact. This has the practical consequence that, as the neutrinos' energy grows, their observation becomes more feasible. At the same time, the most evident effects of the mass of neutrinos become negligible in this regime.

When neutrino masses are small with respect to their kinetic energy, a second and surprising property of interactions emerges: the particles with spin parallel to the direction of motion will produce, as an effect of interaction, positive-charged leptons, while those with antiparallel spin will produce negative-charged leptons, as shown in Fig. 5. Therefore, when we have a neutral lepton in fast motion, it is possible to define the former as antineutrinos and the latter as neutrinos, *independently of the nature of their mass*. This explains the choice of colors used to denote particle states in Fig. 4, analogous to that of Fig. 3.

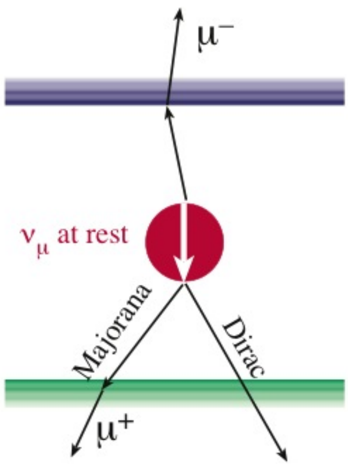

Figure 6: *(A conceptual experiment.) In a room, we consider ν_μ neutrinos with down spin. Accelerating them towards the ceiling, they will produce μ^-. Accelerating them towards the floor they will either produce μ^+, if they are Majorana particles, or will not interact anymore, if they are Dirac particles.*

It follows that, in the Dirac case, the neutrino state with spin parallel to its motion and the antineutrino with spin antiparallel to its motion do not produce any lepton, neither positive nor negative charged. This would be the case of the hypothesized sterile neutrinos. This point is further explained by means of the conceptual experiment of Fig. 6.

We note *en passant* that Universe itself acts as a source, and, after its expansion, as a neutrino decelerator. The possibility of performing real experiments on the basis of these general ideas it at the moment under consideration.

> **Direct neutrino's mass searches**
>
> NEUTRINO VELOCITY: From the observations of supernova 1987A we inferred that their mass is smaller than 5.8 eV.
>
> β-SPECTRUM: Electrons corresponding to neutrinos with a small kinetic energy are measured. Mainz and Troitsk experiments obtained an upper limit of 2 eV.
> COSMOLOGY: Neutrinos are produced in the first moments of life of the Universe, and when the cosmic background becomes visible, their temperature is around 0.2 eV. Current constraints indicate that the masses are smaller than 0.1 eV.

A new conservation law – or not? In all the known reactions, using fast-moving particles, it has been observed that the sum of charged and neutral leptons remains the same. This fact can be accounted for by postulating the existence of a conserved leptonic charge. But as we previously observed, it is not possible to give a definition of neutrinos and antineutrinos which is valid in all reference frames, if the particles are of the Majorana type.

Let us elaborate on this point. If neutral leptons had the kind of mass put forward by Dirac (or if they had no mass), neutrinos and antineutrinos would be distinct. If on the other hand they had the kind of mass postulated by Majorana, such distinction would not have absolute validity, and there should exist processes in which the leptonic charge is violated, as we will discuss in more detail below. Hence, the issue of the leptonic charge conservation is worth the most accurate experimental investigations.

Evidences of nonzero neutrino mass The direct attempts to measure neutrino masses have

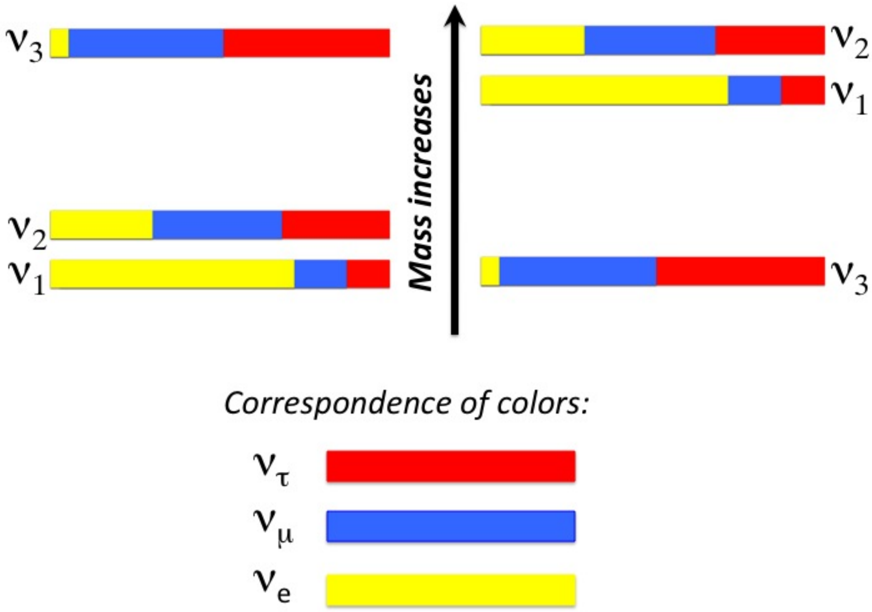

Figure 7: *We know the distribution of the three mass states ν_1, ν_2, ν_3 of the electronic neutrino ν_e (in yellow), which is the most important point for the subsequent discussion.*
We measured the differences of the squared masses, but not the lightest neutrino's mass: based only on empirical information, one can speculate that it could be relatively large.
We still do not know whether the mass spectrum of neutrinos is closer to the spectrum of charged fermions (the case depicted in the top left panel, called normal spectrum*), or not (the case in the top right panel, known as* inverse spectrum*).*

not succeeded yet. The known methods are three and are illustrated in the box. Only a fourth (rather indirect yet extremely sensitive) method has so far provided convincing evidences that the masses are nonzero. This method exploits the wave nature of the neutrinos.

To understand its principle, let us start from the analogy between neutrinos and light. As it is well known, a light ray that propagates in a given direction has two possible polarization states orthogonal to the direction of motion. We can produce light with a given direction of polarization using a filter called polarimeter. If, with a second filter, we try to polarize light in the direction orthogonal to the previous one, we do not find anything: light is completely absorbed. This allows us to conclude that the two polarization states are as different as a ν_e and a ν_μ neutrino. On the other hand it is possible to transform polarization states into each other by means of particular crystals, which allow the states with different polarization to propagate at different velocities. At this point we wonder: can something similar happen for neutrinos?

Let us consider a ν_μ neutrino produced in a decay. Let us assume that this neutrino is a composite state (or, in quantum mechanics jargon, *a superposition*) of three mass states with masses m_i with $i = 1, 2, 3$. Due to this fact, each component travels at a different velocity. Therefore, their relative phase will change during the time evolution. This means that a ν_μ neutrino will acquire a certain probability of becoming ν_e or ν_τ: in other words, it mutates. This scenario is referred to as *neutrino oscillations* or, perhaps more correctly, neutrino transformations.

(A more elaborate argument, that leads to the same conclusion, is as follows: The wave functions of each component oscillate with frequencies f_i, proportional to their energies. This is given by $E_i = hf_i$, where h is the Planck constant and where $E_i = \sqrt{(pc)^2 + (m_i c^2)^2}$, according to Einstein's special relativity, p is the neutrino's momentum and c is light speed. Since the masses are different, energies and frequencies are different as well, so the wave functions of the three components do not oscillate in phase. This changes the nature of the neutrino in the course of its propagation.)

Experiments with neutrinos produced in the Sun, in the atmosphere, by reactors and artificial beams, allowed the test of these ideas, first proposed by Pontecorvo. We learned a lot about the masses of neutrinos and we refer to Fig. 7 for a summary of the current available information.

We still do not know the mass of the lightest neutrino and still have to solve a puzzling ambiguity on the type of mass spectrum. The two spectra, compatible with the experimental information available today, are called *normal* and *inverse.* But certainly, the evidences of nonzero neutrino masses make it compelling to determine what kind of mass they have, whether that corresponding to Dirac or to Majorana particles.

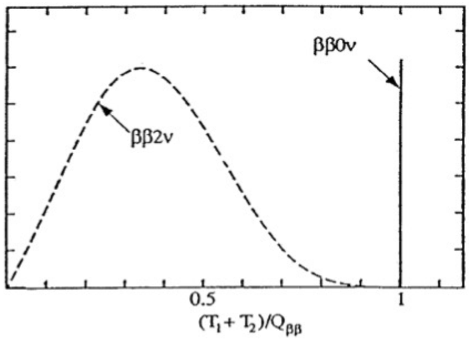

Figure 8: *Energy spectra expected in the two kinds of β decays. The quantity in the horizontal axis is the sum of electronic kinetic energies T_i, divided by the maximum energy available for the decay, $Q_{\beta\beta}$, that is given by the difference between the atomic mass of the initial and final species.*

The search for creation of electrons

Since 70 years, researchers have been looking for an hypothetical nuclear transition that, if observed, would provide an answer to Majorana's question. The reaction is the following: an atomic nucleus transforms increasing its charge by two unities and emitting two electrons,

$$(A, Z) \to (A, Z + 2) + 2e^- \qquad [0\nu\beta\beta] \, .$$

This reaction is known in nuclear-physics jargon as *neutrinoless double β decay* and it is denoted by $0\nu\beta\beta$ for the sake of brevity (we comment on the effect of this terminology in the next section). It can be compared with another, analogous reaction,

$$(A, Z) \to (A, Z + 2) + 2e^- + 2\bar{\nu}_e \quad [2\nu\beta\beta]$$

known as *double β decay with emission of neutrinos*, and denoted $2\nu\beta\beta$ in short.

While the second reaction was observed for different nuclei, the first one has yet to be observed. Its salient feature, used for the experimental search, is that electrons take the maximum available energy, as shown in Fig. 8.

Let us now explain the connection of this process with Majorana's question. A useful tool is the diagram in Fig. 9, called Feynman diagram.

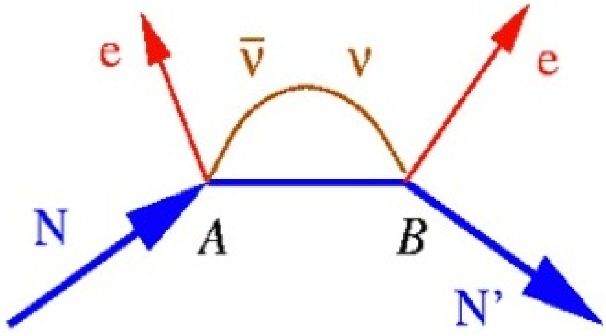

Figure 9: *A Feynman diagram that shows how a Majorana neutrino leads to neutrinoless double β decay.*

It shows that the presence of a Majorana neutrino implies the existence of the nuclear transition $0\nu\beta\beta$, which we are now examining. Let us clarify its meaning. The blue lines in Fig. 9 describe the initial nucleus N with charge Z which transforms into the final nucleus N' with charge $Z + 2$, after becoming, along the line connecting vertices A and B, a nucleus with charge $Z + 1$. Consistently with Fermi's theory, the vertices correspond to the emission of electrons (β rays) and neutral leptons ν_e, but the latter annihilate. This is possible only if neutrinos are Majorana particles, which implies that neutrinos and antineutrinos are descrived as suggested by Majorana, since, as we have seen, this implies that neutrinos and antineutrinos are the just the same particle. In this situation, the neutrino emitted in A is reabsorbed in B.

Several experiments have contributed to the search of neutrinoless double β decay. The greatest developments have been achieved in experiments based on Germanium crystals (Heidelberg-Moscow, IGEX, GERDA) and on the noble gas Xenon (KamLAND-Zen, EXO-200). They showed that the decay mean lifetime exceed the notable figure of 10^{25} years. New experiments are close to starting taking data. Two of the experiments hosted in Gran Sasso National Laboratories seem to be very promising: CUORE (Fig. 10), whose core is made of Tellurium oxide crystals, and GERDA, which exploits the decay of Germanium nuclei, and which, after a first phase of data-taking, is starting a second operational phase. Moreover, designing a next generation of experiments, with larger and more sensitive detectors, is now under consideration.

Figure 10: *The cryostat in CUORE experiment.*

Obtaining the predictions of $0\nu\beta\beta$ mean lifetime is hampered by two bottle-necks. First, we do not know yet accurately the masses of neutrinos, and therefore we cannot confidently predict the value of the parameter $m_{\beta\beta}$ described in some details in the box here above. Second, while the behavior of neutrinos is essentially understood, atomic nuclei are complex objects, so that it is difficult to describe them accurately. We will discuss this point in a subsequent section, but previously we would like to comment on the traditional terminology used to describe this important process.

Interlude on the term 'neutrinoless double beta decay'

Following the terminology introduced by Rutherford, the expression 'β-rays' indicates the emission of high energy electrons in nuclear physics. However, this usage heavily hinders the clarity of exposition: while the word 'electron' is widely known, 'β-ray' belongs to the specialized nuclear-physics jargon. Furthermore, referring to *neutrinoless double β decay* amounts to defining a process through the absence of something, which surely does not help a layman understand the concept. In addition to this, the traditional nomenclature tends to hide the fact that we are not dealing with a ordinary nuclear process, one among many other ones. We deal with a process in which the creation of electrons takes place. In other words, this nuclear process offers us the possibility of experimentally scrutinizing the origin of matter. This is by no means trivial: despite numerous theoretical speculations, no experimental clue is available yet. For all these reasons, we believe that (in popular accounts at least) the expression,

> nuclear transformation where electrons are created

is better than "neutrinoless double β decay". Let us come back to the core of the scientific discussion.

The parameter $m_{\beta\beta}$

The transition $0\nu\beta\beta$ takes place if neutrinos have a nonzero Majorana mass. What matters is the mass of the electronic neutrino $m_{\beta\beta}$ (or, more precisely, the absolute value of the matrix element of the mass of the electronic neutrino). Its value is computed as a sum of the masses of individual neutrinos m_i, weighted by the electronic-neutrino mixing matrix U_{ei}:

$$m_{\beta\beta} = \left| \sum_{i=1}^{3} U_{ei}^2 m_i \right| \quad .$$

The $0\nu\beta\beta$-decay average lifetime is inversely proportional to $m_{\beta\beta}^2$.

An evolving context

In recent years, new, important developments in cosmology and theoretical nuclear physics feed the multidisciplinary nature of this kind of research. We discuss these aspects below, clarifying the implications on the interpretation of neutrinoless double β decay.

Impact on cosmology Neutrinos play an important role in astrophysics and cosmology. As a matter of fact, we remind the reader that the expansion rate of the Universe depends on the *number* of neutrino species. It impacts on the

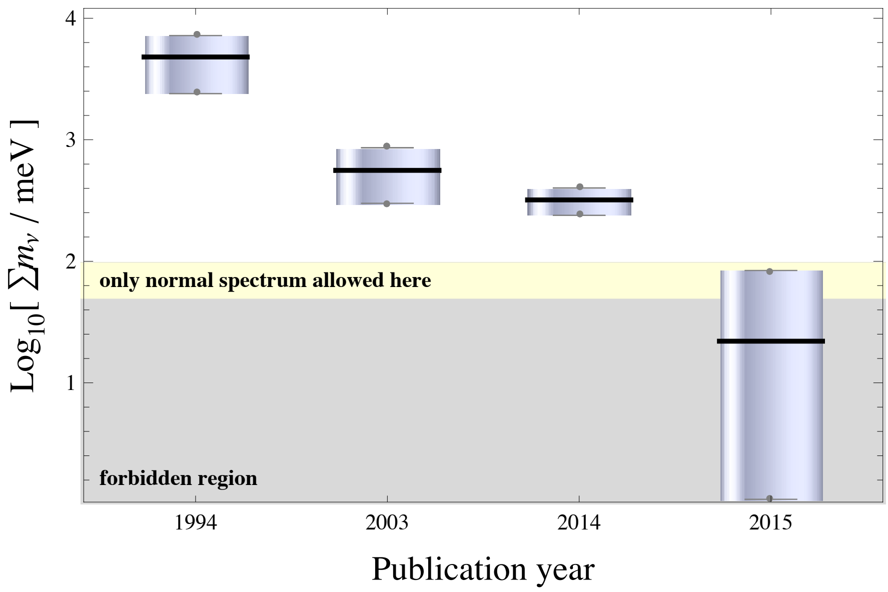

Figure 11: *This graph compares the values of the sum of the masses, obtained from cosmology by various teams of scientists: Primack et al,* $4.8 \times (1 \pm 50\%?)$ *eV (1994); Allen et al,* 0.6 ± 0.3 *eV (2003); Battye et al,* 0.3 ± 0.1 *eV (2014) and finally Palanque-Delabrouille et al,* 0.02 ± 0.06 *eV (2015). The most recent one, the last, is responsible for what has been called "the 2015 neutrino mass crash". The yellow strip emphasizes the region that is compatible only with the normal neutrino spectrum.*

cosmological abundances of light elements (determined in the first seconds of the life of the Universe) and also on the distribution of perturbation in the cosmic background radiation (determined when the age of the Universe was a few hundred thousand years). Both observations are compatible with the hypothesis that only three species of neutrino contribute to the expansion of the Universe.

The cosmological role of neutrino *masses* is even more important for the present discussion. For the effects we are interested in, all that matters is the coupling to gravity, which does not distinguish Dirac or Majorana neutrinos. We find it appropriate to recall that, in the last decades, cosmology has repeatedly hinted at neutrino having nonzero mass, but, during time, these indications weakened. The results of 2015 converge on giving a tight upper limit on neutrino masses, as emphasized in Fig. 11. Assuming that neutrinos are Majorana particles, we conclude that there is an important limit on the mass $m_{\beta\beta}$, which rules the amplitude of neutrinoless double β decay. This is illustrated and discussed in Fig. 12.

For the remainder of the discussion, we will keep in mind both the upper limit on $m_{\beta\beta}$ in the figure, and the rather specific value

$$m_{\beta\beta} = 8 \text{ meV}$$

compatible with current information and possible for a normal mass spectrum (see Fig. 7).

Uncertainties from nuclear physics How accurately can the average lifetime of $0\nu\beta\beta$ be predicted? Ten years ago, the majority of physicists would have plausibly replied as follows: since the various theoretical predictions differ by a factor two or three, it would be incautious to assume that it is possible to obtain much better results. The general opinion started to change when Faeßler and collaborators released calculations with a formal error around 10-20%. Their calculations turned out to be in reasonable agreement with other independent ones, conducted by Iachello and collaborators.

Caution is however mandatory. Let us in fact consider similar processes, as single β decay or electron capture,

$$\begin{aligned} &(A,Z) \to (A,Z+1) + e^- + \bar{\nu}_e && [\beta\text{-}] \\ &(A,Z) \to (A,Z-1) + e^+ + \nu_e && [\beta+] \\ &(A,Z) + e^- \to (A,Z-1) + \nu_e && [\text{capture}] \end{aligned}$$

or even $2\nu\beta\beta$. It is found that the agreement between predictions and measurements is within a factor 2–3. The momentum of neutrinos in these processes is orders of magnitude smaller than the momentum of neutrinos involved in $0\nu\beta\beta$ process, because, in the latter, neutrinos are confined in the nuclear ray, and must satisfy Heisenberg uncertainty principle. But this does not mean that predictions about $0\nu\beta\beta$ are more reliable than the others.

Several authors proposed an interesting conjecture, which might help clarify the situation.

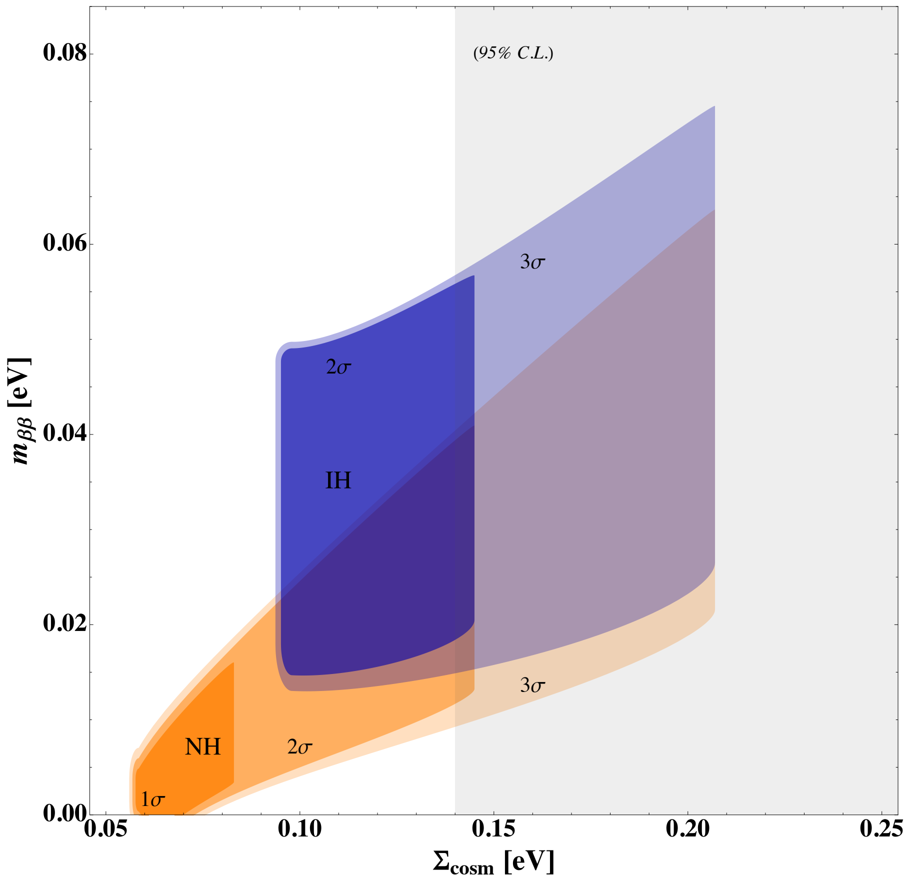

Figure 12: *In order to correctly interpret the assumption that the transition known as neutrinoless double β decay is due to the Majorana masses of the three neutrinos, it is necessary to take into account all the experimental information on neutrino masses.*

In particular, the interpretation of recent cosmological observations leads to an upper limit on the sum of the masses $\Sigma_{cosm} = m_1 + m_2 + m_3$, which in turn implies a constraint on the combination of masses of neutrinos, $m_{\beta\beta}$, that governs the rate of neutrinoless double β decay (see previous box).

In the plot we show the allowed regions for $m_{\beta\beta}$, at different confidence levels, assuming that neutrino mass spectrum is either normal (orange shading) or inverse (blue shading).

In β decay also nucleons participate in typical interactions which correspond to those already discussed for neutrinos. Nucleons are subject to intense coupling with spin currents, which have no analogue in electromagnetic interactions.[3] The corresponding coupling constants, called axial couplings, are measured and well known in the case of free nucleons, but it is reasonable to conjecture that the couplings of nucleons contained within a nucleus (i.e., in the nuclear medium) are different from those when they are free.

Developing this conjecture, and postulating that axial couplings inside the nucleus are modified, it is possible to recover a much better agreement between predictions on β decay with neutrino emission and measurements. Modifying the value of axial couplings, it is found that the predictions for $0\nu\beta\beta$ do change: the expected reaction rate decreases up to 5 or 6 times. If we want to observe a single event of a signal in a given data-taking interval and if we optimistically assume that there are no spurious signals, the correctness of the conjecture implies that we have to rescale by the same factor the mass of the detector.

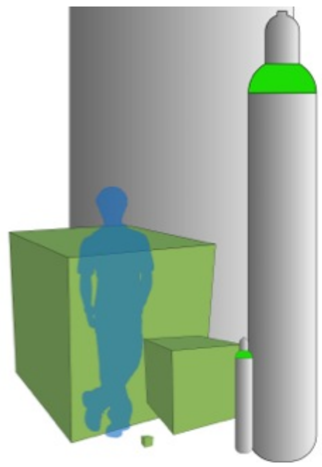

Figure 13: *Masses required to generate a single signal event from neutrinoless double β decay in 5 years of observation. The cubes are made of Germanium, the gas bottle contain Xenon, the largest is not in scale. In the three cases, it is assumed that the true mean lifetime coincides with the current experimental limit, or that it corresponds to $m_{\beta\beta} = 8$ meV with and without the modifications of the axial coupling in the nuclear medium.*

[3] In the modern understanding of weak interactions, these spin currents are tightly connected with the pecular interactions of the neutrinos, that treat differently particles with different helicities.

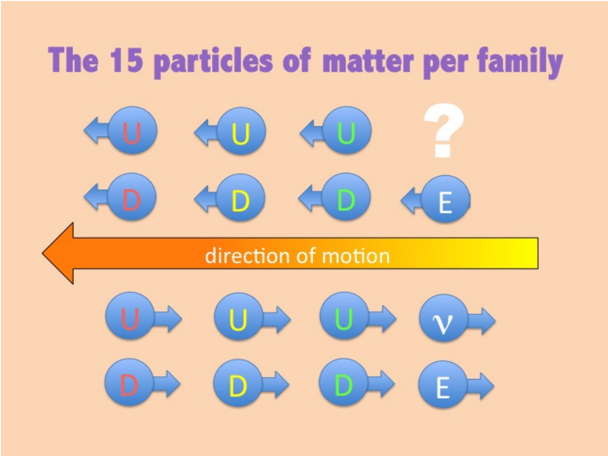

Figure 14: *The 15 particles of a single family of the standard model. In the upper part, particles with spin parallel to momentum; in the lower part, particles with spin antiparallel to momentum. The 3 kind of quarks are distinguished by the "color" quantum number. Neutrinos with spin parallel to the momentum are postulated to be absent, as emphasized by the question mark. In order not to burden the figure, we do not show the other 2 families, nor the antiparticles.*

In Fig. 13, we show the mass needed to detect a single event of $0\nu\beta\beta$ under different assumptions. In particular, we illustrate in the same figure what the implications of the above conjecture would be, assuming that $m_{\beta\beta} = 8$ meV.

Beyond known physics

The evidences that neutrinos have mass show that the theoretical reference model, known as 'standard model', is incomplete and must therefore be modified. There are several plausible options, and, in these last pages, we shortly discuss one which suggests that neutrinos have a Majorana mass.

As it is known, there are two kinds of matter particles: quarks, sensitive to strong interactions, and leptons (charged and neutral), which instead are not, see Fig. 14. All these particles, except perhaps for neutral leptons, are Dirac particles. This means that the direction of their spin can have parallel or antiparallel components with respect to the direction of motion. In the standard model it is postulated that neutrinos have only one of these two states. The other, if present, does not interact with matter.

But it is legitimate to think that also the other kind of neutrino exists and that it participates in new interactions, corresponding to larger mass scales. Indeed, let us have a second look to the way the fermions of the standard model are organized, see again Fig. 14. This inspires the idea that new neutrinos exists and have large Majorana masses. In this manner, we can easily explain the reason why we do not observe them and two interesting consequences can be drawn. First, it follows that known neutrinos have a small Majorana mass. Second, with models of this type it is possibile to explain the origin of matter in the first moments of the Universe. We will not discuss further these important topics, which are the subject of intense theoretical debates and that, hopefully, could be tested with suitable experiments in the future, maybe after the measurement of $0\nu\beta\beta$ mean lifetime.

Summary and discussion

Even if neutrinos are rather far from everyday experience, because of their extremely weak interactions, they have had a prominent role in designing the reference model for elementary particles. Since we realized that they possess small but nonzero masses, they have become more and more important and push us to modify our current ideas on the standard model.

Solving Majorana's conundrum about the nature of neutrino mass has become more urgent than ever. Majorana's hypothesis on its mass is compatible with all the available information and nicely interfaces with the current theoretical ideas. The most reasonable tool to verify its validity is the search for neutrinoless double β transition. A positive result would have an enormous importance, because this process involves the creation of electrons, that is, of ordinary matter. Unfortunately we have not yet obtained any confirmation from the experiments. For what concerns theory, we discussed why we are not able to confidently predict the expected signal, nor to rule out that it is very difficult to be detected.

In this situation, the wisest approach is pursuing the theoretical investigation and, above all, insisting on the experimental efforts.

Francesco Vissani: Researcher at National Institute for Nuclear Physics (INFN) in Gran Sasso National Laboratories (LNGS), coordinator of the Astroparticle Physics PhD at Gran Sasso Science Institute (GSSI) in l'Aquila, he mainly works on theoretical neutrino physics and astrophysics. He is very interested in discussing about physics with curious people. He had the pleasure of working on the topics discussed in this essay with two young experimental colleagues, Simone Marcocci and Stefano Dell'Oro (the latter in lab outfit in Fig. 10), with whom has prepared a review work on neutrinoless double beta decay, and also with the distinguished theoretician Alessandro Strumia, with whom he also wrote a long review on neutrinos. These review papers can be found by in INSPIRE database,

http://inspirehep.net/?ln=en

and contain many more details and information. The nicest figures in this essay are taken from these review papers.

Neutrino interaction with matter

A billion neutrinos go swimming in heavy water: one gets wet
Michael Kamakana

Maria Benedetta Barbaro *Physics Department - University of Turin, Italy*
Omar Benhar *INFN and Physics Department - University of Rome "La Sapienza", Italy*
Carlotta Giusti *Physics Department - University of Pavia, Italy*

Neutrino interactions with atomic nuclei, generating the signals used to detect neutrino oscillations, are a unique example of how, in a scattering process, the roles of probe, target, and detector can become interchangeable.

Introduction

Neutrinos are extremely elusive particles. In Leon Lederman's words: "They win the minimalist contest: zero charge, zero radius, and very possibly zero mass" [1]. Neutrino only get involved in weak interactions, responsible for neutron's beta decay (as well as in gravitational ones, which are anyway negligible).

In 1934 Hans Bethe and Rudolf Peierls, on the basis of an estimate of its cross section obtained by analyzing the inverse beta decay, peremptorily concluded that "There is no practically possible way of observing the neutrino"[2]. For his part, Wolfgang Pauli, who had conjectured the existence of the neutrino four years earlier, commented dismayed: "I have done a terrible thing, I have postulated a particle that cannot be detected".

In fact, cross sections associated to weak interactions are very small, and hence extremely difficult to measure. The value obtained by Bethe and Peierls, $\sigma \approx 10^{-44}$ cm^2, is about twenty orders of magnitude smaller than the typical cross sections for strong interactions between protons and neutrons. This estimate provides a value for the neutrino mean free path in water—namely the average distance a neutrino can travel in water without scattering with the particles of the surrounding medium—of the order of ten light years (a light year is equivalent to 9461 billions of km).

Neutrinos can only be observed indirectly, through the interactions between the other particles produced in the weak interactions and the matter the detector is made of. Since these interactions occur randomly, in order to increase their frequency, sufficiently intense neutrino beams and large quantities of matter are needed: more neutrinos, more matter, more interactions, more events.

This path has been constantly and successfully followed by Frederick Reines and Clyde Cowan [3], who employed as a source the Savannah River nuclear reactor, capable of producing a flux of 10^{13} antineutrinos per centimeter squared per second, and as a detector a device (represented in Fig. 1) made up of three tanks, containing 1200 litres of scinitillating liquid each, alternated with two tanks filled with 400 litres of water and 40 kg of cadmium chloride. The detector was placed at 11 m distance from the source and buried 12 m deep, in order to shield it against cosmic background radiation.

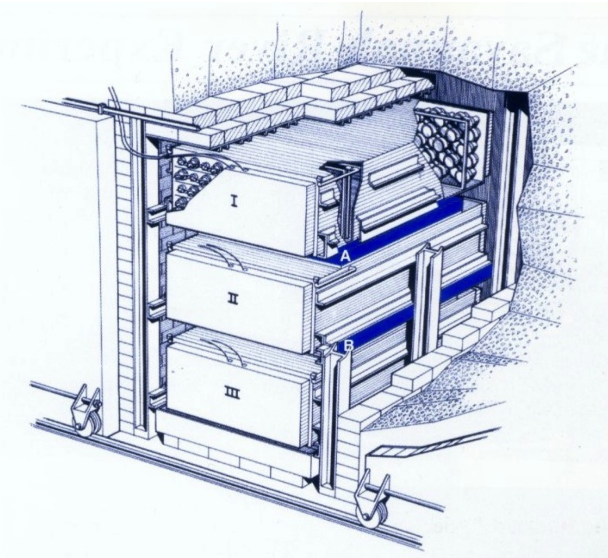

Figure 1: *Detector used by Reines and Cowan for the Savannah River experiment, which provided the first experimental evidence of the existence of neutrinos. The tanks I, II, and III contained scintillating liquid, while those labeled A and B were filled with water and cadmium chloride. 90 photomultiplier tubes were installed on the external sides of the tanks I, II and III.*

The antineutrinos coming from the reactor could interact with the hydrogen in the water through inverse beta decay, that is the process

$$\bar{\nu} + p \rightarrow n + e^{+} \ .$$

The produced positron immediately annihilated with an atomic electron, resulting in the emission of two photons, which were detected by photomultiplier tubes, and, about 10 msec later, the neutron was captured by a cadmium nucleus, with subsequent emission of another photon.

With the operating reactor, Reines and Cowan detected about 3 events per hour, a frequency much larger than the one due to cosmic rays events. On June 14, 1956 they were then able to inform Pauli that the neutrino had been definitely detected.

Modern experiments, whose principal aim is to determine the neutrino properties by observing its oscillations between different *flavor* states, are mostly designed following a scheme similar to the one used for the Savannah River experiment. However, in many cases the observed signals are produced through complex reaction mechanisms, where the structure and dynamics of the atomic nuclei of the materials present in the detector play an essential role. Therefore, the precision measurement of the relevant physical quantities requires that all these mechanisms, which contribute to determine the neutrino-nucleus cross section, must be well understood and accurately described.

Summarizing, we can say that the measurement of neutrino oscillations is based on the observation of neutrino-nucleus scattering processes where the target nucleus acts as a detector, whereas the observed signal is used to determine the properties, largely unknown, of the probe. It should not be forgotten, however, that the same signal can also contain valuable information on still poorly known aspects of the nuclear dynamics, difficult or impossible to study using charged leptons or hadrons as probes.

The observation of neutrino oscillations

According to the Standard Model of electroweak interactions, neutrinos are massless and exist in three different *flavor* states. Besides the electron neutrino, neutrinos emitted or absorbed together with the other two charged leptons, the muon and the tau, have indeed been observed. Electron, muon, and tau neutrinos, ν_e, ν_μ and ν_τ, participate in reactions where only the corresponding charged leptons appear. Hence, in the Standard Model, the leptonic number associated to each flavor is a conserved quantity.

Thanks to the results of a series of experiments carried out over the last two decades, nowadays we know that the neutrino mass is certainly non-vanishing, although it is much smaller than the value, of the same order of magnitude as the electron mass, suggested by Pauli in his famous letter to the "Dear Radioactive Ladies and Gentlemen" (see the box in the article of Giampaolo Co').

If neutrinos had zero mass, different flavor states would be degenerate. In this case, a basis should exist in which the Hamiltonian and the leptonic numbers could be simoultaneously diagonalized. In presence of a non-zero mass, instead, the states describing neutrinos with a given flavor differ from the mass matrix eigenstates, and the typically quantum phenomenon of mixing takes place. In turn, mixing is at the origin of neutrino oscillations, first put forward by Bruno Pontecorvo already in 1957, soon after Reines and Cowan's discovery.

Let us suppose that a weak interaction gives rise to the emission of a neutrino with flavor α. The neutrino state is described by a combination of the mass eigenstates ν_k $(k = 1, 2, 3)$ according to

$$| \nu_\alpha\rangle = \sum_k U^*_{\alpha,k} \mid \nu_k\rangle \ ,$$

where U is the unitary matrix describing the mixing. At the time it is detected, the neutrino will still be in a flavor eigenstate, that we shall call β, but since during its propagation from the source to the detector the phases of the wave function corresponding to different mass eigenstates evolve in time in different ways, a finite probability exists that the detected neutrino is in a different flavor state than the emitted neutrino, namely $\beta \neq \alpha$. For instance, an electron neutrino, after traveling a sufficiently long distance, can be observed as a muon neutrino.

In the simple case of two flavors the matrix U only depends upon one parameter, the mixing angle θ, and the relation between flavor and mass eigenstates is

$$|\nu_\alpha\rangle = \cos\theta|\nu_1\rangle - \sin\theta|\nu_2\rangle$$
$$|\nu_\beta\rangle = \sin\theta|\nu_1\rangle + \cos\theta|\nu_2\rangle \ .$$

The probability that a neutrino produced in a state α, with energy E_ν, is detected in the state β after traveling the distance L can be written in the form

$$P(\alpha \to \beta) = \sin^2 2\theta \ \sin^2\left(1.267 \ \Delta m^2 \ \frac{L}{E_\nu}\right) \ ,$$

where $\Delta m^2 = m_2^2 - m_1^2$, and m_i, E_ν and L are expressed, respectively, in eV, GeV and km. Note that θ and Δm^2 are the intrinsic neutrino properties which one wants to determine through the measurement, while E_ν and L are characteristic quantities of the experimental apparatus. The expression for $P(\alpha \to \beta)$ clearly shows that if neutrinos oscillate then their masses are finite, and viceversa.

In the case of three flavors the description of the oscillation probability is similar, but more complex. The parameters to be determined are three mixing angles, three squared mass differences, and one phase.

A great deal of evidence for neutrino oscillation has been collected from many experiments. In the late 60s, the Homestake experiment[4] observed a deficit in the flux of solar neutrinos with respect to the predictions of the Standard Model of the Sun, whose interpretation in terms of neutrino oscillations has been definitely confirmed in 2001 by data taken at the Sudbury Neutrino Observatory (SNO) [5]. Meanwhile, the first experimental evidence for atmospheric neutrino oscillations was observed by the SuperKamiokande experiment in 1998 [6].

Many recent experiments have employed neutrinos produced by artificial sources, namely nuclear reactors [7, 8, 9, 10] or accelerators, where neutrinos are produced from the decay in flight of pions, in turn obtained by scattering processes of the primary proton beam with a target [11, 12, 13, 14, 15, 16].

In the experiments which make use of neutrino beams produced by accelerators, whose energy varies from a few hundreds of MeV to a few tenths of GeV, the distance L between the source and the detector (*baseline*), chosen to maximize the oscillation probability, is typically of the order of hundreds of km. Experiments designed with these values of L are called *long baseline*.

Neutrino oscillations can be detected by observing, at a distance L from the source, a decrease in the number of neutrinos with a given flavor (*disappearence* experiments) or the presence of neutrinos with a flavor different from the one of the original beam (*appearence* experiments).

Disappearance experiments require high statistics and an accurate knowledge of the incident neutrino beam properties, in particular the intensity and the energy distribution, because both the oscillation probability and the scattering cross section depend on the neutrino energy E_ν. In many cases, since these beam characteristics are not known a priori with the necessary accuracy, two detectors are used, located at different distances from the source: a *near detector*, which allows performing measurements by using the original beam, and a *far detector*, used to repeat the measurements after the neutrinos have traveled the distance L. In *appearance* experiments, on the other hand, a high statistics is not required, but it is important to know if and how many neutrinos of different flavors are initially present in the beam.

In the measurements performed in *disappearance* mode the oscillation parameters are determined by analyzing the energy dependence of the oscillation probability, obtained from the ratio between the number of events detected with the far and the near detector, respectively. The result obtained by the T2K Collaboration with this procedure is reported in Fig. 2, which illustrates the relation between the measured signal and the parameters characterizing the oscillation.

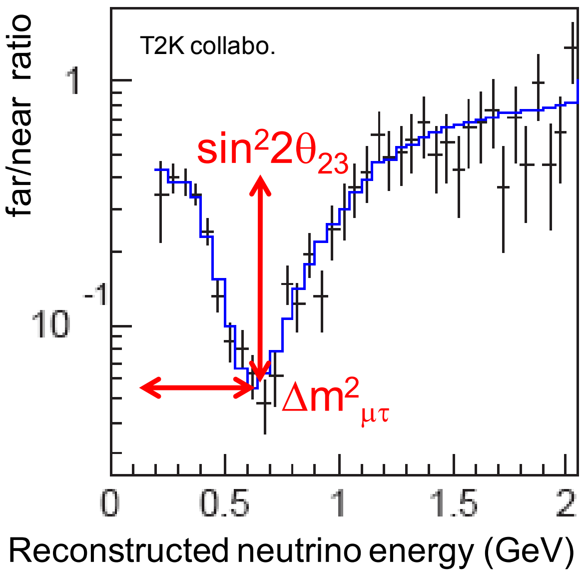

Figure 2: *Behavior of the oscillation probability observed by the T2K Collaboration, as a function of the neutrino energy reconstructed by analyzing the particles produced in the interactions with the target nucleus.*

Neutrinos interact with matter in the detector via charged or neutral currents, transferring energy and momentum to the target. In the charged current (CC) interaction, which occurs through the exchange of a $W^\pm$ boson, the neutrino is absorbed by the particle of matter with which it interacts—a nucleon bound inside an atomic nucleus—and the associated charged lepton is emitted. The charged lepton in the final state is generally the only particle to be detected. In the neutral current (NC) interaction, which occurs through the exchange of a Z^0 boson, the neutrino remains a neutrino and is therefore present in the final state. In this case what is detected can be either the recoil target or, if the nucleus disintegrates, the reaction products.

CC interactions are easier to observe, because electrons and muons have characteristic signatures in particle detectors and are thus easy to identify. Furthermore, the identification of the produced charged lepton allows deducing the flavor of the incoming neutrino. For example, if an electron is detected the initial neutrino was of electron type. Moreover, enough available energy is required to allow the mass of the charged lepton to be created. This implies that for very low-energy neutrinos (solar or reactor neutrinos) CC interactions can only concern electron neutrinos. In contrast, NC interactions do not allow for the identification of the initial neutrino flavor.

Neutrino energy reconstruction

As we have seen, *long baseline* experiments, which make use of neutrino beams produced by accelerators, are based on the observation of the dependence of the oscillation probability upon the incoming neutrino energy, E_ν. This quantity, however, is not known a priori, being distributed according to a flux of the type illustrated in Fig. 3, which refers to the MiniBooNE experiment. It is clearly seen that neutrinos with energies differing by many hundreds of MeV are produced with the same probability. As a consequence, the value of E_ν must be reconstructed from the measured properties of the particles produced in the neutrino-nucleus interaction.

Experiments using neutrino beams with energies peaked around 600 – 800 MeV, like T2K and MiniBooNE, determine the value of E_ν from the events produced by CC interactions using the kinematic variables of the charged lepton present in the final state, namely its kinetic energy and emission angle, which are measured in

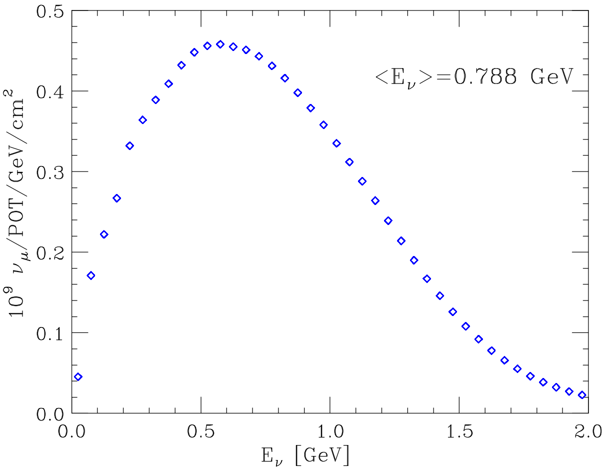

Figure 3: *Energy dependence of the neutrino energy flux used by the MiniBooNE experiment.*

large Cherenkov detectors filled with water and mineral oil.

This technique, called kinematic reconstruction, is mainly used for *quasi-elastic* events, characterized by the absence of pions in the final state, which provide the dominant contribution to the total cross section at relatively low energies. Its applicability requires, however, that a very stringent assumption on the reaction mechanism must be verified.

The reconstruction algorithm is based on the assumption that the neutrino interacts with a single nucleon at rest, whose binding energy inside the nucleus is approximated by a constant, ϵ. In this case the final state consists of a charged lepton, a nucleon emitted by the target nucleus, and a residual nucleus in a bound state.

Experiments performed using electron beams have clearly shown that reaction mechanisms other than the emission of a single nucleon can produce events that, although identified as quasi-elastic from the experimental point of view, are characterized by more complex final states. The accurate neutrino energy reconstruction in events of this kind, which we will discuss later, obviously requires more complex algorithms, based on realistic models of the nuclear dynamics.

At energies larger than ~ 1 GeV the contribution of inelastic processes, resonance production and deep inelastic scattering, increases until it becomes dominant. The determination of the neutrino energy in this kinematic regime requires the reconstruction of events characterized by the presence in the final state of many hadrons, both nucleons and mesons. This kind of analysis is possible, at least in principle, using the calorimetric technique.

Calorimeters are detectors that allow the measurement of the so-called *visibile energy*, that is, the kinetic energy deposited by the particles present in the final states, associated with each event. Devices of this type have already been used by the MINOS [13], OPERA [15] and NOνA [17] experiments and they will play an essential role in experiments presently at the design stage, like the Deep Underground Neutrino Experiment (DUNE) [18].

The calorimetric technique is obviously based on the ability of reconstructing correctly the final state, which in the first place depends on the detector characteristics and performances. However, also nuclear effects are vey important, since they can be at the origin of a significant quantity of *missing energy*, which makes the E_ν reconstruction problematic. For instance, if a pion produced at the primary vertex is reabsorbed inside the nucleus, its energy in not deposited in the calorimeter and it contributes to the missing energy.

In conclusion, regardless of the method used for the reconstruction, the determination of the neutrino energy, essential in order to obtain the oscillation parameters from the analysis of the detected signal, requires that all the reaction mechanisms active in the neutrino-nucleus interaction be accurately described.

Reaction mechanisms

Although neutrino interactions with free nucleons are rather well known, the description of the interactions with atomic nuclei presents considerable difficulties. The complexity of the dynamics of strong interactions, at the origin of the forces acting between nucleons, gives rise to a variety of processes, which contribute to the neutrino-nucleus cross section with a relative weight depending not only on the incident neutrino energy, but also on the kinematics of the scattering process.

A crucial role is played by the momentum transfer, q, which determines the spatial resolution with which the probe "sees" the target nucleus, λ, through the simple relation $\lambda \sim \pi/q$. For λ values of the order of the nuclear radius, which in the case of materials used in the detectors lies between 2.5 – 5 fm, (1 fm = 10^{-13} cm, 1 fm^{-1} = 197.3 MeV), the interaction results in the recoil of the target nucleus, which, depending upon the energy transfer, can remain in its ground state or it can be excited to a state of the discrete spectrum.

At momentum transfers larger than $\sim$ 500 MeV, on the other hand, λ becomes smaller than the average distance separating the nucleons inside the nucleus. In this kinematic regime, the interaction mainly involves a single nucleon that, at least in first approximation, receives all the momentum and energy transferred by the probe. It is however important to recall that this is a moving nucleon, whose response to the weak interaction is very different from the one of a free nucleon at rest.

If the neutrino energy is of the order of hundreds of MeV, in most collisions the fraction transferred to the nucleon is not sufficient to excite its internal degrees of freedom nor, a fortiori, to induce its fragmentation. In this case, the dominant mechanism is quasi-elastic scattering. For example, in the case of NC interaction with the oxygen nucleus, schematically illustrated in Fig. 4, the relevant reaction is

$$\nu_\ell + {}^{16}_{8}\mathrm{O} \to \nu'_\ell + p + {}^{15}_{7}\mathrm{N}^\star \ ,$$

where the index ℓ refers to the leptonic flavor and ${}^{16}_{8}$O denotes the oxygen nucleus, composed by $Z = 8$ protons and $A - Z = 8$ neutrons, in its ground state. In the final state there are, besides the neutrino, a proton emitted by the oxygen nucleus and the residual nucleus, ${}^{15}_{7}\mathrm{N}^*$, which can be in its ground state or in any other bound state. Then, as we anticipated in the previous Section, from the experimental point of view, quasi-elastic processes are characterized by the absence of pions, which are mostly produced in decays of the nucleon excited states.

The mechanism illustrated in Fig. 4 is based on the assumption that the nuclear dynamics can be described in terms of a *mean field* which generates the energy levels occupied by the nucleons. In this scheme, which underlies the nuclear shell

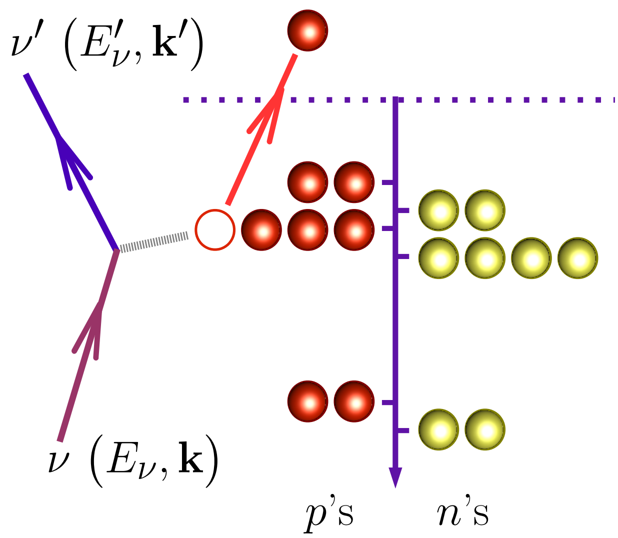

Figure 4: *Schematic representation of neutral current interaction between a neutrino with four-momentum $k \equiv (E_\nu, \mathbf{k})$ and a proton in the $1p_{3/2}$ shell of the oxygen nucleus ground state. In the final state of the process there are, besides the neutrino, a proton, emitted by the oxygen nucleus, and a nitrogen nucleus.*

model, in the ground state protons and neutrons occupy the lowest energy levels, in the case of oxygen the levels $1s_{1/2}$, $1p_{1/2}$, and $1p_{3/2}$ [1], which build up the *Fermi sea* and behave as a system of independent particles. The most radical implementation of this approach is the Fermi gas model, where the nucleus is described as a degenerate gas of nucleons having an average binding energy ϵ.

Since the 1970s, many electron-nucleus scattering experiments have analyzed the limits of the shell model, revealing substantial deviations with respect to its predictions, due to the presence of strong correlations between nucleons.

Correlations show up through collisions between pairs of nucleons in the nuclear ground state, which result in the excitation of both particles to states of the continuous spectrum outside the Fermi sea. The consequent reduction of the occupation probability of the energy levels predicted by the shell model has been confirmed by experiments performed using a wide variety of target nuclei, from helium to lead, and different kinematic conditions.

[1] We use the spectroscopic notation, according to which states of angular momentum $l = 0$ e 1 are labeled, respectively, by the letters s and p. The lower label refers to the total angular momentum eigenvalue, j.

If the neutrino interaction involves one of the particles belonging to the correlated pair, in the final state of the process there are two nucleons emitted by the target nucleus and a residual nucleus with $A-2$ nucleons. For instance, in the case of CC interaction with oxygen the following reactions can take place

$$\nu_\ell + {}^{16}_{8}\mathrm{O} \to \left\{ \begin{array}{l} \ell^- + p + n \ + {}^{14}_{8}\mathrm{O}^\star \\ \ell^- + p + p \ + {}^{14}_{7}\mathrm{N}^\star \end{array} \right. .$$

Since in many experiments the only detected particle is the charged lepton, ℓ^-, from the observational point of view such processes are indistinguishable from the reaction where only one nucleon is emitted

$$\nu_\ell + {}^{16}_{8}\mathrm{O} \to \ell^- + p + {}^{15}_{8}\mathrm{O}^\star ,$$

and their contribution must be included in the data analysis. In the case where two nucleons are present in the final state, the neutrino energy reconstruction is, however, far more complicated and requires a model of the nuclear dynamics including explicitly the effect of correlations between nucleons.

Two more mechanisms give rise to processes with emission of two nucleons: the final-state interaction between the nucleon which absorbed the four-momentum transferred by the neutrino and a "spectator" nucleon, and the interactions where the four-momentum transfer is shared by two nucleons. An example of the latter reaction is the process in which the weak interaction involves a meson exchanged between two interacting nucleons.

Finally, we note that, even in the kinematic regime where quasi-elastic scattering dominates, for instance, at typical energies of the MiniBooNE experiment it contributes by about 60% to the total cross section, the reactions where the final state contains at least one pion represent a very important background, whose description is essential for the correct interpretation of the observed signal.

State of the art and perspectives

During the last 10 years, the activity, both theoretical and experimental one, devoted to the study of neutrino-nucleus cross sections has received a significant boost, mainly due to the growing awareness of the role played by these quantities in the measurement of the oscillation parameters.

Ongoing and planned experiments have the two-fold purpose of measuring the neutrino cross section and shedding light on the underlying mechanisms related to the strong interaction dynamics and to the structure of the nucleus, many of them being still poorly known.

The MINERνA [19] experiment, already at the stage of data taking at the Fermi National Accelerator Laboratory (FNAL), near Chicago, will measure neutrino and antineutrino cross sections of energy $E_\nu \sim 3.5$ GeV, using as a 5 tons detector of plastic scintillator and as targets hydrogen, helium, carbon, iron and lead nuclei.

The MicroBooNE experiment[20], under construction at FNAL, will study the nuclear cross section of neutrinos of energy $E_\nu \sim 1$ GeV using a detector filled with 170 tons of liquid argon. Also at FNAL, the potentialities of this kind of detector have been explored within the ArgoNeuT project[21], which analyzed neutrino interactions in the 100 MeV - 1 GeV energy range.

Despite the modest statistics, the events detected by the Argoneut Collaboration have provided a very convincing evidence of two-nucleon emission processes. The information extracted from these measurements is a valuable complement to that obtained from electron scattering experiments. The argon nucleus, which will play the role of detector in an experiment like DUNE, has in this case perfectly played the role of target, whose internal structure and dynamics have been analyzed by using the neutrino as a probe.

The detection technique based on the use of liquid argon, proposed at the end of the 1970s and implemented for the first time at the Laboratori Nazionali del Gran Sasso in the ICARUS detector[22], will cover an essential role in future experiments. Valuable information on the argon nucleus will be acquired by an electron scattering experiment planned at the Thomas Jefferson National Accelerator Facility, in Newport News, Virginia, in the first half of 2017 [23]. The cross section measurement for the process

$$e + {}^{40}_{18}\mathrm{Ar} \to e' + p + {}^{39}_{17}\mathrm{Cl} ,$$

where the scattered electron and the emitted proton are detected in coincidence, will allow determining the momentum and energy distributions of the nucleons in the ground state of the target nucleus. The knowledge of this quantity will be an essential element for the neutrino energy reconstruction in the events detected by DUNE.

From the theoretical point of view, substantial progress has been made in the development of more and more realistic models of neutrino-nucleus cross sections, in most cases based on approaches already successfully employed for the description of electron scattering cross sections.

The most important specific problem which has to be faced in the case of neutrino scattering arises from the fact that the beam energy is not well defined, and the measured cross section is actually the average over a distribution like the one shown in Fig. 3. As a consequence, it is impossible to know precisely the energy transferred to the target nucleus, whose value, as we have seen, is the main factor determining the reaction mechanism. For instance, a quasi-elastic event of CC type, characterized by, besides the absence of pions in the final state, the measured values of the emission angle and kinetic energy of the charged lepton, may correspond to different transferred energies, and therefore to different production mechanisms.

The challenge to face in the next years is the definition of a scheme capable of describing *consistently* all the reaction mechanisms active at energies ranging from a few hundreds of MeV to a few GeV. Furthermore, the employed formalism will have to lend itself to be *efficiently* implemented in the simulation codes used for the data analysis, many of which are still based on the Fermi gas nuclear model.

[1] L. Lederman (with D. Teresi): *The God Particle: If the Universe is the Answer, What is the Question?*. Dell Publishing, New York (1993).

[2] H. Bethe and R. Peierls: "The neutrino", *Nature* **133** (1934) 532.

[3] C. L. Cowan Jr., F. Reines, F.B. Harrison, H. W. Kruse, and A. D. McGuire: "Detection of the Free Neutrino: a Confirmation", *Science* **20** (1956) 103.

[4] R. Davis, D. Harmer and K.C. Hoffman: "Search for Neutrinos from the Sun", *Phys. Rev. Lett.* **20** (1956) 1205.

[5] Q. Ahmad *et al.* (SNO Collaboration): "Measurement of the Rate of $\nu_e + d \to p + p + e^-$ Interactions Produced by ^{8}B Solar Neutrinos at the Sudbury Neutrino Observatory", *Phys. Rev. Lett.* **87** (2001) 071301.

[6] Y. Fukuda *et al.* (Super-Kamiokande Collaboration): "Evidence for Oscillation of Atmospheric Neutrinos", *Phys. Rev. Lett.* **81** (1998) 1562.

[7] K. Eguchi *et al.* (KamLAND Collaboration): "First Results from KamLAND: Evidence for Reactor Antineutrino Disappearance", *Phys. Rev. Lett.* **90** (2003) 021802.

[8] Y. Abe *et al.* (Double Chooz Collaboration): "Indication of Reactor $\overline{\nu}_e$ Disappearance in the Double Chooz Experiment", *Phys. Rev. Lett.* **108** (2012) 131801.

[9] J. K. Ahn *et al.* (RENO Collaboration): "Observation of Reactor Electron Antineutrinos Disappearance in the RENO Experiment", *Phys. Rev. Lett.* **108** (2012) 191802.

[10] F. P. An *et al.* (Daya Bay Collaboration): "Observation of Electron-Antineutrino Disappearance at Daya Bay", *Phys. Rev. Lett.* **108** (2012) 171803.

[11] P. Astier *et al.* (NOMAD Collaboration): "Search for $\nu_\mu \to \nu_e$ oscillations in the NOMAD experiment", *Phys. Lett. B* **570** (2003) 19.

[12] M. H. Ahn *et al.* (K2K Collaboration): "Measurement of neutrino oscillation by the K2K experiment", *Phys. Rev. D* **74** (2006) 072003.

[13] D. G. Michael *et al.* (MINOS Collaboration): "Observation of Muon Neutrino Disappearance with the MINOS Detectors in the NuMI Neutrino Beam", *Phys. Rev. Lett.* **97** (2006) 191801.

[14] A. A. Aguilar-Arévalo *et al.* (MiniBooNE Collaboration): "Unexplained Excess of Electron-Like Events From a 1-GeV Neutrino Beam", *Phys. Rev. Lett.* **102** (2009) 101802.

[15] N. Agafonova *et al.* (OPERA Collaboration): " Observation of a first ν_τ candidate in the OPERA experiment in the CNGS beam", *Phys. Lett. B* **691** (2010) 138.

[16] K. Abe *et al* (T2K Collaboration): "The T2K experiment", *Nucl. Instrum. Methods Phys. Res.* **A 659** (2011) 106.

[17] D. S. Ayres *et al* (NOνA Collaboration): Fermilab-Proposal-0929: "NOνA Proposal to Build a 30 Kiloton Off-Axis Detector to Study Neutrino Oscillations in the Fermilab NuMI Beamline", arXiv:hep-ex/0503053; R. B. Patterson: "The NOνA experiment: status and outlook", *Nucl. Phys. B, Proc. Suppl.* **235** (2013), 151.

[18] C. Adams *et al.* (LBNE Collaboration): "The Long-Baseline Neutrino Experiment: Exploring Fundamental Symmetries of the Universe" arXiv:1307.7335.

[19] L. Fields *et al.* (MINERVνA Collaboration): "Measurement of Muon Antineutrino Quasielastic Scattering on a Hydrocarbon Target at $E_\nu \sim 3.5$ GeV", *Phys. Rev. Lett.* **111** (2013), 022501. G. A. Fiorentini

et al. (MINERVνA Collaboration): " Measurement of Muon Neutrino Quasielastic Scattering on a Hydrocarbon Target at $E_\nu \sim 3.5$ GeV", *ibidem* **111** (2013), 022502.

[20] T. Katori (MicroBooNE Collaboration), in *Proceedings of the 7th International Workshop on Neutrino-Nucleus scattering in the Few GeV Region*, AIP Conf. Proc. **1405**, 250 (2011).

[21] C. Anderson *et al.* (ArgoNeuT Collaboration): "First Measurements of Inclusive Muon Neutrino Charged Current Differential Cross Sections on Argon", *Phys. Rev. Lett.* **108** (2012) 161802.

[22] J. N. Bahcall, M. Baldo-Ceolin, D. B. Cline, and C. Rubbia: "Predictions for a liquid argon solar neutrino detector", *Phys. Lett. B* **178** (1986) 324.

[23] A. Ankowski *et al* "Measurement of the Spectral Function of ^{40}Ar through the (e,e'p) reaction", arXiv:1406.4080 [nucl-ex].

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The future of neutrino research in Europe

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The discovery of neutrino oscillations has opened new perspectives in elementary particle physics and extraordinary opportunities for European research centres. These opportunities involve all sectors of experimental neutrino physics: the measurement of the absolute masses and of the relations among mass eigenstates, the violation of the leptonic number, the neutrino mixing and the study of CP violation. Thanks to oscillations, we know a priori the accuracies required by next-generation experiments. The experimental techniques under development as well as the size and the cost of experiments are extremely diverse: from projects that can be hosted in university labs to large underground experiments run by international collaborations and based on globally-shared facilities.

All in a rush

The discovery of neutrino oscillations [1] in 1998 opened a research program that, in principle, should have lasted for several decades. The experimentalists had the opportunity to measure all of the three mixing angles, as well as the mass differences among neutrinos. However, had the mixing angles been as small as those of quarks, or had mass differences laid outside the experimentally reachable regions for artificial neutrino sources, such challenge would have been gigantic. Definitely, this was not the case. The smallest mixing angle ($\theta_{13} \simeq 8°$) is almost equal to the largest quark angle (Cabibbo angle: $13°$). In practice, with a suitable L/E, i.e. a suitable ratio between the propagation distance and the energy of neutrinos (see the box "The oscillation formula in vacuum" in [1]) the oscillations probabilities become very large ($>10\%$). In fact, the L/E ratio was no more an unknown parameter already in 1998: oscillations were observed for neutrinos produced by the interaction of primary cosmic rays with the atmosphere (atmospheric neutrinos) and for solar neutrinos. The challenge was to design experiments with artificial sources having the right L/E ratio in order to reproduce accurately the oscillations of solar and atmospheric neutrinos. Several countries contributed to this experimental program. Japan played a leading role by hosting the first (K2K) and the most precise (T2K) experiments capable of observing oscillations at the atmospheric-neutrino energy scale with artificial sources. The first experiment that observed oscillations at solar-neutrino scale with neutrinos produced in nuclear reactors (KamLAND) was hosted in Japan, too. The United States built the most precise experiment to measure the mass difference that drives oscillations at the atmospheric-neutrino scale (MINOS, recently surpassed by T2K). China and Korea showed for the first time that $\theta_{13} \simeq 8^\circ$ using neutrinos produced in reactors. This result was spectacularly confirmed by T2K with neutrinos produced at particle accelerators. The oscillation $\nu_\mu \to \nu_\tau$ was observed for the first time in Europe by the OPERA experiment. OPERA was hosted at the Gran Sasso underground Laboratories in Italy and used a beam of ν_μ produced at CERN and pointing towards Italy. In an impressive series of precision measurements, the BOREXINO experiment (Gran Sasso) proved that the oscillations of solar neutrinos depend on the matter density in the Sun. The results that needed a 40-year long experimental programme in quark physics were achieved in "just" 15 years for neutrinos, although the accuracies in the measurements of the mixing angles are still rather far from those reached for quarks [2].

This enormous progress not only provided information on the oscillation phenomenon but also deeply changed the design philosophy on any future experiment. Until ten years ago, neutrino oscillations were a speculative phenomenon (and an opportunity for discovery). Today, the information gathered in neutrino-oscillation experiments is the pillar of all future projects on neutrino physics, even for projects that do not employ oscillations.

European research centers have always been strongly involved in neutrino physics and gave substantial contributions to this field. Nevertheless, now that the cost and the complexity of the experiments are comparable to those of particle-accelerator physics, planning the future of neutrino physics is a challenge by itself. Do we still have room for "national" experiments or an overall European strategy is strictly mandatory? Moreover, what is the boundary between a scientific enterprise that can be performed in Europe (or in any other country) and projects that require a global effort? The community of the physicists working with large accelerators raises these questions since decades and created infrastructures - e.g. the CERN laboratories in Switzerland - and decision-making processes to deal with them. On the other hand, neutrino physics is a much more diverse field. We can still find experiments that can be built and run in small labs, or even in university campuses, and facilities that need large international collaborations and show costs and a level of complexity that is comparable to large experiments at CERN.

In the following, we shall try to answer some of these questions, putting political and strategical aspects aside and employing as guiding principle what we learned from the discovery of neutrino oscillations.

Masses

Even before a direct observation of neutrinos, it was clear that their rest masses had to be very small. It is not surprising that the original formulation of the Standard Model assumed that neutrinos were completely massless - for details see D. Montanino in this book [1]. Much heavier neutrinos would have modified the kinematics of β decays in a very clear manner. For instance, a tritium nucleus (an unstable isotope of hydrogen composed of one proton and two neutrons), which decays through the process:

$$^3\mathrm{H} \rightarrow ^3\mathrm{He} + \ e^- + \nu_e \ ,$$

cannot produce electrons with energy equal to $m_{^3\mathrm{H}} - m_{^3\mathrm{He}} - m_e$ (m denotes the rest mass). A fixed (and irreducible) fraction of the energy available in this process has to be "employed" to produce the neutrino rest mass. The larger the neutrino mass, the smaller the maximum energy reachable by the electron. Thus, the study of the endpoint of the electron spectrum has always been considered the standard tool to "weigh" neutrinos [3]. As a mater of fact, after more than 70 years this method has not produced a measurement of neutrino masses, yet. The oscillations provide a simple explanation to this striking failure (see the box "Absolute neutrino masses") and show uniquely the path to follow to observe the endpoint distortion due to the ν masses.

Since beta decays involve electronic neutrinos, the electron spectrum is determined by the mass eigenstate the electronic neutrino mostly mixes with. If there exist very heavy eigenstates whose mixing angles with ν_e are negligible, such eigenstates become irrelevant in the study of beta decays. We may however be lucky: the heaviest eigenstate could be the one with the largest mixing to ν_e (in jargon, this is called the "inverse hierarchy" option). Even better, neutrinos could have large masses but mass eigenstates may be very similar: since oscillations are sensitive to the *differences* of the squares of the masses (Δm^2), a small value of Δm^2 could hide large actual masses (in jargon, "degenerate masses"). In the occurrence of inverse hierarchy (or, even better, degenerate masses), oscillations clearly imply that the mass of the neutrino entering the beta decay spectrum cannot be smaller than $\simeq \sqrt{\Delta m_{31}^2} \simeq 5 \times 10^{-2}$ eV. If an experimentalist is able to build an apparatus with a precision better than 50 meV, there are just two possibilities: either he sees the endpoint distortion (and probably he will get a Nobel prize) or he sees nothing, implying that Nature chose the "normal hierarchy" and that the heaviest mass eigenstate is the least mixed with ν_e.

Similar considerations hold for the search of "neutrinoless double beta decay" ($0\nu\beta\beta$) [4]. Such decays (see the articles by F.Vissani and E.Lisi [5, 6], in particular the box "Double beta decay" in [6]) are not allowed by the Standard Model but are possible in most of its extensions. An experimental evidence of $0\nu\beta\beta$ would represent a deep revolution in elementary particle physics: this phenomenon clearly contradicts the Standard Model because it violates one of its symmetries (the conservation of lepton number) but, at the same time, offers a simple explanation on why neutrinos have such small masses as compared to charged particles. Neutrinos would acquire the status of "Majorana particles": they would be the only elementary fermions identical to their antiparticles. Again, oscillations provide very precise information: if the hierarchy is inverse and neutrinos are Majorana particles, an experiment with a sensitivity better than 15 meV would certainly see the effect and, this time without any doubt, the experimentalist would get his Nobel prize. However, the risk of failure is here larger than for beta decays: if nothing is observed, we cannot claim that the mass hierarchy is normal because neutrinos might not be Majorana particles. In this case the $0\nu\beta\beta$ decay does not take place because of lepton number conservation, independently of the values of neutrino masses. Clearly, researchers working in this field (including the author) hope that fortune will favour the bold, just as it did a few years ago with the oscillations. We'll see whether they are right or not.

Europe currently hosts the world most precise experiment for the study of beta decay and its spectrum. It is called KATRIN and is located in Karlsruhe (Germany). It is the most spectacular extension (see Figure 1) of the experiments built in the '90 and exploits the same basic principles. Nonetheless, the accuracy expected to be reached in the next few years (approximately 200 meV) is still far from the critical 50 meV value. Will there ever be a "super-KATRIN" able to reach 50 meV? There are two schools of thought: most of us believe that the techniques implemented by KATRIN (magnetic spectrometry combined with special tritium sources) have reached their intrinsic limitations and new ideas are mandatory. A breakthrough could be, for instance, measuring the total energy in the beta decay through calorimetric techniques, or, more precisely, through the variation of temperature inside a diamagnetic material. This technique takes advantage of the enormous progress achieved in the last 30 years on thermal detectors, which are to-date employed in several experiments for observational cosmology. The main groups pursuing this strategy are based in Europe and, recently, two European experiments (ECHO and HOLMES) started working with a very promising isotope, Holmium-163. The other school of thought believes that there is still room for improvement for the technology of KATRIN. Recently, a US collaboration (PTOLEMY) started a research and development program based on that technique, with the ambitious goal of measuring the neutrinos produced by the Big Bang. Beta-decay physics is one of those sectors where there is still a lot of room for "university lab" experiments aimed at identifying the best strategy to reach the 50 meV threshold. However, the construction of the main experiment will certainly require merging of resources and the development of a unique European program for the precision study of beta decay.

The situation for $0\nu\beta\beta$ is quite different. The current accuracies are already very good (if we assume that neutrinos are Majorana particles)

Absolute neutrino masses

The experimental techniques for the measurement of neutrino masses never involve single mass eigenstates. In beta decays, the distortion of the electron spectrum is due to the presence of ν_e and involves all mass eigenstates mixing with the electron neutrino. The relationship connecting the "effective neutrino mass" (m_β) determining the electron spectrum and the masses of the individual eigenstates is the following:

$$m_\beta = \cos^2\theta_{13}\cos^2\theta_{12}m_1^2 + \cos^2\theta_{13}\sin^2\theta_{12}m_2^2 + \sin^2\theta_{13}m_3^2 \, .$$

Starting from 2012, these angles, as well as $m_2^2 - m_1^2$ and $|m_3^2 - m_2^2|$, have been measured. We can thus determine the minimum m_β when m_3 ("normal hierarchy") or m_1 ("inverse hierarchy") is the heaviest state. In particular, one has:

$m_\beta > 10$ meV - normal hierarchy
$m_\beta > 50$ meV - inverse hierarchy

Similar considerations hold for $0\nu\beta\beta$, for which $m_{0\nu\beta\beta} < 10$ meV for normal hierarchy, and $m_{0\nu\beta\beta} > 15$ meV for inverse hierarchy. Generally speaking, inverse hierarchy is an extremely favorable condition for the experimental observation of these processes.

Figure 1: *Transportation of the spectrometer of the KATRIN experiment to Karlsruhe.*

and the 15 meV target is not too far. Many experimental groups are at work to increase the quantity of isotopes in the experiments, and thus the probability of observing one of these very rare events, and the background rejection. Similarly, nuclear physicists are trying to reduce the theoretical uncertainties in the link between the average lifetime of $0\nu\beta\beta$ and the neutrino masses. At present, this uncertainty is the main source of systematic errors in the study of Majorana neutrinos. The physics of double beta decay has long left university campuses, since all modern experiments require very deep underground laboratories for cosmic-ray background rejection. Europe already has outstanding facilities in this field: a laboratory with very large experimental halls and infrastructures (the above-mentioned Gran Sasso Laboratories) and several smaller labs hosting top-level experiments for double beta decay: the laboratories in Modane (France), in Canfranc (Spain) and in Boulby (England). The world-wide competitors are, however, in very good shape: in parallel with the three most accurate European experiments for double beta decay (GERDA and CUORE - Figure 2 - in Gran Sasso and NEMO-3 in Modane) important results have already been obtained in the United States (EXO) and in Japan (KAMLAND-Zen). New labs and projects are currently under development in the United States, Canada, Japan, China, Korea and India. In this sector a European strategy is thus essential and the European astroparticle community promotes coordinated activities since long. But at the end physics will drive all strategies: the experiments mentioned above use very different techniques and, at present, it is not clear which ones can be extended to 15 meV. In the next ten years we will gain additional information and down-select the most promising approaches. All in all, the research and development phase is still open and substantial technological progress, in particular for what concerns the purity of materials and background rejection, is necessary to reach the goals set by our current understanding of oscillations.

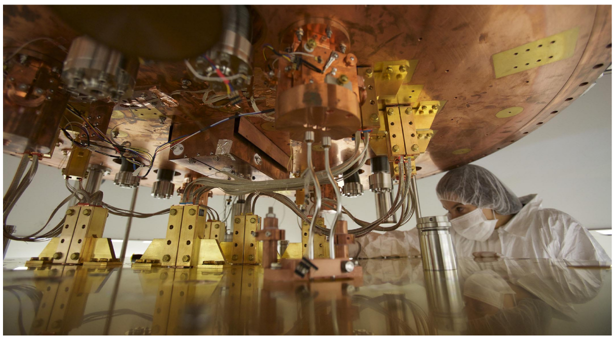

Figure 2: *The CUORE cryostat is able to cool down to 10 mK about 740 kg of thermal detectors employed for the study of Tellurium rare decays.*

Mass hierarchies

In the physics of absolute masses, the heaviest eigenstate and its mixing with ν_e can make the difference between an "exploration" experiment and a real discovery. Is there a way of disclosing the mass hierarchy without explicitly measuring the mass eigenstates? There is, once more thanks to neutrino oscillations. Since the end of the '90, many proposals have been put forward. Nearly all of them are based on the Mikheyev–Smirnov–Wolfenstein (MSW) effect described in [1]: neutrino oscillations in matter are perturbed by the presence of atoms and the oscillation probability shows a clear dependence on the mass hierarchy, i.e. not only on the absolute value of Δm^2, but also on its sign. All the experiments proposed in Europe, United States and India for the measurement of the hierarchy are based on this idea but none of the experiments that are currently running has the sensitivity to observe such a small perturbation. The only exception is the NOVA experiment in the US, which has just started data taking; still, NOVA will be able to observe the effect only in particular regions of the parameter-space and with reduced statistical sensitivity.

The race for the measurement of the mass hierarchy [7] is open and, unlike the measurement of absolute masses, this observable is clearly accessible to the existing technologies. The possibility of observing this phenomenon is linked to the probability of the oscillation $\nu_\mu \to \nu_e$ at the atmospheric-neutrino energy scale (a few GeV's). The probability amplitude depends on the angle θ_{13}. Had this angle been small, or even comparable to the corresponding angle for quarks, the measurement would have been as difficult as that of absolute masses. In 2012, experiments in China, Korea, Japan and, more recently, the French experiment Double-Chooz showed that θ_{13} is very large (8°), indeed. Therefore, even the most speculative techniques proposed in the past have a chance of performing the measurement.

One of the most speculative ideas was proposed by S.Petcov and M. Piai in 2002 [8] and is based on the observation of beats in the oscillation probabilities of neutrinos produced in nuclear reactors. The beats are due to the fact that $\Delta m^2_{31} \neq \Delta m^2_{32}$ and from the measurement of the beats it is possible to determine the mass hierarchy. I remember the impression I got when I read Petcov's paper 14 years ago. In the Conclusions of the paper, the authors clearly stated that the technique would work only if $\theta_{13} > 6°$. At that time the value of this mixing angle was unknown but previous reactor experiments demonstrated that $\theta_{13} < 9°$. Needless to say, I filed the paper in the list of "smart ideas that will never work". I was definitely wrong: today the largest Chinese project in neutrino physics (the JUNO experiment) is based on this idea and it involves hundreds of physicists, including a large European collaboration. Nature chose $\theta_{13} \simeq 8°$ and, once more, has been very kind with neutrino physicists.

Will it be possible to measure the mass hierarchy in a European experiment, maybe directly competing with JUNO? Probably yes: since $\theta_{13} \sim 8°$, matter effects and the perturbations induced by the mass hierarchy will be visible also in atmospheric-neutrino oscillations. The large underwater neutrino telescopes designed to observe high-energy astrophysics neutrinos can be re-optimized to observe neutrinos at the GeV scale by installing a dense network of detectors in small portions of sea volumes. This re-optimization has been recently proposed by the Ice-Cube collaboration (for ice) and by the KM3-Net Collaboration (for water - see [9]). The observations in water will be performed by the ORCA experiment (Figure 3) in the Mediterranean sea, close to the French coasts, while data will be collected in the South Pole by the PINGU experiment.

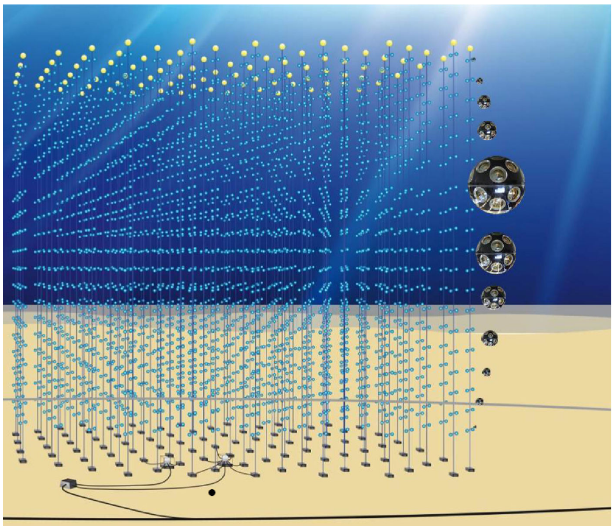

Figure 3: *Arrangement of underwater photomultipliers for the observation of atmospheric neutrinos in ORCA.*

The main advantage of these experiments is the use of neutrino sources that are already available in the environment: atmospheric neutrinos for ORCA/PINGU and nuclear-reactor neutrinos for JUNO. It comes to the price of a poor control and knowledge of the source energy spectrum, which represents the main limitation to the experimental sensitivity. A completely controlled source, produced at accelerators, at the energy optimized for the amplification of matter effects would be the ideal solution. But is this a viable solution, too?

Neutrino beams

Artificial neutrino sources - in particular at accelerators - have been a crucial tool to gain evidence of the oscillations of neutrinos. In neutrino beams [10], ν_μ are produced by the two-body decays of pions: $\pi^+ \to \mu^+\nu_\mu$. Pions are, in turn, produced by the interaction of protons with graphite or beryllium targets and are focused by magnetic lenses. It is thus possible to produce muonic-neutrino beams at any energy in the range 0.1 to 100 GeV and, deflecting pions before their decay, to point them towards any place on Earth. These beams are the perfect tool to study $\nu_\mu \to \nu_e$ and $\nu_\mu \to \nu_\tau$ oscillations with accuracies of the order of 1%. They are the ultimate tool in neutrino physics but also the most expensive ones.

A neutrino beam with 1 GeV energy pointed toward a detector located 1000 km far from the source can measure the mass hierarchy with a precision much higher than JUNO, ORCA and PINGU and remove the systematic errors plaguing environmental sources. Still, is it worth the trouble (and cost)? Building a beam just to determine the mass hierarchy can be risky because the mass hierarchy is not a continuous variable. It is binary: the mass hierarchy can be either normal or inverted. Thus accuracy is needed to suppress statistical fluctuations and systematic errors but does not improve our knowledge of the oscillation parameters. JUNO, ORCA and PINGU could find a statistical evidence with a confidence of 3-4 sigmas and, by combining their data, those experiments would provide a solid measurement of the hierarchy. Obviously, things may go wrong: conflicting data could lead to an inconclusive result, as it occurred recently with sterile neutrinos [1] (see the essay by P. Bernardini [11] in this book). But then, why not wait and see what happens?

The reason is that neutrino beams can do much more than determining the neutrino mass hierarchy and perform a measurement that was considered nearly impossible ten years ago. Since all mixing angles are large, laboratory experiments can observe an important interference effect among the three mass eigenstates. In quarks, this effect generates the violation of the charge conjugation parity (CP) symmetry (see the box in the essay by Montanino [1]) and such violation is partially responsible for the matter-antimatter asymmetry in the universe. Neutrino mixing can produce a similar effect and represents a further source of CP-violation in the universe. Its observation is trivial from the conceptual point of view (but very challenging experimentally): CP violation produces a difference between the $\nu_\mu \to \nu_e$ oscillation probability and the oscillation probability of the corresponding antiparticles ($\bar{\nu}_\mu \to \bar{\nu}_e$). This difference depends on a complex phase in the mixing matrix [1]: if the phase is maximal ($\delta = \pi/2$), the difference is maximal, if the phase is zero ($\delta = 0$), the CP symmetry is preserved.

Experiments with artificial neutrino beams are the only realistic possibility to observe CP violation in the neutrino sector of the Standard Model. These experiments require ten times the intensity of current beams, detectors with a mass of 10^5 tonnes and anticipated costs that exceed a billion Euros. There is no doubt that these facilities can only be "global projects" and require a world-wide effort and coordination of all particle physicists. What are the chances for Europe to host such a facility? Europe has two important assets: the CERN laboratories near Geneve and the European Spallation Source near Lund. Both can provide the extremely bright proton sources necessary for the study of CP violation. The former allows also to study the mass hierarchy [12], the latter is limited to the study of CP violation [13]. Both, however, call for the construction of a detector with a suitable mass.

Outside Europe, the United States are proposing a project similar to that based on CERN: protons are produced and accelerated at Fermilab (Illinois) and neutrinos are pointed towards the DUNE experiment (South Dakota), at a distance of approximately 1300 km. At the time of writing, the US project is the only one that got substantial funding (about 75% of the cost) by the hosting institutions. Japan is planning to use the proton accelerator of the JPARC laboratory to send neutrinos towards a new detector (HyperKamiokande) located at a distance of 230 km. The Japanese proposal has not been funded yet and does not have high sensitivity to mass hierarchy but has definitely the best sensitivity to CP violation.

Much could be said about the pros and cons of these proposals. At this stage, however, physics should be complemented by strategical and economical assessments, which are well beyond the scope of this essay.

Conclusions

In the last 15 years neutrino physics has been developing with a fast pace. The key of this acceleration was the discovery of neutrino oscillations, a phenomenon that deeply changed this research field and allows to pin down very precisely the goals for the next generation of experiments. Today, neutrino physics offer opportunities for several type of experiments, from “university-sized” projects to facilities that challenge the complexity and cost of high energy accelerators. Europe benefits from many infrastructures that are ideally suited for neutrino physics: underground laboratories, large accelerators and research centers focused on the development of new technologies. Thanks to these assets it will likely play a major role in this field also for the next decade.

It is quite common to hear that “neutrino physicists have been very lucky in recent times”. I hope I was able to explain why. Still, we should not underestimate the ingenuity and perseverance behind the experimental programmes that brought to the discovery of neutrino oscillations and we should be inspired by them for the future. Nature won’t always be prodigal with us but, hopefully, it will be inclined to favor the bold.

[1] D. Montanino, ”Neutrino oscillations”, in this book.

[2] K.A. Olive et al. (Particle data Group): “Review of Particle Physics”, *Chin. Phys. C* **38** (2014) 090001.

[3] G. Drexlin et al.: “Current Direct Neutrino Mass Experiments”, *Advances in High Energy Physics* **2013** (2013) 293986.

[4] A. Giuliani and A. Poves: “Neutrinoless Double-Beta Decay,”, *Advances in High Energy Physics* **2012** (2012) 857016.

[5] F. Vissani, ”Majorana’s conundrum”, in this book.

[6] E. Lisi, ”Neutrinos: messengers of new physics”, in this book.

[7] R.B. Patterson, ”Prospects for Measurement of the Neutrino Mass Hierarchy”, arXiv:1506.07917 [hep-ex].

[8] S.T. Petcov and M. Piai: “The LMA MSW Solution of the Solar Neutrino Problem, Inverted Neutrino Mass Hierarchy and Reactor Neutrino Experiments”, *Phys. Lett. B* **533** (2002) 94.

[9] V. Flaminio, ”Neutrinos astrophysics”, in this book.

[10] S. Kopp: “Accelerator-based neutrino beams”, *Phys. Rep.* **439** (2007) 101.

[11] P. Bernardini, ”The frontier of sterile neutrinos”, in this book.

[12] A. Rubbia: “LAGUNA-LBNO: Design of an underground neutrino observatory coupled to long baseline neutrino beams from CERN ”, *J.Phys.Conf.Ser.* **408** (2013) 012006.

[13] M. Dracos: “ The ESS Based Neutrino Super Beam for CP Violation Discovery”, *Phys. Procedia* **61** (2015) 459.

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Neutrino experiments in the USA

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Introduction

The United States host a number of projects for the study of neutrino oscillations and their interactions with matter.

We can classify the experiments in three categories, according to the time in which they will take data: "present", "near-future" and "far-future" experiments. The list of the present experiments includes NOνA, Minerva and MINOS. The near- and far-future experiments are MicroBooNE and DUNE respectively. Another kind of classification involves the technology adopted to measure neutrino properties. Experiments such as MicroBooNE or DUNE will employ liquid-argon technology to precisely identify neutrino interactions.

NOνA

NOνA is an experiment based in the United States, which uses the Fermilab neutrino beam called NuMI with an intensity increase, and a far detector positioned at a distance of about 800 km. The NuMI beam (Neutrinos at Main Injector), uses the proton beam produced by the Fermilab main injector on a graphite target that resembles a long metal cylinder. The collisions between the protons and the graphite target produce many different types of fundamental particles, including pions, which are charged particles. Pions are then steered by the use of magnets (horns) in a given direction and short after their creation (100 m), they decay into muons and muon neutrinos, which continue to travel in the same direction of the pions. The NuMI's target and horns, which determine the direction of the neutrino beam, are shown in Fig. 1.

Figure 1: *NuMI neutrino beam and target. Photo courtesy of Fermilab.*

The neutrino beam is aimed downward at a 3.3° angle. Although the beam starts out around

50 m below ground at Fermilab, it will travel approximately 10 km below the hearth surface before reaching NOνA's far detector in Ash River (Minnesota), around 800 km North West, close to the Canadian border. In its journey from Fermilab to Ash River, the beam crosses three states and a lake: Illinois, Wisconsin, Lake Superior (the underlying Crust) and Minnesota.

The Fermilab accelerator facility is currently capable of delivering 400 kilowatts of power to the NuMI beam, but part of the NOvA project will include an upgrade to the accelerator to allow it to provide at least 700 kilowatts of power to NuMI.

In addition to the 14 metric-kiloton far detector in Ash River (Minnesota), the NOνA experiment uses a 30 metric-ton near detector at Fermilab. The detectors are made up of 34,4000 cells of extruded, highly reflective plastic PVC filled with liquid scintillator, see Fig. 2. The NOνA blocks are filled with a liquid composed of 95% mineral oil and 5% Pseudocumene (a colorless inflammable liquid), which is toxic, but nevertheless essential in neutrino experiments because it amplifies the incident light, allowing neutrinos to be more easily identified and measured. Each cell in the far detector measures 3.9 cm wide, 6.0 cm deep and 15.5 meters long. The cell assembly is shown in Fig. 2.

When a neutrino strikes an atom in the liquid scintillator, it releases a trail of charged particles. As these particles come to rest in the detector, their energy is collected using wavelength-shifting fibers connected to photodetectors. Using the pattern of light seen by the photo-detectors, it is possible to determine which kind of neutrino caused the interaction and what its energy was.

The NOνA data-taking started officially in September 2013, while the Ash River facility was completed in the fall of 2014. The first phase of the experiment will last six years.

NOνA will allow a better characterization of neutrinos, determining their lifetime, direction and energy. By studying the oscillations for the different neutrino flavors scientists hope to unveil the mass hierarchy and why the Universe contains, nowadays, more matter than antimatter. The task of researchers at NOνA is, literally, to catch neutrinos with very large and expensive

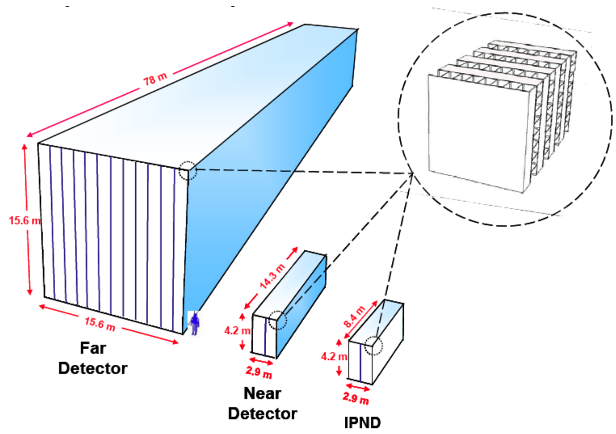

Figure 2: *The PVC-cell assembly scheme in NOνA detectors.*

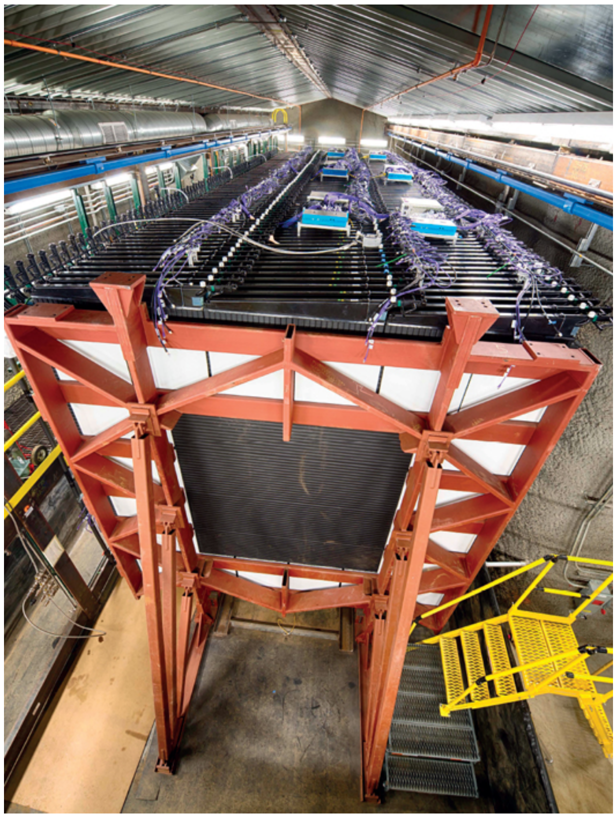

Figure 3: *The NOνA near detector.*

equipments. NOνA has already found the first evidences of neutrino oscillations.

MINOS

The MINOS experiment uses the muon-neutrino beam produced by the Fermilab's main injector, also used by the NOνA experiment. The neutrino beam is in this case sent 735 km far through the Earth towards a 5,000-ton neutrino detector at 800 m depth at Soudan Underground Laboratory, in Minnesota. The pictures of MINOS near and far detector are presented in Fig. 4 and 5.

Figure 4: *The MINOS near detector, at Fermilab.*

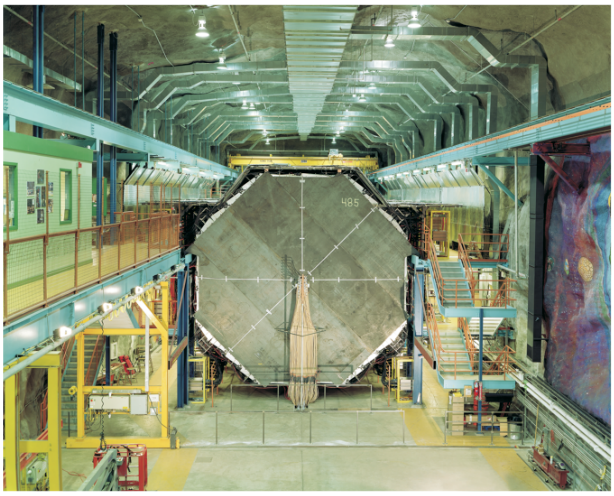

Figure 5: *The MINOS far detector, in Minnesota.*

The MINOS experiment, like the NOνA, uses two almost identical detectors: the near detector, located at Fermilab, is used to control the muon neutrino beam, while the one in Soudan is employed for the search of electron and muon neutrinos. Neutrinos travel the distance from Fermilab to Soudan in four hundredths of second, a sufficient time to change their identity. Both the detectors are composed of plastic scintillator. The light coming from the charged particles emitted by neutrino interactions is captured by optical fibers and transformed into electric signals by photomultipliers. Both detectors are immersed in a magnetic field.

The observation of events in the Soudan detector allows the researchers of the MINOS experiment to obtain information on the quantity $\sin^2 2\theta_{13}$. If muonic neutrinos did not transform into electron neutrinos, this quantity would be zero. The allowed range of values obtained in the last measurement performed by MINOS overlaps with that of T2K experiment, by it puts a more stringent limit. MINOS reduces this range to 0-0.12, improving the results it obtained in 2009 and 2010 with a narrower data set. The range obtained by T2K is 0.03-0.28.

Minerνa

The detector Minerνa is located in front of MINOS near detector. Minerνa has the goal of studying in detail neutrino interactions in different materials. The detector is composed of many layers of parallel plastic scintillator strips (as in MINOS) alternating with carbon, iron and lead layers, as shown in Fig. 6.

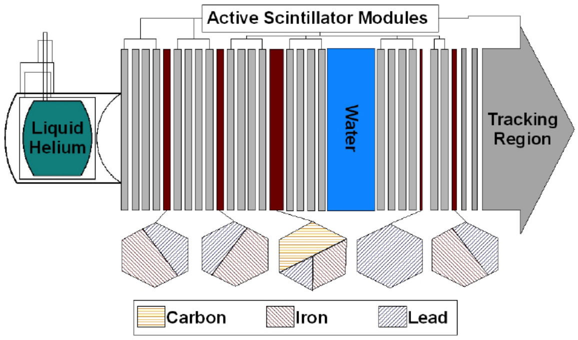

Figure 6: *Layer assembly scheme in Minerνa.*

DUNE

The Deep Underground Neutrino Experiment (DUNE) will be the largest experiment ever built for the study of neutrino oscillations. The new neutrino beam (which will be produced in Fermilab) will send particles at around 1,300 km distance towards a 40,000-ton liquid-Argon detector hosted at Sanford Underground Research Lab in South Dakota. The technology used by DUNE for detecting neutrino interactions is based on liquid Argon. The far detector will be filled with liquid Argon, which will allow to use a highly advanced technology to capture through thin-wire layers three-dimensional images of the tracks left by the charged particles produced by neutrino interactions. DUNE will use also a near detector, similar to that of T2K by still under development, to characterize both the neutrino beam produced in Fermilab and neutrino interactions in liquid argon. A part of the DUNE project consists in a series of ("short baseline“ or SBND) experiments currently under construction in Fermilab and performed with a number of liquid-argon detectors, including the detector ICARUS (see Fig. 7) developed in Italy.

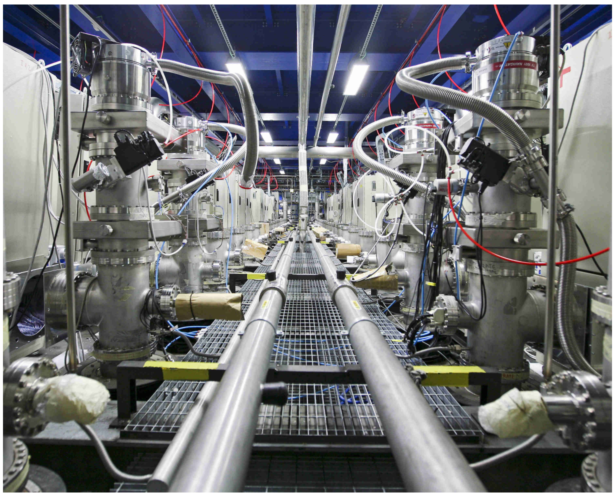

Figure 7: *The ICARUS detector.*

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Neutrino astrophysics

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Our understanding of the very high-energy events taking place in astrophysical objects, such as Supernova explosions, Gamma Ray Bursts, Active Galactic nuclei and others has drastically improved over the last decades, mainly due to the technological progress in the field of gamma and x-ray astrophysics. Moreover, the observation of solar neutrinos and later on of those emitted in the explosion of supernova 1987a has answered several questions concerning processes taking place inside stellar objects and revived the interest in High Energy neutrinos coming from cosmic sources. The interest has more recently been revived by the observation of very high-energy neutrinos in the IceCube experiment, located under the ice at the South Pole. Here we plan to illustrate the role that neutrinos have had and continue having in astrophysics, paying particular attention to the field known as *high-energy astrophysics*.

A very short review of modern astronomy

While the earliest astronomical observations and detailed recordings go back to the Babylonians, Chaldeans, Chinese, the Greeks and, in more recent times to the Arabs arriving in southern Europe, it was only with Copernicus and with Galileo and his refracting telescope, that modern optical astronomy was born. Following the first demonstration of his telescope, that took place in Venice in 1609, Galileo managed to exploit it to make a number of important observations, like that of the lunar mountains and craters, of the moons of Jupiter, of the rings of Saturn, the phases of Venus. Since then, an impressive progress has been made in the field of optical astronomy and, more generally, in the branch of astronomy based on the detection of electromagnetic radiation by cosmic sources. The drawback that ground-based optical telescopes have, related to atmospheric light absorption, have been overcome thanks to the construction and operation of satellite-based telescopes like the Hubble Space Telescope (HST) and, more recently, of mountain-top telescopes using adaptive optics to correct atmospheric blurring and thus improving image sharpness to a level far exceeding that of the HST and characterized by angular resolutions better than 0.1 arc sec.

A further important progress came with the development of infrared astronomy, pioneered by Charles Piazzi Smyth who made in 1896 a detailed study of the heat emitted by the Moon, using a thermocouple. Probing the infrared region of the spectrum is important for it allows to explore dense gas clouds, to study molecules and to observe distant galaxies that emit most strongly in the infrared during the star formation bursts. The infrared radiation moreover penetrates the dust clouds located between us and the Galactic center. For many years mountain-based telescopes equipped with infrared filters have been used to scan the Galactic center region. Of great help were the first lead sulphide detectors (that became available to astronomers in the 1950s) operated at liquid nitrogen temperature.

In the early 1930s a further important development took place thanks to Karl Jansky, who for the first time observed radio emission from the center of the Milky Way, later identified with Sagittarius A. The intrinsic limitation on angular resolution of radio telescopes was later overcome with the development of Radio Interferometry by Martin Ryle, Joseph Lade Pawsey and Ruby Payne-Scott in 1946, bringing the resolution from the tens of arc minutes of individual radio telescopes to the milliarcsecs achieved by modern Very Long Baseline Interferometry (VLBI). The advent of radio astronomy brought a further advantage, related to the reduced atmospheric absorption of radiation in the wavelength window between a few cm and a few m, as shown in figures 1 and 2. This in contrast with the high atmospheric absorption of visible light, infrared radiation (with the exception of a few "windows" in the region of a few microns) and long wavelengths radio waves. A large number of important astronomical discoveries came with the advent of radio astronomy. Among this we would like to mention the discovery of radio galaxies powered by super massive black holes, that of neutron stars, the gravitational lensing and, most important, the cosmic microwave background radiation.

The transparency of the dusty interstellar medium to radio wavelengths allows astronomers to see through the disk of our Galaxy and observe objects otherwise hidden. This in particular allowed the discovery of the compact radio source SGR A*, thought to be powered by a super massive black hole at the center of our Galaxy.

As figure 2 shows, the detection of X and γ rays from astrophysical sources is strongly limited, for earth-based detectors, by atmospheric absorption. This is particularly true for X rays, that have required the use of satellite based detectors, like Bepposax [2]. This Dutch-Italian satellite was launched in 1996 and was the first to detect several sources of X rays correlated to γ ray bursts, establishing them as extragalactic. This was later followed by other successful satellite missions, like CHANDRA [3].

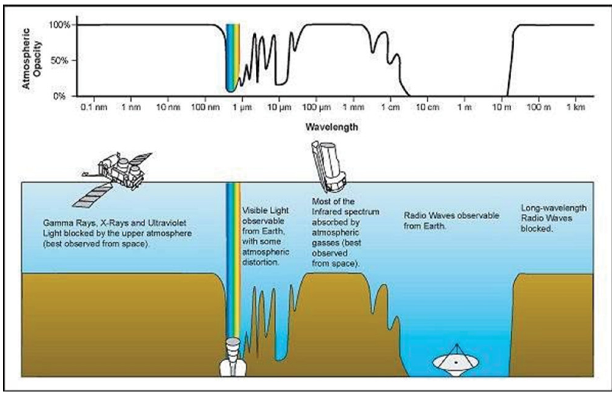

Figure 1: *The half-absorption altitude in the atmosphere is plotted as a function of wavelength (on a logarithmic scale). As the graph shows, the dominant windows in the atmosphere lie in the visible and radio frequency regions, while X-Rays and UV are seen to be very strongly absorbed. Gamma Rays and Infrared radiation is less strongly absorbed.*

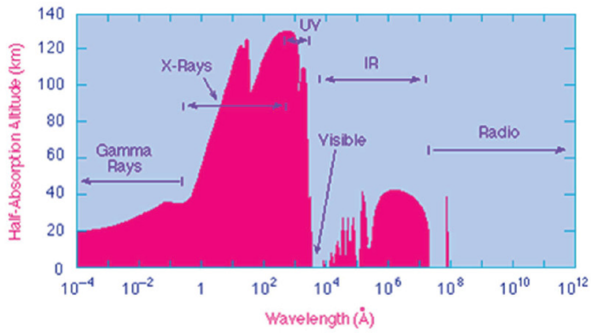

Figure 2: *Atmospheric opacity as a function of wavelength (on a logarithmic scale). This graph is similar to that of figure 1 but shows in addition the range of possible detectable wavelengths.*

As far as γ ray observations are concerned, these have relied for many years on ground based detectors, of two different types. The first of these is based on the detection of the Cerenkov light generated by electromagnetic showers originated by high energy γ rays impinging on the atmosphere. In these detectors, the Cerenkov light is collected by a system of mirrors and focused on an array of photo detectors. Among these is worth mentioning the HESS detector [4], installed in Namibia; the MAGIC detector [5], installed at the top of the Roque de los Muchachos on the Canary island of La Palma and the VERITAS detector [6], installed in southern Arizona.

Under construction is finally the CTA detector [7], that will provide a complete view of both the northern and the southern sky.

More recently, in order to obtain a global vision of the sky and to bypass the problems due to atmospheric absorption, advanced gamma ray detectors have been installed on satellites. Among these it is worth mentioning the EGRET satellite detector [8]. This, installed on board the Compton Gamma-Ray Observatory has been for a long time the most sensitive high-energy γ-ray telescope. The goals of EGRET were to map the entire sky in the energy range 20 MeV to 30 GeV, at angles of up to 40^o and to investigate astrophysical sources of high energy gamma radiation. A recent evolution of EGRET, has been the FERMI/GLAST detector [9]. This has been launched on June 11, 2008 and is in operation since then. It is worth mentioning that ground based γ detectors are somehow complementary to those operating on satellites. This is related to the fast decrease of the γ ray flux as a function of energy. This requires large-area detectors, difficult to install on satellites. It is indeed worth reminding that the latter type of detectors may cover an energy range that does not exceed 100 GeV, to be contrasted with ground-based telescopes, that typically cover an energy range above 50 GeV.

We know today that the source of energy powering the Sun and other stars are the nuclear fusion processes taking place within them. Enormous fluxes of neutrinos are emitted in such processes. The earliest calculations of such processes go back to 1938-39, thanks to Bethe and Critchfield [10, 11].

It is worth recalling that no mention was made in these works of the fact that an important confirmation of these calculations could eventually come from the observation of the neutrinos expected to be emitted in such processes. It took several decades and the painstaking efforts of Raymond Davis [12] and later on of Masatoshi Koshiba [13] before the observation of solar neutrinos could provide a definitive confirmation of the theory. For this discovery Raymond Davis and Masatoshi Koshiba were granted, in 2002, the Nobel prize. Furthermore, the Kamiokande experiment, also led by Koshiba, observed for the first time the neutrinos emitted in the explosions of a Supernova, the SN1987A [14]. Thanks to these experiments the field of Astrophysics underwent a considerable enlargement of its horizon, previously limited to electromagnetic radiation, giving birth to what is now known as Neutrino Astrophysics. Figure 3 shows an image of the Sun obtained through the observation of solar neutrinos detected in the SuperKamiokande [15] experiment. Neutrinos emitted by the Sun and those coming from Supernovae explosions, have relatively small energies. Several details of the underlying processes are, at least partially, understood. On the other hand it is commonly believed that neutrinos having enormously larger energies must be emitted in various types of astrophysical processes. This is the realm of high energy neutrino astrophysics, that will be the subject of this article.

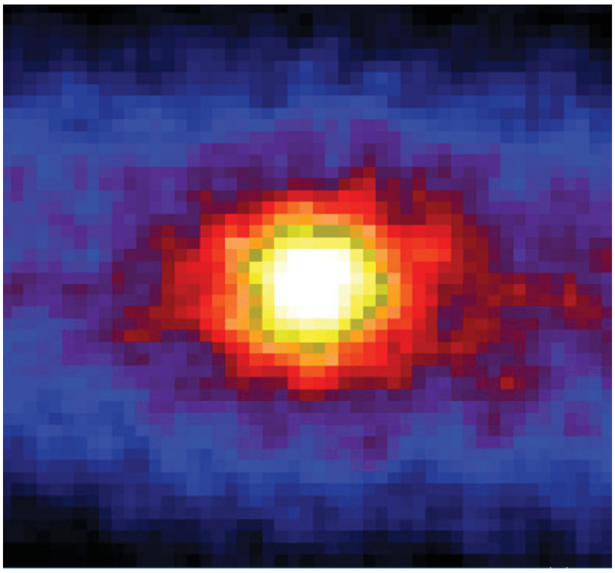

Figure 3: *Image of the Sun obtained through the detection of the emitted neutrinos, as observed in the SuperKamiokande experiment. The image, centered on the Sun, covers a wide angular region, of $90^o \times 90^o$ both in right ascension and in declination.*

What is a neutrino? From Pauli to our times

The existence of the neutrino was suggested by Pauli in the '30s and shortly afterward placed on a solid basis by Fermi. Up to that time, the only known particles were the proton, the neutron and the electron.

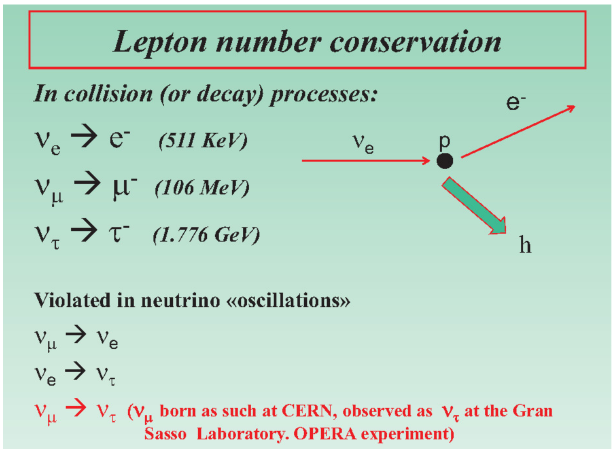

Figure 4: *Neutrinos and corresponding "leptons". In the lower part of the figure: transitions related to typical neutrino "oscillations".*

Others will write about neutrinos in the current issue of *Ithaca*. Here I will just recall that there are three different types or "flavors" of neutrinos:

The electron-neutrino ν_e, the muon-neutrino ν_μ and the one associated with the τ meson, ν_τ (see also figure 4). Each of these has its own antiparticle, denoted by a bar above the corresponding symbol ($\overline{\nu}_e$...). The ν_e was the first to be experimentally seen (more precisely its antiparticle $\overline{\nu}_e$, emitted in radioactive decays, and in particular in very large numbers by nuclear reactors). An example of a decay with the emission of a $\overline{\nu}_e$ is that of tritium ^{3}H into ^{3}He, shown in figure 5. Here one of the neutrons present in the tritium nucleus becomes a proton, with a simultaneous emission of an electron and a $\overline{\nu}_e$

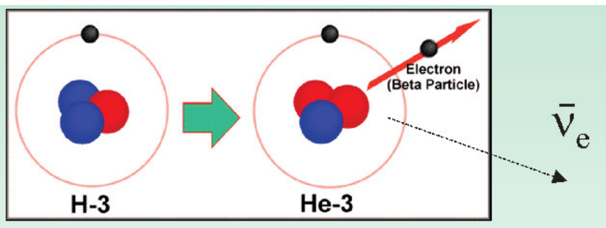

Figure 5: *Beta decay of tritium ^3He, with production of a $\overline{\nu}_e$ and an electron. The lifetime for this decay is approximately 17.8 years.*

The reason for the association of each of the three neutrinos with one of the leptons, such as the electron, the μ and the τ, is in the fact that, as schematically shown in Figure 4, in the interaction of a ν_e with matter is always produced an electron and never a μ or a τ, and analogously for each of the remaining two neutrinos. Such an association of the ν_e with the electron, of the ν_μ with the μ, and so on, continues to hold, with a corresponding sign change, for the corresponding antiparticles. Thus, if a $\overline{\nu}_e$ interacts with matter it will yield a positive electron e^+; analogously to what happens for the $\overline{\nu}_\mu$ and $\overline{\nu}_\tau$, that will give rise to a μ^+ and a τ^+ respectively. Such a "lepton number conservation law" is however in a certain sense violated in those processes that are now known as as "neutrino oscillations". If a ν_e is produced in a certain interaction, we may in some cases, observe after a certain time (or equivalently a certain distance travelled) that it has undergone a transformation into a neutrino of a different flavor, that is a ν_μ or a ν_τ. An example that has lately had in the last few months wide publicity in the media, is that of the observation in the OPERA experiment (at the Italian Gran Sasso Laboratory) of ν_τ starting from a beam of ν_μ produced at CERN (Geneva) [16]. We must hasten to add that the probability of such a conversion (or oscillations as is commonly referred to) is extremely small, but can be measured with great precision. Another example that is worth mentioning is that of the electron neutrinos ν_e emitted in nuclear fusion processes taking place within the Sun. It is well known that the Sun produces energy through the fusion of protons into He nuclei (nuclear fusion). About 600 millions of tons of protons are "burned" every second to feed the solar luminosity. The process that is the basis of the entire chain of "nuclear fusion" is:

$$p + p \to {}^2\text{H} + e^+ + \nu_e$$

This is a "weak" process, thus a slow one. The subsequent reactions, involving the fusion of ^{2}H nuclei with protons or other ^{2}H nuclei, are much faster. However the rate of the overall process is determined by that of the first of the above reactions, the weak process providing the material burned in the subsequent ones. It was found, with considerable surprise, that of the emitted ν_e only a fraction of about 30 % arrives on Earth as ν_e, the rest undergoing, on the flight to the Earth, a conversion into ν_μ or ν_τ. Such an observation has historically been the first evidence of neutrino oscillations, in the already mentioned experiments of Davis and Koshiba.

Elementary particles and particle detectors

We wish to start explaining what we mean when we speak of "seeing" an elementary particle. What we really see is the pattern left over after the particle has crossed a medium. This in analogy with the stream left over by a plane flying high in the sky, as shown in Figure 6.

Figure 6: *Stream left over by a high-flying airplane.*

Even if, as it often happens, we cannot see the plane, we are aware of its passage just by the pattern it has left over. An easy example is that of an electrically charged particle (either with a positive or negative charge). To this category belong those particles of which our world (and ourselves) is made of: protons and electrons. Other charged particles are those that continuously reach us from space: those known as *cosmic rays*, that include, besides electrons and protons, other particles such as muons (μ), π mesons and others. The masses of all elementary particles are extremely small. Physicists, recalling from relativity, the equivalence between mass and energy, are used to express particle masses in units of energy: *electron volt* or simply eV. This basic unit is the energy acquired by an electron accelerated by potential difference of 1 Volt. The correspondence with the more conventional units is: 1 eV = $1.60217733 \times 10^{-19}$ J. This unit is extremely small and most often one uses multiples of it, as shown in the box. Thus the mass of the electron is about 511 eV, that of the μ meson 106 MeV, that of the proton 938 MeV and so on. The values of some of the masses are shown in Figure 4.

Coming back to the pattern left by a particle upon crossing a detector, a classical example is that of the track left by a particle crossing a photographic emulsion. A few examples are shown in Figure 7. If a high energy (in the case of Figure 7 the energies involved are hundreds of MeV or a few GeV) charged particle crosses a photographic emulsion, it "damages" the atoms/molecules in the region crossed. Once the emulsion undergoes an appropriate chemical treatment (development) the sequence of atoms/molecules involved will turn out to be somehow darker than the rest of the image. This is the case of the examples shown in the figure. These are historical examples, that we are not going to discuss in detail, except for saying that they have represented important discoveries in particle physics.

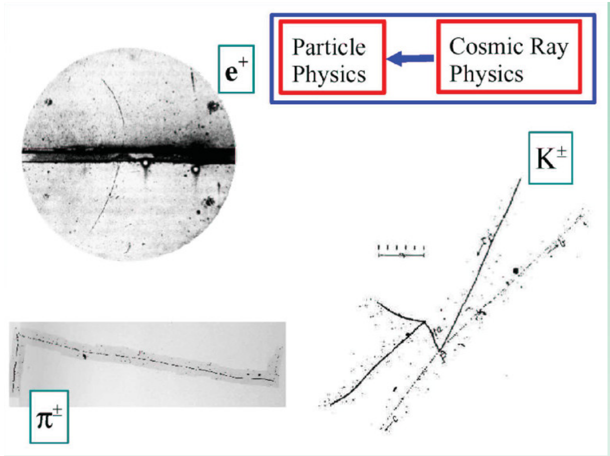

Figure 7: *Tracks left by charged particles crossing a photographic plate (emulsion)*

A further example of particle detection (visualization) is that shown in Figure 8. Here we see the tracks left by particles crossing a "bubble chamber". In this example, charged particles crossing a transparent liquid, under appropriate pressure and temperature conditions, give rise along their path to the formation of tiny bubbles, whose sequence shows the particle trajectories. In the example shown the particle trajectories are curved, since in this particular case the tank containing the liquid was located in a high magnetic field region.

Positive particles are bent one way, negative ones the opposite way. In the example shown we may moreover notice that all particles seem to originate from a common origin, in the lower part of the picture. In the current instance all these particles (both positive and negative) were the result of a high energy collision: that of a

Energy units used in particle physics.

Unit	keV	MeV	GeV	TeV	PeV	EeV
Value	$1000\,eV$	$1000\,keV$	$1000\,MeV$	$1000\,GeV$	$1000\,TeV$	$1000\,PeV$
..	$10^3\,eV$	$10^6\,eV$	$10^9\,eV$	$10^{12}\,eV$	$10^{15}\,eV$	$10^{18}\,eV$

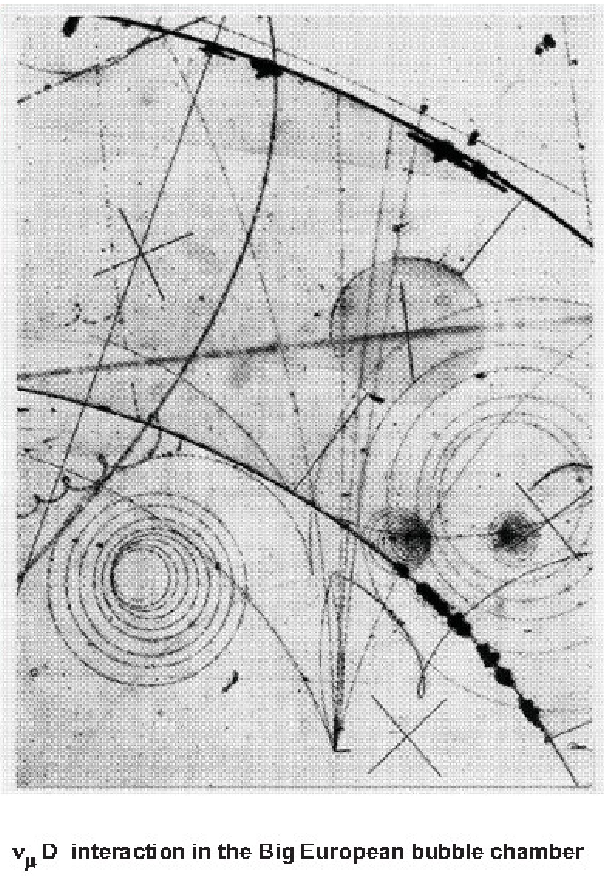

Figure 8: *Tracks left by charged particles crossing a bubble chamber. It is possible to see the primary interaction vertex, from which several charged particles emerge. Also visible, a few cm above, an e^+ e^- pair.*

neutrino with a nucleus.

On the other hand the neutrino, with no electric charge, does not give rise to any visible track. This example shows a clear case of the detection of a neutral particle, such as the neutrino.

It is rare for a neutral particle to undergo collisions with atomic electrons. As a result, it does not leave behind any visible track, such as those shown. In order to detect a neutral particle we must hope that it undergoes a collision with an atomic nucleus, giving rise to one or more charged particles, that will be "visible". In other words, we must hope that the particle "dies". In the figure we note in addition, a few cm above the "primary" interaction vertex, a pair of particles, of opposite sign, that seem to originate from the approximately the same point in which the neutrino has interacted. This is an electron-positron pair (e^- e^+) originated from the "conversion" of a high energy photon (γ) born from the same collision event that gave rise to the charged particles. The γ, a neutral particle like the neutrino, does not leave behind any charged tracks.

The probability for a particle to undergo a collision, thus "dying" and giving us a signal of its presence, is a function of the particle energy. It also depends strongly on the type of particle. Such a probability is related to a property known as "cross section". This is extremely small in the case of the collision of a neutrino with a nucleon (proton or neutron) If we take as a reference value such a probability for a proton having an energy of 10 GeV, it will be 200 billion times smaller for a neutrino having the same energy. This explains why neutrinos coming from outer space can freely cross the entire diameter of the Earth hardly undergoing any collision. Particularly large is the flux of neutrinos originating from the Sun. It is a well known fact that about 70 billion neutrinos per second arrive on each cm^2 of the surface of the Earth. The number of neutrinos crossing our body is essentially the same both in daytime and at night!

Such a probability grows at a fast rate with increasing neutrino energy. For a neutrino having an energy of 10^{20}eV (100 million TeV) it is about 100 million times larger than for a 10 GeV neutrino. We are in any case dealing with extremely small probabilities, unless the energy becomes extremely large. [1]

[1] If the neutrino energy becomes extremely large, absorption by the Earth starts becoming important.

A third type of particle detector that is mandatory to recall here for an easier understanding of our subject is that based on the "Cerenkov radiation". We come back again to the example of an airplane. If this is traveling at a speed larger than the speed of sound in the atmosphere, then a sonic wavefront arises, in the shape of a cone, as shown in the upper part of Figure 9. This wavefront is known as a shock-wave.

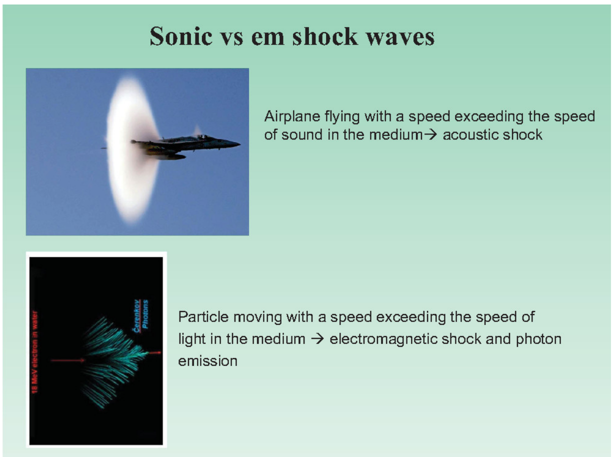

Figure 9: *Image at the top: acoustic shock generated by an airplane traveling at supersonic speed. Bottom: electromagnetic shock generated by a particle traveling at a speed larger than the speed of light in the given medium.*

Analogously, if a particle travels in a transparent medium (e.g. water) at a speed larger than the speed of light in the medium, a kind of electromagnetic shock arises, having a conic shape. This shock is nothing also than light (photons). This is shown in the lower part of the same figure. What happens is schematically illustrated in Figure 10.

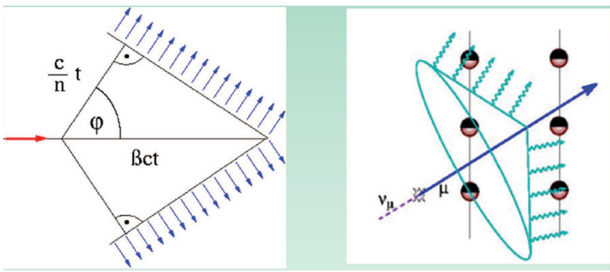

Figure 10: *Left: schematic view of the Cerenkov cone of light emission. Right: tri-dimensional view of the same cone and of the emitted photons. Also shown, in a schematic way, a matrix of detectors of the emitted light.*

Starting from the surface of the cone shown in the figure, light (photons) is emitted. The cone axis coincides with the direction of the particle. If a set of light detectors has been installed in the region crossed by the particle, such that each of them provides with high accuracy the exact time of arrival of the photon, and if we know the exact position of each of the detectors, we shall be able to reconstruct to a very high precision the axis of the cone and therefore the direction along which the particle travels. Light detectors used in this type of arrangement are photomultipliers (PMT). A further example is shown in Figure 11.

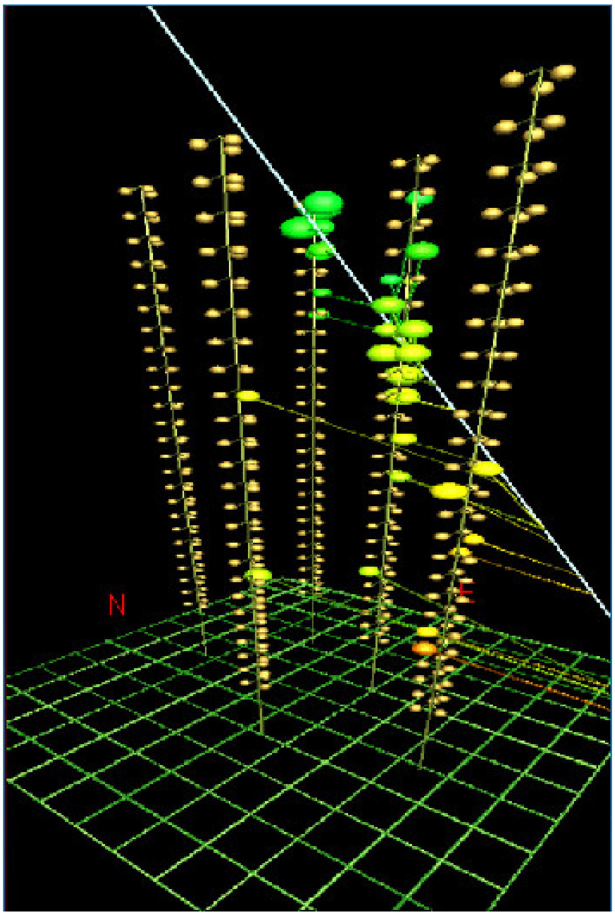

Figure 11: *An example of a detector of μ^s, using the Cerenkov light emitted by the particle when it crosses a water mass. In the Figure colors are used to label the relative arrival times of the Cerenkov signals on the PMTs : yellow before green. Also shown, in thin lines, the (reconstructed) trajectories of the Cerenkov photons.*

The first detectors we have shown (photographic emulsions, bubble chambers) find very little use nowadays, with very rare exceptions. Other detectors find widespread use, such as *proportional chambers*, *"drift" chambers*, TPC's (*Time* *projection chambers*), *microstrip/micropad silicon detectors*, *calorimeters*, etc. [17]. In the experiments that we are going to discuss the only detectors being used are those based on the Cerenkov radiation.

Neutrino interactions with matter

We are here mainly interested in very high energy collisions: hundreds of GeV at least. When a high energy neutrino interacts with matter (in most cases an atomic nucleus) there will in general be a variety of different particles produced, according to the flavor of the neutrino ($\nu_e\, \nu_\mu\, \nu_\tau$ or corresponding anti neutrino) as shown in Figure 12. The most relevant process, for the detection of astrophysical neutrinos, is the first one shown in the figure. Here a high energy μ is produced. This carries on average 50% of the energy of the neutrino undergoing the collision (this percentage becomes 75% in the case of an anti neutrino) together with a number of protons, neutrons, π mesons, k mesons etc.. The latter ones share among them the rest of the neutrino energy and quickly lose energy, through successive collisions while crossing the liquid or solid medium. This is a chain process, in which new particles of the same type, having lower and lower energies, are produced. The outcome of such a chain process is what is termed an *hadronic shower*, schematically shown in the figure. The individual particles in the shower are not, in the type of experiments we are interested in, detectable, but is often possible to obtain a rough measurement of the total energy of such a shower, together with its direction.

The process can be described as:

$$\nu_\mu + N \;\rightarrow\; \mu^- \;+\; X \tag{1}$$

where X is the shower.

Analogously, for an anti neutrino, we have:

$$\overline{\nu}_\mu + N \;\rightarrow\; \mu^+ \;+\; X \tag{2}$$

At very high neutrino energies, in both processes the μ is emitted at a very small angle ($\ll\; 1^o$) to the direction of the incoming neutrino. This turns out to be of great importance in searches of point like sources of high energy cosmic neutrinos. The direction of the produced μ *points directly to the source of neutrinos*.

Analogous considerations[2] hold for the cases of the other processes shown in the figure:

$$\nu_e + N \;\rightarrow\; e^- \;+\; X \tag{3}$$

$$\nu_\tau + N \;\rightarrow\; \tau^- \;+\; X \tag{4}$$

As well as for the analogous processes induced by the corresponding anti neutrinos:

Finally, the last process shown in the figure:

$$\nu \;+ N \rightarrow \;\nu \;+\; X \tag{5}$$

may occur equally well for all flavors of neutrinos or anti neutrinos. For example:

$$\nu_{e,\mu,\tau} + N \;\rightarrow\; \nu_{e,\mu,\tau} \;+\; X \tag{6}$$

And analogous ones for the corresponding anti neutrinos. In such processes, being the produced neutrino undetectable, only the shower X can be seen. In such case the detectability of the event and the possibility to obtain a reliable estimate of the neutrino energy and direction will be much more problematic.

Additional details are necessary in the case of process (3). Here, the produced electron, being its mass so much smaller than that of the μ^- produced in process (1), quickly loses energy through a large number of collisions while traversing the medium where the interaction took place.

More in detail: the electron undergoes a large number of collisions with atoms, losing energy in each collision. The energy lost shows up in the form of photons (γ^s). Each γ, in turn, while crossing the medium yields pairs of electrons and positrons that again lose energy, yielding new γ^s, of lower and lower energy. This chain process continues yielding an increasing number of electrons, positrons and photons, of lower and lower energy. The process stops when the energy of the produced particles becomes so small that a further production of new particles becomes energetically impossible. At this point the further production of e^+, e^- and photons comes to an end. In the process one has, analogously to the already described case of the *hadronic shower*

[2] However the "pointing" capability mentioned in the case of the μ does not hold for these ones

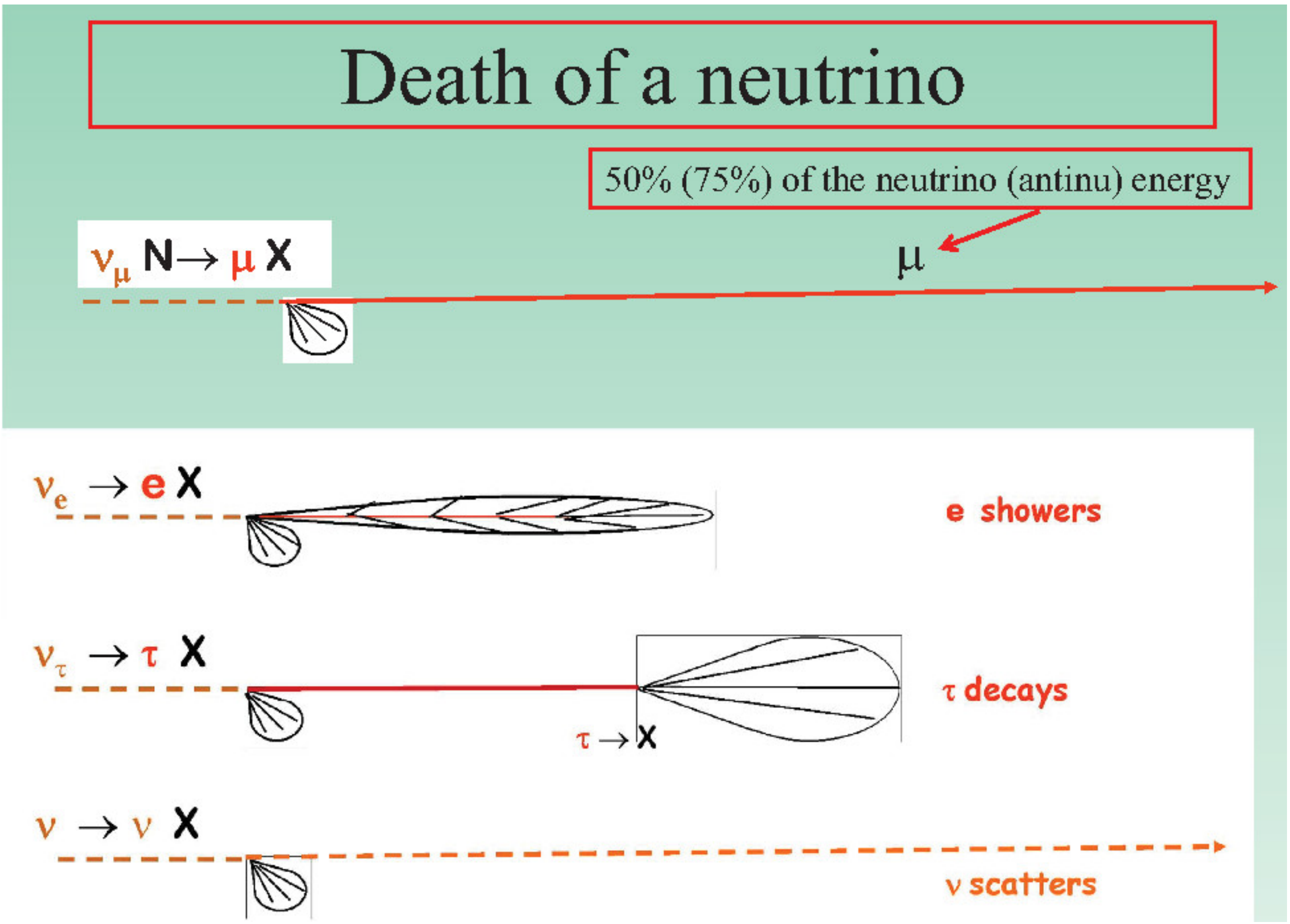

Figure 12: *The different types of interaction of neutrinos with matter.*

the development of an *electromagnetic shower*, as shown in the figure. Such a shower has a morphological shape quite different from that of the its hadronic counterpart. The electromagnetic shower is much longer and narrower than the hadronic one, as schematically shown in the figure.

Cosmic rays

In order to understand the problems one faces in attempts to detect astrophysical neutrinos, it is necessary to understand which other particles arrive on Earth from outer space. This also in view of the fact that many of such particles turn out to be a source of spurious signals in the detectors, often referred to as *sources of background* or simply as *noise*. Other particles are themselves sources of neutrinos, that will be difficult to disentangle from cosmic neutrinos.

An enormous flux of particles coming from outer space arrives continuously on top of the Earth's atmosphere. Such particles are referred to as *primary cosmic rays*, and they consist mainly of high energy protons and nuclei, with a much smaller contribution of electrons, positrons, γ^s etc. A large flux of particles arrives on the surface of the Earth. These are *secondary cosmic rays* resulting mainly from the collision of primary cosmic rays with air nuclei in the atmosphere. They consist mainly of muons (μ), together with γ^s, electrons, positrons and neutrinos. In the collision of primary cosmic rays with air nuclei, high in the atmosphere, one has the production of short-lived particles, in processes such as:

$$p + N \rightarrow \pi^{+/-} + \text{other}$$

where N is a generic nucleus. The π^+ (π^-) decays in about 10^{-8} seconds in a μ ed a neutrino:

$$\pi^+ \rightarrow \mu^+ + \nu_\mu$$

The produced μ^+ decays in 10^{-6} seconds in:

$$\mu^+ \rightarrow e^+ + \overline{\nu}_\mu + \nu_e$$

In summary, these processes, and the analogous ones in which the produced particle is a π^-, give rise to the production of neutrinos and antineutrinos, of both flavors.

$(\nu_e,\ \overline{\nu}_e,\ \nu_\mu,\ \overline{\nu}_\mu)$

The interaction of protons or nuclei in the atmosphere may also give rise, with rates about equal to those of the above processes, to the production of the neutral partner of the $\pi^{+/-}$, the π^0 (mass approximately equal to 135 MeV):

$$p + N \rightarrow \pi^0 \ + \text{ other}$$

The produced π^0 decays in a very short time (10^{-10} seconds) in two photons:

$$\pi^0 \rightarrow \gamma + \gamma$$

In summary, we know that high energy neutrinos (antineutrinos) and photons are present, with approximately equal abundances, among secondary cosmic rays. Such neutrinos and γ^s are the result of the collisions with air nuclei, of the primary protons (nuclei) impinging on top of the atmosphere.

Coming now to our subject, that of cosmic neutrinos; the question that has plagued researchers for decades is: which are the possible galactic (or extragalactic) sources of *high energy neutrinos*. Here we are not talking of solar neutrinos nor of those neutrinos that are expected as the outcome of a supernova explosion. All of these have much lower energies, limited to a few tens of MeV.

It is tempting to think that such sources are the same ones (mainly Supernova Remnants) that are believed (as we shall discuss later on) to produce and accelerate primary cosmic rays. These, interacting with the outer layers of the source (the Supernova Remnant in our case) may give rise to neutrinos and photons, by a mechanism entirely analogous to that described above, that takes place in the atmosphere. This hypothesis would imply that cosmic sources of γ^s also be sources of neutrinos. Unfortunately such a simple-minded reasoning ignores the well known fact that mechanisms different from that mentioned above (known as *hadronic mechanism*) exist that explain the production of high energy photons. These do not imply any production of neutrinos. The most often mentioned in the class of such mechanisms (known as *leptonic mechanisms*) is known as *Synchrotron-inverse-Compton*, that we are not going to discuss [18]. It is however true that a class of γ sources exists which is believed to also be a likely source of neutrinos.

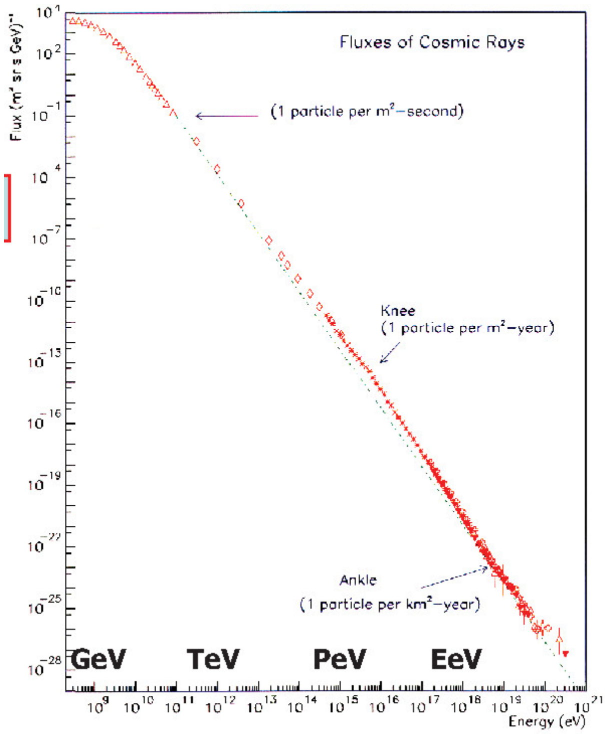

Figure 13: *Energy spectrum of primary cosmic rays.*

Production and acceleration of cosmic rays

The energy spectrum of primary cosmic rays has been measured in a large number of experiments, using various techniques. As Figure 13 shows, it covers a wide energy range, up to 10^{21} eV (about 1000 EeV). Over this range the spectrum drops dramatically, from a rate of a few tens of particles per m^2 per second up to one particle or less per km^2 per century!

The mechanism which provides, in galactic or extragalactic objects, the observed acceleration to protons and nuclei constituting cosmic rays, is still not fully understood. The most frequently accepted mechanism is the one known as *First order Fermi mechanism* [19]. Such a mechanism would, in the model, take place mainly inside *supernovae remnants*, that is in what remains after a supernova explosion. Following such an explosion, the star collapses into a *neutron star* or in a *black hole*, while a shock-front of gas and

Figure 14: *The supernova remnant snr 0509-67.5. From NASA, ESA, CXC SAO. The Hubble space telescope Team. Well visible the expanding shell of gas and dust, in a process that may go on for centuries.*

dust propagates into space at relativistic speed, away from the collapsed star. See for example Figure 14. The propagation of the shock-front may go on for centuries, and it is over this period that protons and nuclei may, through a series of subsequent back and forth collisions with the shock-front itself and the interstellar medium, acquire the enormous observed energies .

The mechanism is much more complex than can be here described. However it may qualitatively be understood with reference to the toy-model of two colliding trains traveling in opposite directions, as shown in Figure 15.

The two trains A and B travel in opposite directions on the same track, with equal and opposite velocities V. If now a small ball is thrown from train B towards train A, with a velocity -w in the reference frame of train B, it will have a velocity -(w+V) for a standing observer (laboratory frame). Its speed in the reference frame of A can easily be seen to be -(w+2V). If the collision of the ball with A is assumed to be head-on and elastic, the speed of the ball after the collision will be (w+2V) in the reference frame of train A. It will thus be (w+3V) for the standing observer. Repeating the process in the subsequent series of collisions, it may easily be seen that, after a large number of collisions the ball will have acquired an enormous velocity.

In the case of particle acceleration in Supernovae Remnants the problem is much more complicated, for the following reasons:

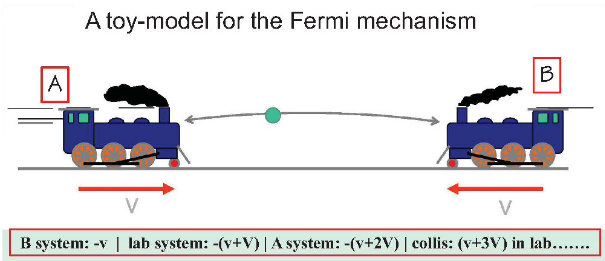

Figure 15: *A toy-model to illustrate the Fermi acceleration mechanism.*

1. The problem is 3-dimensional
2. The speeds are relativistic, requiring the use of Lorentz transformations
3. The presence of magnetic fields plays an important role in the process
4. The maximum energy that can be reached depends upon the duration of the expansion process of the shock-front

The detailed calculations needed to reach the final result and thus obtain the particle energy spectrum are complicated and affected by considerable uncertainties. It is in any case necessary to have at least a rough estimate of the density of Supernova Remnants in our Galaxy and/or in nearby ones. For a recent review of acceleration mechanisms in the shocks of Supernova Remnants we refer to [20]. The energy spectrum that such calculations provide goes like $E^{-2.7}$, in qualitative agreement with experimental data.

Recently, direct evidence for the production of π^0 in the interaction of protons accelerated in Supernova Remnants has been provided by the FERMI experiment [21].

Possible neutrino sources

A rich literature exists on the possible astrophysical sources of neutrinos [22, 23, 24, 25, 26]. Here we limit ourselves to list a few of them, with some additional information in the case of Supernovae Remnants.

Among all possible sources, a number of studies have concentrated on the following ones:

1. The quasars. A quasar (contraction for QUASi-stellAR radio source) is an active galactic nucleus extremely bright and in general very far from the Earth.

2. The microquasars. The characteristics of these are similar to those of quasars but, contrary to quasars, the black hole inside them has a mass of only a few solar masses. Microquasars are present in our galaxy as well.

3. The pulsars. These are rapidly rotating neutron stars. The emitted electromagnetic radiation is concentrated in narrow angular regions and observed in the form of pulses emitted at very regular intervals.

4. Active galactic nuclei. These are Galaxies whose very bright nucleus is characterized by an extremely high radiative power (even hundreds of time that of normal galaxies), with a frequency spectrum ranging from the radio to hard X-rays and a time variability on very short time scales (even of just a few days or less). Such emission is believed to originate from material infalling towards a super massive black hole (hundreds of millions solar masses).

5. The blazars. The blazars are very compact quasars, probably associated to super massive black holes, which give rise to powerful jets of radiation which, either continuously or in a variable way, point towards the Earth.

6. The gamma-ray-bursts.The gamma ray bursts are short but extremely powerful explosions taking place in distant galaxies, with a strong γ emission . These are the most powerful explosions taking place in the cosmos. They have durations ranging from a fraction of a second to several minutes.

The Supernovae are of particular interest in the light of what we said earlier when speaking of the acceleration mechanism of cosmic rays.

Stars are in general in dynamical equilibrium, as a result of a balance between the internal pressure, due to the thermal energy from nuclear fusion processes, and the gravitational pressure which would cause a collapse of the star towards its inner nucleus. The nuclear fusion processes begin, as mentioned before, with the fusion of hydrogen nuclei, then of ^{2}H, of ^{12}C, and so on with that of the heavier and heavier produced nuclei. Such processes go on up to the point when the most abundant produced nuclei fall in the group of iron. Being the fusion of Fe nuclei an endothermic process, which does not produce but absorbs energy, the nuclear fusion processes come to an end. Once this point is reached, the internal pressure becomes insufficient to balance the gravitational one. What happens next is extremely complex, but the final outcome is the implosion of the star, with a simultaneous appearance at its center of a neutron star or a black hole. At the same time a thick shell of material is emitted at extremely high speed. What we are left with is a Supernova Remnant. In particular, if the Fe nucleus of the original star had a mass between 1.39 and 3 solar masses, we shall have the formation of a neutron star, while for values larger than 3 solar masses a black hole will be formed. [3] The milky way contains a few hundred thousands black holes. There are, in the Universe, a number of super massive black holes (they seem to be the majority). They have masses of millions of solar masses, and is commonly believed that there is one at the center of each Galaxy including ours, that has at its center Sagittarius A*, with a mass of about 4 million solar masses.

For equal fluxes of neutrino emission from Supernova Remnants, the flux observed on Earth will be larger for the closer ones. For this reason particular attention is paid to those Supernova explosions that took place, over the last thousands of years, in our Galaxy or in nearby ones. In the first group we have:

- the SN of 1006 (observed by Chinese, Japanese and Arabs)

[3] Already in 1796 Laplace advanced the hypothesis of the existence of "invisible stars", being so massive that light could not escape from them. What we now know as black holes.

- the SN of 1054 (the CRAB)
- the SN of 1572 (the Tycho SN)
- the SN of 1604 (the Kepler SN)

Among those in nearby galaxies:

- the SN of 1885 (in Andromeda)
- the SN of 1987 (in the Magellanic clouds)

Experimental searches for astrophysical neutrinos

One of the most interesting subjects in cosmic ray physics is the search for possible astrophysical sources of such high energy particles. Being they mainly protons and other light nuclei, electrically charged, they are deflected by galactic/extragalactic magnetic fields, making it impossible, except at extremely high energies, an association to given astrophysical sources. Moreover, over long distances, because of interactions with interstellar gas and dust, they undergo absorption. Neutrinos on the other hand, being electrically neutral and having such a small interaction probability with matter, do not suffer from any of these drawbacks. As already mentioned, they are believed to originate from the decay of "mesons" (π and other) produced in the interaction of protons and light nuclei in Supernovae Remnants (or analogous cosmic sources). They share, in other terms, the same origin with charged cosmic rays but have the advantage of "pointing" directly to their sources.

A further advantage of neutrinos stems from the fact that, undergoing as they do such a modest absorption by the outer layers of stellar objects, they could reach us even if their production took place in the innermost regions of such sources. Their very small cross section, however, implies the need of an extremely massive detector. The first idea of a large volume (massive) detector to this aim goes back to M.A. Markov [27] who made the first suggestion in 1960. The basic idea was to use the sea, or a lake or, as was done later on, the south-pole ice, as a target, and to detect the μ produced by the neutrino in the charged current interaction (process (1)).

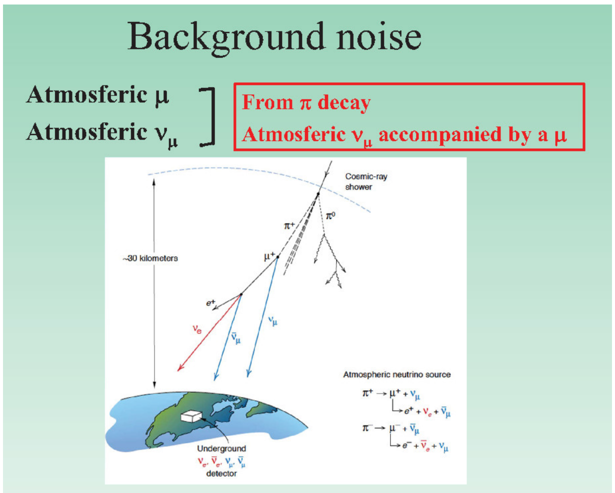

Figure 16: *Sources of spurious signals in searches of neutrinos of astrophysical origin*

The μ can be detected through the Cerenkov light it emits while crossing the transparent medium. This is relatively easy since, at high energy ($\gg$100 GeV) the produced μ carries, as already seen, a large fraction of the neutrino energy and, as a result, it can cover hundreds of meters in sea water. A large number of optical detectors (photomultipliers) is obviously necessary for the detection of the produced Cerenkov photons. They must have a good sensitivity to the Cerenkov radiation emitted by the muons. Being they so sensitive they could easily be damaged by stray optical sources, such as solar radiation or even smaller quantity of light due to various types of biological activity. It is therefore mandatory to install them at great sea depths (few kilometers) where darkness is absolute, and biological activity very limited.

As already mentioned in the section on cosmic rays, and as can be seen in figure 16, secondary cosmic rays, and in particular atmospheric μ^s are an important source of spurious signals ("noise") for such type of detector. At the surface of the Earth the flux of atmospheric μ^s is about 100 per m^2 per second. At a sea depth of 3 km such a flux, because of muon energy loss in water, turns out to be smaller by a factor of 10^6, an undoubtable advantage for these experiments, although sometimes not enough.

It is often convenient, in order to get completely rid of the flux of atmospheric muons, to design the experiment in such a way as to optimize the acceptance for neutrinos coming from

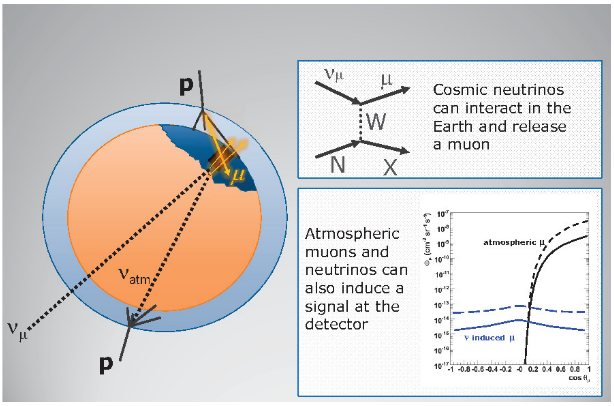

Figure 17: *Typical installation of a detector near the sea-bottom. Here we show the various background sources; μ^s from cosmic ray interactions in the atmosphere; neutrinos from the same processes, also in the opposite hemisphere. The diagram on top-right shows the typical production process of μ^s by neutrinos. Bottom: the flux of atmospheric μ^s compared with that of atmospheric neutrinos, as a function of the angle of arrival.*

"below", from the opposite hemisphere. These neutrinos will have crossed the entire Earth and a few of them will eventually interact in the earth-crust or sea water just below the detector, yielding eventually a muon aimed towards the detector itself. This is shown in Figure 17. Here we also show the other particles that could still be a source of background.

The first attempt to install at great sea-depths such a type of detector goes back to 1980, with the DUMAND experiment [28]. A prototype was installed close to the Hawaii islands, at a depth of about 4.5 km. Further attempts came with the Baikal [29] experiment, installed in lake Baikal at a depth of about 1100 m in 1990. Later on, in 1995, a detector (the Amanda experiment [30]) was installed underneath the south-pole ice at a depth between 1500 and 2000 m and took data for several years. A further attempt was the NESTOR [32] experiment, a prototype of which was installed at a depth between 4000 and 5000 m off the coast of Greece and worked for a few months in 2003. The NEMO collaboration [33, 34] installed a prototype at a depth of about 1 km off the harbor of Catania and took data for a few months. The ANTARES experiment [35, 36, 38, 39, 40] was installed starting in 2002 off the Toulon harbor at a depth of 2400 m. Finally the IceCube experiment was installed underneath the polar icecap at the south pole. In the following we shall concentrate our attention on the two experiments that have operated for many years and are still in the data-taking phase: ANTARES and IceCube. We shall then briefly mention the new large experiment now under construction in the Mediterranean: KM3.

The ANTARES experiment

The ANTARES detector, built and operated for many years by a large number of (mainly European) Institutions and Universities, is installed about 40 km off the Toulon harbour, at a depth of 2400 m. It consists of 875 large-area optical sensors (photomultipliers/PMTs) held, as shown in Figure 18 by 12 electro-optical cables, where they are assembled in triplets. The PMTs look downward, at an angle of 45^o to the vertical direction. The cables, anchored to the sea-bottom and held under tension by buoys at the top of each, play the triple role of mechanically holding the PMTs, of providing the needed electrical power to the PMTs and the associated electronics and of transmitting to the shore-based control station the signals from the PMTs. A 40 km long electro-optical cable is also used for such purposes. The PMTs are enclosed in pressure resistant glass spheres. It has to be noted that sea currents can move laterally the buoys together with all PMTs. Since, for an accurate event reconstruction the position of each PMT has to be know at each moment with great precision, a system of hydrophones, together with compasses and tilt meters is used in addition. The main purpose of the experiment is the search for neutrinos (mainly ν_μ and $\overline{\nu}_\mu$) having energies in excess of about 50 GeV, through the detection of the produced μ^s The orientation of the PMTs is such as to optimize the acceptance for muons coming from below, as explained previously.

The deployment of the detector and the needed repair operations require the use of ships and of undersea remote-operated-vehicles (ROV) An example is shown in Figure 19.

One of the problems one is faced with in such type of experiment is that of spurious, tiny sources of light. These have two different origins:

1. The presence in sea water of a radioactive isotope of potassium (^{40}K). The decay of

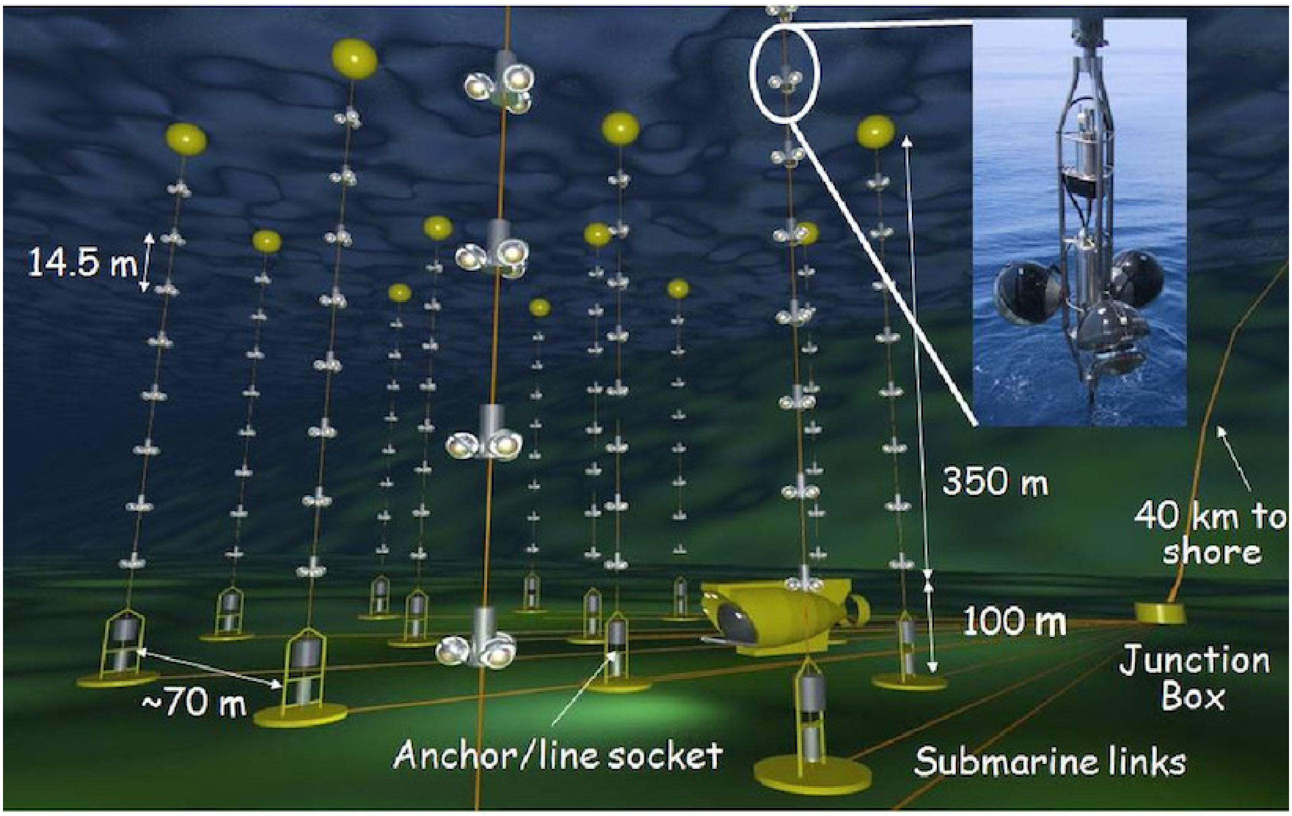

Figure 18: *Sketch of the ANTARES detector. The picture in the inset shows a typical PMT triplet and the container of the associated electronics.*

this gives rise to electrons which, through the Cerenkov effect, gives small amounts of light.

2. The presence, even at such depths, of living organisms, which emit small light signals.

The first of these sources of noise is relatively constant in time and is somehow manageable. The second one is much more worrying and may sometimes become a real problem because of the influx of large numbers of small living organisms, often related to undersea currents. It is well known that such an effect decreases strongly with depth. It is therefore convenient to install experiments of this kind at large depths and far from the sea shore.

Data have been collected since 2007. In the period up to 2013 about 6300 neutrino/anti neutrino induced events had been obtained[41]. In this data analysis events having $\cos\theta \geq 0.1$ where θ is the μ zenith angle, had been removed. In addition a large number of events had been obtained in which only the hadronic/electromagnetic shower was visible.

Two different analyses had been carried out on such events (more precisely on all events collected up to 2012):

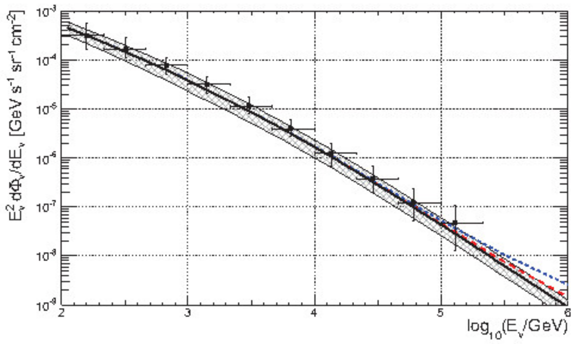

Figure 20: *Energy spectrum of atmospheric neutrinos measured in several experiments.*

1. A search for neutrino point sources in a region close to the center of our galaxy

2. A search for a "diffuse neutrino flux". By which is meant an excess of extremely high energy events with respect to the background expected from atmospheric neutrinos

In the first of the two cases one looks for an

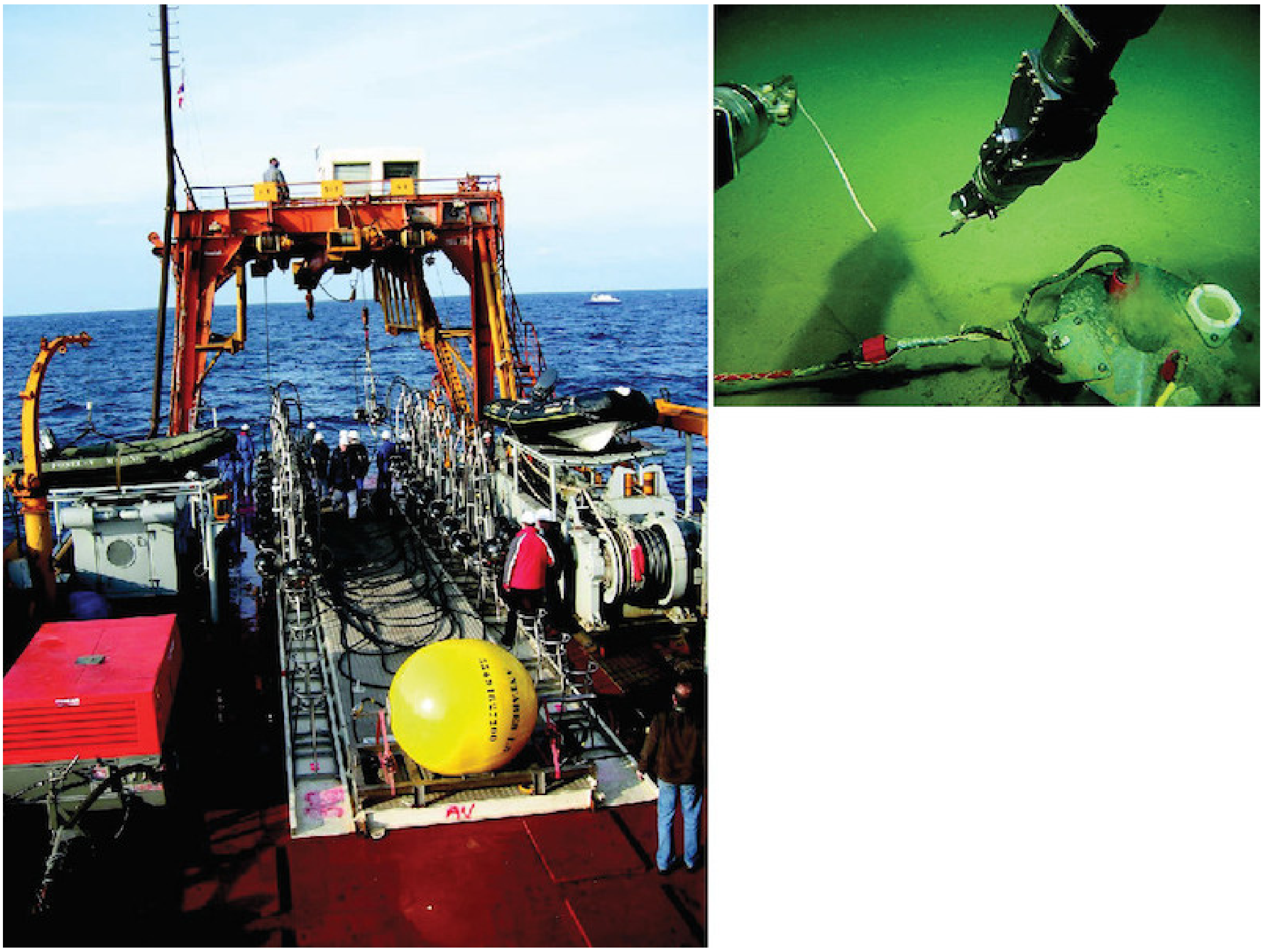

Figure 19: *The picture on the left shows one of the ANTARES lines, loaded on a ship and ready for deployment. Well visible in the foreground the buoy. The picture on the right shows two of the "arms" of the remote controlled submarine performing an undersea connection.*

excess of events in a given solid angle (in galactic coordinates) compared to a relatively uniform distribution due to atmospheric neutrinos. This particular analysis has been carried out in two different ways:

1. By looking for an excess in a generic direction
2. By looking for an excess in particular directions, corresponding to 50 known galactic sources of γ^s.

In both cases the energy dependence of the cosmic neutrino flux was assumed to be proportional to E^{-2}. In neither of the two searches performed a signal was found. As customary in such cases an *upper limit* on the flux (particles per unit energy interval and unit surface area) was reported [37]. Such a limit is normally expressed in units of the square of the energy times the flux (GeV $\mathrm{cm}^{-2}\,\mathrm{s}^{-1}$). In both of the analyses mentioned the limit turns out to be of the order of: ($3.5 \div 5.1 \times 10^{-8}$ GeV $\mathrm{cm}^{-2}\,\mathrm{s}^{-1}$).

As already said, an alternative search is that of a *diffuse neutrino flux*, meaning an excess of neutrinos above the "conventional" atmospheric neutrino flux. A search [42] for such an excess requires a measurement of the energy of the detected muons which, as already mentioned, is on average a large fraction of the neutrino energy. This allows getting rid of the atmospheric neutrino background which, as can be seen in Figure 20 has a fast decrease with energy.

Applying therefore a cut on the energy of the detected muon, one looks for an excess of events above such value. [4]

We should clarify that by "excess" is meant a larger number of events than the one ex-

[4]The measurement of the muon energy is based on the amount of light seen by the optical detectors.

pected both due to mis-reconstructed atmospheric muons and to the high energy tail of the atmospheric neutrino spectrum. By applying a cut on energy at 45 TeV, the authors find 8 events, where the expected background is 8.4 events. They report therefore an upper limit to the flux of astrophysical neutrinos:

$$E^{-2}\,\Phi \;=\; 5.1\,\mathrm{GeV}\;\times\;10^{-8}\,\mathrm{cm}^{-2}\mathrm{s}^{-1}\mathrm{sr}^{-1}$$

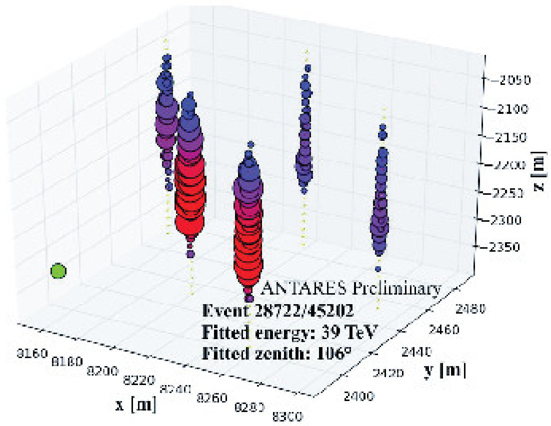

Figure 21: *A typical "shower" event. We show the signals induced in 5 of the 12 detector lines.*

A further search for a diffuse neutrino flux has been performed using events having only a shower. These could either be induced by a ν_τ a ν_e or a ν_μ in which the muon carries only a small fraction of the initial neutrino energy. They could also be events of the type described before, in which no charged lepton is produced, and in the final state we only have a neutrino an other charged/neutral charged particles making a "shower". A shower event is shown in Figure 21.

Also in this case no excess has been found. The corresponding limit on the flux of cosmic neutrinos, over the energy range (23 TeV $\div$ 7.8 PeV) is found to be:

$$E^{-2}\,\Phi \;=\; 4.91\;\times\;10^{-8}\,\mathrm{GeV\,cm}^{-2}\mathrm{s}^{-1}\mathrm{sr}^{-1}$$

A search for neutrinos from blazars in ANTARES

As already mentioned, a background source hard to suppress is that of atmospheric neutrinos. Being their energy typically lower (smaller than 40 $\div$ 50 TeV) the method normally used is that of selecting events having much bigger energies. It is however sometimes possible to adopt an alternative scheme.

If we indeed assume that a source acts only in a short time slot, and this is known, it will be possible to select only those events occurring in that time slot, where the flux of atmospheric neutrinos will be much smaller. Such a

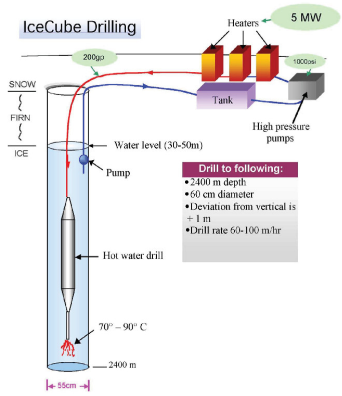

Figure 22: *Technique used in the IceCube experiment to melt the ice for the subsequent installation of a string.*

class of astrophysical objects indeed exists: the *blazars*. They are characterized by a strong γ emission ("flares") concentrated in narrow time intervals. Such emission is monitored by the FERMI satellite detector in the energy region up to the GeV and, for much higher energy values, by ground based air Cerenkov detectors like H.E.S.S., MAGIC and VERITAS. ANTARES has carried out a search for neutrinos from such sources in time coincidence with γ detections. One isolated neutrino has been seen in time coincidence with γ observations in the GeV region from blazar 3C79. However the probability that such an event could have been caused by one of the background sources mentioned is non negligible. Therefore only upper limits to the neutrino flux from such type of sources could be set by ANTARES [43].

The IceCube experiment

The IceCube detector, built and operated by a large international collaboration, has been installed under the south pole icecap between 2005 and 2010. The detector is located at a depth between 1450 and 2450 m. and it occupies a total volume of approximately 1 km^3. There are 5160 optical sensors (PMT) distributed over 86 strings. One of the advantages of operating under the ice stems from the total absence of any biological activity, otherwise present in the sea.

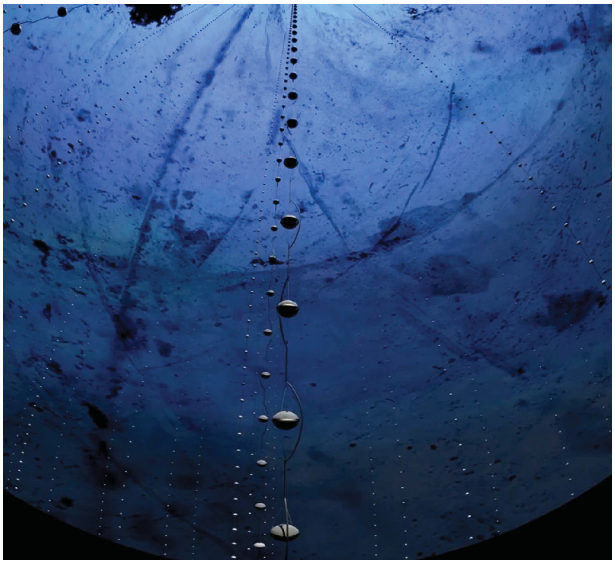

Figure 23: *A view of the IceCube strings from below the ice.*

Equally absent is the ^{40}K. These advantages are partly counterbalanced by the fact that, once the strings are placed under the ice, they cannot easily be removed without damaging them, making it hazardous any recovery/repair operation. As Figure 22 shows, the installation of each individual string requires the use of hot water, that is used to melt the ice, thus obtaining a deep hole. The string is then immersed in the hole that shortly afterward freezes again. Such an operation requires time and power (to produce hot water). The installation of an individual string takes 2 days on average. Figure 23 shows a few of the IceCube strings as seen from below the ice. A large number of results has been obtained and published over the last years. These include, for the first time, the observation of astrophysical neutrinos. We shall here limit our discussion to a few of the results, concerning:

1. neutrino induced atmospheric and cosmic μ^s, having an origin either in the Earth or in the ice below the detector,
2. events from interactions occurring inside the region occupied by the detector itself.

Events with a μ

The results on such events have been published recently [44]. They have been based on all the data collected in the early years of data taking (35000 ν_μ detected between may 2010 and may 2012). In such an analysis only events from the upper hemisphere of the Earth have been accepted.

To this purpose they have selected events (muons) having a zenith angle larger than 85^o, corresponding to a total amount of material crossed by neutrinos equivalent to at least 12 km of water. The μ energy, roughly related to the neutrino energy, has been evaluated on the basis of the amount of light seen by the PMTs. It has to be noted however that when the muon reaches the detector it may have traveled already over several hundred meters and lost therefore a sizable fraction of its energy. Moreover, since the neutrino cross section increases with energy, for very high energy neutrinos one expects they to be strongly absorbed while crossing the Earth, an effect particularly relevant for those arriving vertically from above the detector. Figure 24 shows the energy spectrum of the detected muons. The black dots with error bar are the experimental data. In red we show the expected distribution for atmospheric neutrinos. It can be noticed that for energies larger than about 30 TeV an excess is present in the data with respect to the expected contribution of atmospheric neutrinos.

Here the flux of atmospheric neutrinos has been computed as a sum of those from the decay of $\pi^{+/-}$, $\mu^{+/-}$, $K^{+/-}$.

An additional contribution is expected from the decays of short-lived heavier particles (mainly D mesons). Such a contribution is shown in blue in the same figure. As it can be seen, such a contribution appears negligible. The excess seen at energies larger than about 30 TeV corresponds to 3.7 standard deviations.

The flux of astrophysical neutrinos, as obtained in this analysis, is shown by the green curve in the figure. The observed excess at high energies is consistent with an astrophysical neutrino flux given by:

$$\Phi(E_\nu) = 9.9^{+3.9}_{-3.4} \times 10^{-19} \left(\frac{E_\nu}{100\,\mathrm{TeV}}\right)^{-2}$$

$$\mathrm{GeV^{-1}cm^{-2}sr^{-1}s^{-1}}$$

A search has also been made for possible point sources of such neutrinos [45] with negative results.

This is a first hint for the presence of astrophysical neutrinos.

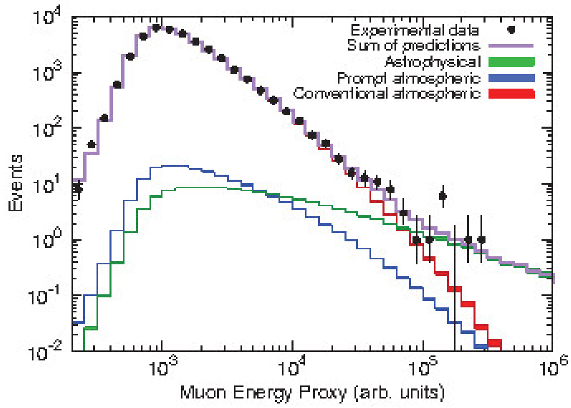

Figure 24: *Energy spectrum of muons detected in IceCube. The black points with error bars are the experimental data. In red the expected contribution from atmospheric neutrinos. In blue the contribution from decays of short-lived heavier (D) mesons. In green the computed contribution of astrophysical neutrinos, where a E^{-2} energy dependence of the flux has been assumed. The horizontal scale is not exactly the muon energy, but the value of about 3×10^3 is approximately the same quantity in* GeV.

Events having an origin inside the instrumented region of the detector

In order to avoid any residual background due, either to atmospheric muons or to neutrinos having interacted underneath the detector region, the selection has been restricted to only those events originating inside the detector region itself [46, 45, 47]. To this purpose those events have been rejected which gave hits in the outermost PMTs, in local time coincidence and at times compatible with the position of the reconstructed interaction point, as shown in Figure 25. We note in addition that, at high energies, atmospheric neutrinos from the $\pi \to \mu\nu$ decays, are often accompanied by a μ. Therefore the rejection of muons entering the detector from outside helps in rejecting atmospheric neutrinos as well. Further details can be found in reference [46].

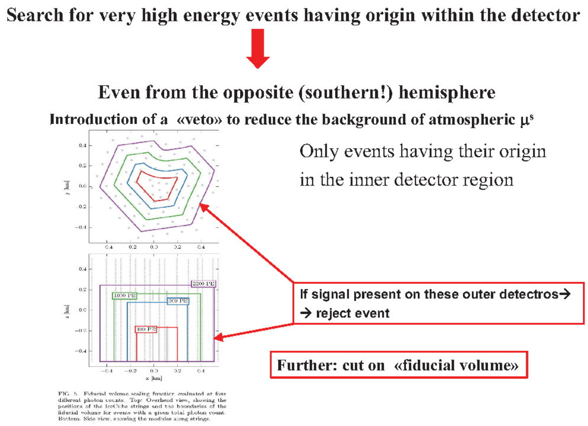

Figure 25: *Sketch of the IceCube detector, showing the veto system used for the rejection of events occurring outside the instrumented detector region.*

A first analysis, based on events collected in 642 days of data taking, has led to the selection of 388 events having a starting point within the instrumented region of the detector and energy greater than 1 TeV. A detailed analysis of such events leads to an estimate of the following number of astrophysical neutrinos: 87^{+14}_{-10}. The corresponding flux, in the energy range 25 TeV $\div$ 1.4 PeV is:

$$\Phi_\nu = 2.06^{+0.4}_{-0.3} \times 10^{-18} (E_\nu / 100\,\mathrm{TeV})^{-2.46 \pm 0.12}$$

$$\mathrm{GeV^{-1}cm^{-2}sr^{-1}s^{-1}}$$

It has to be noted that such an estimate refers to the sum of the three neutrino "flavors" (ν_μ, ν_e, ν_τ), while the one reported in the previous analysis included only the muon contribution. The two results are thus in agreement within errors. IceCube has thus provided a first observation of high energy neutrinos from astrophysical sources. However at the time being no possible association of such neutrinos to specific galactic or extragalactic sources has been found.

A search for point sources of astrophysical neutrinos located in the southern hemisphere has been made by combining the ANTARES data and the ones from IceCube (the latter from the south). The results have been negative [48].

The KM3 project

It is worth recalling that the basic idea of those experiments which do not limit themselves to events occurring within the detector volume, is the detection of all events coming from "below", the ones in which the neutrino has crossed the whole Earth. Looking at the position and orientation of the Earth in our Galaxy, it can be seen that, with such a choice, an experiment located in the northern hemisphere has an optimal acceptance for neutrinos coming from sources located near the central regions of the Galaxy, where many possible sources exist; see Figure 26. This

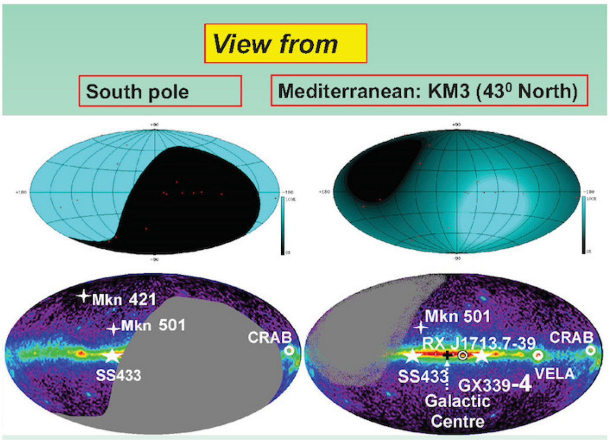

Figure 26: *Comparison between views of our Galaxy by a detector located in the Mediterranean and by one located at the south pole.*

is an undoubtable advantage compared to experiments located at the south pole, like IceCube. A further advantage of experiments located in the sea, compared to the ones installed in ice, is the better angular resolution in the reconstruction of the muon direction. [5]

Moreover, as mentioned above, in order to minimize the presence of spurious light sources, such as those from biological activity, it is convenient to work at great depths and far from shore. From this point of view the choice of the ANTARES site is not an ideal one, in spite of the logistic advantages due to the proximity of large marine infrastructures such as those present in Toulon.

A site has therefore been chosen in the eastern Mediterranean sea, south of Sicily. The site has

[5]This results from the fact that diffusion processes of Cerenkov photons in water are much less important than in ice.

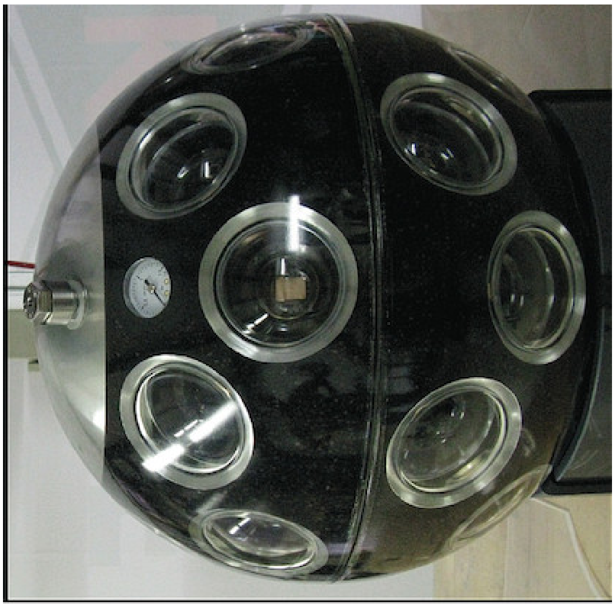

Figure 27: *One of the optical modules used in the KM3 experiment. Each module houses 31 small-diameter PMTs, eight of which are visible in the picture.*

a depth of 3500 m. and is about 100 km away from shore . A long electro-optical cable has been installed, connecting the site to the shore station (located in Capopassero- Sicily).

The interface systems between the undersea cable and the detector have been installed at the bottom of the sea, where a prototype of the detector has already been deployed and successfully operated. The full detector is now being built. It will consist of a large number of optical modules, each consisting of a pressure-resistant glass sphere housing, in place of a single large photomultiplier as in ANTARES and IceCube, 31 small size PMTs, as shown in Figure 27. Such a choice allows on one side to minimize the effect of spurious light signals (through the use of time "coincidence" requirements between nearby PMTs) and on the other to improve the precision in track reconstruction. The optical modules will be held by 115 strings, each 700 m. high, with 18 modules per string. The final detector size will be equivalent to about three times IceCube [49].

Summary and conclusions

Following the observation of solar neutrinos in several different experiments and that of neutrinos emitted in the explosion of Supernova

SN1987/A, the efforts of several experimental groups have focused on a search for very high energy neutrinos expected to be emitted from a number of galactic and extragalactic sources.

Experiments have been successfully built and operated for several years. In this summary, after a short introduction to the subject, two experiments have been analyzed in some more detail. ANTARES in the Mediterranean and IceCube at the south pole. The two experiments, located in the two opposite hemispheres of the Earth, have a somewhat complementary view of the sky. The first of these, of a much smaller size than the other one, but with a better angular resolution in the reconstruction of the muon, has not, until now, detected any source of astrophysical neutrinos. The second one has instead found a number of neutrino induced events. Some of these through the observation of neutrino induced muons at very high energies, others through the observation of neutrino induced hadronic/electromagnetic showers. However, all attempts to associate such events to possible astrophysical sources have given negative results. A new experiment, KM3, potentially with a much better sensitivity than both the two previous ones, is now under construction/installation in the Mediterranean and is expected to be fully operational within a few years.

[1] F. De Paolis, M. Giordano, G. Ingrosso, L. Manni, A. Nucita, F. Strafella: "Macro / Micro / Retro lensing gravitazionale", *Ithaca* **5** (2015) 19.

[2] http://www.asdc.asi.it/bepposax/

[3] http://chandra.harvard.edu/

[4] www.mpi-hd.mpg.de/hfm/HESS/

[5] magic.mpp.mpg.de/

[6] http://veritas.sao.arizona.edu/about-veritas-mainmenu-81

[7] B. S. Acharya et al.: "Introducing the CTA concept", *Astroparticle Physics* **43** (2013) 3.

[8] D. J. Thompson: "Gamma ray astrophysics: the EGRET results", *Reports on progress in physics* **71** (2008) 116901.

[9] http://www.nasa.gov/content/fermi-gamma-ray-space-telescope

[10] H.A. Bethe: "Energy production in stars", *Physical Review* **55** (1939) 434.

[11] H.A. Bethe and C.U. Critchfield: "The formation of deuterons by proton combination", *Physical Review* **54** (1938) 248.

[12] R. Davis et al.: "Search for neutrinos from the Sun", *Physical Review Letters* **20** (1968) 1205. R. Davis; *Proc. Informal Conf. on Status and Future of Solar Neutrino Res.*, Upton, NY, (1978).

[13] M. Koshiba et al.: "Constraints on Neutrino Oscillation Parameters from the Measurement of Day-Night Solar Neutrino Fluxes at Super-Kamiokande", *Physical Review Letters* **82** (1999) 1810.

[14] K. Hirata et al.: "Observation of a neutrino burst from the supernova SN1987A", *Physical Review Letters* **58** (1987) 1490. R. M.Bionta et al.: "Observation of a neutrino burst in coincidence with supernova 1987A in the large magellanic cloud", *Physical Review Letters* **58** (1987) 1494.

[15] http://apod.nasa.gov/apod/ap980605.html

[16] N. Agafonova et al.: "Discovery of tau neutrino appearance in the CNGS neutrino beam with the OPERA experiment", *Prog. Theor. Exp. Phys.* (2014) 101C01.

[17] D. Green: *The Physics of Particle Detectors.* Cambridge University Press, Cambridge, UK (2000).

[18] Mailcolm S. Longair: *High Energy Astrophysics.* Princeton Series in Astrophysics, Princeton, USA (2011).

[19] E. Fermi: "On the Origin of the Cosmic Radiation", *Physical Review* **75** (1949) 1169-1174.

[20] A.R. Bell: "Cosmic ray acceleration", *Astroparticle Physics* **43** (2013) 56.

[21] M. Ackermann et al.: "Detection of the characteristic pion-decay signature in supernova remnants", *Science* **339** (2007) 807-811. Also: arXiv:1302.3307 v1 [astro-ph.HE].

[22] J. N. Bahcall: *Neutrino Astrophysics.* Cambridge University Press,Cambrigde, UK (1989).

[23] T. Stanev: *High Energy Cosmic Rays.* Springer, Berlin (2004).

[24] M. D. Kistler, J.F. Beacom: "Guaranteed and prospective galactic TeV neutrino sources", *Physical Review D* **74** (2006) 063007.

[25] F. Aharonian, L. Anchordoqui, D. Khangulyan, and T. Montaruli: "Microquasar LS 5039: a TeV gamma-ray emitter and a potential TeV neutrino source", *J. Phys. Conf. Ser.* **39** (2006) 08.

[26] A. M. Taylor et al.: "Revisiting the diffuse neutrino flux from the inner Galaxy using new constraints from very high energy γ-ray observations", *Nuclear Instruments and Methods in Physics Research A* **602** (2009) 113.

[27] M.A. Markov, *Proc. 1960 Ann. Int. Conf. on High Energy Physics (Rochester)* (1960).

[28] Arthur Roberts: "The birth of high-energy neutrino astronomy: A personal history of the DUMAND project", *Reviews of Modern Physics* **64** (1992) 1.

[29] http://www.ifh.de/baikal/baikalhome.html

[30] http://amanda.uci.edu/

[31] http://icecube.wisc.edu/ http://amanda.uci.edu/

[32] http://www.nestor.org.gr/

[33] http://nemoweb.lns.infn.it/

[34] S.Aiello et al.: *"Measurement of the atmospheric muon flux with the NEMO Phase-1 detector", Astroparticle Physics* **66** (2015) 1.

[35] The ANTARES Collaboration *Proposal for a 0.1 km^2 detector*, (1999), available at *http://antares.in2p3.fr*

[36] V. Flaminio; *Proc. XIII Intern. Works. on Neutrino Telescopes* M.B.Ceolin Ed. (2009).

[37] S.Adrián-Martinez et al.: "Searches for point-like and extended neutrino sources close to the galactic center using the ANTARES neutrino telescope", *The Astrophysical Journal Letters* **L5** (2015) 786.

[38] J.A. Aguilar et al.: "Transmission of light in deep sea water at the site of the ANTARES neutrino telescope", *Astroparticle Physics* **23** (2005) 131.

[39] P. Amram et al.: "Background light in potential sites for the ANTARES undersea neutrino telescope", *Astroparticle Physics* **13** (2000) 127.

[40] M. Ageron et al.: "Studies of a full scale mechanical prototype line for the ANTARES neutrino telescope and tests of a prototype instrument for deep-sea acoustic measurements", *Nuclear Instruments and Methods in Physics Research A* **581** (2007) 695.

[41] S. Adrián-Martinez et al.: "Searches for Point-like and extended neutrino sources close to the Galactic Centre using the ANTARES neutrino Telescope", *The Astrophysical Journal Letters* **786** (2014) L5.

[42] S.Adrián-Martinez et al.: "Measurement of the atmospheric ν_μ energy spectrum from 100 GeV to 200 TeV with the ANTARES telescope", *Eur. Physics Journal C* **73** (2013) 1.

[43] Adrián-Martinez et al.: *"Search for muon-neutrino emission from GeV to TeV gamma ray flaring blazars using five years data of the ANTARES telescope", Journal of Cosmology and Astroparticle Physics* **in press** (2015) .

[44] M.G. Aartsen et al.; *Evidence for astrophysical muon neutrinos from the northern sky with IceCube* arXiv:1507.04005 v1 [astro-PH.HE] (2015).

[45] M.G. Aartsen et al.; *Search for extended and point-like neutrino sources with four years of IceCube data* arXiv:1406.6757 v1 [astro-PH.HE] (2014).

[46] M.G. Aartsen et al.; *Atmospheric and astrophysical neutrinos above 1 TeV interacting in AceCube* arXiv:1410.1749 v2 [astro-PH.HE] (2015).

[47] M.G. Aartsen et al.; *Observation of high-energy astrophysical neutrinos in three years of IceCube data* arXiv:1405.5303 v2 [astro-PH.HE] (2014).

[48] J. Barrios-Marti and Chad Finley; *First combined search for neutrino point-sources in the Southern Sky with the ANTARES and IceCube neutrino telescopes.* 34th International Cosmic Ray Conference The Hague, The Netherlands, (2015).

[49] http://www.km3net.org/home.php/

Vincenzo Flaminio: has been for many years full professor of Experimental Physics at the University of Pisa, where he has taught courses in particle and astroparticle physics and held a number of administrative and scientific responsibilities, both at the national and at the international level. He has been working for many years on high energy physics experiments at CERN (Geneva) and in the United States. Starting from about 1980 he has concentrated his experimental activity on high energy neutrino physics, with experiments carried out at CERN. Over the last decade he has moved his interests to the field of astrophysical neutrinos, with experiments such as ANTARES and KM3.

Neutrinos and Supernovae

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The most spectacular source of neutrinos in the Universe is the explosion of a supernova, which is the final stage of a very massive star. During this process, the power emitted in neutrinos is comparable to that of the entire universe. Because of this and other outstanding reasons, the detection of neutrinos from supernova detectors, located in underground laboratories, is one of the next frontiers of neutrino astrophysics.

Stellar collapse and supernova explosion

Stars with masses larger than 8 solar mass units ($M_\odot$) become unavoidably unstable in the final phase of their evolution. These stars, as all the other ones, generate energy through nuclear fusion. For most of their life, the most important reaction is hydrogen fusion into helium; however, in an advanced stage of their life cycle, not only they fuse helium into carbon, but thanks to their large mass, they can proceed in the more advanced cycles of nuclear transformations, and this leads to the formation of heavier elements. These stars evolve into an "onion structure," with a sequence of concentric layers, where the nuclear reactions of fusion take place. The outermost layer is made of hydrogen (H). Then, proceeding toward the center of the star, we have the layers of helium (He), carbon (C), oxygen (O), neon (Ne), magnesium (Mg), silicon (Si), and finally the inner core made mostly of iron (Fe): see Fig. 1.

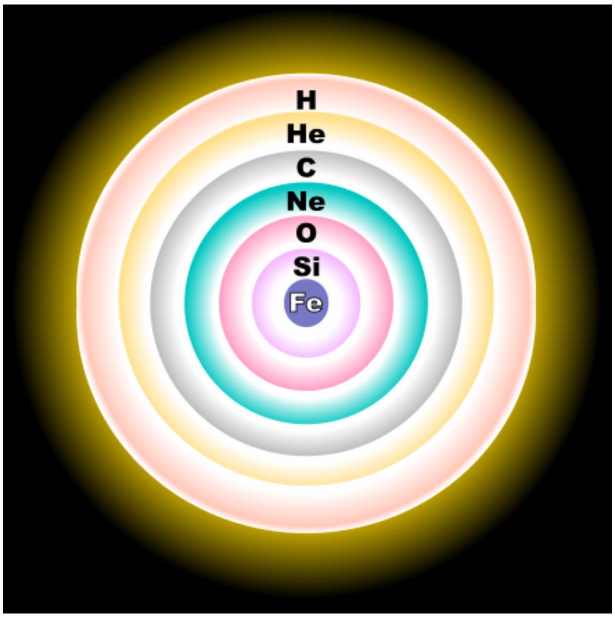

Figure 1: *Graph illustrating the "onion structure" of a massive star in the last phases of its life. (Not on scale).*

The last one, with radius somewhat less than $\sim 10^4$ km, is held by the *degeneracy pressure* of electrons (see box), till its mass becomes larger than the Chandrasekhar critical mass, that is the maximum one when the degeneracy pressure can overcome the gravitational pressure. When the

Degeneracy pressure

The pressure in the iron core of a massive star originates from the Pauli exclusion principle. This was discovered in atomic physics, where it was understood that electrons have to occupy different energy levels, from the lower to the higher one. Thus, when we try to bring two electrons of the star in the same point, they are forced to have different velocities and energies; since we have many electrons, many of them will have very high energies. The high velocities and energies of the electrons lead to a pressure that counteracts gravity. However, when the electron move at velocities close to the velocity of the light, the pressure lessens and eventually, if the weight is large enough, the gravitational pressure wins. This is the point that defines the Chandrasekhar mass, mentioned in the text.

mass of the iron core exceeds this limit ($\sim 1.3 M_\odot$) the core becomes unstable and collapses under its weight. The collapse is halted by the repulsive nuclear forces (i.e., on the nucleon degeneracy pressure) at a density of $\rho_{\text{nucl}} \sim 2.8 \times 10^{14}$ g/cm^3, when nuclear matter becomes incompressible. At this point, the pressure can stop the collapse and causes a *bounce* from the innermost part of the core. Strong pressure waves are reflected from the center and they proceed toward the outer part of the star. As a result, the inner part of the core, acting as a piston, generates a *shock wave* in the external part of the core, at a distance of 50-100 km from the center. This mechanism can change the implosion into an explosion; assuming that enough energy is stored in the shock wave, it can heat and expell the stellar mantle. In this manner, we obtain a *core collapse supernova*. The various phases of a supernova are illustrated in Fig. 2.

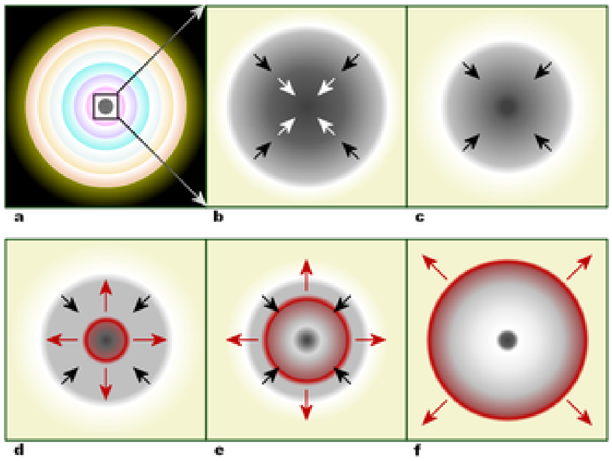

Figure 2: *Phases of the gravitational collapse of a massive star. In the inner part of the star, that has already reached a late evolutionary stage (a) fusion reactions end after iron synthesis. A massive core forms (b) that in a short time reaches Chandrasekhar mass, beginning to collapse under its own weight. (c) The innermost part forms a degenerate neutron core that heats and emits copiously neutrinos. (d) The matter bounces and (e) forms a shock wave that slows down in the interface with the outermost part of the core. (f) However, various processes including neutrino interactions contribute to relaunch the shock wave, that sweeps out the external layers of the star, leaving only a compact stellar remnant: the neutron star.*

Supernova neutrinos

The shock wave, during its propagation from the inner core, looses energy by dissociating the atomic nuclei of iron. The protons that are produced in this way transform rapidly into neutrons thanks to the *beta process* $e^- + p \to n + \nu_e$, which leads to an emission of electronic neutrinos, called *neutronization emission*. Thanks to this process, the core evolves into a proto-neutron star. In the meantime, the external part of the core continues to fall into the center, accreting the proto-star, whose mass reaches $1.4 - 1.6 M_\odot$. The emitted electronic neutrinos can escape freely till the density of the core becomes so high as to make it opaque to neutrinos. The most important processes that produce the neutrino trapping are: *(i)* diffusion on free nucleons ($\nu + N \to \nu + N$), *(ii)* coherent diffusion on heavy nuclei ($\nu + (Z, A) \to \nu + (Z, A)$), *(iii)* absorption by nucleons ($\nu_e + n \to p + e^-$), *(iv)* neutrino-electron scattering ($\nu + e^- \to \nu + e^-$). The impact of these processes can be estimated calculating the neutrino's mean free path $\lambda = 1/\rho\sigma \sim 10$ m,

Type of supernovae

The most useful classification is the astrophysical one, based on the mechanism of the explosion: thermonuclear *vs* core collapse. Let us begin with the former class. Stars with masses between $4 < M < 8M_{\odot}$ that evolved as white dwarfs, and that belong to a binary system, can accrete matter from the companion star. The amount of accreted mass can lead to the reactions of carbon fusion. This triggers a thermal runaway process that destroys the white dwarf star completely. In this case, the neutrino emission is negligible. Instead, stars with larger mass, $M > 8M_{\odot}$, explode through the gravitational collapse mechanism, illustrated previously.
Astronomers classify supernovae depending on their light curve and absorption spectra, that allow us to probe the chemical elements present in their outer layers. The first criterium is the presence or absence of hydrogen lines in the spectrum (that are called Balmer lines, when they fall in the visible part of the spectrum). In the first case, we have a *type II* supernova; otherwise is of *type I*. The last class is further divided: the presence of ionized silicon line (Si II) indicates *type Ia* supernova. The rest is classified in *type Ib* supernova, when we have non-ionized helium lines; finally, when also this line is absent we have *type Ic*. The thermonuclear supernovae correspond to type Ia supernovae (i.e., with Si II lines); these have a luminosity that is standard within a factor of two and for this reason they are used in cosmology. The other ones, namely type II, Ib, Ic (without SI II lines) are core collapse supernovae, and their difference is attributed to a difference in the external layers of the star.

where $\rho \sim 10^{38}$ nucleons/cm^3 is the proto-star density, and $\sigma \sim 10^{-41}$ cm^2 is the typical size of the cross sections for the above processes. The mean free path is much smaller than the radius of the proto-neutron star. Thus, the trapped neutrinos diffuse inside the proto-star. An estimation of the diffusion time is given by the travel time during a single free path, times the number of steps, $\tau \sim (\lambda/c)(R/\lambda)^2 \sim 10$ s. It is also useful to introduce the concept of *neutrino-sphere*, that indicates the radius within which a neutrino undergoes the last scattering event before exiting freely from the core. Inside the neutrino-sphere the neutrino is subject to thermal diffusion (=it is trapped) whereas outside it is free.

In the interval of time from 0.5 to 10 s after the bounce, the proto-neutron star can be considered as an object of about 30 km that contracts slowly and that cools down by radiating neutrinos and antineutrinos of all types. The most relevant emission processes are: $p+e^- \to n+\nu_e$, $n+e^+ \to p+\bar{\nu}_e$, $e^+ + e^- \to \nu + \bar{\nu}$, $N+N \to N+N+\nu+\bar{\nu}$. The emission in this phase is called *thermal emission*. At the end of this phase, we have a true *neutron star*. During this phase, a supernova can be considered as a *black body* that cools down by emitting neutrinos of all flavors. Almost all the binding gravitational energy (about 3×10^{53} erg) is carried away by neutrinos, emitted with quasi-thermal spectra and with average energies of $12 - 15$ MeV.

Supernova 1987A

Detectors able to observe a signal of neutrinos from supernovae in the Milky Way have existed since 1980, when the BST (Baksan Scintillator Telescope) became operational. However, we have to wait the first supernova observed in 1987 (SN 1987A) in order to receive the first signal. This supernova exploded on February 23 in the Large Magellanic Cloud, a small galaxy, that is a satellite of our Galaxy, at a distance of about 170.000 light years (Fig. 3).

For the first time it was possible to find in astronomical archives the progenitor star, a blue supergiant star, with mass of about 20 $M_{\odot}$. Being the star relatively close and thanks to its huge luminosity, it was possible to conduct observations with an unprecedented accuracy. Moreover, for the first (and up to now the only) time, it was possible to measure the signal from supernova explosion.

Two water Cherenkov underground detectors,

Figure 3: *The region of the sky where SN1987A exploded. Before (left) and after (right).*

Kamiokande II in Japan and IMB in Ohio, detected 11 (Fig. 4) and 8 events respectively within a lapse of about 10 seconds. The observations of BST were less significant but consistent with the same signal. Despite the low statistics, and the fact that these detectors were sensitive only to electronic antineutrinos (in very good approximation), the amount of information extracted by the scientists from these events is remarkable.

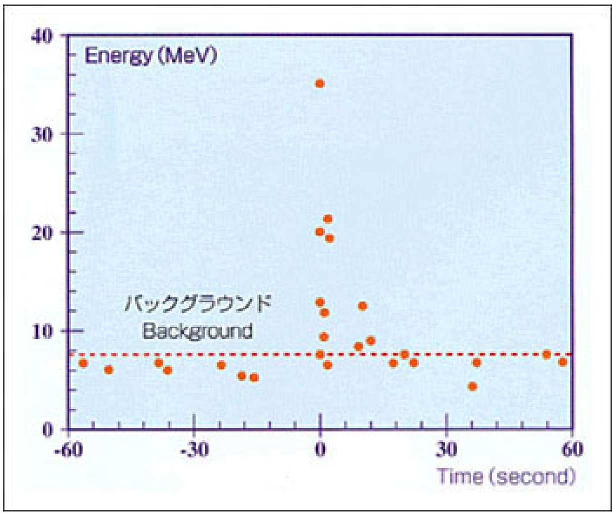

Figure 4: *The 11 events above the line, at the origin of the time ($t = 0$), are the observations of the Kamiokande II detector in correlation with SN1987A.*

There is no doubt that a signal was observed. This signal confirms the description of a proto-neutron star that cools by emitting neutrinos. The energy of the individual neutrinos corresponds to the initial temperature of a proto-neutron star, and the duration of the signal corresponds to the time-scale of $\sim$ 10 s expected for the cooling process. The excellent agreement between theory and observations allowed scientists to conclude that the star lost energy through new speculative process, associated to the emission of exotic particles such as axions or sterile neutrinos. Furthermore, the energy spectrum allowed to obtain an estimation of the total energy emitted by the supernova, that is consistent with the formation of a neutron star of mass of $1.4\ M_{\odot}$ and radius of 15 km.

Moreover, these measurements disclosed fundamental properties on the nature of neutrinos. Due to the fact that neutrinos reached the Earth about 3 hours before the supernova was seen in optical, they travelled at a velocity very close to the velocity of the light. Since the delay of neutrinos is proportional to the square of the ratio of their mass over the energy, scientists have concluded that the mass of neutrinos should be quite small; this allowed them to conclude that they cannot be the dominant component of dark matter in the Universe.

Future observations of supernova neutrinos

The lesson provided by SN 1987A is that neutrinos and supernova physics are tightly connected. Thus it is not unexpected that one of the greatest desire of neutrino astronomers and physicists is an explosion of a supernova in the Milky Way. Surprisingly, none of them has been seen since 1604, when a "new star" was observed in the Ophiuchus constellation. This one was studied among the others by the German astronomer Johannes Kepler (and we name the supernova after him) and by the Italian Galilei. Just three decades before, in 1572, European astronomers, including the legendary Danish astronomer Tycho Brahe, happened to observe another one. Present evidences suggest that both of them were of thermonuclear type rather than due to gravitational collapse.

Based on the observations in other galaxies, astronomers expect that there are 1-3 supernova explosions per century in the Milky Way. Even if the interstellar material absorbs the light of a supernova after a small fraction of the typical galactic distance, this will not stop neutrinos, whose detection would announce the death of a massive star in the Milky Way.

Owing to the fact that neutrinos are emitted by a supernova before the light, their detection announces astronomers that a supernova is going to be visible in a few hours. In this regard there is a network of neutrino detectors, called *Supernova Early Warning System* (SNEWS) designed to give an early warning on supernovae in our galaxy. This includes among other detectors BOREXINO and Large Volume Detector (LVD) at Gran Sasso National Laboratories in Italy, Super-Kamiokande in Japan and IceCube located at the South Pole. These detectors are highly sensitive to a neutrino signal from a galactic explosion. For example, Super-Kamiokande should register several thousand events from a supernova in the Galactic center, that is at 25,000 light-years from us. These neutrinos may allow us to locate the supernova in the sky with a resolution of a few degrees. IceCube, that should receive a million events, is the best detector to reconstruct the temporal structure of neutrino signals. The high neutrino statistics expected in the currently operating detector will provide us a detailed picture of gravitational collapse. Among other things, scientists will be able to determine if the gravitational collapse of the star has produced a black hole, from which nothing (even neutrinos) can eventually escape, differently from a neutron star. In the case of the formation of a black hole, the stream of neutrinos emitted by the supernova would undergo an abrupt halt. Instead, if the result of the explosion was a neutron star, neutrinos will be emitted on a time-scale of about 10 s during its cooling, so that the neutrino flux should decrease gradually rather than be subjected to a sudden interruption.

Also particle physicists are interested in neutrinos from supernovae, which offer a rare opportunity to understand how these particles behave in extreme conditions, that cannot be reproduced in the laboratory. In particular, in the innermost regions of a supernova, the density of neutrinos is so high that their own self-interactions, usually negligible, can affect their evolution of flavor. In these conditions, neutrinos form a dense gas that can show unusual behavior, in the form of *collective oscillations*. Moreover, neutrino oscillations in the supernova are sensitive to the dynamics of the explosion. In fact the time evolution of the neutrino signal could allow us to follow, in real time, the propagation of shock waves in the star. Finally one of the main open questions in neutrino physics is the so-called "mass hierarchy", i.e. how the neutrino mass states are arranged. Two options are allowed: *(i)* normal mass hierarchy, when there are two light mass eigenstates and a heavy one *(ii)* inverted hierarchy when there is only one light states and the other two are heavy (and very close in mass). Measuring neutrinos from supernova could help to address this fundamental question.

From what has been discussed, it is clear that the observation of a signal of neutrinos from galactic supernova will have an enormous physical potential. However, galactic explosions are rare events. On the other hand, there are about 10 supernova explosions per second in the visible universe. The cumulative emission of neutrinos from these supernova explosions has produced a cosmic background neutrino, the so-called *diffuse supernova neutrino background*, whose existence was predicted already before SN 1987A. Albeit weak, this diffuse flux is guaranteed to exist, and it can offers us a chance to probe different physics than the one of galactic explosions, including processes that occur on cosmological time scales. In particular, the diffuse supernova neutrino signal is sensitive to the rate of star formation. To date, this signal has not yet been revealed, but the Super-Kamiokande experiment has obtained a stringent bound, that is only a factor ~ 2 larger than the typical theoretical estimates. This limit is encouraging. Actually, the Super-Kamiokande experiment is developing advanced experimental techniques to attempt or allow the detection of this signal in the coming years.

Although galactic supernova explosions are rare, there is a good chance that it will happen in the next decades. In addition, the measurement of the diffuse flux from cosmological supernovae may be imminent. What remains to do, then, is to be patient and get ready, through the development of theoretical models and experimental procedures, apt to reveal and analyze in the best possible manner such an event, since this will be a once-in-a-lifetime occasion.

[1] F. Vissani: "Comparative analysis of SN1987A antineutrino fluence", *Journal of Physics G* **42** (2015) 013001.

[2] A. Mirizzi, I. Tamborra, H.-T. Janka, N. Saviano, K. Scholberg, R. Bollig, L. Hüdepohl, S. Chakraborty : "Supernova Neutrinos: Production, Oscillations and Detection", *Riv. Nuovo Cim.* **39** (2016) 1.

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Neutrinos and cosmology

Elles sont engendrées par un raisonnement mathématique, établies sur des calculs, réductibles à des schémas d'une grande sécheresse. Mais dans ces cadres sévères, une sorte de fièvre presse et multiplie les figures; un étrange génie de complication enchevêtre, replie, décompose et recompose leur labyrinthe.

H. Focillon, Vie des Formes

Gianpiero Mangano *Istituto Nazionale di Fisica Nucleare, Sezione di Napoli, Italy*

Among the presently known elementary particles, neutrinos are the most elusive. *Invented* by Wolfgang Pauli to save energy and statistics conservation in β decays, their direct detection and properties have challenged physicists for decades. They feature an incredibly rich phenomenology and leave a clear imprint in many environments, from nuclear plants to earth interior, from star burning to supernova explosions. In this brief essay I will describe how they affect many stages of the evolution of the universe, whose study is usually referred to as *Cosmology*.

Neutrinos

Neutrinos first came on the scene in 1930, when Wolfang Pauli proposed that to save energy conservation and the relation between spin and statistics in nuclear β decays where a neutral particle with spin 1/2 was emitted (at that time he called this new particle *neutron*) along with an electron.

Pauli later confessed to his colleague, the astronomer Walter Baade, that (quoted in [1]):

> *"I have done a terrible thing today, something which no theoretical physicist should ever do. I have suggested something that can never be verified experimentally.* "

This was, perhaps, the only time Pauli was mistaken. Less than thirty years later, in 1956, neutrinos were discovered by Reines and Cowan.

We presently know a lot about neutrinos, but they stil keep some secrets. Since their properties are reviewed in detail in other essays in this volume, see in particular [3, 4, 5], I will briefly summarize the present state of the art and introduce the minimal set of necessary concepts which will be used in the following.

Cosmology distilled I: evidences

The hot Big Bang model is our present description of the evolution of the universe. In fact, one of the main results of applying Einstein General Relativity to such a large system is that we can think about an evolving universe, something which in Newton language is difficult to implement. There are three main observations in favour of the Big Bang:

1) Hubble's law. 1929 is the year of Edwin Hubble's galaxy recession law: objects such as galaxies observed in deep space at sufficiently large distances (few megaparsecs or more) are found to have a Doppler shift due to relative velocity away from Earth. This velocity v, of a galaxy receding from the Earth, is approximately proportional to its distance d from the Earth, at least for galaxies up to a few hundred megaparsecs away, see Figure 1, $v = H_0\, d$, with $H_0 \sim 70$ Km/s Mpc^{-1} the Hubble constant. Actually, Hubble's law was theoretically derived few years before by Georges Lemaître from Einstein general relativity, as a typical feature of an expanding universe.

2) The CMB background. Up to small fluctuations of relative amplitude of order 10^{-5}, Earth receives an isotropic photon radiation with a remarkable property: the frequency (ν) shape is a perfect black–body! See Figure 2. First detected by Penzias and Wilson in 1964 while they were working on a new microwave antenna, it was soon understood as the echo of some early expansion stage of the universe, as first hypothesized by George Gamow in the 40's.

   A black body distribution is the analogous of Maxwell-Boltzmann equilibrium velocity distribution for photons

$$\text{flux}(\nu) = \frac{2h\nu^3}{c^2}\frac{1}{e^{h\nu/kT}-1}\text{W/m}^2\text{/str/Hz}$$

   If photons keep such a perfect equilibrium distribution it is because they were in equilibrium conditions in the past, since the present universe is too much diluted and cold on average, and electromagnetic interaction is not strong enough to maintain equilibrium. This can be achieved only if once the universe was much hotter and denser than today, so that photons were interacting quite efficiently with matter. CMB temperature today is $T = 2.752 \pm 0.002$°K. In the expression above k, h and c are the Boltzmann constant, the Planck constant and the speed of light.

What we do know

i) Neutrino flavours and interactions.

   There are three known neutrino species (or *flavours*), ν_e, ν_μ and ν_τ, and three corresponding antiparticles (antineutrinos) $\overline{\nu}_e$, $\overline{\nu}_\mu$ and $\overline{\nu}_\tau$, which always appear in interaction processes accompanied by their charged lepton partners, $e^\pm$, $\mu^\pm$ and $\tau^\pm$, respectively. Differently than the latter and quarks, they interact with other particles (including themselves) via weak and gravitational forces only. When the typical energy and linear momentum transfer are sufficiently small (in the following we will be mainly concerned with the MeV energy scale or below (MeV=10^6 eV)) weak processes can be described by the $Fermi - Gamow - Teller$ model, the first coherent description of weak interactions, proposed by Fermi as early as 1934. In this low energy regime the interaction strength is set by the Fermi constant $G_F \simeq 1.166 \cdot 10^{-5}$ GeV^{-2} (GeV= 10^9 eV). Since the seventies of the last century, Fermi's theory has been beautifully embedded in the Standard Model of electro–weak interactions of Glashow, Weinberg and

3) The Big Bang Nucleosynthesis. All elements which are naturally found on Earth and surroundings are thought to have been produced in stars during their life or, for very massive stars, during their catastrophic endings as Supernovae. However, the expected amount of ^{4}He, a typical product of proton burning produced by all generation of stars, is much smaller than what is observed. What is responsible for the extra Helium? The answer is again rooted in the idea that in the past the universe was much hotter and denser, and in a particular epoch it was working as a huge nuclear fusion reactor. The main product of this phase is, in fact, ^{4}He, but also deuterium, ^{3}He and ^{7}Li. This is Big Bang Nucleosynthesis (BBN), a typical nonequilibrium phenomenon: as the universe expands, the probability of nuclear processes taking place becomes smaller and smaller and at some point the abundances of different nuclear species freeze. There is a simple way to understand why this is the case: otherwise all nuclei would have evolved into the most energetically convenient species, ^{56}Fe, which has the largest binding energy per nucleon. BBN involves a complicated set of nuclear reactions, sketched in Figure 3.

Salam. As for electromagnetic forces, where electrically charged particles interact by photon quanta exchange, weak processes are mediated by the massive $W^\pm$ and Z^0 *intermediate bosons*. The short range and weaker intensity of these processes is ultimately due to the large mass of these particles (80 GeV and 91 GeV for $W^\pm$ and Z^0, respectively).

Neutrinos gravitational interactions are typically negligible in colliders, where the gravitational mass of the two bunches of colliding particles is too small to produce observable effects (at least till now!). In this case neutrinos only scatter, appear or are absorbed via weak interactions. In dense and very large environments, such as the universe as a whole, gravity is quite important and, as we will see, neutrino contribution to the total gravitational field is not negligible.

ii) Neutrino masses and flavour oscillations.

Though Pauli explicitly mentions in his famous letter to the "Radioactive Ladies and Gentlemen" in 1930 that neutrinos "*...further differ from light quanta in that they not travel with the velocity of light. The mass of neutrons* (as we said, Pauli named the new particle neutron) *should be of the same order of magnitude as the electron mass and in any event not larger than 0.01 proton mass...*", till the big revolution after the discovery of neutrino oscillations, neutrino masses were typically assumed to be zero. The theoretical framework supported this idea since in the simplest version of the Standard Model of electro–weak interactions there is no need for introducing a right–handed neutrino (or left-handed antineutrino) component. In this case a neutrino is represented by a Weyl massless spinor (see [4]). However, in the last three decades, experimental results on the neutrino flux from our Sun and that produced by cosmic rays impacting nuclei in the Earth atmosphere have clearly shown that neutrinos feature flavour oscillations during their propagation, see [5]. This is a neat evidence that there are three neutrino states with different masses, and that the three *flavour eigenstate* neutrinos ν_e, ν_μ and ν_τ, are a linear superposition of these mass eigenstates. This is a typical quantum mechanical effect: since de Broglie's hypothesis in 1924, particles are known to have wave-like behaviour too, in particular they can interfere and, similarly to electromagnetic waves, also *matter* waves satisfy the linear superposition principle during their propagation.

Actually, oscillation results probe the (squared) mass differences among the three

Pauli idea

In β decays of unstable nuclei such as tritium ^{3}H, the electron kinetic energy E_e would be a constant if it were the only emitted particle

$$^3\text{H} \rightarrow ^3\text{He} + e^-$$

and given by the $Q-value$ of the reaction, $Q = M(^3\text{H}) - M(^3\text{He}) - M(e^-)$, where M is the mass of the corresponding particle. This is not what is found in experiments, which show that electron energy covers a continuous range from a minimal up to the maximum value Q. Energy conservation is violated, unless a neutral particle (so that electric charge is conserved) is also emitted: an *electron* antineutrino

$$^3\text{H} \rightarrow ^3\text{He} + e^- + \overline{\nu}_e$$

The (anti)neutrino should have half-integer spin to preserve the relation between spin and statistics (again a fundamental idea of Pauli: the exclusion principle). From ^{3}H β decay we know that the neutrino mass scale m_ν cannot be larger than 2 eV, a bound which is obtained by observing the largest energy carried by the electron, $E_e \leq Q - m_\nu$. The KATRIN experiment, which is presently running [2] is expected to lower this upper bound by an order of magnitude, or to find an evidence for neutrino masses, if this mass is larger than 0.2 eV.

neutrino mass values m_i, $i = 1, 2, 3$, which are now determined with quite a high accuracy (few percent)

$$\sqrt{m_2^2 - m_1^2} = 0.009 \text{ eV}$$

$$\sqrt{m_3^2 - m_2^2} = 0.05 \text{ eV}$$

This means that at least two neutrinos have a non zero mass, while the lightest state may be massless. In fact, what oscillation experiments cannot tell us is the *absolute* neutrino mass scale m_0.

What we don't know

i) Neutrino mass scale.

The strongest bound on the neutrino mass scale, i.e. the value of the lightest neutrino mass m_0, comes from the analysis of electron energy spectrum in ^{3}H β decay. From energy conservation, the largest kinetic energy of the emitted electron is given by the Q value of the process minus the smaller neutrino mass value. The present bound is around 2 eV. As we will see, indirect information on m_0 comes from cosmology. The value of m_0 sets the scale in the evolution of the universe when neutrinos become nonrelativistic particles, i.e. their typical mean kinetic energy falls below the value of their mass. When this phenomenon takes place, they start falling in the gravitational potential wells of local gravitational fields around the forming inhomogeneous structures (galaxies, clusters), and contribute to their formation.

The fact that, in any case, the electron neutrino mass cannot exceed few eV, which is several orders of magnitude smaller than the value of charged lepton masses (the lighter, the electron, has a mass of 0.511 MeV) has puzzled the physicist community for decades, and is still triggering one of the main research activities from both the theoretical and experimental point of view. Presently, perhaps, the most elegant (theoretical) solution to understand why neutrinos are so special is the see-saw mechanism: since they are neutral particles, they are special in the sense that they can coincide with their own antiparticle (for the electron this would be impossible since the anti–electron (positron) has an opposite electric charge, and the same holds for the other charged leptons and quarks!). This opens the possibility that neutrinos can be Majorana particles and that their masses, in addition to the celebrated Higgs mechanism, are also the effect of some new very large physics scale.

ii) Dirac or Majorana?

In 1937 Ettore Majorana [6] found that it is perfectly consistent with Einstein special relativity to assume the existence of particles which coincide with their antiparticles. These are now known to be described in terms of *Majorana spinors*, while particles which are different from their antiparticles are related to *Dirac spinors*. All electrically charged particles are necessarily Dirac particles, but neutrinos are in this respect "special". Are they speaking sicilian dialect (Majorana was from Catania) or perfect Oxbridge (Dirac)? We don't know yet the answer to this question, but we have some experimental handle to attack the problem: neutrinoless double beta decay. Finding evidence for this very rare process would be a clear signature that indeed, neutrinos are Majorana particles. For a review on this issue see [7]. Let me only stress that if neutrinos would be found to Majorana–like, this would be not only pointing towards a solution of why they are so light particles (the already mentioned see- saw mechanism at work!). It would be perhaps, the only evidence we have so far for some new phenomenon which cannot be described in terms of our understading of fundamental interactions (what is now in jargon defined as *Physics beyond the Standard Model*).

iii) Are there extra neutrino species?

The magic number three for neutrino species is doubly rooted. On one side it is predicted to be three from the fact that we have clear experimental evidences that they are always paired with charged lepton partners and that there are three charged lepton species. On the other side, any extra neutrino species which is weakly interacting would have been found in the Z^0 decays at LEP experiments at CERN. This is not what data say: LEP result is that the number of *active* neutrinos (i.e. weakly interacting) is $2.98 \pm 0.07(stat) \pm 0.07(syst)$ ($stat$ is the statistical error, $syst$ the systematic error). Experiments and theory perfectly match! Yet, theoretician fantasy is always going further. Not only! In fact, there is a bunch of experimental anomalous data, see [8], which seem to suggest that there might be other neutral particles, interacting only gravitationally (the word $sterile$ neutrinos is usally used, which means that they have no whatsoever currently known interactions, apart, as we said, gravitational ones). I must say that the laboratory experimental situation at the moment is still a bit involved. We will see that some independent information may come from cosmology.

Cosmology

Cosmology is the quantitative study of the properties and evolution of the universe as a whole. The discovery of the redshift-distance relationship by Hubble in 1929 was the first clear hint in favour of an expanding universe, which can be beautifully described in terms of the Friedmann and Lemaître solution of Einstein equations. Were not for the great achievements of Einstein, a new perspective for a description of gravity, cosmology would not exist at all.

At the basis of Friedmann and Lemaître model there is the empirical observation that on large scales the universe is remarkably homogeneous (observations are independent of the position of the observer) and isotropic (observations are the same in any spatial direction). This experimental fact is usually called the *Cosmological Principle*. Assuming that our observation point is not privileged, in the spirit of the Copernican revolution, one is naturally led to the conclusion that all observations made at different places in the universe should look pretty the same and independent of direction. Homogeneity and isotropy single out a unique form for the spacetime metric, the basic ingredient of Einstein theory. Cosmological models can then be quantitatively studied after specifying the matter content which acts as source for curvature. Results can be then compared with astrophysical data, which in the last decades have reached a remarkable precision.

Actually, the Cosmological Principle only works on scales larger than about 100 Mpc, yet it is a powerful assumption. Many observations, as the distribution in the sky of the Cosmic Microwave Background (CMB), first detected by Penzias and Wilson in 1964, show inhomogeneities which are quite small, so that they can be treated as perturbations of a reference model which is homogeneous and isotropic.

The idea of an expanding universe leads to the non trivial point that all matter was characterized in the past by a larger density and a higher temperature than today, back to an initial singularity where quantum aspects of gravity are expected to be important, and one is forced to abandon the classical Einstein theory. Apart from this poorly understood initial stage, the *hot Big Bang* model gives quantitative predictions for many observational features which can be tested experimentally. This model is self-consistent provided that at early times the expansion was accelerated during a phase known as *inflation*. This stage is now a real cornerstone, and predicts very robust signatures that influence the later evolution, as the fact that inhomogeneities develop starting from some inital seed produced during this stage, or that CMB photons coming from very different directions share the same distribution in energy, up to very small fluctuations of order 10^{-5}, as first detected by the COBE satellite.

The validity of the hot Big Bang model is deeply related to the observation that CMB photons are characterized by a remarkably accurate black-body distribution, with a present temperature $T = 2.725 \pm 0.002$ K . This is a clear signal that photons were once in thermodynamical equilibrium with other particles (electrons, nuclei etc.), and thus, that the universe was filled by a plasma of nuclei, charged leptons, photons, neutrinos etc. In other words, as we go back in time and imagine to take snapshots of the universe's conditions, it would look hotter and denser. The natural tool to describe the properties of this plasma is equilibrium statistical mechanics. As long as interactions among particles are strong enough to guarantee equilibrium conditions, as it happens for example to atoms or molecules of a gas in a box, it is possible to introduce the concept of temperature and describe the time evolution of all species using equilibrium statistical mechanics, or its macroscopic counterpart, equilibrium thermodynamics.

However, the empirical fact that systems always spontaneously evolve toward equilibrium configurations holds if the system is unperturbed. In the universe, if the rate of expansion is too fast, particles may fail to reach equilibrium at certain epochs. This observation is crucial in order to explain the production of light nuclei during primordial nucleosynthesis, the relic abundance of baryons (protons and light nuclei such as deuterium, ^{3}He and ^{4}He) or the expected relic dark matter density today. To describe all these phenomena, it is necessary to abandon equilibrium thermodynamics and use kinetic theory, a mathematical tool which describes how a system made of many particles evolves in time, and eventually tends to reach an equilibrium configuration. It was pioneered by Ludwig Boltzmann in his famous paper of 1872. His visionary approach consists in looking at the time evolution of the particle distribution function as the solution of an integro-differential equation, which after him is now popular as the Boltzmann equation.

Why should we use kinetic theory to describe (at least some) features of the evolution of the universe? The reason is that, as we said, during the expansion, equilibrium is not always guaranteed. In an expanding universe there are two competing effects in attaining equilibrium: expansion and interaction processes among particles. The expansion rate is encoded in the Hubble parameter H, while equilibrium is established by interaction processes such as scatterings (which redistribute particle momenta) and those where the number of particles of a given species is not conserved, which enforce chemical equilibrium among different species. Since the universe is expanding, equilibrium is maintained if the rate of microscopic interactions is larger than the expansion rate. In this case the evolution of the system is *quasi–static*, and can be considered as a sequence of equilibrium states. The condition of equilibrium is thus $\Gamma \gg H$, where Γ is the typical interaction rate (the number of interaction processes per unit time).

Actually, the most interesting epochs in the history of the universe are those when equilibrium is not achieved! The evidence of a large amount of *dark matter*, the absence of antimatter in the observable universe, the early formation of nuclei after few seconds from the big bang, the CMB itself: all these phenomena are clear indications of several out–of–equilibrium stages. Last but not least, the Cosmic Neutrino Background (CNB), the analogous of the photon relic trace of the early expansion, keeps a clear signature of some non equilibrium phenomenon: that, when the universe was few seconds old, weak interactions became too slow to keep neutrinos in thermal contact with photons and electron–positron pairs.

A very incomplete, yet brief and more quantitative introduction to standard cosmology is presented in the two boxes *Cosmology distilled* I and II. In the following section, using Einstein's theory, I will then describe equilibrium statistical mechanics, kinetic theory and the Standard Model of electro–weak interactions, and how neutrinos are expected to fill the universe during its evolution. Moreover, and more interestingly, comparing observations with theory we can also gain a further insight on some of their yet unknown properties.

Before discussing this issue, I will slightly digress and summarize the present understanding of the different phases of the evolution of the universe. Each phase predicts a different expansion rate and can be constrained by observational data. For example, a matter dominated epoch, i.e. when non relativistic particles (their kinetic energy is much smaller than their rest mass) are the main source of gravitational field, would be simply a disaster during Big Bang Nucleosynthesis (BBN)xs.

i) Inflation.

   Einstein equations predict that as long as *particles*, either relativistic as photons, or non relativistic as the unknown dark matter or baryons, represent the only source term for gravity, the universe expansion would be always decelerated. Not differently than the Newton apple, which can travel till infinite distances, but always feeling the Earth attraction. Innocent as it might appear, this observation raises conceptual problems on the overall expansion history of the universe. In the early eighties of the last century, it was found that an initial *accelerated* initial stage may solve these problems, at the prize of assuming that there is a gravity source which is accelerating the expansion: something whose energy density does not change in time, a *cosmological constant* or something very close to it. It was later found that this scenario, called inflation, is also able to make simple predictions about how from initial random inhomogeneities all structures we see in the sky (galaxies, clusters etc.) developed.

ii) Radiation domination.

   For quite a long period (not in terms of time, but for what in the meantime the universe was experiencing!) all was radiation, a fluid made of particles with large kinetic energy with respect to their masses. There is a remarkably robust probe telling us that this was the case when the universe was from few seconds to minutes old: Big Bang Nucleosynthesis. The formation of light nuclei would not be consistent with observational data if at that time the universe had been expanding with a rate just few percent different than what is sourced by radiation. The only question still partially open is how much radiation was present at that time. We will discuss this point later on, since it is relevant to understand how many neutrinos were in the universe at that epoch.

iii) Matter domination.

   Radiation is moving too fast to allow structure formation. Galaxies and clusters would form at a much slower rate than observed, if relativistic particle were responsible for the total energy budget in the universe, because they are not easily caught in gravitational potential wells. They are too fast, and the net effect is that they suppress the growth of local structures. Evidences at different length scales (the rotation curves in galaxies, the mass deficit in galaxy clusters if we only count luminous matter, the CMB properties etc.) all point towards the idea that there are heavy particles which have been non relativistic in the last billion years. Along with baryons, these *Dark Matter* particles represented the main contribution to the right hand side of Einstein equation (see insert Cosmology distilled II) till very recent epochs, and being very slow, they are the main responsible for the growth of inhomogeneities, leading to the complicated pattern we see in the sky on sufficiently small scales (galaxies, clusters, filaments and large voids). The quest for the nature of dark matter is still open but all experimental data call for its existence.

iv) Cosmological constant wins today.

This is a subject for another essay. Astrophysical data, mainly the observation of recession velocity of very distant Supernovae of type Ia, tell us that the universe expansion today (and in the recent epochs) is accelerated. Since it is not relevant for the main subject of our analysis, I don't go further in describing this extremely interesting issue, but simply mention how science is once more in debt with philosophy: it seems that the beginning of universe expansion and its late fate are both accelerated, an *eternal return* in Nietsche words in the *The Gay Science* and *Thus spoke Zarathustra*.

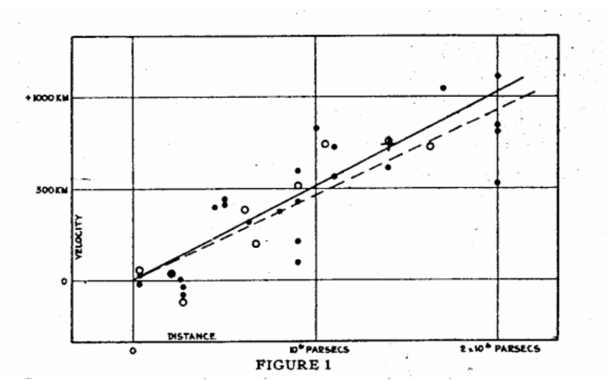

Figure 1: *The original plot of recession velocity versus distance in 1929 Hubble paper.*

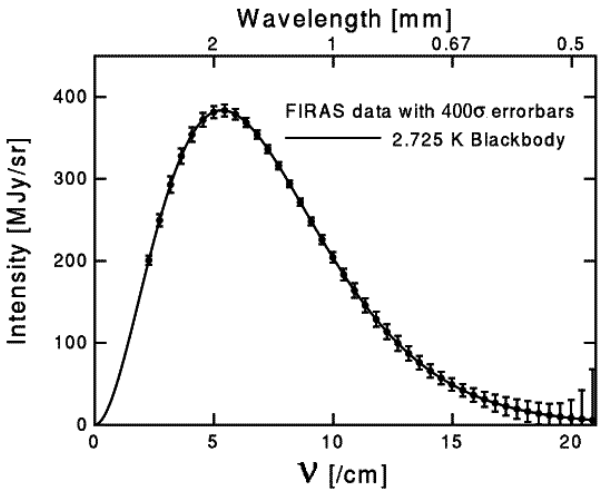

Figure 2: *The CMB frequency distribution as observed by FIRAS experiment (points) compared with a black-body distribution (solid line). Notice that error bars correspond to 300 times the experimental measurement error!*

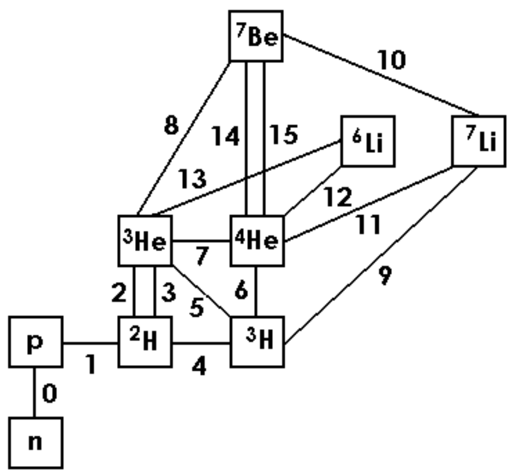

Figure 3: *A diagram illustrating the main nuclear reactions during BBN.*

Neutrinos and Cosmology

A universe filled with neutrinos

The standard picture of the early stages of the universe is that it was filled by a dense and hot plasma of all known (and presumably other species we don't yet know!) which at that time were all relativistic because of the high mean kinetic energy. Their continuos interactions soon lead to a thermodynamical equilibrium state. Because of the expansion, like it happens to a gas in an expanding and thermally insulated box (adiabatic expansion), their temperature T, number density, density and energy density decrease . In particular, the energy–pressure conservation law discussed in the box *Cosmology distilled II: tools* predicts that the temperature decreases with a law of inverse proportionality with respect to the scale factor, $Ta(t) = constant$. This is what is known as the $redshift$[1]. Notice that since $a(t)^3$ is the way volumes scale in an expanding universe, we have $T \sim V(t)^{\gamma-1}$, and the adiabatic

[1]Redshift is more fundamental than a decrease of temperature, i.e. of the mean kinetic energy of a relativistic species in thermal equilibrium. Even a single particle with no thermal contact undergoes the same effect. In expanding universes, in fact, the linear momentum of a particle always decreases as $a(t)^{-1}$, as long as it is freely falling, i.e. follows the shortest path in the Friedmann, Roberston, Walker and Lemaître metric.

Cosmology distilled II: tools

Despite the mathematical intricacies of general relativity, Einstein's theory of gravitational interactions is beautifully simple. For a given distribution of mass bodies, fluids etc., which produce a gravitational field, the basic quantity is represented by the particular structure of spacetime encoded in the form of the *metric*, which decides what is the shortest path between two points in space and time. The basic equations, analogous to Newton universal gravitational law, are Einstein equations, which read

$$gravity = 8\pi G_N(energy\ density\ /\ pressure)$$

The left hand side (gravity) is what we are looking for, once the right hand side is specified, i.e. once the properties of celestial bodies, fluids etc. producing the gravitational field are given. The latter contribute via their energy density ρ *and* pressure P (something which is not a source of gravity in Newton theory) or more generally, through their *stress–energy tensor*. G_N is, of course, Newton gravitational constant. All *acceptable* sources of gravity should obey the analogous of energy conservation in classical mechanics, which in Einstein words is the covariant conservation of the stress–energy tensor.
A test particle put in a given gravitational field, and which is not subject to other forces, moves following the shortest path, a *geodesic* motion which depends upon the metric, the solution of Einstein equation, given once celestial body properties and distribution are assigned. A different language, with the non trivial new feature that it encodes the fact that there is maximal propagation speed for signals (the velocity of light), but basically the same way of reasoning of Newton's construction: source $\rightarrow$ gravity $\rightarrow$ motion of a test body.

index is $\gamma = 2/3$ (compare with the analogous standard result for a monoatomic classical gas , $\gamma = 5/3$).

Sooner or later particles will become non relativistic, unless they are massless. This is because their kinetic energy decreases with expansion. When it falls below the particle mass, In order to minimize the energy, the annihilation of these particle becomes more convenient. Consider for example a muon lepton. At equilibrium, a process like muon pair annihilation $\mu^+\mu^- \rightarrow \gamma\gamma$ is compensated by the inverse process, $\gamma\gamma \rightarrow \mu^+\mu^-$, which establishes kinetic equilibrium among muons and photons. At some point however, photons have not enough energy to produce muon pairs, and only the first process is possible. All muons then transform into photons (and electrons, neutrinos etc. via similar processes). Today for example, there is not a single primordial muon left in the universe!

For reasons which will appear clear soon, the phase when the universe temperature is of order MeV is particularly relevant. A snapshot of the relativistic particle content at this age shows that only electron-positron pairs, photons and neutrinos are left, the species which are still relativistic. Also neutrons and protons, though they are very massive, are present, in tiny fraction with respect to photon abundance. The baryon to photon density ratio can be measured by two different cosmological observables, BBN and CMB, and is found to be $n_b/n_\gamma \sim 10^{-9}$. The reason why baryons are still populating the universe is related to the fact that baryon number conservation, a symmetry of fundamental interactions at low energy scales, protects them from a complete annihilation in lighter species (as it is the case for muons!). I will come back to this point later on. At $T \geq$ few MeV epoch, radiation is largely dominating the total energy budget. Photon energy density at equilibrium can be simply estimated, and takes the standard Stefan–Boltzmann expression (energy density is proportional to T^4)

$$\rho_\gamma = 2 \times \frac{\pi^2 k^4}{30\hbar^3 c^3} T^4$$

with $\hbar = h/2\pi$ the Planck reduced constant. Electron and positrons and neutrinos contribute by

Friedmann, Roberston, Walker and Lemaître (FRWL), were the first finding how Einstein's theory can be applied to the universe dynamics, by simply exploiting one single hypothesis: that on sufficiently large scales our universe looks pretty spatially homogenous and isotropic. This idea, known as *Cosmological Principle*, is enough to single out the form of the metric up to one unknown function, the scale factor $a(t)$ which depends on time only, and fixes at any given time the distance between two observers: if $a(t)$ is an increasing function of time, their distance grows with time: this is an expanding universe. In the FRWL model Einstein's theory reduces to two simple relations: the Friedmann law

$$H^2 = \left(\frac{1}{a(t)}\frac{da(t)}{dt}\right)^2 = \frac{8\pi G_N}{3}\rho - \frac{k}{a^2}$$

which states how the universe expansion rate (H) depends on the energy density of matter, and the energy-pressure conservation law

$$\frac{d\rho}{dt} + 3H(\rho + P) = 0$$

What Hubble found to be the constant relating the distance of a given astrophysical source with it regression velocity is, in FRWL cosmology, simply the value of H today. A final remark about the parameter k known as the spatial curvature. It is a free parameter which can be positive, negative or zero. Its value decides about the eventual destiny of a given universe. For $k \leq 0$ expansion will go on for ever (since the right hand side is always positive, and so is the expansion velocity). For $k > 0$ there is a value of a for which the expansion stops (when the right hand side is zero) and the universe recollapses. Thanks to the last decade experiments, in particular WMAP and Planck [9], we know that our universe is remarkably close to a spatially flat universe (i.e. $k = 0$).

a similar amount

$$\rho_{e^\pm} = 2 \times 2 \times \frac{7}{8}\frac{\pi^2 k^4}{30\hbar^3 c^3}T^4$$

$$\rho_\nu = 3 \times 2 \times \frac{7}{8}\frac{\pi^2 k^4}{30\hbar^3 c^3}T^4$$

The factor $7/8$ is due to the different statistical properties of electrons and neutrinos (they satisfy the Pauli exclusion principle, while photons do not) and the numerical factors are due to the sum over the possible spin orientations (2), the sum over particle and antiparticle states (2) and (for neutrinos) the number of flavours (3). It is now a well established tradition to rephrase the neutrino energy density into the *effective neutrino number* parameter, N_{eff}, so that the total relativistic species energy density ρ_R when $e^\pm$ are still relativistic particles (see later) reads

$$\rho_R = \rho_{e^\pm} + \rho_\gamma\left(1 + \frac{7}{8}N_{\text{eff}}\right)$$

This notation may seem a bit baroque, since from the above formulae it seems obvious that $N_{\text{eff}} = 3$. However, this is the case only if: i) there are only three neutrino species; ii) they are in full equilibrium with photons (i.e. they share the same temperature); iii) there are no exotic features in their distribution as function of linear momentum (given by $h\nu/c$ according to de Broglie relation). This is given by the analogue of the black-body function of photons, with a crucial plus sign in the denominator signalling that they are fermionic particles (they satisfy exclusion principle) (compare with photon distribution in the box *Cosmology distilled I: evidences*

)

$$\text{flux}_{\text{neutrino}}(\nu) = 3 \times \frac{2h\nu^3}{c^2} \frac{1}{e^{h\nu/kT}+1}$$

in units of W m^{-2} str^{-1} Hz^{-1}.

In other words, N_{eff} is a simple way to parametrize what we don't know about neutrino behaviour in the MeV age. I will show how it can be strongly constrained by experimental data.

We said already that neutrinos are kept in equilibrium with other species via weak interactions. At temperatures of order few MeV their typical rate falls below the Hubble expansion parameter, and neutrinos *decouple*. From this time on, they can be only felt by the universe dynamics via their gravitational effect. Being no more affected by scattering processes, they freely stream and their distribution is frozen, apart from the redshift of their temperature. This means that the expression for their flux reported above is what we would measure today, provided we scale the temperature to its actual value.

Actually, soon after neutrino decoupling, electrons and positrons start feeling themselves intolerably heavy. At $T \sim 0.511$ MeV, they all annihilate into photon pairs via the process $e^+e^- \to \gamma\gamma$, *but not into neutrinos*[2], since the analogous process $e^+e^- \to \nu\overline{\nu}$ is a weak process, which at this epoch is too slow to take place. This means that all energy stored in electrons and positron heat photons but not neutrinos. **EC dov'è il verbo? C'è un is mancante?** After this stage the neutrino temperature T_ν is thus smaller than the photon temperature T_γ by a factor which can be calculated by using entropy conservation during expansion, $T_\nu = (4/11)^{1/3}T_\gamma$. Since we know quite accurately T_γ today, we can infer the temperature of neutrinos in the present universe

$$T_\nu(today) = (4/11)^{1/3}\, 2.752\,^\circ\text{K} = 1.964\,^\circ\text{K}$$

, which is extremely low! Correspondingly, the neutrino and antineutrino number per unit volume is of order 56 cm^{-3} per flavour, smaller than CMB photons (411 cm^{-3}), but remarkably large (it represents the largest neutrino flux of astrophysical origin. Much more abundant, for example, than neutrinos coming from the Sun!). If the hot big bang model is correct, we are surrounded by an intense flux of relic neutrinos, which in principle, as photons of the CMB found by Penzias and Wilson, could be detected by some *neutrino antenna*. Unfortunately, this is very challenging, because CNB neutrinos are very cold (few Kelvin degrees) and thus, they carry a very low kinetic energy which they may transfer in interaction processes in a detector. Furthermore, they are only weakly interacting, so the interaction rate is extremely low too. In any case, a direct proof of the existence of CNB would be of extraordinary importance, being, as CMB, Hubble's law and the primordial nucleosynthesis a key prediction of the big bang model. Physicists are thinking about how it could be possible to detect them and there are nice ideas which hopefully might be experimentally implemented in a not too far future.

[2] There is a small energy release to neutrinos at the level of percent.

Neutrinos and the synthesis of primordial elements

There is another clear evidence that neutrinos populated the universe since at least as early as few seconds after the big bang: the Big Bang Nucleosynthesis. BBN is a short period in the history of the universe during which light nuclear species, mainly ^{4}He, ^{2}H, ^{3}He and, to a minor extent, ^{7}Be and ^{7}Li were produced by nuclear fusion reactions, as (in general, with different nuclear mechanisms) in the interior of stars. At sufficiently high energies, above the typical nuclear binding energies (the typical scale is 1-10 MeV per nucleon) any nuclear species produced via some fusion reaction would be dissociated by the high energy photon background or other dissociation process. The picture is that when the temperature of the plasma in the universe (the photon temperature) is above few MeV, all baryons are in the form of free protons and neutrons.

For what I just said previously (heavy particles tend to disappear from the thermal bath in order to minimize the total energy), the reader may be surprised by the fact that such heavy particles (nucleons have a mass of order GeV) are still around at such low temperature. The reason why this is possible is related to the fact that the universe is matter–antimatter asymmetric, in particular it contains more baryons (protons, neutrons) than anti–baryons (antiprotons, antineutrons). In fact, protons and light nuclei (along with electrons) are the building blocks of planets, stars, galaxies etc., but there is no trace of antiprotons, anti–nuclei or positrons, but those produced by high energy–interactions of cosmic rays or by energetic astrophysical sources. This observation was first considered as an *ad hoc* hypothesis about the initial conditions of the universe at *big bang*. It was then realized, mainly due to the insights of the russian physicist Andrej Sacharov, that a more elegant solution is to assume that, at some early epoch, some baryon violating interactions were at work, producing such an asymmetry. When the temperature dropped with the expansion, these interactions became too feeble (their rate falls below the Hubble expansion rate). All other processes, those we experience in laboratory experiments (electromagnetic, weak, strong and gravitational) cannot further change the initial baryon number (i.e. the number of baryons minus the number of antibaryons) since they are all *baryon number conserving*, exactly as, say, electromagnetic interactions are *electric charge conserving*. At a value of the temperature of order of the nucleon mass, nucleons and anti–nucleons become non relativistic particles and their rapid annihilations into lighter particles would lead to a baryonless universe, were not for the small baryon excess over antibaryons. This baryon fraction survives and represents the whole baryon content of the universe today.

After this digression let us now go back to BBN. Neutrons and protons are kept in equilibrium by weak processes

$$n\,\nu_e \leftrightarrow p\,e^-,\;\; n\,e^+ \leftrightarrow p\,\overline{\nu}_e,\;\; n \leftrightarrow p\,e^-\,\overline{\nu}_e$$

Since neutrons are slightly heavier than protons, at low temperatures, smaller than the neutron–proton mass difference $\Delta m_N = 1.29$ MeV, these reactions would preferentially take place in the right direction (as always to minimize energy, since protons weigh slightly less!) and all neutrons would disappear. This would mean a universe with only hydrogen atoms! The point is that shortly before, similarly to the weak processes maintaining neutrinos in equilibrium, also these processes become too slow and the ratio of neutron to proton number *freezes* to a fixed value, which can be explicitly computed. It is amazing that *just because* of the values taken by the Fermi constant G_F (weighting the weak process reaction rate), the Newton constant G_N (which appears in the Friedmann law, see the box *Cosmology distilled II: tools*) and the value of Δm_N, neutrons survived, nuclei were able to be produced, and thus complex structures evolved, including human beings!

Soon after this freezing of weak processes, deuterium nuclei start forming. There is in fact a small gain in energy due to its nuclear binding energy, 2.23 MeV. Temperature and density conditions at this epoch allow for a complicated set of nuclear reactions to be efficient enough to produce even heavier nuclei, till ^{7}Be and ^{7}Li (see Figure 3). At some point however, the whole nuclear chain stops, because the universe expansion takes over, and for example no *metals* are significantly produced (in the astrophysicist jargon metals are for example C, N, O etc., whatever is not produced during BBN). The evolution with photon temperature of light nuclei during BBN is shown in Figure 4. The key parameter in fixing their final yield is the already mentioned amount of baryons per photon, called η_b. It is a free parameter, linked to the initial asymmetry between matter and anti–matter. In fact, BBN was historically the first way to bound its value. The present best estimate is, as quoted before, $\eta_b \sim 10^{-9}$. For this value the theoretical predictions for primordial light nuclei abundances are in very good agreement with astrophysical observations, in particular deuterium and ^{4}He. For the primordial ^{3}He yield we have presently only an upper bound. The status of ^{7}Li is slightly more involved, and it is not clear if experimental data are really measuring its *primordial* value.

What is the role of neutrinos in BBN? It is twofold:

i) electron neutrinos are directly involved in the weak processes maintaining neutrons and protons in equilibrium, see above. If there were no ν_e and $\overline{\nu}_e$ around, or if their number were much larger or smaller than what we discussed in the previous subsection, prediction of BBN would be completely wrong.

ii) The universe expansion rate, apart from the

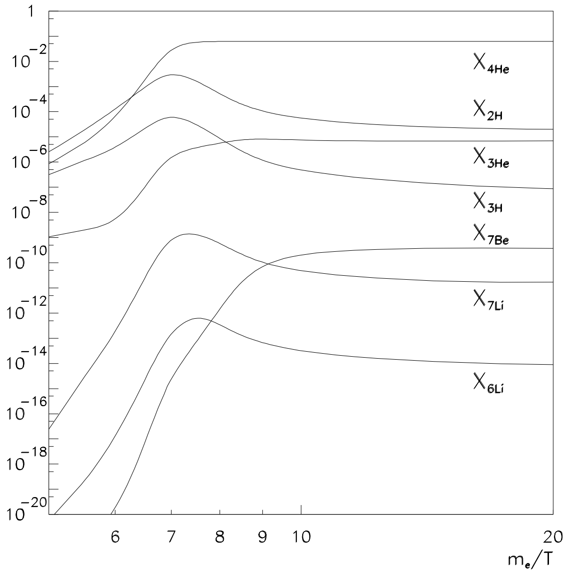

Figure 4: *The evolution of nuclear abundances produced during BBN versus m_e/T, with m_e being the electron mass. The quantities X_i are the fractions of the nuclide i normalized to the total number of available protons and neutrons in the universe.*

value of G_N, crucially depends on the energy density ρ during BBN. A first result is that during BBN the universe *should be radiation dominated*. If dark matter or, even worst, a cosmological constant were driving the expansion, the nuclear abundances would be completely different than what is observed.

We saw that the relativistic-species energy density can be cast in terms of a single parameter, $N_{\rm eff}$. If its value is just what expected (3), the BBN scenario works pretty well. This means that the CNB should be very close to our standard expectations. Too many neutrinos, or too few, or some exotic feature in their flux would spoil the nice agreement of theory and experimental data. The latter presently exclude that $N_{\rm eff}$ might be 4 or 2, for example.

The last point also brings us to another important observation. Apart from the standard three neutrinos, all particle species, provided they are relativistic, contribute to $N_{\rm eff}$. This is because gravity (the Friedmann law) is blind to all particle properties but their energy (and pressure). We mentioned earlier that there are laboratory results suggesting that there might be extra sterile neutrino species. If they were produced in the early universe, and this seems the case if the experimental results have to be explained in terms of these species, the value of $N_{\rm eff}$ would be larger than three. This is disfavoured by BBN results. We will see that the constraint on these sterile states is even stronger if one uses CMB data.

The neutrino imprint on Cosmic Microwave Background and Large Scale Structures

CMB formed when the universe was approximately 380.000 years old. The photon temperature at this age was fraction of eV, and electrons and protons (and ^{4}He, the most abundant species after protons) recombined to form neutral atoms. Shortly after, photon scatterings via Thomson processes off the few remaining free electrons became also very rare. Thus, the universe became *transparent* to light. Photons *redshift* and eventually reach us today. This is pretty similar to what happens when we see the Sun light emission. Photons in the deep interior of the Sun scatter many times, are continuously emitted and absorbed. Only at the surface the density of ions and electrons is low enough, and photons are then free to travel until they reach the Earth. The surface in the sky from which we receive the CMB photons is the *last scattering surface*, one of the oldest observational tools we have to investigate the evolution of the universe, the equivalent of the Sun surface.

The CMB radiation is remarkably isotropic. Light appears to have the same properties independently of the arrival direction and shares a common average temperature T. In particular, the photon distribution, as we mentioned already, is a perfect black body. Yet, there are small fluctuations in the temperature by looking at different angles in the sky. This is not only unexpected, but rather it is a bless, since it gives us the possibility to understand the way the universe is not *perfectly homogenous and isotropic*.

The standard lore is again rooted on the inflationary paradigm. During the initial accelerated expansion phase, tiny perturbations of the gravitational potential on microscopic length distances were streched to cosmological scales, and are the primeval seeds for all inhomogeneities we presently see, from the CMB anisotropies to structures such as galaxies, clusters etc.

As it is meaningless to ask why Earth is exactly at the distance from the Sun which allowed life to develop, it is equally of no interest to understand why, looking at the CMB sky, photons from a particular direction are slightly hotter or colder with respect to the average value of the CMB temperature. What is really interesting is rather to understand the statistical properties of the fluctuations. If we had many universes to observe, we could see that they would share some common features, though they would not be identical. The closest star to Earth would not be α-Centauri, but the *probability* that there would be a closeby star at around few lightyears would be as in our observable universe. In other words, all different universes, provided they start with the same initial conditions, would be quite similar to each other, if we describe them in terms of the probability distribution of having a certain number of galaxies or clusters in a given volume. What is really meaningful is to understand the properties of inhomogeneities, which are stochastic variables. This teaches us to which class of universes we belong to! Are these stochastic perturbations gaussian distributed? What is their amplitude spectrum as we move from small to large scales?

Observations tell us that all originated from small gaussian inhomogeneities. These initial perturbations undergo a different fate depending on their wavelength. As the universe evolves, there is a maximal distance over which light can travel, that is usually called *particle horizon*. Perturbations of a given amplitude can be changed by some dynamical mechanism (diffusion, damping, amplification by gravitational instabilities) only on distance scales (wavelengths) which are smaller than the particle horizon. All these regimes are clearly visible in the CMB anisotropies. This is because causality implies that there are no physical mechanisms which can transfer information faster than the speed of light.

The CMB basic observable is the temperature-fluctuation correlation function. For a given point in the sky, identified by two angles

θ and ϕ (for example, right ascension and declination), one measures the actual value of the CMB $T(\theta, \phi)$ temperature, and defining

$$\delta T(\theta, \phi) = \frac{T(\theta, \phi) - T}{T}$$

, the correlation function

$$\overline{\delta T(\theta, \phi)\, \delta T(\theta', \phi')}$$

represents the excess probability, compared with a random distribution of temperatures, of finding close values of T at a given distance $(\theta - \theta', \phi - \phi')$.

The overline means the average over the probability distribution of temperature fluctuations. This quantity is usually recast in terms of the C_l coefficients, which technically are obtained by Legendre transforming the correlation function, see the box *The C_l and the power spectrum $P(k)$*. It is shown in Figure 5. There are three features which can be appreciated from this plot:

i) in the small l regime (large angular distances) the CMB spectrum is rather flat. It is the remnant of the primordial fluctuations produced by inflation.

ii) in the intermediate region there is a series of peaks and valleys. These are due to the dynamics during the last scattering phase. Photons, electrons and baryon plasmas oscillate under the effect of two competing forces: the photon pressure on one side and the baryon and electron gravity on the other.

iii) At large values of l, the coefficients C_l drop exponentially. Photons can diffuse on short distances via Brownian motion. This leads to a damping of inhomogeneities and of the values of the C_l.

There are two ways neutrinos can influence this pattern: through their background properties and via their perturbations. By background I mean their homogeneous properties, such as their average energy density, or physical properties, as the value of their mass. But neutrinos, as all species, feature some inhomogeneity which also contribute to either the growth of matter structures or their damping. Here is a summary of their effects on CMB power spectrum.

i) During CMB formation (when the temperature of photons is of fraction of eV) neutrinos contribute to the radiation energy density (the N_{eff} we introduced before), unless they have a mass larger than the eV scale. If the value of N_{eff} is increased (lowered), this would change the ratio between the amount of radiation and matter in the universe, and thus, the so called *Integrated Sacks-Wolfe* (ISW) effect . During their journey from the last scattering surface to the Earth, photons experience potential wells and peaks produced by the (growing) inhomogeneities. As we said, the way gravitational potential changes with time depends on the background expansion. In a radiation or cosmological-constant dominated universe local wells or peaks decay with time. When a photon falls into some well, it accelerates and transforms its gravitational energy into kinetic energy (temperature). The opposite takes place when it climbs out of the wells. Because of energy conservation, the final kinetic energy of the photon would be the same if the gravitational potential would not change in time, and CMB photons would keep their initial temperture distribution (redshifted by the expansion, of course). This is true during matter radiation, but not, as we said, when radiation or a cosmological constant. **frase incompiuta** Thus the final CMB spectrum would be changed due to ISW, both at the transitions from radiation to matter stages (Early ISW) or from matter to cosmological constant (basically today, the Late ISW).

ii) On small scales (in Figure 5, the range $l > 1000$) photon diffusion erases the temperature fluctuations. The typical length scale for this mechanism is $c\sqrt{t_u}$, t_u being the universe age at CMB. The square root behaviour is the standard feature of a Brownian motion: random collisions lead to a displacement of particles which, on average, is zero, but whose variance grows with time, but slower than a free particle motion (the displacement would be proportional to time in this case). On the other hand, the first peak in the C_l spectrum, clearly visible around $l = 200$, corresponds to the largest causally connected scale at recombination, the final oscillation of photon–electron– baryon plasma before decoupling. This scale is of the order of the particle horizon at decoupling, and is a linear function of time t_u. Comparing the peak position in the l plot with the l–range of damping we can grasp some information on t_u, i.e. on the universe expansion speed H during CMB (a faster speed means of course, a younger universe at CMB). Since the value of H depends on the total amount of radiation (and matter) energy density, this turns into a constraint on N_{eff}. The Planck experiment uses this phenomenon to bind the number of effective neutrinos quite severely, $N_{\text{eff}} = 3.04 \pm 0.18$ [9]. There is no room for a fourth neutrino species, unless its density in the early universe is much lower than standard active ones.

iii) Neutrino mass has a double effect on CMB, if not too small with respect to the last scattering surface temperature, which amounts to fractions of eV. On one hand, it fixes the time in the expansion history when neutrinos become non–relativistic, thus when they are no more *radiation* and become *matter*. Remarkably, neutrinos have a small mass, and they are the only particles for which we can see this transition using observations! If they become non–relativistic during CMB formation, this changes the already mentioned Integrated Sacks-Wolfe. At some point the universe feels more matter than expected if neutrinos were massless particles, and inhomogeneity starts to grow earlier as in a matter dominated universe. The second effect of neutrino mass is on CMB lensing. Photons emitted at the last scattering surface travel to the Earth and along their path encounter galaxies, clusters etc. Their effect is a famous prediction of Eistein's theory: lensing, the bending of their trajectories, and a change of their energy in the gravitational field of massive bodies. The lensing effect is of course related to the amount of matter along the line of sight, and its relative weight compared to radiation. A massive neutrino would contribute to lensing quite differently than a massless one. Increasing the neutrino mass suppresses clustering on scales smaller than the size of the particle horizon at the time of the non–relativistic transition (before this age in fact neutrins are radiation), and %thus, lensing is smaller on these scales. lensing is thus smaller on these scales. CMB lensing has been measured by the Planck experiment, and they find a tight constraint on the *total neutrino mass* (the sum of their masses, in other words the absolute mass scale m_0 we mentioned earlier) of order 0.2 eV. Notice that this value is the sensitivity goal of Katrin experiment.

iv) Not differently than photons, also neutrinos have small perturbations, representing the initial imprint of the inflationary stage. These perturbations would evolve differently if neutrinos were massless particles, if they were *freely streaming* during CMB epoch (i.e. if they did not have any interaction process, scatterings, annihilations etc.) or if they are massive particles. The recent Planck results tell us that our standard expectation is quite consistent with the data. Neutrinos are as Pauli imagined them: they are weakly interacting, light particles, moving at the speed of light during CMB.

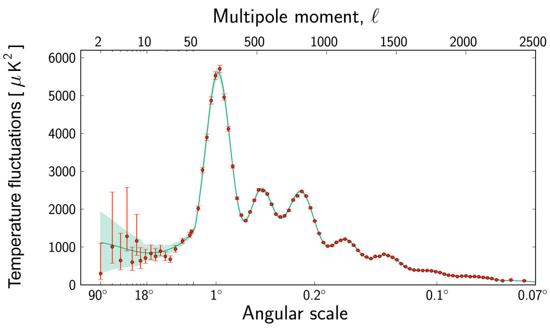

Figure 5: *The CMB power spectrum (C_l) versus the angular distance $l = \pi/\Theta$, as measured by the Planck experiment (2015).*

Neutrino mass can be also constrained by the observed amount of galaxies and clusters we see in the universe. The basic mechanism is the same we saw in the case of CMB. Neutrino background transition from a relativistic to a non–relativistic fluid changes the way they impact structure formation. The equivalent of the C_l for matter in-

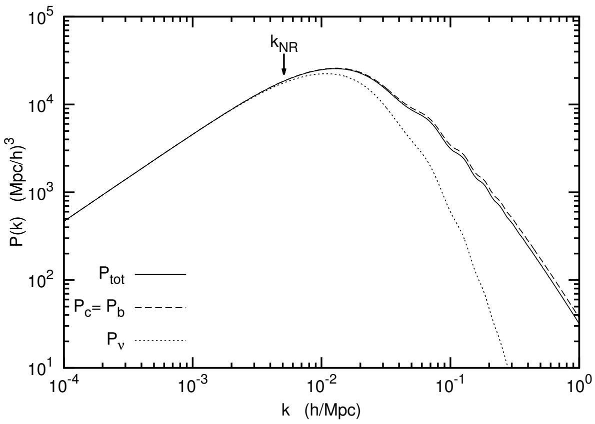

Figure 6: *The matter power spectrum $P(k)$ versus the inverse distance $k = 2\pi/d$, measured in unit of h Mpc^{-1}. The uncertaintiy on the present value of the Hubble constant is encoded in the h parameter, defined as $H_0 = 100\, h$ Km/s Mpc^{-1}. The solid line is the total $P(k)$, the dashed curve is the contribution of dark matter (c=cold dark matter) and baryons (b). Finally, the dotted line is the neutrino perturbation spectrum for three neutrinos with mass of 0.3 eV each. The wavenumber k_{NR} is the inverse length scale at which neutrinos become non–relativistic particles.*

homogeneities is the so called *Power Spectrum*, $P(k)$. It gives the two–point correlation function for galaxies, clusters, etc at spatial distances d of order $k = 2\pi/d$, another way to study: i) the initial values of inhomogeneities produced during the early inflation epoch and ii) the dynamics of these random perturbations under the effect of gravity. The definition of $P(k)$ is recalled in the box *The C_l and the power spectrum $P(k)$*, and its behaviour versus k, measured in Mpc^{-1}, is shown as a solid line in Figure 6. This behaviour is again consistent with our present understanding on how structures formed in the universe. Tiny fluctuations were amplified by gravitational instability in the presence of sufficiently heavy particles (the Dark Matter), which trigger the collapse.

The role of neutrino is related to their mass also in this case. If they were massless they would suppress the growth of structures indipendently of the scale $1/k$ at which we observe them. However, if their mass is not negligible, there is a peculiar scale $1/k_{NR}$ which distinguishes two different regimes. I mentioned already that structures can develop via gravitational instability on scales which are smaller than the particle hori-

The C_l and the power spectrum $P(k)$

The main observable in the CMB maps is the temperature–temperature correlation function

$$\overline{\delta T(\theta,\phi)\delta T(\theta',\phi')}$$

(see the text for definition), where the average is over the probability distribution of the stochastic variable $T(\theta,\phi)$. Averaging means that if we had many universes at our disposal, we could make many experiments and deduce the properties of $T(\theta,\phi)$. This is impossible. Yet, if we look for correlations at sufficiently small angular scales, we have many domains in the sky we can average over and which evolved quite independently. The universe is inhomogenous on small scales, but it is isotropic, so the correlation function can only depend upon the relative angle between the observation points, ϑ. Its value at a definite ϑ is encoded in the C_l parameter

$$C_l \sim \overline{\delta T\,\delta T}(\vartheta)\big|_{\vartheta=\pi/l}$$

In a more formal mathematical language, the C_l are the Legendre transforms of the two–point correlation function. A similar approach can be used to deal with the galaxy–galaxy (cluster-cluster, etc.) correlation function. In this case, differently than the CMB radiation, which comes from a sphere at a given distance from us, the last scattering surface, galaxies are distributed in a three dimensional space. If $\overline{\delta(\mathbf{x})\delta(\mathbf{x}')}$ is the matter density constrast correlation function (see text), it can only depend on the modulus $|\mathbf{x}-\mathbf{x}'|$ (isotropy). Its *Fourier transform*, the Power Spectrum, is the analogous of the C_l for the CMB temperature fluctuations

$$k^3 P_k \sim \overline{\delta\,\delta}(|\mathbf{x}-\mathbf{x}'|)\big|_{|\mathbf{x}-\mathbf{x}'|=\mathbf{2}\pi/\mathbf{k}}$$

zon. This means that small-scale structures develop before larger scales, simply because the particle horizon grows with time, since it is the distance travelled by a photon. In the early epochs neutrinos are relativistic, and their role is to partially damp structure formation. They have a large velocity (speed of light) and are free to move around and homogenize gravitational potential. All scales which are small enough, in particular smaller than the particle horizon at this epoch, suffer from this effect and *grow less than if neutrinos were not present in the universe*. On the other hand, large scales inhomogeneities, which start to collapse after neutrino became non– relativistic, are not affected by their free-streaming. In addition to that, also neutrinos start feeling gravitational potential wells, since their velocity can be smaller than the escape velocity from, say, a forming galaxy cluster, and they start collapsing as well. This further enhances the formation of structures. From galaxy surveys, as the Sloan Digital Sky Survey [10], we can thus infer an upper bound on neutrino mass. As for the case of CMB, what we can measure is the neutrino mass scale, more precisely the sum of masses over the neutrino species. The bound is of the same order of magnitude of what CMB suggests: fraction of eV.

Conclusions

Neutrino Cosmology is more than I have described in this brief review. It is a very active research field, whose aim, as I tried to illustrate, is to bind neutrino properties using cosmology. Some aspects have been discussed here. Many others, as neutrino–antineutrino asymmetries, exotic neutrino interactions, electromagnetic neutrino properties, their role in producing the initial baryon–antibaryon asymmetry, would deserve another essay. It is remarkable that we can learn a lot about neutrinos from the role they played in the evolution of the universe. Occasionally, cosmology provided hints before laboratory measurements, as in the case of the number of active neutrinos (N_{eff}), which was already found to be three from BBN, before the direct evidence of LEP experiments.

Maybe, the perspective of a direct detection of relic neutrinos, another echo of the big bang, is presently only a dream, dreamt by many theoretical and experimental physicists. Using the words of Pauli, thinking about them

"...is a terrible thing..., something which no theoretical physicist should ever do. ... something that can never be verified experimentally..."

If Pauli was wrong about neutrino detection, we can hope that also neutrinos filling the universe will be, maybe serendipitously, discovered in a not too far future.

[1] F. Hoyle: "Concluding Remarks", *Proceedings of the Royal Society* **A 301** (1967) 171.

[2] https://www.katrin.kit.edu

[3] G. Co': "Neutrinos and weak interaction", *this volume* (2016) .

[4] E. Lisi: "Neutrinos: messengers of new physics", *this volume* (2016) .

[5] D. Montanino: "Neutrino oscillations", *this volume* (2016) .

[6] E. Majorana: "Teoria simmetrica dell'elettrone e del positrone", *Il Nuovo Cimento* **14** (1937) 171.

[7] F. Vissani: "Maoirana's conundrum", *this volume* (2016) .

[8] P. Bernardini: "The frontier of sterile neutrinos", *this volume* (2016) .

[9] http://www.cosmos.esa.int/web/planck

[10] http://www.sdss.org

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The frontier of sterile neutrinos

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Neutrino oscillations are nowadays a well known phenomenon. The *natural* neutrinos produced by cosmic rays in the Earth atmosphere and by nuclear reactions in the Sun oscillate. Also the *artificial* neutrinos produced in nuclear reactors or by particle accelerators oscillate. The oscillation parameters have been measured more and more precisely and the puzzle looks nearly completed. But some experimental tiles have not found their location yet. If these anomalous measurements should be confirmed a new exciting horizon would open to researchers. While new physics is currently searched for in large colliders, it could instead be hiding in the bizarre properties of neutrinos. Sterile neutrinos interacting only gravitationally would revolutionise the physics of elementary particles, but up to now there is not evidence of their existence. The anomalous measurements, the hypothesis of other neutrinos beyond the three known flavours and the status of the search for sterile neutrinos will be synthetically presented here without in-depth technical details.

Introduction

Since Wolfgang Pauli suggested in 1930 the existence of a neutral and massless particle in order to explain the continuous spectrum of electrons in beta-decay , neutrinos have held big surprises for theoretical and experimental physicists. The probability that they interact with matter is extremely low, therefore very intense fluxes and very large detectors are required to study the neutrino physics. At the end of the nineties it was discovered that neutrinos oscillate, that is , neutrinos change flavour in their path (see the article by D. Montanino in this book). For instance the experiment OPERA in Gran Sasso National Laboratories verified that a muon neutrino (ν_μ) with an energy of 20 GeV has a significant probability to become a tau neutrino (ν_τ) and to be detected in such flavour after a path of 730 km. It is worthwhile to stress that the appearance and disappearance are both effects of the oscillation phenomenon. In other words , new neutrino flavours appear (like in OPERA) whereas the number of neutrinos with the original flavour is reduced.

At present, the main part of the experimental results is coherent with a scenario where neutrinos have mass and can assume three flavours (ν_e, ν_μ, ν_τ). These flavour states are a superposition (*mixing*) of three mass eigenstates (m_1, m_2, m_3). The model is defined by the *mixing* angles

Z^0 decay

The LEP collider (Large Electron Positron) allowed many highly accurate measurements , such as the decay width of the neutral Z^0 boson (Figure 1) generated and destroyed in the neutral-current weak interactions. The width increases with the number of possible decay channels, that is the number of particle-antiparticle pairs with a total mass lower than the Z^0 mass (91.2 GeV). The directly observable channels are those of charged letpton-antilepton (e^-e^+, $\mu^-\mu^+$, $\tau^-\tau^+$) and the hadronic ones (quark-antiquark). It is impossible to observe directly the neutrino-antineutrino channels but they contribute to the total width. The latter is a function of the number of neutrinos with mass lower than half the Z^0 mass. The experimental points in Figure 1 are consistent with three neutrino flavours and exclude the existence of other light neutrinos coupled with Z^0. Then other neutrinos must be sterile or very heavy.

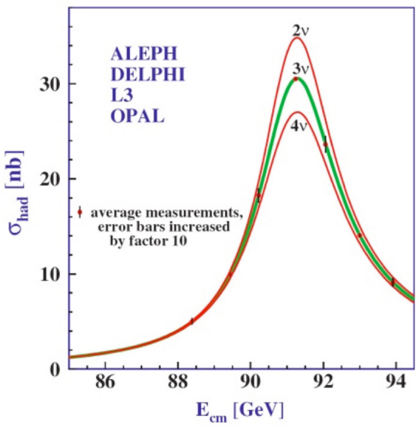

Figure 1: *Measurements at LEP of the decay width of the Z^0 boson. The experimental points are compared with different models assuming 2, 3 or 4 neutrino families. It is evident that the experimental data are compatible with the existence of only 3 neutrino families (green curve). It is remarkable that the experimental errors have been 10-times enlarged to be visible. Therefore the agreement with the 3-neutrinos model is very strong.*

($\theta_{12}, \theta_{23}, \theta_{13}$) and by the squared mass differences (Δm^2_{21} and Δm^2_{32}). All these parameters have been measured and the research on neutrino oscillations is now devoted to precision measurements. In the meanwhile the scientific community is attracted by other topics (mass hierarchy, CP violation and astrophysical neutrinos). Yet, in spite of the irrefutable successes of the present oscillation theory with three flavours, some experimental results suggest that the theory is incomplete and that other neutrino flavours might exist. A first experimental anomaly is due to electron antineutrinos ($\bar{\nu}_e$) generated in nuclear reactors. A careful reanalysis of the reactions in the nuclear fuel brings to the conclusion that the measured fluxes are lower than the expected ones. A similar deficit has been observed also in the neutrino fluxes from MegaCurie-radioactive sources. These sources have been used in order to calibrate radiochemical detectors built to study solar neutrinos. In the end, two American experiments (LSND and MiniBooNE) revealed electron antineutrinos in a beam of muon antineutrinos. These disappearance and appearance phenomena have been observed on short baseline (that is , at short distances with respect to the neutrino energy, as clarified in the forthcoming) and it is impossible to explain them assuming the neutrino model with only three flavours. After all, the measurements of the decay width of the Z^0 boson performed at the LEP collider (see the box on this topic) put severe limits on the number of *active* neutrinos: there are only three weakly-interacting neutrinos (ν_e, ν_μ, ν_τ), coupled with $W^\pm$ and Z^0 bosons and able to generate charged leptons (e, μ, τ) [1]. Therefore these anomalous measurements can be explained only assuming the existence of other neutrinos already postulated by B. Pontecorvo around fifty years ago [2]. Such neutrinos could not couple with the weak-interaction mediator bosons, they should not have an associated charged lepton and are therefore defined sterile. Given that neutrinos neither interact electromagnetically nor partecipate in the strong interaction, which involves mainly protons and neutrons, sterile neutrinos would be sensitive only to gravitational interaction unless new interactions are introduced.

They could only be observed thanks to oscillations, and therefore they would be even more elusive than active neutrinos. Anyway their discovery would be of huge importance in cosmology because neutrinos have a fundamental role in the evolution of the universe. In order to examine in depth the many implications of the possible existence of sterile neutrinos, we suggest reading reference [3].

Experimental anomalies

Before making a list of the measurements conflicting with the 3-flavours theory, it is important to understand why this theory does not predict neutrino appearance or disappearance on short baseline. In a simplified picture of the oscillation with only two flavours and two mass eigenstates the probability that a neutrino created with α flavour is detected as a neutrino with β flavour is given by:

$$P_{\alpha\to\beta} = \sin^2 2\theta_{ij} \sin^2\left(1.27\,\Delta m^2_{ij}\, L_{\mathrm{km}}/E_{\mathrm{GeV}}\right), \quad (1)$$

where i and j are referred to the mass eigenstates, L_{km} is the neutrino path in km, E_{GeV} the energy in GeV and the unit of measurement for Δm^2_{ij} is eV^2. The oscillation parameters have been determined with increasing precision in the last years. The most updated values for the differences of the squared masses are [4]

$$\Delta m^2_{21} = (7.53 \pm 0.18) \times 10^{-5}\ \mathrm{eV}^2,$$

$$\Delta m^2_{32} = (2.44 \pm 0.06) \times 10^{-3}\ \mathrm{eV}^2.$$

Using these values to calculate the second factor in the expression (1) and assuming an experiment on short baseline, that is , with the ratio $L_{\mathrm{km}}/E_{\mathrm{GeV}} = L_{\mathrm{m}}/E_{\mathrm{MeV}} \simeq 1$, for Δm^2_{21} we get :

$$\begin{aligned} & \sin^2\left(1.27\,\Delta m^2_{21}\, L_{\mathrm{km}}/E_{\mathrm{GeV}}\right) \\ = & \sin^2\left(1.27 \times 7.53 \times 10^{-5}\right) = 9 \times 10^{-9}, \end{aligned}$$

and for Δm^2_{32}

$$\begin{aligned} & \sin^2\left(1.27\,\Delta m^2_{32}\, L_{\mathrm{km}}/E_{\mathrm{GeV}}\right) \\ = & \sin^2\left(1.27 \times 2.44 \times 10^{-3}\right) = 1 \times 10^{-5}. \end{aligned}$$

In other words, observing that the factor $\sin^2 2\theta_{ij}$ cannot be higher than 1, the probability to observe some *oscillated* neutrino (ν_β in the previous example) is practically zero for a short-baseline experiment. Consistently, the probability that neutrinos keep their original flavour is 100% and no disappearance will be observed in the α-neutrino flux. A more careful calculation taking into account that there are three flavours and mass eigenstates leads to very similar results. Therefore one can conclude that the oscillation phenomenon could not arise on short baseline. On the other hand it is trivial to verify that the oscillation probability should become significant also for short-baselinemeasurements assuming another value for the difference of the squared masses ($\Delta m^2_{\mathrm{sterile}}$) much higher than Δm^2_{21} and Δm^2_{32}. The short-baselinemeasurements presented below found oscillation signals and suggest even $\Delta m^2_{\mathrm{sterile}} \gtrsim 1\ \mathrm{eV}^2$.

Antineutrinos from nuclear plants - The first neutrino (actually an antineutrino) was observed by Reines and Cowan in the fifties, at the nuclear reactor of Savannah River, thanks to a process called inverse-beta decay. The antineutrinos are produced in fission processes in the reactor and captured by protons in the detector. As a consequence the proton turns into a neutron and a positron is emitted ($p + \bar{\nu}_e \rightarrow n + e^+$). Since then many other measurements have been carried on in order to monitor the nuclear-plants operation and to study neutrino physics. Typically the measurements were performed with single detectors. The lack of a second detector closer to the reactor prevents from measuring the neutrino flux before the beginning of the oscillation. Then the only possible comparison is with theoretical predictions. In 2011 a new estimate of antineutrino flux was published thanks to updated nuclear databases and more refined calculation techniques [5]. The antineutrino fluxes from some isotopes of uranium (^{235}U, ^{238}U) and plutonium (^{239}Pu, ^{241}Pu) were recalculated in the range $2 - 8$ MeV with an average increase of 3% with respect to the past estimates. This called for a reanalysis of the results published by 19 experiments at a distance from the reactor core lower than $100\ m$.

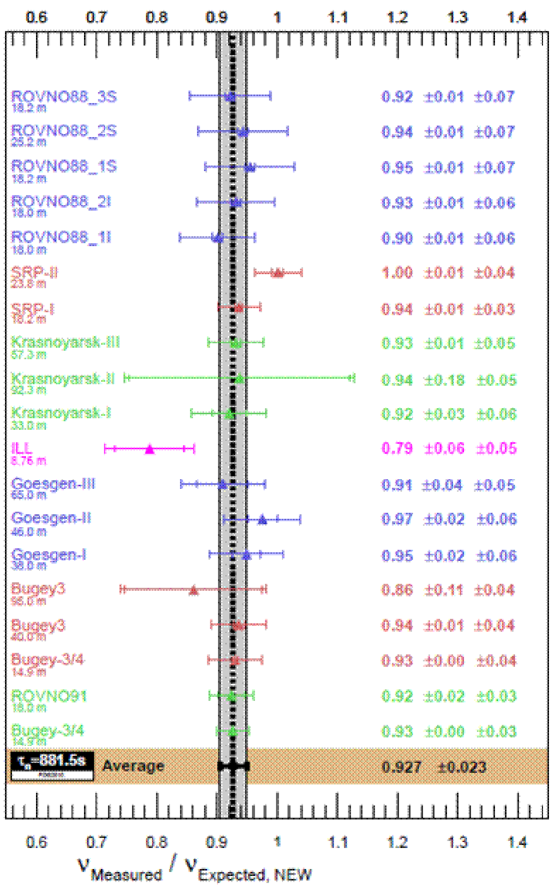

Figure 2: *Reactor neutrinos - Ratio of flux measurement with respect to the expected flux (19 experiments). A clear deficit of the measured neutrinos is visible.*

The new analyses took into account also the new estimate of the neutron lifetime. In Figure 2 the experimental data are compared with the updated expected values. Taking into account all the experiments the ratio between measured and expected value is $R = 0.927 \pm 0.023$ with a statistical significance higher than 3 σ. In other words the neutrino disappearance (more than 7%) is observed and this result can be explained assuming neutrino oscillations with $\Delta m^2 \simeq 2.4\ \mathrm{eV}^2$.

Radioactive sources for calibration - The experiments GALLEX and SAGE measured the neutrino flux from the Sun by exploting the transformation of gallium into germanium ($^{71}\mathrm{Ga} + \nu_e \rightarrow {}^{71}\mathrm{Ge} + e^-$). This measurement technique requires calibration by means of very strong radioactive sources of chromium and argon. These sources emit neutrinos as an effect of electron capture:

$$
\begin{aligned}
{}^{51}\mathrm{Cr} + e^- &\rightarrow {}^{51}\mathrm{V} + \nu_e \\
{}^{37}\mathrm{Ar} + e^- &\rightarrow {}^{37}\mathrm{Cl} + \nu_e \ .
\end{aligned}
$$

The emitted electron neutrinos were detected with the same radiochemical procedure adopted for solar neutrinos. Both the experiments observed neutrino disappearance, since the number of neutrino events was lower than expected. Combining the results obtained by GALLEX and SAGE the ratio measurement/expectation is $R = 0.86 \pm 0.05$ (statistical significance 2.8 σ) corresponding with $\Delta m^2 \geq 0.35\ \mathrm{eV}^2$. For a more accurate review about the so-called gallium anomaly we refer to the paper [6].

LSND and MiniBoone - The experiment Liquid Scintillation Neutrino Detector (LSND) at Los Alamos was designed to search for oscillation effects in a muon-antineutrino beam ($\bar{\nu}_\mu$), in particular the transition $\bar{\nu}_\mu \rightarrow \bar{\nu}_e$. The beam neutrinos had an energy in the range 20-75 MeV, they were generated in the decay of positive muons (μ^+) and flew for 30 m before the detection. Like in previous cases, the experiment has a short baseline, because the

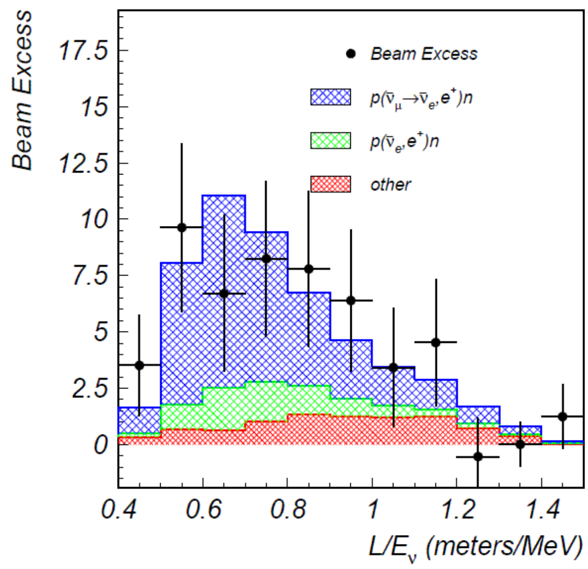

Figure 3: *LSND - The $\bar{\nu}_e$-event distribution as a function of the ratio $L_{\mathrm{m}}/E_{\mathrm{MeV}}$ [7]. The oscillation hypothesis has been introduced (blue area) in order to make the experimental data compatible with the expectation.*

order of magnitude of the ratio $L_{\mathrm{m}}/E_{\mathrm{MeV}}$ is one. As for the reactor antineutrinos, the oscillation signal (appearance of electron antineutrinos) is detected through the capture reaction $p + \bar{\nu}_e \to n + e^+$. This reaction is characterized by a double signature: the positron-annihilation signal is followed by a 2.2 MeV gamma due to the neutron capture. Figure 3 synthetically summarizes the result of the measurement: the experimental data (black dots) are not compatible with the expected background (red and green areas). Only by introducing another signal (blue area) from *oscillated* neutrinos we get a distribution compatible with the measurement [7]. The value of $\Delta\mathrm{m}^2$ is in the range $0.2 - 2.0\ \mathrm{eV}^2$. Another experiment called KARMEN performed similar measurements without finding oscillation signals. Anyway the KARMEN measurements do not exclude at all the LSND result.

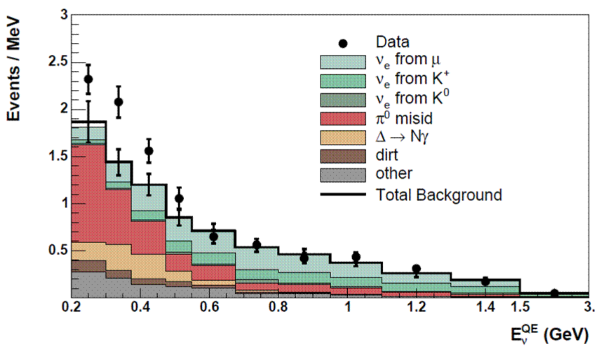

Figure 4: *MiniBooNE - Energy distribution of the ν_e-events. The black dots stand for the measurement, meanwhile the coloured areas stand for the various backgrounds [8]. At low energy the observed neutrinos are more than expected.*

The MiniBooNE experiment at Fermilab was designed essentially to verify the LSND measurement and was operative with beams of muon neutrinos and antineutrinos. The electron neutrinos (ν_e) generated by the oscillation were detected exploiting interactions with carbon nuclei ($\nu_e + \mathrm{C} \to e^- + \mathrm{X}$). The experimental results [8] are reported in Figure 4 where an excess of events at low energy is visible. This result is not compatible with the LSND one, unless we introduce more complex oscillation models and the CP violation, that is , an asymmetry between neutrinos and antineutrinos. The measurements were repeated with an antineutrino beam, in

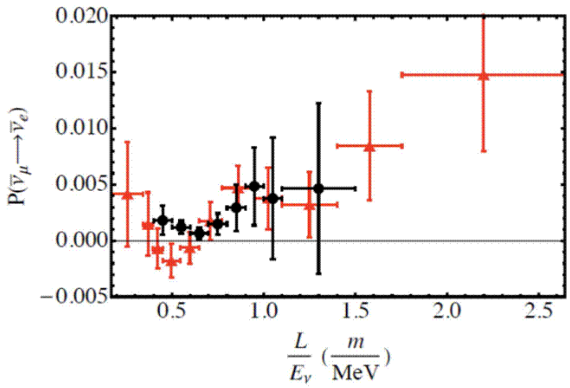

Figure 5: *Probability of oscillation $\bar{\nu}_\mu \to \bar{\nu}_e$ measured by LSND (black dots) and MiniBooNE (red dots) as a function of the ratio $L_{\mathrm{m}}/E_{\mathrm{MeV}}$ [9]. The results of the two experiments are compatible within the errors.*

this case the results [9] are compatible with the LSND ones (see Figure 5).

Possible explanation - The single anomalous results are not so significant. The higher significance is that of LSND ($3.8\ \sigma$), the lower one is that for the MegaCurie sources ($2.8\ \sigma$). But the combination of these anomalies has much higher significance and strengthens the hypothesis of sterile neutrinos. Then the Δm^2-values suggested by the measurements can be interpreted as $\Delta m^2_{\mathrm{sterile}}$, that is the difference between the squared mass of the sterile ν and that of the active ν. The possible discovery of sterile neutrinos would open the way to new physics. It would be possible to conceive non-standard interactions beyond the four ones already known (electromagnetic, weak, strong and gravitational). The cosmological models could take into account these new massive particles. Perhaps the most fascinating eventuality is that the dark matter is made of sterile neutrinos. Actually also the active neutrinos (ν_e, ν_μ, ν_τ) could be natural candidates for dark matter, but they are too light and do not explain the large-scale structures observed in the universe. The sterile neutrinos look like good candidates because of their mass and their very weak interaction with ordinary matter. The hypothesis of sterile neutrinos as dark matter is reinforced by some theoretical studies which assume the existence of many kinds of sterile neutrinos, even with keV-masses.

It is correct to remind that other measurements did not find any evidence of anomalous oscillations. Anyway they are not conclusive and do not exclude completely the existence of massive sterile neutrinos. The experiment KARMEN has been already quoted, another important measurement has been performed by the PLANCK satellite devoted to study the cosmic microwave background. PLANCK put severe constraints [10] on the existence of sterile neutrinos because they could contribute to the radiation in the universe, heating in the oscillation-scattering sequence

Search for sterile neutrinos

As discussed above the interpretation of the experimental scenario is not simple. It can be clarified only by conclusive measurements performed with high-sensitivity detectors. Many new experiments have been planned with the aim of investigating the three anomalies. For what concerns the neutrino flux from reactors, already existing equipments used to monitor the nuclear plants will be reused and upgraded , and completely new detectors will be implemented. Such projects are being developed in Belgium, France, Russia, Korea and China. Two experiments (CeLand and SOX) are devoted to check the neutrino flux from very-high-activity sources. Caesium (^{144}Ce) and chromium (^{51}Cr) isotopes will be put close to or inside the detectors KamLand in Japan and Borexino at Gran Sasso Laboratory. In order to investigate the LSND and MiniBooNE anomaly, a neutrino beam and proper detectors are required. A possibility was the combined use of a $Time\ Projection\ Chamber$ (TPC), able to "take pictures" of ν_e-events in a beam of muon neutrinos, and a spectrometer to measure the charge and the flux of muons generated in charged-current neutrino scattering [11, 12]. This project was mainly Italian and consisted of two pairs of detectors at different distances in order to measure the oscillation effects as a function of the neutrino path. Unfortunately the project stopped because CERN management gave up the construction of a neutrino beam, at least up to now. Anyway a $Neutrino\ Platform$ is under construction at Geneva. The latter is an experimental area dedicated to developing and testing the detectors which will be used in neutrino research programs in the United States and Asia. At the moment, only the United States, with a European contribution, have started a program for the search of sterile neutrinos in a beam. This US effort is justifiable taking into account that LSND and MiniBooNE are American experiments and that the $Booster\ Neutrino\ Beam$ is already operative at Fermilab. The chosen technique for the neutrino detection is the liquid-argon TPC to be used in three different detectors (LAr1-ND, MicroBooNE and Icarus) at 100, 470 and $600\ m$ respectively from the tunnel where the neutrinos are produced. MicroBooNE was designed essentially to investigate the anomalous measurements by MiniBooNE, eventually completed by LAr1-ND as a $Near\ Detector$ to measure the beam features before the starting of the oscillations. Later, the Icarus Collaboration directed by the Nobel-prize laureate Carlo Rubbia suggested to use the 600-ton detector already operational at Gran Sasso Laboratories, in order to complement the experimental setup at Fermilab with a $Far\ Detector$. This allows to observe the possible appearance of $\nu_e$in optimal conditions The three collaborations are working in coordination with the goal to start the combined data taking in spring 2018.

Another, mainly Italian, collaboration (NESSiE) to which also the author of this paper belongs, has proposed to exploit the magnetized spectrometers of the OPERA experiment already operative at Gran Sasso. These spectrometers would be used to observe the ν_μ-disappearance, another possible signature of the oscillation phenomenon [13]. The Program Advisory Committee (PAC) at Fermilab evaluated the proposal as scientifically founded but also incompatible with the present commitments of Fermilab.

Conclusions

The model with three massive neutrinos allows to explain the main part of the observed oscillation phenomena. Only few disputable measurements suggest that the scenario is not completely understood. A prudence principle would suggest giving up any research program on sterile neutrinos. But the enthusiasm connected to a completely new physics seems much stronger than prudence. The discovery of sterile neutrinos would be an historical turning point in the understanding of the universe, so it is worth the hassle. In the next years we will know if neutrinos have other surprises in store for us.

[1] ALEPH, DELPHI, L3, OPAL and SLD collaboration: "Precision electroweak measurements on the Z resonance", *Physics Report* **427** (2006) 257.

[2] B. Pontecorvo: "Neutrino experiments and the question of leptonic-charge conservation", *Sov. Phys. JETP* **26** (1968) 984.

[3] K.N. Abazajiana et al. "Light Sterile Neutrinos: A White Paper", arXiv:1204.5379v1.

[4] K.A Olive et al. (Particle Data Group): "The Review of Particle Physics", *Chin. Phys. C* **38** (2014) 090001.

[5] Th. A. Mueller et al.: "Improved predictions of reactor antineutrino spectra", *Phys. Rev. C* **83** (2011) 054615.

[6] C. Giunti, M. Lavade: "Statistical significance of the gallium anomaly", *Phys. Rev. C* **83** (2011) 065504.

[7] A. Aguilar et al. (LSND Collaboration): "Evidence for neutrino oscillations from the observation of $\bar{\nu}_e$ appearance in a $\bar{\nu}_\mu$ beam", *Phys. Rev. D* **64** (2001) 112007.

[8] A. A. Aguilar-Arevalo et al. (MiniBooNE Collaboration): "Unexplained Excess of Electronlike Events from a 1-GeV Neutrino Beam", *Phys. Rev. Lett.* **102** (2009) 101802.

[9] A.A. Aguilar-Arevalo et al. (MiniBooNE Collaboration): "Event Excess in the MiniBooNE Search for $\bar{\nu}_\mu \to \bar{\nu}_e$ Oscillations", *Phys. Rev. Lett.* **105** (2010) 181801.

[10] A. Mirizzi et al: "The strongest bounds on active-sterile neutrino mixing after Planck data", *Phys. Lett. B* **726** (2013) 8.

[11] P. Bernardini et al. (NESSiE Collaboration) "Prospect for Charge Current Neutrino Interactions Measurements at the CERN-PS", arXiv:1111.2242.

[12] M. Antonello et al. (ICARUS Collaboration), M. Benettoni (NESSiE Collaboration) "Search for *anomalies* from neutrino and anti-neutrino oscillations at $\Delta m^2 \sim 1\ eV^2$ with muon spectrometers and large LAr-TPC imaging detectors", arXiv:1203.3432.

[13] A. Anokhina et al. (NESSiE Collaboration) "Prospects for the measurement of muon-neutrino disappearance at the FNAL-Booster", arXiv:1404.2521. A. Anokhina et al. (NESSiE Collaboration) "Search for sterile neutrinos in the ν_μ disappearance mode at FNAL", sottomesso per la pubblicazione a *Phys. Review D*

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Neutrinos: messengers of new physics

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We know experimentally that neutrinos have masses much smaller than the corresponding charged leptons. Why? An intriguing conjecture suggests a deep relation between small masses and new physics at very high energy scales. The profound implications and ramifications of this conjecture are at the focus of a worldwide experimental and theoretical program.

The small neutrino masses

In the last two decades, neutrino oscillation searches have taught us that the three neutrinos ν_α with flavor $\alpha = e$, μ and τ are linear combinations of three neutrinos ν_i with masses m_1, m_2 and m_3, through a unitary matrix U: $\nu_\alpha = \sum_i U_{\alpha i}\nu_i$. Flavor oscillations $\nu_\alpha \to \nu_\beta$ are sensitive to the squared mass differences ($\Delta m^2_{ij} = m^2_i - m^2_j$) but not to the **absolute masses** (m_i) which, however, are subject to upper limits (see the contribution by D. Montanino in this volume).

Historically, the first limit to neutrino masses (derived from β decay) was already set by Wolfgang Pauli in his famous 1930 letter: $m_\nu < 0.01\, m_p$ (i.e., roughly $m_\nu < 10^7$ eV in natural units, $c = 1 = \hbar$). After more than 85 years of searches, this kinematic limit has improved by almost seven orders of magnitude, and it can be expressed in a form which takes into account the mixing U_{ei} between the electronic neutrino ν_e emitted in β decay and the states ν_i:

$$m_\beta = \sqrt{\textstyle\sum_{i=1}^{3} |U_{ei}|^2 m^2_i} < 2\ \mathrm{eV}\ . \qquad (1)$$

Recently, independent limits have been obtained from precision cosmology: Indeed, the standard cosmological model predicts a diffuse cosmic background of primordial neutrinos with a density of 110 $\nu + \overline{\nu}$ per cm^3 (for each flavor). They act as a source of gravity with strength proportional to the sum of their masses Σ, which is tightly constrained by current cosmological data,

$$\Sigma = m_1 + m_2 + m_3 < 0.3\ \mathrm{eV}\ , \qquad (2)$$

although this limit can be significantly weakened (up to an order of magnitude) in variants of the standard cosmological model.

On the one hand, the above data imply that each of the neutrino masses $m_{1,2,3}$ must be smaller than a (conservative) **limit of about 1 eV**. On the other hand, oscillation experiments have determined the two independent quantities $|\Delta m^2_{12}|$ e $|\Delta m^2_{23}|$. Therefore, at least two masses must be greater than $\sqrt{|\Delta m^2_{12}|} \simeq 0.009$ eV and $\sqrt{|\Delta m^2_{23}|} \simeq 0.05$ eV, while it is not yet excluded that one of the three masses m_i is zero.

These allowed intervals for the neutrino masses are summarized in Fig. 1, together with the mass values of the other fundamental

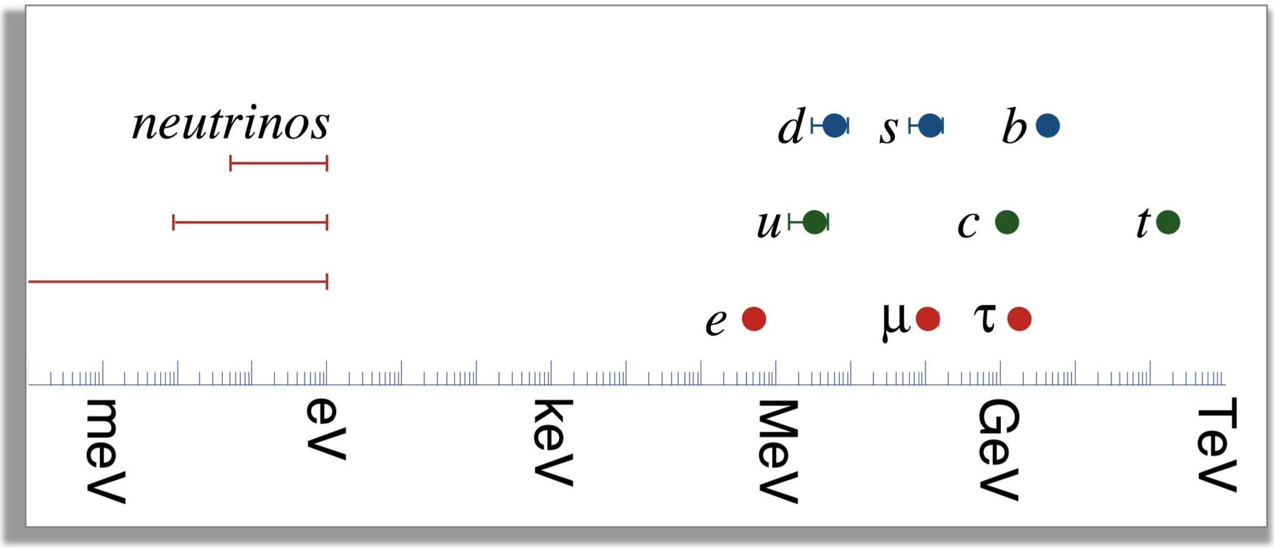

Figure 1: *Masses of fundamental charged fermions (leptons and quarks) and allowed intervals for neutrino masses.*

fermions of the standard model (the charged leptons ℓ and quarks q) in logarithmic scale. Neutrinos appear to be isolated, at the bottom of the scale. **Why?**

Let's say right away that a possible answer is that... there is no answer! In principle, the values of the fundamental fermion masses in Fig. 1 could be (at least in part) "random" and not indicative of a deeper layer of new physics: *... This deed has so been willed where One can do whatever He wills - and ask no more questions (Dante, Inferno III 95-96).* Sometimes, such a pessimistic approach is grounded in the hypothesis of a multiverse (where our universe would coexists with innumerable others, characterized by different values of the fundamental parameters) and in the so-called anthropic principle (which would select only those universes leading to intelligent life). Fortunately, it is too early to succumb to such "interpretations", as we shall try to discuss below.

Neutrinos: Weyl, Dirac, Majorana

All the elementary particles have at least two fundamental properties: the **mass** (that can also be zero, as for the photon) and the intrinsic angular momentum or **spin** (that can be zero or multiple of 1/2, in natural units). For instance, the Higgs boson has a mass of about 126 GeV and spin 0, while each neutrino has a mass smaller than 1 eV and spin 1/2.

Mass and spin can be fully understood in the fascinating language of group theory, in particular of the group of coordinate transformations of special relativity, that leave the speed of light invariant. These kinematical properties are then supplemented by the dynamical ones, described by the symmetry group of the standard model of elementary particles, and by the breaking of this symmetry through the Higgs mechanism.

Here we shall limit ourselves to a heuristic understanding of the deep relation linking the neutrino masses and their spinorial properties, by considering the simplest case of a single type of **neutrino** $\boldsymbol{\nu}$ with its companion **antineutrino** $\boldsymbol{\overline{\nu}}$, both endowed with a mass m, that can be eventually zero.

Figure 2 shows the neutrino ν created in a weak interaction process, hence with its spin opposite to its motion, like a top that is spinning anti-clockwise or **left-handedly** (LH). Viceversa, the antineutrino $\overline{\nu}$ is always created like a top spinning **right-handedly** (RH).

What happens to these (LH or RH) states as they further propagate? There are three different possibilities, named after three giants of last century's theoretical physics: Hermann **Weyl**, Paul **Dirac** and Ettore **Majorana**.

The first case is realized for $\boldsymbol{m = 0}$, as it was assumed in the standard model until less than twenty years ago. In this case, the neutrino (antineutrino) moves at the speed of light and remains exactly LH (RH), just as it was created in Fig. 2, until it "dies", e.g., by generating the cor-

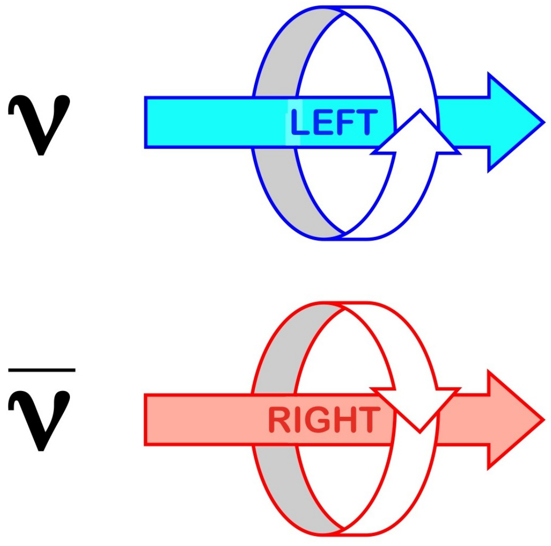

Figure 2: *Schematic representation of a ν and a $\overline{\nu}$ created in a weak interaction process.*

responding charged lepton ℓ^- (ℓ^+) in a charged current interaction. The neutrino quantum field is then named after **Weyl** and has **two components**: ν (LH) and $\overline{\nu}$ (RH).

In the case $\boldsymbol{m \neq 0}$, the neutrino speed v is less than the speed of light, although only by a tiny amount, since its energy E is such that $E \gg m$ in many situations of experimental interest. In this case, the property of being LH cannot be invariant: A hypothetical observer moving with speed $v' > v$ would see a flip of the direction of motion (but not of the spin) of the neutrino, that would then appear as a right-handed (rather than left-handed) spinning top. In other words, a neutrino is always born LH but, if massive, it develops a small RH component during its propagation, with a probability amplitude of order m/E. Analogously, an initially RH antineutrino develops a small LH component, as depicted in Fig. 3. The neutrino quantum field is then named after **Dirac** and has **four components**: ν (LH and RH) and $\overline{\nu}$ (RH and LH).

The (generally independent) four components of a Dirac neutrino can be halved in two special subcases. We have already seen one such subcase: it's the Weyl neutrino, trivially obtained by the Dirac neutrino in the limit $m \to 0$. However, a second and highly nontrivial possibility is realized when the RH and LH components of ν and $\overline{\nu}$ are identical in pairs, as indicated in Fig. 4. This possibility is excluded for a spin-1/2 parti-

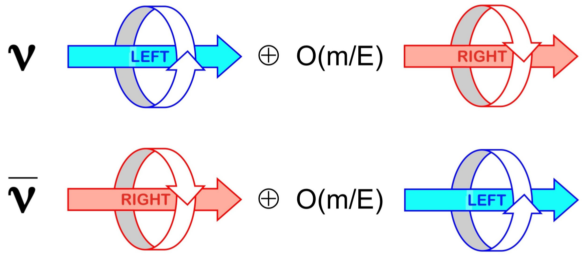

Figure 3: *Case $m \neq 0$: Heuristic representation of a four-component Dirac spinor.*

cle endowed with a charge (electrical, or related to other quantum numbers), since the RH (or LH) components of the particle and of its antiparticle would have opposite charge. However, it may be realized with neutrinos, provided that they have absolutely no "charge" of any type (not just electrical). If Nature has chosen this option, then there is no real difference between neutrino and antineutrino ($\boldsymbol{\nu \equiv \overline{\nu}}$), but only two possible RH and LH states of the **same particle-antiparticle** (see box). The neutrino quantum field is then named after **Majorana** and has only two independent components.

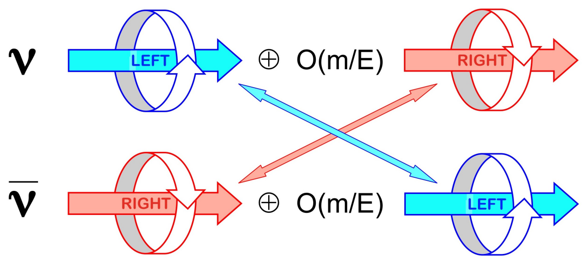

Figure 4: *Case $m \neq 0$: Heuristic representation of a Majorana spinor, with components identical in pairs. In this case, $\nu \equiv \overline{\nu}$.*

Summarizing: Dirac fermions are endowed with both mass and "charge(s)", and are characterized by four independent components (particle, antiparticle, LH and RH). The Dirac case applies to quarks q and charge leptons ℓ, and it could also apply to neutrinos. By zeroing the mass of a Dirac fermion one gets a Weyl fermion: An option not excluded yet for the lightest ν. Alternatively, by zeroing any "charge(s)" (but not the mass) one gets a Majorana fermion: An option that, for neutrinos, is not only possible but also very interesting from a theoretical and experimental viewpoint, as we shall see. Finally, we

The apparent paradox of the neutrino-antineutrino identity

The attentive reader might wonder how to reconcile the possible existence of Majorana neutrinos (identical to their own antiparticles) with the fact that some processes seem to be induced only by neutrinos but not antineutrinos, or vice versa. For instance, if we call ν_e the particle produced in a β^+ decay (and $\overline{\nu}_e$ the one produced in a β^- decay), we know that the following reactions have been observed,

$$\nu_e + n \to p + e^- \qquad\qquad \overline{\nu}_e + p \to n + e^+ \, , \tag{I}$$

while those obtained by replacing ν_e with $\overline{\nu}_e$ have never been observed so far:

$$\overline{\nu}_e + n \to p + e^- \qquad\qquad \nu_e + p \to n + e^+ \, . \tag{II}$$

It is then demonstrated that $\nu \neq \overline{\nu}$, isn't it? Well, not really ... but there is no paradox! If the neutrinos are of **Weyl** or **Dirac** type, then ν_e and $\overline{\nu}_e$ are really different, and can be tagged by a **lepton number *L*** with value $+1$ for the (ν_e, e^-) doublet and -1 for the $(\overline{\nu}_e, e^+)$ doublet. The observed reactions (I) conserve the leptonic number ($\Delta L = 0$), while those not yet observed (II) are forbidden, as they would imply lepton number violation by two units ($\Delta L = 2$).

If the neutrinos are of **Majorana** type, there is no paradox because they have no charge (and no leptonic number), thus making the reactions (II) possible *in principle*, although extremely unlikely in practice. Indeed, the "ν_e" produced in a β^+ decay and the "$\overline{\nu}_e$" produced in a β^- decay are simply the LH and RH components of one and the same particle ν, identical with $\overline{\nu}$. The transformation from one state to the other is possible but, as illustrated in Fig. 4, it is strongly suppressed by a factor $m/E \ll 1$. Even at the lowest detectable energies, $E \sim O(1)$ MeV, the suppression factor turns out to be $< 10^{-6}$ for $m < 1$ eV, thus making the reactions (II) so unlikely to escape (at least so far) the experimental observation. Therefore, the patient search of **very rare processes with $\Delta L = 2$** is crucial to prove the existence of Majorana neutrinos.

recall that for $m = 0$ (Weyl) the RH or RH state is a constant of motion, while for $m \neq 0$ (Dirac or Majorana) both states develop during propagation: it is then said that the masses "couple" the LH and RH states.

(Non)standard mass terms

The impact of the Higgs boson discovery on the media has been so vast to popularize the concept that this boson "gives mass to all the other particles" (apart from gluons and the photon). In the standard model, the Higgs field couples to the LH and RH components of a generic fermion with strength y and, after electrowaek symmetry breaking, provides it with a mass $m \sim yv$, where $v = 174$ GeV is the vacuum expectation value of the Higgs field. In particle physics jargon, this mechanism involves "Yukawa couplings" (hence the y symbol) and "standard mass terms" for fermions, which turn out to be unavoidably of Dirac type. The top quark t, with its mass $m_t \simeq 173$ GeV, represents the Dirac fermion with most natural Yukawa coupling, $y_t \simeq 1$, while the other charged fermions have $y \ll 1$ by up to a few orders of magnitude.

For neutrinos, the issue is more involved. Historically, in constructing the standard model it was assumed that the three neutrinos ν_e, ν_μ e ν_τ were Weyl LH spinors (hence with no RH component), contrary to all the other charged fermions. Under this assumption, the neutrino mass terms are absent, and the masses remain zero even after symmetry breaking. However, the discovery of flavor oscillations implies the existence of massive neutrinos and makes it necessary to include mass term, thus introducing RH states to be coupled to the LH states. In this case, after electroweak symmetry breaking one gets Dirac mass terms also for neutrinos, but the extreme smallness of their Yukawa couplings remains unexplained: Indeed, $y_\nu < O(10^{-11})$ is required to get a mass $m_\nu \sim y_\nu v < O(1)$ eV.

However, for neutrinos, there is a further and peculiar option available. The RH states introduced above have no electromagnetic interactions and no weak interactions related to charged or neutral currents (which are only coupled to LH states): They are completely chargeless, so as to be named as "sterile". In this case, no symmetry of the standard model forbids that they are Majorana neutrinos, with a mass Λ completely unrelated with the electroweak scale v. Therefore, only for neutrinos, the most general case is the one which includes both the standard **Dirac mass terms** (i.e., those associated with the Higgs mechanism and the electroweak scale v) and the nonstandard **Majorana mass terms** (unrelated to the electroweak scale).

This possibility emerges in a natural way in various extensions of the standard model. For instance, the extension to the symmetry group SO(10) remains a promising candidate for the unification of the electroweak and strong interactions at high energy scale [$\Lambda \sim O(10^{15})$ GeV $\gg v$], and it allows to organize each fermion family in a representation of dimension 16, which also contains a RH neutrino. In particular, the first family would include the LH and RH states of the electron and of the corresponding neutrino, as well as this of the quarks u (up) and d (down) in the three "colors" (red, green and blue) of the strong interaction,

$$\begin{pmatrix} u_L & u_L & u_L & \nu_L \\ d_L & d_L & d_L & e_L \\ u_R & u_R & u_R & \boxed{\boldsymbol{\nu_R}} \\ d_R & d_R & d_R & e_R \end{pmatrix}, \qquad (3)$$

so that it would be natural to associate to the state ν_R a Majorana mass term at the scale Λ.

For the sake of simplicity, let us stick to the case of one neutrino family. In the presence of two mass terms (of Dirac type at the scale v and of Majorana type at a scale $\Lambda \gg v$), the LH and RH neutrino components turn out to be coupled via a "mass matrix" of the form:

$$\begin{pmatrix} 0 & \sim y_\nu v \\ \sim y_\nu v & \sim \Lambda \end{pmatrix}, \qquad (4)$$

where the nondiagonal entries represent the Dirac mass term (coupling the Higgs field to the LH and RH states), while the nonzero diagonal entry represents the Majorana mass term (generated by the RH neutrino), with "$\sim$" indicating that one is just dealing with orders of magnitude. Diagonalizing this simple mass matrix leads to two peculiar results: 1) the two eigenstates are, in general, Majorana neutrinos; 2) the two eigenvalues are equal to $M \sim \Lambda$ for the heaviest state and to

$$m \sim y_\nu^2 \frac{v^2}{\Lambda} \qquad (5)$$

for the lightest state (up to an irrelevant sign). This equation provides us with an intriguing explanation, called the "see-saw mechanism" (see box), for the extreme smallness of m : the greater the mass scale Λ associated to the RH neutrino (with respect to the electrowaek scale v), the smaller the neutrino mass.

In order to get $m < O(1)$ eV with a "natural" Higgs coupling $y_\nu \sim O(1)$, the scale of new physics must thus be $\Lambda > O(10^{13})$ GeV, consistent with the energies predicted by grand unification models. Alternatively, lower values of Λ may be obtained by assuming that $y_\nu \ll 1$, like in the case of the other charged fermions apart from the quark top. Eventually, models with $\Lambda \sim O(1)$ TeV and $y_\nu \sim 10^{-5}$ (*TeV-scale see-saw*) are already tested at the energies of the Large Hadron Collider (LHC).

Of course, there are a number of possible variants to the simple model described above, both to account for the three known lepton families, and because the number of possible new RH states is arbitrary, thus enriching the neutrino phenomenology associated to the scale Λ. There is thus a wide spectrum of theoretical possibilities, that are still in the infancy of possible experimental tests.

Summarizing, the conjecture discussed above represents an elegant **answer to the initial question**: *Why are neutrino masses so small with respect to the electroweak scale v?* The answer provided by the **see-saw** mechanism implies that **neutrinos are of Majorana type** and that they "talk" not only with the Higgs boson but also, at higher energies, with a **new physics scale Λ**.

Neutrinoless $\beta\beta$ decay

The possible Majorana nature of neutrinos may possibly emerge in rare lepton number violation processes, suppressed by a factor $m/E \ll 1$ (see the first box). The only such process which appears to be experimentally observable is the **neutrinoless double beta decay**.

The $0\nu\beta\beta$ process, illustrated in Fig. 5, predicts the decay of a nucleus $(A,\, Z)$ into another one $(A,\, Z+2)$ characterized by two more protons and two missing neutrons, with the simultaneous emission of two electrons but no associated neutrino. The sum of the two electron energies would then show up as a "spectral line", emerging from a continuous background at exactly the Q-value of the reaction.

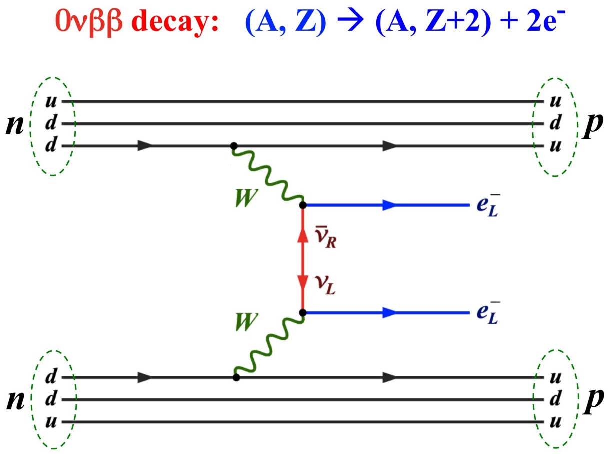

Figure 5: *Neutrinoless double beta decay mediated by a Majorana neutrino.*

The diagram in Fig. 5 shows the process at the microscopic quark level. From top to bottom, a neutron's quark d turns into a proton's quark u by emitting a charged boson W, which in turn decays into an electron (LH) and an antineutrino (RH). If the $\overline{\nu}$ has nonzero mass, it can flip from RH to LH at order m/E. Moreover, if it is of Majorana type, such a state coincides with the LH component of the ν that, by interacting with a W boson emitted in another $d \to u$ transition (at the bottom of the figure), generates the second electron (LH). Since the process violates the lepton number, it cannot occur via Dirac (or Weyl) neutrinos, and its observation would then represent an unmistakable signature of Majorana neutrinos. In any case, the decay would be extremely rare, both because it involves dynamically two W-exchange weak processes, and because it is kinematically suppressed at order m/E.

In the general case of three Majorana ν's, the $0\nu\beta\beta$ probability amplitude is proportional to a linear combination of the masses m_i,

$$m_{\beta\beta} = \left| \sum_{i=1}^{3} U_{ei}^2\, m_i \right| \;, \tag{6}$$

also called the **effective Majorana mass**, where the (generally complex) weight factors U_{ei}^2 account for the ν_e mixing with any of the ν_i in the two weak vertices in Fig. 5. Current upper limits to $m_{\beta\beta}$ are already below the 1 eV scale, although their interpretation is affected by large theoretical nuclear uncertainties. In terms of half-lives, limits at the level of 10^{24}–10^{25} years have been placed, well beyond the age of the universe (1.4×10^{10} years)! In order to observe at least one $0\nu\beta\beta$ decay per year, one must then gather a large number of candidate nuclei (much larger than the Avogadro number), and patiently wait for a possible signal in ultra-low background conditions. A strong competition is taking place among various experiments in different laboratories around the world (including the INFN underground facility at Gran Sasso), given the paramount importance of a potential Majorana neutrino discovery.

Towards wider horizons

In conclusion, from the experimental viewpoint, the three quantities m_β, Σ and $m_{\beta\beta}$ defined in Eqs. (1), (2) and (6) are linked to three different ways of probing the absolute neutrino masses, respectively by means of β decay, precision cosmology, and $0\nu\beta\beta$ decay. Measuring these quantities is at the focus of a a worldwide research program that, in the near future, will hopefully turn current upper limits into a positive signal for at least one such observable.

From a theoretical viewpoint, the discovery of Majorana neutrinos would provide us with an extremely relevant piece of information in favor of the hypothesis of a new mass scale Λ independent of the electroweak scale. In the seesaw mechanism, this is usually identified with

The see-saw mechanism and ... a 25-year anniversary with surprise!

If we were to find information on the **"see-saw mechanism"** in a neutrino physics textbook older than about ten years, we would invariably see references to four famous theoretical works, independent and almost contemporaneous, authored by M. Gell-Mann, P. Ramond e R. Slansky (1979), T. Yanagida (1980), R.N. Mohapatra and G. Senjanovic (1980), and by J. Schechter and J.W.F. Valle (1980). The impact of these papers on the subsequent theoretical works in the fields has been so impressive, that the **25 years of the see-saw idea** were celebrated in 2004 in a dedicated international conference entitled *Seesaw'25* (Paris, 10-11 June 2004). During the meeting and soon afterwords, various neutrino physics pioneers of that time contributed, with their memories, to recall the atmosphere and the ideas circulating in the second half of the '70s.

It was then that... to the surprise of many, a work by **P. Minkowski (1977)** emerged from oblivion. Despite being completely unknown to most, it contained — clearly and completely — the basic elements of the see-saw mechanism, two years ahead of any other. The author, far from any pretension, had never claimed primacy for his paper, leaving other people to dig it up and recognize its importance 27 years later. Even today, he remembers his old paper and its subsequent "rediscovery" with surprising modesty. In any case, the importance of Minkowski's 1977 paper was immediately realized as soon as it was circulated, already at the time of the Proceedings of the *Seesaw'25* conference. Now the paper counts more than 2200 citations (the number is steadily growing), on a par with the above famous works of 1979-1980.

Then, let's save the date in 2027, for the (true) 50-year celebration of the see-saw mechanism!

Figure 6: *The small neutrino masses as possible messengers of new physics beyond the electroweak (EW) scale.*

the grand unified scale related to proton decay, but it is not excluded that Majorana neutrinos can also "talk" with lower mass scales related to other very interesting phenomena, e.g., the generation of the baryon asymmetry of the universe via leptonic CP violation ("leptogenesis"), the possible contribution of "heavy" sterile neutrinos to the dark matter, the effects of light sterile neutrinos in flavor oscillations — and more, as illustrated in Fig. 6. The tiny neutrino masses could then lead us towards unexplored horizons of new physics.

The bibliography related to the previous topics is immense. A good starting point for orientation and further reading is the website: `nu.to.infn.it`.

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His research activity has focussed on the theoretical and phenomenological aspects of electroweak precision physics, with particular attention to the physics of neutrino masses and mixings.

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Viaggio nella Scienza

Neutrino: the Mutant Particle