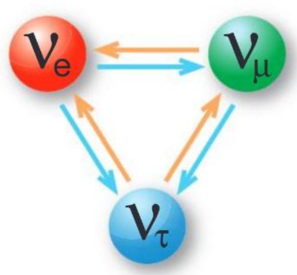
Unravelling the Secrets of the Neutrinos

Neutrinos were first proposed in 1930 to explain an unexpected experimental result. These elusive yet very real particles interact only weakly with matter and are therefore almost invisible in detectors. Sixty years after their discovery, they have yet to reveal all their secrets.



Credit: T2K experiment

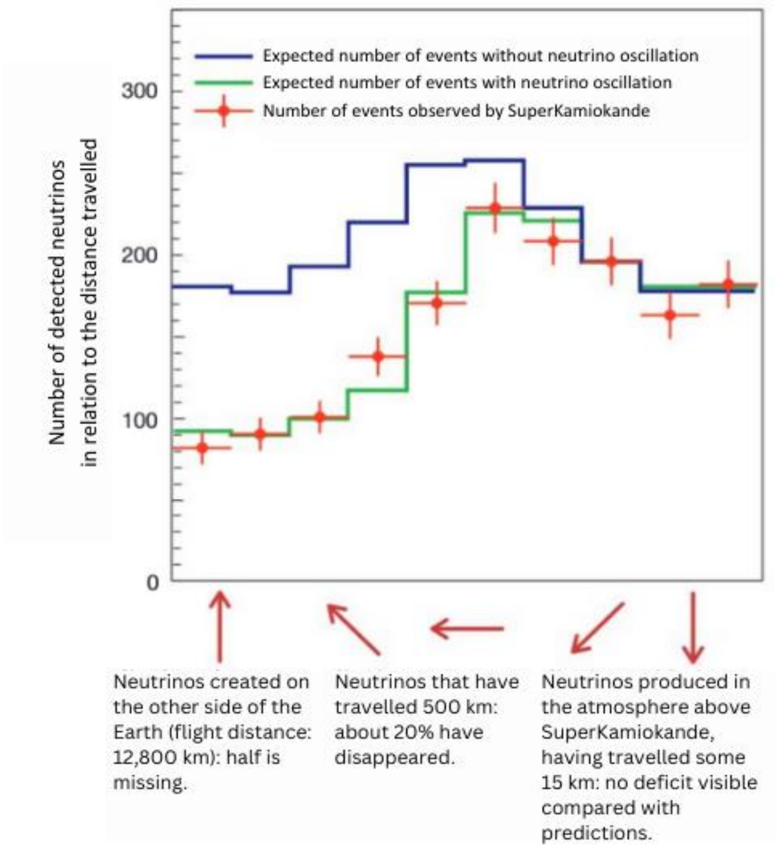
Neutrino oscillations

This diagram illustrates the neutrino oscillation phenomenon and depicts the six possible transformations between the three types of neutrinos: electron (ν_e), muon (ν_μ) and tau (ν_τ) neutrinos. For each experiment, reactions have different probabilities of occurring, depending on the energies of the neutrinos emitted from the source, the distance they travel before detection, and the theoretical parameters being investigated.

In 1930, Wolfgang Pauli introduced a new particle to reconcile measurements of certain radioactive decays with the fundamental principle of energy conservation. The neutrino (meaning 'little neutral' in Italian) had to have an infinitesimal mass, zero electric charge, and interact so weakly with matter that it wasn't detected until 1956. Today, the Standard Model includes three types of neutrinos, associated with the electron (ν_e) and its two more massive 'cousins', the muon (ν_μ) and the tau (ν_τ). Neutrinos interact only through the weak interaction, making them difficult to observe and study. Many experiments are still ongoing to measure their properties.

Neutrinos 'oscillate'. This intuitively strange behaviour arises from their quantum nature: once emitted, a neutrino of a certain type can transform into a neutrino of another type. Detectors are generally sensitive to a single type of neutrinos, so all neutrinos that have oscillated may seem to 'disappear' or 'appear', depending on the source and detector used.

In 1998, the SuperKamiokande experiment (Japan) observed a deficit in 'atmospheric' ν_μ (muon neutrinos produced by cosmic ray interactions with the upper atmosphere) arriving from the antipodes. This anomaly was explained by the oscillation of ν_μ into ν_τ during their 10,000 km travel from the other side of the Earth. In 2001, the SNO detector (Canada) became the first to simultaneously observe the different types of neutrinos, demonstrating that the flux of



Credit: Kamioka Observatory, ICRR, University of Tokyo

Atmospheric ν_μ oscillation observed by SuperKamiokande

The ν_μ detected by SuperKamiokande come from the interaction of cosmic rays with the atmosphere. Depending on their arrival direction (determined by the detector and symbolised by the arrows at the bottom of the image), we know where they were produced. Neutrinos coming from 'above' (above the detector) have barely travelled a few kilometres and, therefore, have not had the time to oscillate into another type of neutrino: measurements (red dots) and predictions with no neutrino oscillation (blue curve) match. Conversely, neutrinos arriving from 'below' (produced on the other side of the Earth) have travelled long enough for around half of them to have oscillated: measurements match the green curve (a model including neutrino oscillation).

electron neutrinos from the Sun matched predictions, and that the deficit in ν_e (observed since the 1960s) was due to their oscillation into ν_τ or ν_μ. These discoveries were awarded the Nobel Prize in Physics in 2002 and 2015. Since then, numerous experiments have focused on studying the neutrino oscillations to measure all the parameters governing them. The oscillation phenomenon can occur between two types of neutrinos only if they have different masses. Therefore, its observation indirectly shows that at least two of the three types of neutrinos are massive, a result at odds with the Standard Model, which supposes that neutrinos have zero mass. However, neutrinos are by far the lightest leptons, weighing a few millionths of the electron's mass at most – and probably (much) less.

The unique properties of neutrinos have driven the scientific community to combine sources and measurements. In addition to the three known types of neutrinos, there may be others, known as sterile neutrinos, which do not interact with matter at all. Oscillations into such particles would experimentally result in a neutrino deficit that could not be explained, even with detectors sensitive to the three Standard Model neutrinos. Since the neutrino has zero charge in the Standard Model, it could be its own antiparticle. If so, it might have played a crucial role in the creation of matter-antimatter asymmetry a few fractions of a second after the Big Bang. To test this hypothesis, experiments in underground laboratories are searching for neutrinoless double beta decay, a very specific form of radioactivity. Results have been unsuccessful so far, but a new generation of more sensitive detectors is expected to provide more data in the coming years.

Translated from 'Percer les secrets des neutrinos',* Passeport pour les deux infinis, *IN2P3/Dunod, https://pass2i.ijclab.in2p3.fr/ (French); updated with ICHEP2024 conference (https://ichep2024.org) for IPPOG