THE APPEARANCE OF THE TAU-NEUTRINO

Alessandro Bettini,
University of Padua, Department of Physics; INFN, Padua division (Italy) - Laboratorio Subterráneo de Canfranc (Spain)
E-mail: bettini@pd.infn.it

DOI: 10.1051/epn/2010604

On August 22nd 2009 a very special event was recorded by the OPERA experiment at the INFN Gran Sasso Laboratory produced by a neutrino coming from CERN. Born as mu-neutrino, it had transformed into a tau-neutrino on its 730 km long route. This is a long-awaited achievement of an enterprise started 30 years ago.

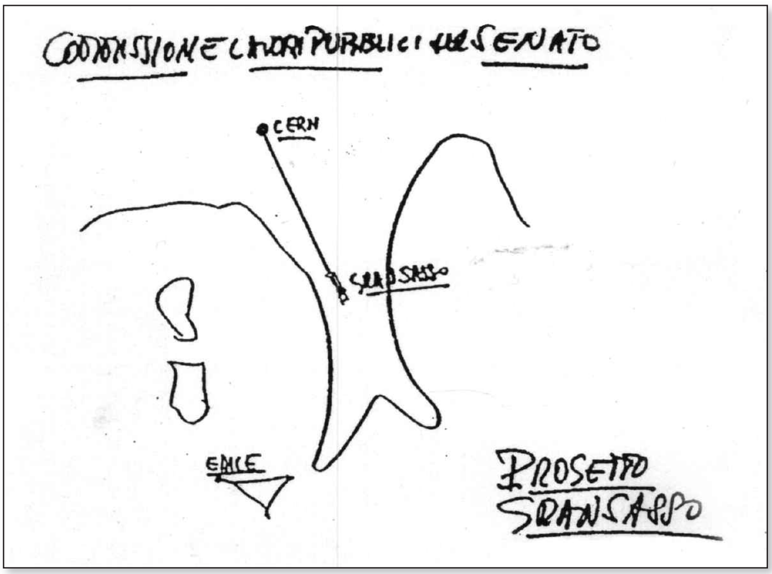
▲ OPERA detector. Photo on permission of LNGS-INFN

Neutrinos change family

The spin ½ elementary particles come in three different groups, called families, of identical structure. Each family is made of two quarks, of charge +2/3 q and –1/3 q (q is the proton charge), and two leptons, one of charge $-q$ and one neutral. The neutral leptons are collectively called neutrinos, but are three different particles, distinguished by an additive quantum number called "lepton flavour". The electron (e^-) and the electron-neutrino (ν_e) have one unit of electronic flavour (–1 their antiparticles); the muon (μ^-) and the muon-neutrino (ν_μ) have one unit of muon-flavour, and similarly for the tau (τ^-) and the tau-neutrino (ν_τ).

The charged leptons are distinguished by their different masses (increasing with the family number) and lifetimes, neutrinos only by their lepton flavours, which are conserved in the interactions. Neutrinos are produced in states of definite flavour, as ν_e, ν_μ or ν_τ, each with an antiparticle of the same flavour, its antineutrino or e^+, μ^+ or τ^+, respectively. When a neutrino of a certain flavour interacts with a target producing a charged lepton, the latter always has its flavour; for example a ν_μ produces a μ^-, never an electron or a tau.

Experiments in underground laboratories have shown that neutrinos do not behave as assumed in the Standard Model (SM): they do change, "oscillate", between one flavour and another. The evidence has gradually grown in the last four decades, by studying the ν_es produced by the fusion reactions in the core of the Sun and the ν_μs indirectly produced by the cosmic rays collisions in the atmosphere.



▲ **FIG. 1:** Geographical sketch of the neutrino beam from CERN to Gran Sasso by A. Zichichi (1979)

Neutrino oscillations

Neutrino oscillations happen because neutrinos of definite flavour, ν_e, ν_μ and ν_τ, are not stationary states, *i.e.*, states of definite mass, but linear combinations of those. We call the latter ν_1, ν_2 and ν_3 and m_1, m_2 and m_3 their masses.

Oscillations phenomena are common in physics. Consider for example two identical pendulums, *a* and *b*, of mass *m* and length *l* weakly coupled by a spring of constant *k*. The system has two normal modes, obtained by defining its initial state. In each mode the two pendulums oscillate harmonically and synchronically with (proper) frequencies, say, ω_1 and ω_2. The first mode is obtained by letting them go from the same initial elongation with zero initial velocities. The squared frequency is $\omega_1^2=g/l$. In the initial state of the second mode the two elongations are equal and opposite and the velocities are zero. The squared frequency is $\omega_2^2=g/l+2k/m$. Considering for the moment a world with only two neutrinos, the analogues of the modes are ν_1 and ν_2 and the analogues of the frequencies are the masses m_1 and m_2.

▼ **FIG. 2:** A. Bettini (left) and L. Maiani (right), together with a representative of local Swiss authorities celebrating at the "ground breaking" event for the CNGS project on 12/10/2000. Photo CERN

The analogue of a neutrino of flavour *a* is the initial state with pendulum *a* abandoned with zero velocity at a certain initial elongation and pendulum *b* in its at rest position. Vice versa for flavour *b*. One observes that the motion does not have a definite frequency. Rather, the amplitude of the vibrations of *a* gradually decreases down to zero, while that of those of *b* increases up to a maximum. Then the evolution inverts. Hence, the energy "oscillates" periodically from *a* to *b* with a frequency ω_2-ω_1. In the quantum system the analogue of energy is the probability to observe the flavour, because both are proportional to the square of the amplitude. To observe the phenomenon one needs to leave a time long enough to allow for its development. In practice this means having the detector far enough from the source. Then there are two alternatives: to look for the disappearance of the initial flavour (looking at *a*) or for the appearance of the new one (looking at *b*).

However, there are *three* neutrinos. The analogue is a system of three coupled pendulums. Moreover, the pendulums may not be equal. Clearly the phenomenology becomes much richer.

In 1968 R. Davis [1] published his measurement, started in 1964, of the flux of neutrinos from the Sun with an experiment sensitive to ν_e. The flux was smaller, about 1/3, than the theoretical calculations by J. Bachall [2]. When the preliminary results became known, B. Pontecorvo [3] claimed that the disappearance might be due to neutrinos changing flavour through oscillation, a concept he had introduced in 1957. Further ν_e disappearance experiments, in different energy ranges, KAMIOKANDE [4] and Super KAMIOKANDE [5] in Japan, GALLEX/GNO [6] at Gran Sasso and SAGE [7] at Baksan, had established by 1998 that the Pontecorvo idea was right. The final proof came from the SNO [8] in Canada in 2002. All neutrino flavours can interact with nuclei producing a neutrino in the final state, instead of a charged lepton. The final neutrino cannot be detected, but the effect on the nucleus can. This was done by SNO, proving that the total neutrino flux interacting in this way corresponded exactly to the missing ν_e flux. A confirmation came from the KamLAND experiment in

Japan that observed the oscillation in anti-electron neutrinos from nuclear power plants.

By 1998 the Super-KAMIOKANDE [9] experiment had measured, with high statistics and high accuracy, the dependence of the atmospheric ν_μ flux on the flight-length and on energy. The shape of this function proved the oscillation phenomenon and made it possible to determine the corresponding oscillation parameters. Also in this case, confirmation of the oscillation interpretation came from disappearance experiments with artificial neutrinos, ν_μ produced at the KEK accelerators in Japan (K2K experiment) and later at the Fermilab in the USA (MINOS experiment).

From the third family to CNGS

As mentioned above, ν_τ and its charged partner τ are part of the third "family". As a matter of fact, the existence of the third family, and the concept of family itself, was experimentally established in the lepton sector much earlier than in the quark sector. We briefly recall that the neutrino was introduced as a "desperate hypothesis" by Pauli in 1930, when only the electron was known, to explain the apparent non-conservation of energy in beta decay. It was discovered in 1956, when also the muon had been discovered, by F. Raines [10]. It was in 1962 that an experiment at Brookhaven [11] established that neutrinos were two, ν_e and ν_μ. Not much later, the idea of the possible existence of a third lepton family, called "heavy lepton" H_l and its neutrino ν_{Hl} was introduced by A. Zichichi. The idea was to search for lepton pairs, which, in the case of $e^-\mu^+$ would be a clear signature of the H_l. The search started at CERN in 1963, with the PAPLEP experiment, and continued at the e^+e^- collider ADONE [12] at Frascati in 1967. The H_l did indeed exist, but was found, and called τ, only in 1975 by M. Perl [13] and collaborators at the SPEAR collider, which, differently from ADONE, had enough energy to produce it.

Thirty years ago, A. Zichichi, then president of INFN (Istituto Nazionale di Fisica Nucleare), succeeded in having approved by the Italian Parliament the Gran Sasso project, to build a large, technologically advanced, laboratory under the Gran Sasso massive. The laboratory halls were oriented, in particular, toward CERN, in order to be able in a future to host experiments on a neutrino beam from CERN. The draft presented by Zichichi to the Parliament is shown in Fig. 1.

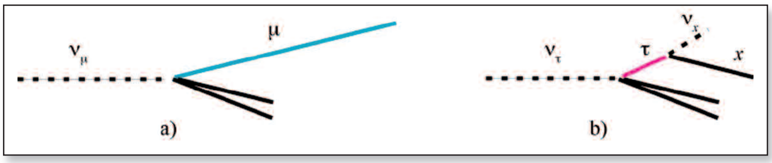
The vision started to become reality around 1997. Recalling that accelerators produce (almost pure) ν_μ beams, the alternative ν_μ disappearance vs. ν_τ appearance was open. Notice that they require different characteristics both for the beam and the experiments. Vivid discussions started in the community leading to proposals for both. In particular, the OPERA experiment was proposed in that year by A. Ereditato, K. Niwa and P. Strolin [14]. The study of the proposals led to a common decision by the CERN Director General, L. Maiani, the INFN President, E. Iarocci, and the LNGS Director, myself, for the more risky (but much more rewarding if successful) appearance experiments. The project was approved by the INFN and CERN Councils in 1999. It was funded with ad hoc contributions mainly from Italy and from several other countries.

Neutrinos do not behave as assumed in the **Standard Model** (SM): they do **change, "oscillate"**, between **one flavour** and **another**

The civil engineering works at CERN and the construction of the beam took place between Autumn 2000 (see Fig. 2) and Summer 2004. The subsequent delicate and complex phases of testing and commissioning were completed by the Spring 2006. In August of the same year the large detectors at LNGS, LVD, OPERA and BOREXINO detected the first events produced by the neutrino beam. In the same period the OPERA and ICARUS experiments were developed.

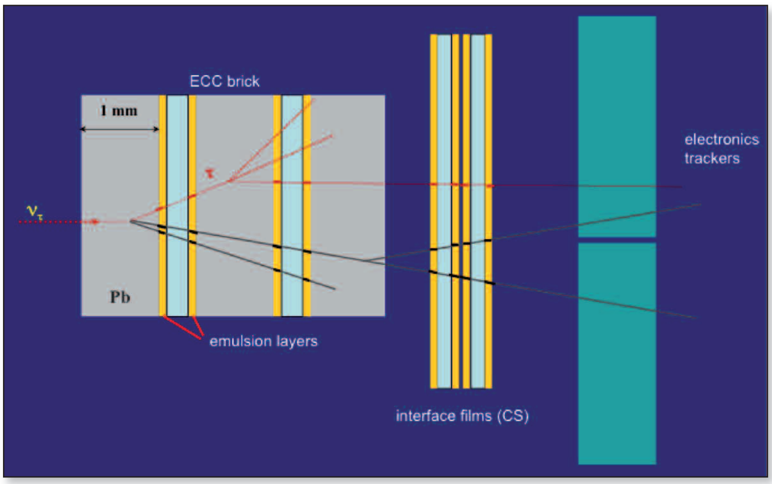
The first appearance

As mentioned, the beam produced at CERN is mainly composed of ν_μ with no ν_τ. Consequently, the observation of any ν_τ at LNGS must be due to the appearance in the oscillation phenomenon. Experimentally, the two types of neutrinos can be distinguished, when they produce a charged lepton: a ν_μ produces a μ and a ν_τ produces a τ. The principle is shown in Fig. 3.



▲ **FIG. 3:** Basic topologies of a) ν_μ interaction and, b) ν_τ interaction

▼ **FIG. 4:** The neutrino interaction detection principle of OPERA. Electronic trackers are used to identify the brick containing the interaction, which is then removed and processed.



In a tracking detector the μ appears as a long almost straight track, while the τ, which has a very short lifetime, picoseconds, decays already after few hundreds micrometres. Consequently, to observe the τ track a micrometre scale spatial resolution is necessary, something that only nuclear emulsions can provide.

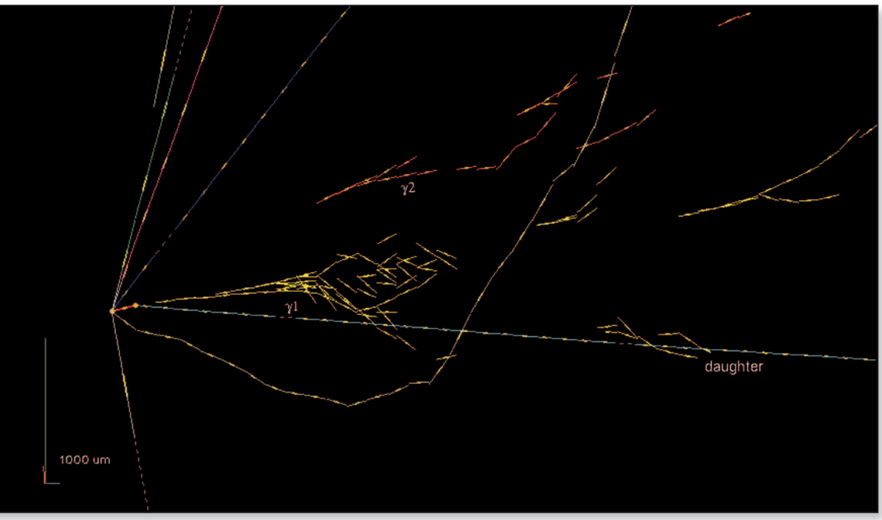
However, there is a further problem. Indeed, even a distance of 730 km is small for the oscillation phenomenon, because the corresponding 2.5 ms flight time is only a small fraction of the oscillation period. Consequently, only a very small fraction of neutrinos, 1-2%, are expected to "oscillate". Considering in addition the very small neutrino cross section the conclusion is reached that the detector target mass needs to be considerably larger than 1000 tons.

This is why the "Emulsion Cloud Chamber" (ECC) technique, so called because it provides images similar to a cloud chamber, was chosen. It is based on sandwiches of thin (50 µm) emulsion sheets, providing the ~1 µm resolution tracking, interleaved with 1 mm thick Pb sheets, providing the mass.

ECC is a rather old technique, which was continually developed in Japan, with increasing levels of automation of the read-out, mainly at Nagoya. Historically, ECC detectors were successfully employed for the study of the high-energy cosmic-rays. Particularly important is the discovery by Kiyoshi Niu of a meson of a new flavour (in modern terms) in 1971 [15]. It was the charm, three years earlier than the discovery of hidden charm with the J/ψ particle by Burton Richter and collaborators and Samuel Ting and collaborators. The discovery of the ν_τ in 2000 by Kimio Niwa and collaborators [16] at Fermilab was obtained with an evolution of the same technique. OPERA is the latest and largest chapter of this evolution, composed, just to give a few numbers, of 150 000 sandwiches, called "bricks", including about 110 000 m^2 emulsion films and 105 000 m^2 lead plates, for a total of about 1250 tons.

ECC are, however, only a component of OPERA, which is a very complex structure: It includes different tracking elements and magnetic spectrometers, developed by the collaborators, both INFN groups and from other countries. The detection principle is shown in Fig. 4. Further fundamental elements are the automatic scanning and measuring microscope systems that are needed to extract the information from the emulsion. A big effort was invested in increasing by an order of magnitude the speed of these devices to cope with the above mentioned enormous emulsion area.

In 2008 – 2009 OPERA has collected about 1/5 of the total foreseen data; of these about 35% have been analysed and the first ν_τ candidate event has been already found[16]. It is shown in Fig. 5. The τ lepton is the short red track. It decays in a charged hadron, presumably a pion and a π°, which in turn decays into 2 gammas, which are detected. Even if the calculated probability for any background to simulate a τ is only 1.8%, it is too early to claim the discovery of the appearance phenomenon. But a few other similar events will hopefully lead to this long-awaited discovery in the next years. ■



◀ FIG. 5: The first ν_μ to ν_τ oscillation candidate. Notice the different scales on the two axes. Picture OPERA. You can watch an animation at http://dx.doi.org/10.1051/epn/2010604.s001

References

[1] R. Davis Jr., D.S. Harmer and K.C. Hoffman, *Phys. Rev. Lett.* **20** (1968) 1205.

[2] J.N. Bachall, N.A. Bachall and G. Shaviv, *Phys. Rev. Lett.* **20** (1968) 1209.

[3] B. Pontecorvo, *Zh. Eksp. Teor. Fiz.* **53** (1967)1717, [*Sov. Phys. JETP* **26** (1968) 984].

[4] Y. Fukuda *et al.*, *Phys. Rev. Lett.* **77** (1996) 1683.

[5] M.B. Smy *et al.*, *Phys. Rev. D* **69** (2004) 011104.

[6] W. Hampel *et al.*, *Phys. Lett. B* **447** (1999) 127; M. Altmann *et al.*, *Phys. Lett. B* **616** (2005) 174.

[7] N. Abdurashitov *et al.*, *J. Exp. Theor. Phys.* **95** (2002) 181, [*Zh. Eksp. Teor. Fiz.* **122** (2002) 211].

[8] Q. R. Ahmad *et al.*, *Phys. Rev. Lett.* **87** (2001) 071301.

[9] Y. Fukuda *et al.*, *Phys. Rev. Lett.* **81** (1998) 1158.

[10] C. L. Cowan, *et al.*, *Science* **124** (1956) 103.

[11] G. Dandby *et al.*, *Phys. Rev. Lett.* **9** (1962) 36.

[12] M. Bernardini *et al.*, INFN/AE-67/3, 20 March 1967; V. Alles-Borelli *et al.*, *Lett. Nuov. Cim.* **4** (1970) 1156, M. Bernardini *et al.*, *Nuovo Cimento* **17A** (1973) 383.

[13] M. Perl *et al.*, *Phys. Rev. Lett.* **35** (1975) 1489.

[14] A. Ereditato, K. Niwa and P. Strolin, INFN/AE-97/06, DPNU-97-07; H. Shibuya *et al.*, CERN-SPSC-97-24, LNGS-LOI-8-97.

[15] K. Niu, E. Mikumo and Y. Maeda, *Prog. Theor. Phys.* **46** (1971) 1644.

[16] N. Agafonova *et al.*, arXiv: 1006.1623v1, to appear on *Phys. Lett. B.*