Neutrinos: the Messengers of the Invisible World.

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Abstract. Among elementary particles, neutrinos have unique features. The knowledge of their properties has progressed tremendously in the past years, in particular concerning their masses. Remaining questions are discussed and perspectives for the future are sketched. This introductory talk gives a general view of the experimental searches in neutrino physics with special emphasis on the French activity.

1. Unique properties of neutrinos (1)
Neutrinos are the only fermions with zero electric charge. They were imagined by Wolfgang Pauli in 1930, to explain the puzzle of the apparent energy loss occurring in nuclear $\beta$ decays. The physicist proposed that the detected electrons are emitted together with a neutral particle, having very little interactions with matter, thus "undetectable". Three years later, Enrico Fermi developed the theory of a new interaction, the so-called Fermi interaction known today as weak interaction. Fermi gave the name neutrino (little neutral in Italian) to the new particle, and it was necessary to wait until 1956 to obtain the experimental existence proof of neutrinos by Reines and Cowan at the Savannah River nuclear reactor plant.

Neutrinos are elementary particles at the basis of the construction of matter. The full list of constituents includes 3 families, each of them having one quark of charge 2/3, one of charge -1/3, one charged lepton (electron, muon and tau) and its associated neutrino. This list of 12 elementary objects must be doubled with 12 anti-constituents having the same properties except for the charges (electric and leptonic) which are opposite.

They are 3 different types of neutrinos which are experimentally well distinguishable: when it interacts, the first neutrino $\nu_e$ gives an electron, the second $\nu_\mu$ a muon and the third $\nu_\tau$ a tau. This is exemplified for the first two species on figure 1 which shows interactions as seen in the NOMAD experiment in the CERN neutrino beam (2).
Quarks are sensitive to all interactions while leptons do not participate in strong interactions. Neutrinos being leptons with no electric charge are only sensitive to weak interactions. This explains their extremely small probability of interaction with matter. A solar neutrino has a $10^{-9}$ probability to be stopped while traversing the Earth.

2. Sources of neutrinos
There are numerous emitters of neutrinos. Natural sources are the following: the Sun, the Earth, the supernovae explosions, the cosmic rays, the Big Bang. Because of $\beta$ radioactivity, even the human body emits neutrinos at the level of about 5000 per second. Artificial sources, mainly accelerators and nuclear reactors, are also important contributors. All of these neutrinos have been detected except for the cosmological neutrinos born during the Big Bang. Experimentally, there are two handles to discriminate between the various origins; the arrival direction in case of a point source, and the energy which is very different from one source to the other.

2.1. Solar neutrinos
The origin of the solar energy has been a historical puzzle since the 18th century. Its explanation became understood around 1930 with the development of nuclear physics. The solar energy comes from the phenomenon of fusion. The main channel fuses 4 protons to give a He nucleus together with 2 positrons and 2 $\nu_e$. Knowing the solar energy received on Earth (1 kW/m$^2$), it is possible to calculate a total production rate of $10^{38}$ neutrinos/s. This rate results in a neutrino flux on Earth at the level of about $60 \times 10^9$ cm$^{-2}$/s. Solar neutrinos are of low energy, the ones coming from the main channel extend up to 430 keV, but higher branches exist which produce neutrinos with energies up to 15 MeV. Note that, at production all the solar neutrinos are of type $\nu_e$.

The Borexino experiment situated under the Gran Sasso mountain in Italy will be presented (3).

2.2. Supernova neutrinos
February 17th, 1987 is a famous date among neutrino physicists. On that day, a neutrino flux passed by the Earth. It came from a supernova explosion which happened in the large Magellanic cloud, 150000 years before. Two detectors were ready to intercept it: Kamiokande in Japan and IMB in Ohio (4). Each of them saw about 10 neutrinos interacting in a 1 kiloton water detector. This was enough to check the models of star explosions and put a limit on neutrino mass.
A supernova (type 2) explosion signals the death of a star for those having about 10 solar masses. This happens when its fuel is exhausted and 99% of the energy is released in the form of neutrinos of the 3 species, with energies in the range 20-30 MeV. During this extraordinary event, a total of $10^{58}$ neutrinos are produced in about 10 seconds. The detectors saw an increase of phototube hits lasting about 10 seconds in agreement with the prediction.

New and larger detectors wait for the next occurrence.

2.3. **Atmospheric neutrinos**

Primary cosmic rays are essentially protons, with a fraction of some heavier nuclei. They come from unknown sources in the cosmos. They can carry extremely large energies, million times more than energies available at accelerators. Entering into the atmosphere, these protons interact in the upper levels and generate showers in which all possible particles are produced.

Due to the production process through meson decays, the neutrinos are essentially of the two first types with a ratio of 2 $\nu_\mu$ for 1 $\nu_e$. The flux reaching the Earth is around $100/m^2/s$, with a very large energy spectrum showing a maximum around 1 GeV.

2.4. **Accelerator neutrinos.**

The flux of neutrinos produced at accelerators can be accurately calculated and this gives a unique opportunity for precise measurements of neutrino properties. Since 1964, we know how to build a neutrino beam (5). Extracted protons from an accelerator impinge on a target. Pions and kaons are produced and they decay over a long enough distance. Neutrinos are among the products of these decays. A magnetic horn is used to focus mesons of one polarity, thus selecting at will neutrinos or antineutrinos and concentrating the flux in a well-defined direction.

Neutrino beams are composed of 99% $\nu_\mu$ for 1% $\nu_e$ and they can reach up to several 100 GeV. At high energy the third type coming from charm decays is present at less than $10^{-4}$. Several generations of experiments using different detection techniques have given results.

2.5. **Nuclear reactor neutrinos.**

Nuclear reactors are powerful sources of neutrinos and the experimental first discovery was made with such a device. A commercial nuclear reactor produces on the order of $10^{21}$ anti-$\nu_e$ per second. They are produced in the fission process of uranium and their energy is low, around 2 MeV. Several generations of experiments have been performed, and to-day three large experiments are taking data: Daya Bay in China, Reno in South-Korea and Double Chooz in France (6).

2.6. **Big Bang neutrinos.**

Last but not least, the Big Bang itself has filled the whole Universe with the so-called cosmological or fossil neutrinos. In fact, this is the main contribution to the total number of existing neutrinos. Overall it amounts to 300 neutrinos/cm$^3$, with similar amounts from the three flavours, neutrinos and antineutrinos being equally present. This seems a small number compared to Avogadro’s number, but it extends to the whole space, and globally it results in $2 \times 10^9$ times more neutrinos than protons or neutrons in the entire Universe.

Unfortunately, despite this huge number, these neutrinos have never been experimentally seen and there is very little hope to succeed even in the distant future. These neutrinos have a tiny energy of some $10^{-4}$ eV (temperature of 1.9 K) and nobody has the slightest idea how to detect them. Nevertheless, one believes in their existence since they have the same origin as the cosmological background photons which have been precisely measured at the expected level.

3. **The challenge of detecting neutrinos**

As already emphasised, neutrinos are only sensitive to weak interactions and their cross-section is usually very tiny (it increases with energy). Fortunately, sources of neutrinos are in general quite
intense. Nevertheless, it is a challenge to obtain large data samples, and one must compensate the small probability of stopping neutrinos by the use of very massive detectors.

3.1. Bubble chambers
Bubble chambers were used for a long time as ideal neutrino detectors offering masses up to 30 tons. The technique allows to follow each track of secondary particles, and to measure the individual energies with a magnetic field. Very important results have been obtained, in particular the discovery of neutral weak interactions with the Gargamelle heavy liquid bubble chamber in 1973 at CERN (7). Unfortunately, bubble chambers are slow devices, registering 1 event per second, and this is not adapted to the search of very rare events. The technique was discarded in the years 1980.

3.2. The SuperKamiokande detector
The archetype of the neutrino detectors is represented by the Japanese detector SuperKamiokande (8). It is an underground huge reservoir containing 50 ktons of purified water. Figure 2 shows the device during the filling phase. The water is spied by 11000 large phototubes which cover all the walls of the volume. When a neutrino interacts on either electrons or nucleons of the water atoms, it produces secondary charged particles which generate Cerenkov light along their track. Water being transparent, this light reaches the phototubes and rings of hits are formed, allowing to measure the direction of the incoming neutrino and the released energy.

![Figure 2. The SuperKamiokande detector during filling.](image)

Other techniques are also used, in particular scintillating liquids like in the Borexino or Double Chooz detectors.

4. Oscillations?
The discovery of neutrino oscillations is the major progress of the recent years in neutrino physics. It is a quantum mechanical process which arises from the existence of non-zero masses.

4.1. The solar neutrino deficit
Several experiments measured the flux of neutrinos coming from the Sun before the advent of SuperKamiokande and found a deficit with respect to the expectation. The Japanese detector confirmed that the flux of $\nu_e$ measured on Earth was about 40% of the flux predicted by the theory.
This disappearance of neutrinos was also observed with artificial neutrinos in the Kamland detector measuring neutrinos from Japanese nuclear reactors which were 180 km distant in average. Later the Canadian experiment SNO (Sudbury Neutrino Observatory) using 1 kton of heavy water confirmed that neutrinos are produced in the Sun in agreement with the calculations, but part of them change flavour between their production and their detection point. Heavy water allows to detect the three kinds of neutrinos (9).

4.2. The atmospheric neutrino deficit
A new neutrino disappearance was confirmed by SuperKamiokande: it concerned atmospheric neutrinos (10).
While the neutrinos of type $\nu_e$ are detected at the predicted level, the neutrinos of type $\nu_\mu$, which have crossed the whole diameter of the Earth before detection show a deficit with respect to the neutrinos coming from above. The former have travelled 13000 km, the latter only 30 km. The result is shown in figure 3.

![Figure 3. Angular distributions of $\nu_e$ (left) and $\nu_\mu$ (right) interactions. Data points and expectations are shown. $\theta$ denotes the angle of the neutrino direction with respect to the vertical axis.](image)

This result was confirmed by an accelerator experiment called Minos running at Fermilab, and subsequently by the Opera detector studying $\nu_\mu$ coming from CERN after 730 km of travel. High energy $\nu_\mu$ change flavour over such a distance. SuperKamiokande and Minos detected the disappearance of $\nu_\mu$, while the Opera experiment fulfilled the complementary task of detecting the appearance of $\nu_\tau$.

4.3. Phenomenology of neutrino oscillations
All these deficits can be explained by the phenomenon of oscillations. This is basically a quantum mechanical process, in which interaction eigenstates are not identical to propagation eigenstates. The three weak interaction states $\nu_e$, $\nu_\mu$ and $\nu_\tau$, can be written as combinations of mass eigenstates $\nu_1$, $\nu_2$, and $\nu_3$ which are characterized by 3 different masses $m_1$, $m_2$ and $m_3$. The two sets of states are related by a 3x3 unitary mixing matrix. The propagation states evolve differently and the oscillation probability depends on the difference of square masses, in agreement with the Heisenberg uncertainty relations. Overall, with three known neutrino states, the complete picture of oscillations involves 3 mixing angles $\theta_{12}$, $\theta_{23}$, and $\theta_{13}$, one phase $\phi$ and 2 mass differences. This gives the full list of parameters to be measured by experiments.

The results of solar neutrinos give: $\delta m_{12}^2 = 8 \times 10^{-5}$ eV$^2$ and $\theta_{12}$ around 30°.
The atmospheric neutrino sector gives: $\delta m_{23}^2 = 3 \times 10^{-3}$ eV$^2$ and $\theta_{23}$ around 45°.

4.4. The last mixing angle

The last mixing angle called $\theta_{13}$ remained unknown until last year. It measures the change of $\nu_e$ over distances given by the atmospheric neutrino oscillations.

In 2012, the three nuclear reactor experiments in operation gave consistent results of a disappearance of anti-$\nu_e$ over distances of order 1 km. Figure 4 shows the behaviour of the neutrino flux as a function of the distance from the reactor, with the main oscillation channel (solar disappearance) being modulated by the second order process of atmospheric oscillations.

![Figure 4. Calculated neutrino flux showing the main oscillation channel (solar) modulated by the atmospheric channel (smaller wiggles).](image)

In particular the Double Chooz experiment consists in 2 identical detectors made of 8 tons of liquid scintillators, the far detector being at 1 km from the two reactors and the close detector (still in construction) at 400 m. The aim is to measure a difference of spectra between the two positions.

At the same time the Japanese experiment T2K which observes accelerator neutrinos in the SuperKamiokande detector after a travel of 295 km, saw the appearance of $\nu_e$ in the $\nu_\mu$ beam. The results are consistent and give a measurement of the last mixing angle: $\sin^2 (2\theta_{13}) = 0.096 \pm 0.013$ (11). No theory predicts the value of the mixing angles and it was a relief to find $\theta_{13}$ large enough to envisage the next step, namely the search of CP violation.

5. Neutrino masses

Neutrino masses are extremely small compared to the mass scale of other elementary particles. For many years, they were tested without success in various processes, and oscillations proved to be the most sensitive way to measure them. Unfortunately, oscillations do not measure separately the masses but only give information on mass differences.

We do not know yet the hierarchy, namely the ordering, among the three neutrino masses. The simplest scenario suggests the following result: $m_3 = 50$ meV, $m_2 = 9$ meV, with $m_1$ unknown and much smaller.

These masses are extremely small, the heaviest neutrino has a mass 10 million times smaller than that of the electron which is the lightest charged particle. This seems negligible for the mass-energy content at the level of the Universe. But neutrinos are much more abundant than the rest of the matter particles and the amazing result is that neutrinos contribute as much as all the stars to the global content of the Universe.

This result seems remarkable, but one should remember that stars only contribute 0.5% of the total content, dark energy and dark matter contributing more than 95% of the Universe as a whole.
Coming experiments will check the true hierarchy among neutrino masses and will give further information about the absolute value of the masses.

6. Neutrino astronomy
We know many different sky maps: visible, radio, X-rays, infrared... We would like to obtain a map of neutrino progenitors. In the past, only two celestial objects have been seen emitting neutrinos: the Sun and SN1987A. One would like to find more.

6.1. Why neutrinos?
Neutrinos interact very rarely. This is a disadvantage when tempting to detect them, but this is an advantage when trying to explore the Universe in all its depth. Protons or high energy photons can explore a small part of the cosmos, about 1% in distance, because they interact with the cosmological background and magnetic fields disturb the proton trajectories. Neutrinos do not present these limitations, they allow a much deeper scan, in principle. They are produced in violent phenomena arising in space: galaxy collisions, collapses in active galactic nuclei... They give an information different from the one obtained with visible light. But they require huge detectors to be seen on Earth, 10000 times bigger than SuperKamiokande.

6.2. Neutrinos telescopes.
In order to build huge detectors, it is necessary to instrument natural media. Two possibilities can be envisaged, either ice or water.
The IceCube detector (12) built at the South Pole is based on a 1 km$^3$ volume of ice, inside which photomultipliers have been distributed. The apparatus was completed 3 years ago. It has registered thousands of atmospheric neutrinos showing the expected energy distribution. In 2012, it announced two giant events reaching 1 PeV = 10$^{15}$ eV. The probability to come from atmospheric neutrinos is small, and this signal is the first evidence of extraterrestrial neutrinos of very large energy. The two events show a huge shower extending over 500 m and coming from either $\nu_e$ interactions or neutral current, they do not show a muon. The direction is not well known. The task is immense to go further. Finding sources would require a much increased number of such enormous events and this will take quite some time to be achieved.
Closer to us, the Antares detector (13) is built under sea water in the depth of the Mediterranean. Its size is still substantially smaller than IceCube, but the aim is to complete a 1 km$^3$ water detector. This, together with IceCube, would allow a full survey of both sky hemispheres.

7. Perspectives
Progress in neutrino physics has been remarkable. We now know that neutrinos have mass and mix. But the number of open questions is still very large:
- Why 3 and only 3 left-handed neutrinos?
- What is the correct hierarchy, normal or inverted?
- Are neutrino masses degenerated?
- Is CP violated in the lepton sector? This question is related to the puzzle of antimatter disappearance since the time of the Big Bang. Huge projects are in preparation to tackle this question, they will try to discover a small difference between oscillations among neutrinos and among antineutrinos.
- Are neutrinos Dirac or Majorana particles, namely is the neutrino its own antiparticle? The only realistic approach to this problem is the search for neutrinoless double $\beta$ decays. Many experiments are deployed for this study, this is in particular the unique aim of the SuperNemo project.
- Have neutrinos electromagnetic couplings, magnetic moments, radiative decays?
- What are the sources of very high neutrinos?
- What about the Big Bang neutrinos?
8. Conclusion

Neutrino physics has progressed tremendously in the past 15 years. Oscillations have been proven beyond doubt, and this gives the first crucial information about neutrino masses. But a large program of research is still ahead of us to clarify several points. In particular the hope is to find CP violation at a level which could explain the disappearance of antimatter in our Universe.

Beyond this obvious program, ideas are also developed that sterile neutrinos exist. Sterile neutrinos go beyond the scheme of the three left-handed active neutrinos. They do not participate in weak interactions and couple to the rest of the particles only through mixing. Such objects are advocated in models trying to understand the origin of neutrino masses. If they exist, they could be responsible for the missing mass of the Universe in form of Warm Dark Matter.

References

[1] For a general review (in French): “Le Miroir aux Neutrinos”, F. Vannucci, 2003 Odile Jacob ed.
[2] F. Vannucci, 2014 Advances in High Energy Physics, vol.2014, art.ID129694
[3] G. Ranucci et al., 1993 Nucl. Instrum. Methods in Phys. Res A 333, 553
[4] W. D. Arnett et al., Supernova 1987A, 1989 Annual Review of Astronomy and Astrophysics, 27, 629-700
[5] G. Danby et al., 1964 Phys. Rev. Letters 9, 36
[6] M. Apollonio et al., arXiv:0301017; Daya Bay Collaboration, arXiv:1201.6181
[7] http://public.web.cern.ch/public/en/About/History73-en.html
[8] S. Fukuda et al., 2003 Nucl. Inst. and Methods in Physics Research A 501 (2–3): 418
[9] Y. Fukuda et al., 1996 Phys. Rev. Lett., 77, 1683; Q. R. Ahmad, et al., 2001 Phys. Rev. Lett., 87, 071301
[10] Y. Fukudae et al., 1998 Phys. Rev. Lett., 81, 1562
[11] F. P. An et al., arXiv:1203.1669v2; Y. Abe et al., arXiv:1406.7763
[12] R. Abbasi; et al., 2009 Nucl. Inst. and Methods A 601: 294; V. Van Elewyck, arXiv:1311.7002