4th Lisbon Mini-School on Particle and Astroparticle Physics

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Costa da Caparica

Hands on Neutrinos

INTRODUCTION, A BRIEF HISTORY OF NEUTRINOS

The neutrino was first postulated by Wolfgang Pauli in 1930 to explain how particles emitted in beta decay could have a continuous energy spectrum, without violating the principle of energy, linear and angular momentum. Pauli hypothesized a neutral (and, therefore, undetected) particle that he called "neutron", later renamed to "neutrino", the little neutral one", after neutrons were found. This new particle would be emitted together with the electron and share its energy, thus explaining the continuous spectrum of the electron energy (see Fig.1).

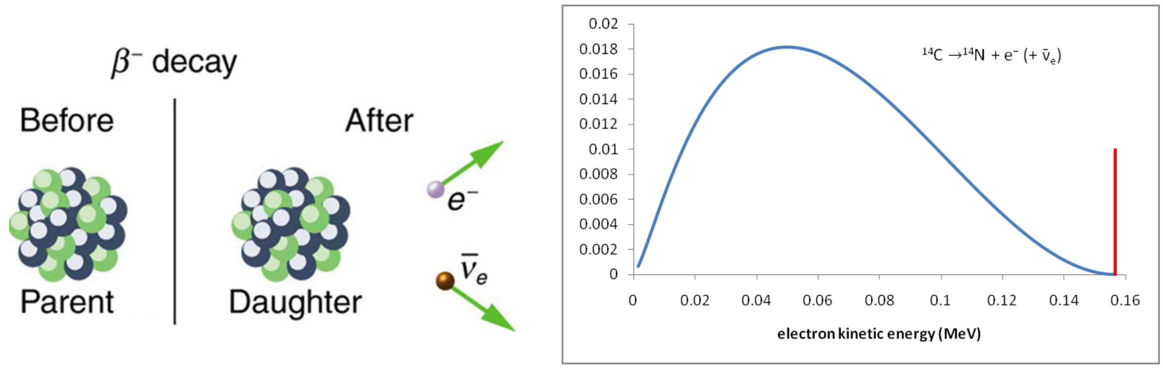

Fig. 1 – (Left) Representation of decay. A parent Nucleus decays into a daughter nucleus with emission of a very light neutral particle, the (anti)neutrino . (Right) b-decay spectrum (blue solid line) and the would-be spectrum if only the electron is emitted (vertical red line).

In 1956, Clyde Cowan, Frederick Reines and collaborators confirmed that they had detected Pauli's neutrino. For this discovery Reines was awarded the 1995 Nobel Prize (shared with Martin Perl). In this experiment, antineutrinos produced in a nuclear reactor interact with protons to produce neutrons (n) and positrons (e^+): $\bar{\nu}_e p \rightarrow e^+ n$. The positron will find an electron, producing two gamma rays (g) which are detectable. The neutron is subsequently captured by a nucleus, releasing another gamma. The coincidence of both events – positron annihilation and neutron capture – provides a unique signature of an anti-neutrino interaction.

In 1962, Leon M. Lederman, Melvin Schwartz and Jack Steinberger found the muon neutrino, another kind of neutrino, appearing in muon interactions. Later, in 1975, a third type of lepton, the tau, was discovered and, similarly to what happened for the muon and the electron, it was expected that the tau neutrino would also exist. The first evidence for this particle arose from the observation of missing energy and momentum in tau decays (which are analogous to beta decay), and the actual detection of tau-neutrino interactions was announced only in 2000 by the DONUT collaboration at Fermilab in the United States. Before that, the existence of this particle had already been inferred by both theoretical consistency and experimental data from the Large Electron–Positron Collider (LEP) at CERN. At this point, it was established that neutrinos come in three flavours: the electron (ν_e), the muon (ν_μ), and the tau (ν_τ) neutrino.

Starting in the late 1960s, several experiments concluded that the number of electron neutrinos arriving from the Sun was between 1/3 and 1/2 of the number predicted by the model which describes the dynamics of the Sun: the Standard Solar Model. Such discrepancy, which rapidly became known as the solar neutrino problem, lacked from a definite solution for about thirty years. Only recently the problem was solved. The solution relies on the fact that neutrinos oscillate between flavours and, therefore (as you will show), must be massive (contrarily to what is predicted by the Standard Model of particle physics).

In this activity we want you to study the basics of neutrino oscillations

HANDS ON NEUTRINO OSCILLATIONS

Quantum systems are described by wave functions that can be a superposition of states. Therefore, at the level of elementary particles, where quantum mechanics is obviously at work, we can describe a neutrino of a given flavor X as being represented by a state $|\nu_X\rangle$. We call these states "flavor eigenstates". Let us take the case of only two flavors, ν_e and ν_μ, associated to quantum states $|\nu_e\rangle$ and $|\nu_\mu\rangle$. Moreover, we will consider that these states are not mass eigenstates in the sense that they do not coincide with the eigenstates of the Hamiltonian for a free particle with mass m_i and energy $E_i^2 = p_i^2 c^2 + m_i^2 c^4$. Therefore, we will consider that the two flavor eigenstates $|\nu_e\rangle$ and $|\nu_\mu\rangle$ are quantum superpositions of the two mass eigenstates $|\nu_1\rangle$ and $|\nu_2\rangle$.

1. The first thing we want you to do is to write $|\nu_e\rangle$ and $|\nu_\mu\rangle$ as a combination of $|\nu_1\rangle$ and $|\nu_2\rangle$. You should choose a parameterization with only one parameter (think about the best way to do it). Remember… These quantum superpositions should obey the probability conservation law of quantum mechanics and should be orthogonal.

Suppose now that at an electron neutrino described by the state $|\nu_e\rangle$ is produced (for instance at the Sun) as a result of some some nuclear reaction. Taking into account that the propagation of mass eigenstates follows the time-dependent Schrödinger equation:

$$i\hbar \frac{\partial\, |\, \nu_i\,(t)\rangle}{\partial t} = H|\, \nu_i(t)\rangle\,,$$

2. Obtain $|\nu_x(t)\rangle$, which represents your flavor state at any instant of time t.
3. What is the probability that, at a time t your electron neutrino has oscillated into a muon neutrino?
4. What are the necessary conditions for neutrino oscillations to occur?
5. How do you express the probability that at a distance L from the source, the neutrinos of a given energy E, can be detected in the same flavor as they were produced?

As you must have concluded by now, neutrino oscillations have an amplitude that depends on mass mixing, and a "propagation term", where $m_{1,2}$ are the neutrino masses (fixed by Nature), L the distance travelled by neutrinos, and E their energy, usually written as:

$$\sin^2\left(\frac{\Delta m^2 c^4}{4\hbar c}\,\frac{L}{E}\right) = \sin^2\left(1.27\,\frac{\Delta m^2[\mathrm{eV}^2]\; L[\mathrm{m}]}{E[\mathrm{MeV}]}\right), \qquad \Delta m^2 = m_2^2 - m_1^2$$

CONGRATULATIONS! YOU HAVE JUST DONE NOBEL PRIZE PHYSICS!

IN PRINCIPLE… NOW LET'S CHECK IF WE CAN REALLY MEASURE IT!

Solar neutrino oscillations in the Sun are actually more complex, since we need to consider their interactions with the dense matter inside the star. In the following we will optimize an experiment to check if the same parameters can be used to describe the oscillation of anti-neutrinos produced on Earth (where we can just consider propagation in vacuum), knowing that the solar neutrino oscillation parameters have been measured to be: $\Delta m^2 = 8.0\times10^{-5}\text{eV}^2$, $\sin^2(2\theta) = 0.856$.

We will use electron anti-neutrinos from a nuclear reactor, and the same detection principle as in the first discovery. The interaction cross-section is $\sigma(\bar{\nu}_e p \rightarrow e^+ n) \sim 10^{-42}$ cm², and we will assume our detector medium has a density similar to water. Consider a nuclear reactor with 10 GW of power. The energy is given by uranium and plutonium fission chains, each releasing ~200 MeV of energy and 2 electron-anti-neutrinos.

6. How many anti-neutrinos are produced as a function of time? How many will reach a detector at 100 m from the reactor? How many will produce signals in a 10 m³ detector?

We will use this near detector to measure the visible reactor anti-neutrino energy spectrum. The reactor flux decreases with energy, and the interaction cross-section increases with energy, and so the visible spectrum peaks at E=4 MeV.

7. What it the best distance L at which to place another detector in order to measure the oscillation and check if it can be described by the solar oscillation parameters given above? How would you scale the volume of the far detector in relation to the near detector?

For illustration purposes (and remembering that we cross-check it using the near detector) we will assume that the visible spectrum can be approximated by a Gaussian distribution, centered at 4 MeV with a standard deviation of 2 MeV. The neutron is used to tag anti-neutrino interactions, and the positron kinetic energy is used to measure the anti-neutrino energy, related to it by $E_{\nu_e} = E_{e^+} + \Delta$.

8. What is the minimum energy threshold Δ, for this interaction to occur? What does happen to the electron anti-neutrinos that oscillated into muon anti-neutrinos? What is the energy spectrum that you expect to see in the near and in the far detector?

You can use the root macro, Neutrino.C, to help you through the rest of the exercise. It allows you to simulate the energy spectra as measured in the two detectors, changing the data acquisition time, the detector volumes and distances, and experimental energy resolution. You can also change the number of energy bins you use in your data analysis.

Most of the anti-neutrino detectors have as interaction medium a liquid scintillator, which emits ultra-violet photons, in number proportional to the deposited energy. The detector energy resolution is at first order given by a statistical uncertainty in the number of photons detected, $\frac{N_{P_{UV}}}{MeV}$.

9. What do you see in your near and far detectors after one month, and after one or ten years? How much does it depend on the detector energy resolution (or on scintillator light yield)?
10. How would you measure the two oscillation parameters from the visible energy spectra? Get a first estimate from a single energy point, and improve the result by using the all data.

CONCLUDING WITH AN INVITATION

Neutrino oscillations occur, of course, among three flavors and with three masses states. All three mixing angles and two mass differences have by now been measured in a combination of natural sources, reactors and accelerators. We can now use neutrinos to study the interior of the Sun and the Earth or to detect and model Supernovas. They are a key ingredient also in cosmology studies.

A lot of questions remain, namely what is the absolute neutrino mass scale and the mass ordering (we have only mass-squared differences), and if is there a CP-violation in the neutrino sector, to help explain the matter/anti-matter asymmetry in the Universe. It is also extremely important to find out whether neutrino mass is generated via the Higgs mechanism, or if neutrinos can be Majorana particles (and so their own anti-particles, contrary to the charged leptons).

Neutrinos are still a very active field of research. All these questions are a field of theoretical work on the Standard Model extensions, and are being addressed by different experiments, either running or being planned for the future. A lot of work remains for you to get involved in the next years.