2nd Lisbon Mini-School on Particle and Astroparticle Physics

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Hotel do Mar – Sesimbra

Hands on Neutrinos

I. BRIEF HISTORY OF NEUTRINOs

The neutrino was first postulated by Wolfgang Pauli in 1930 to explain how β particles emitted in β decay could have a continuous energy spectrum, without violating the principle of energy, linear and angular momentum conservation. Pauli hypothesized a neutral (and, therefore, undetected) particle that he called “neutron”. 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).

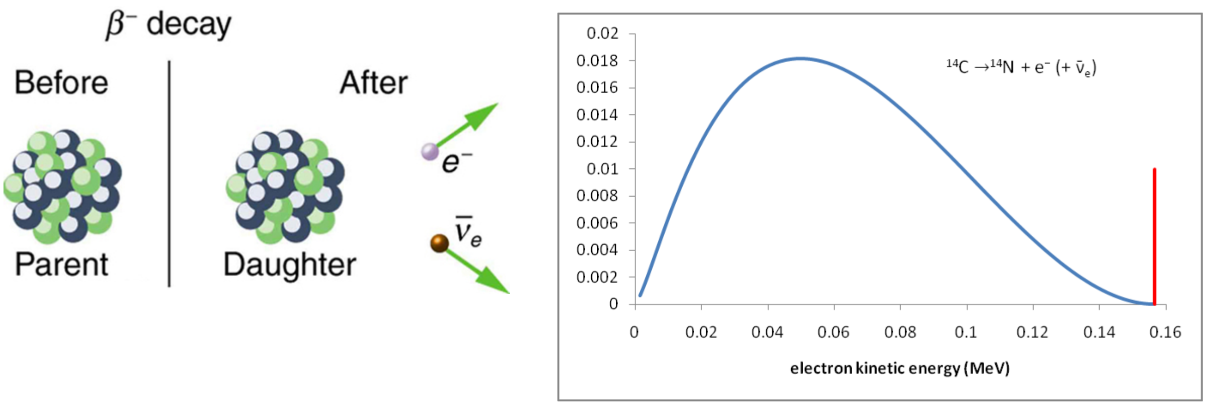

Fig. 1 – (Left) Representation of β decay. A parent Nucleus decays into a daughter nucleus with emission of a very light neutral particle, the (anti)neutrino $\bar{\nu}_e$. (Right) β-decay spectrum (blue solid line) and the would-be spectrum if only the electron is emitted (vertical red line).

In 1932, James Chadwick discovered a “heavy” nuclear neutral particle and also named it a neutron. The name "neutrino" (which in Italian would mean “little neutral one”) for Pauli’s particle was proposed by Enrico Fermi, who started using it during a conference in Paris in July 1932 and at the Solvay Conference in October 1933.

The publication of the experimental neutrino detection happened in the 20 July 1956 issue of the journal *Science*, where 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, known today as the Cowan–Reines neutrino experiment, antineutrinos produced in a nuclear reactor by β decay interact with protons to produce neutrons (n) and positrons (e^+): $\bar{\nu}_e + p \rightarrow n + e^+$. Posteriorly, the positron finds an electron, producing two gamma rays (γ) which are detectable. The neutron is subsequently captured by a nucleus, releasing another photon. 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 that, besides the electron one, there is another kind of neutrino. This new neutrino was first detected by looking at muon interactions, and it was therefore called muon neutrino (the 1988 Nobel Prize in Physics was awarded for the discovery of this particle). Later, in 1975, a third type of lepton, the tau, was discovered at the Stanford Linear Accelerator Center (SLAC). 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 β decay), and the actual detection of tau-neutrino interactions was announced 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.

II. HANDS ON NEUTRINO OSCILLATIONS

As you have learned in Quantum Mechanics I, quantum systems are described by 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 $t = 0$ 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 $|\nu_e(t)\rangle$, 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?

CONGRATULATIONS! YOU HAVE JUST DONE NOBEL PRIZE PHYSICS!

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

Neutrino oscillations in the Sun are actually more complex, since we need to consider interactions with the dense matter inside the star. We want to check if the same oscillation effects exist for electron anti-neutrinos in the Earth (which has a much lower density and, therefore, matter effects can be safely neglected). We will use electron anti-neutrinos of a few MeV, from a nuclear reactor.

5. Considering that anti-neutrinos travel a distance L from the nuclear reactor to the detector (in vacuum), and that the flux of electron anti-neutrinos coming out from the reactor is Φ_{reac}, how do you express the flux of anti-neutrinos detected in your experiment Φ_{det}?

As you must have concluded by now, neutrino oscillations depend on the "propagation term"

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

where $m_{1,2}$ are the neutrino masses (fixed by Nature), L the distance travelled by neutrinos, and E their energy. Knowing that the solar neutrino oscillation parameters have been measured to be:

$$\Delta m^2 = 8.0\times 10^{-5}\text{eV}^2 \ , \sin^2(2\theta) = 0.856,$$

we will optimize an experiment to check if the same parameters can be used to describe the oscillations of anti-neutrinos in vacuum.

We will place a detector close to the reactor, to correctly measure the original spectrum (peaking at 4 MeV), and one far away, to measure the spectrum distortion caused by oscillations. Remember, (anti)neutrinos have a very low interaction cross-section. Therefore, detectors must be big and expensive. The near detector, placed as close as possible to the source, let's say 500 m, can very well be a smaller copy of the far detector, so as to minimize the project cost.

6. What is the best distance L at which to place the far detector?
   How would you scale the volume of the near detector, so that you can collect there 100 times more statistics than in the far detector for systematic studies?

Actually, reactor anti-neutrino energies extend to around 8 MeV. They are detected through inverse β decay process $\bar{\nu}_e p \to e^+ n$ (with a threshold of $E > 1.8\,\mathrm{MeV}$), being the visible spectrum roughly approximated (for illustration purposes of this exercise, and remembering you cross-check it in the near detector) by a Gaussian distribution centered at 4 MeV and with standard deviation of 2 MeV (notice part of it will be below threshold). The anti-neutrino energy is obtained from the positron energy, which is linearly related to it.

Use the root macro, Neutrino.C, to guide you. Just start by "root Neutrino.C".

7. Using both functions (the Gaussian and the Oscillation Probability) plot the energy spectrum of the anti-neutrinos you expect to see in the near and in the far detector.

Choose a particular point of the spectrum which allows you to better estimate the two oscillation parameters Δm^2 and $\sin^2(2\theta)$.

Your experiment is designed and ready to go. Let's turn it on!

Getting enough data takes some time and detectors are not perfect: they have a finite energy resolution. Consider typical values of 10%, 5% for state-of-the-art and 1% for future developments, at $E = 1\,\mathrm{MeV}$.

Having collected a reasonable number of anti-neutrinos in the near detector, and checked everything is working well, you can start data analysis.

8. Shall we start after seeing 10 000 events (1 month)? Or maybe 100 000 (1 year)? How many anti-neutrinos do you collect in the far detector, in each case?

Determine the oscillation parameters in each case and comment about how does the running time and energy resolution affect your measurements.

Neutrino oscillations occur, of course, among three flavors. All three mixing angles and two mass differences have by now been measured in a combination of natural sources, reactors and accelerators. A lot remains to be done, namely measuring the absolute mass, and the mass ordering (we have only mass-squared differences), and measuring possible CP-violating phases. It is also extremely important to find out whether neutrino mass is generated via the Higgs mechanism, or neutrinos are Majorana particles. Most of this is still to be done in future experiments!