Hands-on on Neutrinos

Basics on neutrino's oscillations

We will now start the hands on part

You will have a series of questions to answer online

You have 5 min for question and then we will discuss the answers together

A little bit of quantum mechanics

Quantum systems are described by wave functions that can be a superposition of states.
Therefore, a neutrino of a given flavor ***X*** as being represented by a state $|\nu_X\rangle$ = "flavor eigenstates".

Let us take the case of only two flavors, ν_e and ν_μ, associated to quantum states $|\nu_e\rangle$ and $|\nu_\mu\rangle$ and further assume that these states are not mass eigenstates.

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It means that they do not coincide with the eigenstates of the Hamiltonian for a free particle with mass m_i and energy $E_i^2 = p_i^2 c^2 + m_i^2 c^4$
However, this means that we can also have "mass eigenstates" for the neutrinos. Let's call them $|\nu_1\rangle$ and $|\nu_2\rangle$ which are eigenstates of the free particle's hamiltonian.

Can you think of a way to write the flavour eigenstates as a combination of the mass eigenstates?

Hints:

- Think of the simples parametrisation
- This superposition should obey the probability conservation law of quantum dynamics
- The two states should be orthogonal

A little bit of quantum mechanics

Suppose now that at an electron neutrino described by the state $|\nu_e\rangle$ is produced in 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:

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

Obtain $|\nu_e(t)\rangle$, which represents your flavor state **e** at any instant of time t.

- Use the natural units! $c = \hbar = 1$

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What is the probability that, at a time $\boldsymbol{t_1}$ your electron neutrino has oscillated into a muon neutrino?

Hint:

- The probability is defined as

$$P(\nu_e \to \nu_\mu) = |A(\nu_e \to \nu_\mu)|^2 = |\langle\nu_\mu|\nu_e(t)\rangle|^2$$

- Use the natural units! $c = \hbar = 1$
- Remember that: $E_i^2 = p_i^2c^2 + m_i^2c^4$ and generally p>>m

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What are the necessary conditions for neutrino oscillations to occur?

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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?

Congratulations! You have just done Nobel Prize Physics

Experimental neutrino physics: (Anti)neutrinos produced in a reactor

Electron anti-neutrinos from a nuclear reactor were the first ones to be detected.

Their detector is extremely challenging since neutrinos have an extremely small interaction cross section with matter = $\sim 10^{-42}$ cm^2.

In order to detect neutrinos we need therefore a large target mass. One of the most common and cheap materials is WATER = density = 1 g/cm^3.

Finally we need a large neutrino flux. A nuclear reactor has generally 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. The energy spectrum of the emitted neutrinos peaks at 4 MeV.

How many anti-neutrinos per second are produced?

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How many will reach a detector located at a distance of 100 m from the reactor?

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How many will produce signals in a 10 m^3 detector? Assume the interaction is with protons

This is called the near detector and is generally used to study the characteristics of the emitted neutrino flux

Can you guess why?

Hint: think about the oscillation effect you just study and its dependence with the distance

$$P_{osc} = \sin^2(2\theta)\sin^2\left(\frac{\Delta m^2 c^4}{4\hbar c}\frac{L}{E}\right) = \sin^2(2\theta)\sin^2\left(1.27\frac{\Delta m^2[eV^2]L[m]}{E[MeV]}\right), \Delta m^2 = m_2^2 - m_1^2 = 8\times 10^{-5} eV^2$$

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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

$$\Delta m^2 = 8 \times 10^{-5} eV^2 \text{ and } \sin^2 2\theta = 0.856$$

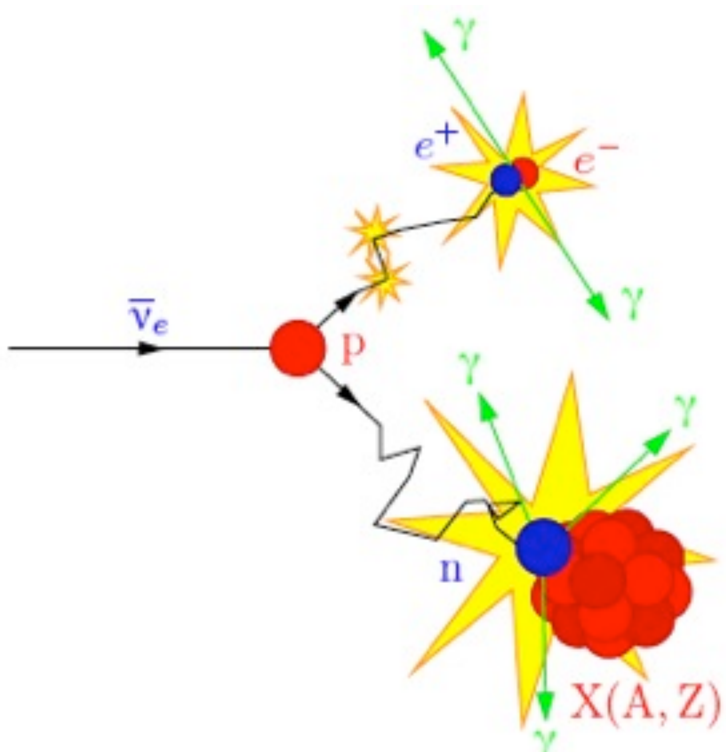
This is called the far detector and is used to study if neutrinos do actually oscillate

Experimental neutrino physics: The interaction

The main reaction of anti-neutrinos with water is the called INVERSE BETA DECAY: $\bar{\nu}_e + p \rightarrow n + e^+$

In the final state a neutron and a positron are emitted.

The neutron is used to tag anti-neutrino interactions.
The positron kinetic energy is used to measure the anti-neutrino energy, related to it by $E_{\nu_e} = E_{e^+} + \Delta$



What is the minimum energy threshold Δ, for this interaction to occur?

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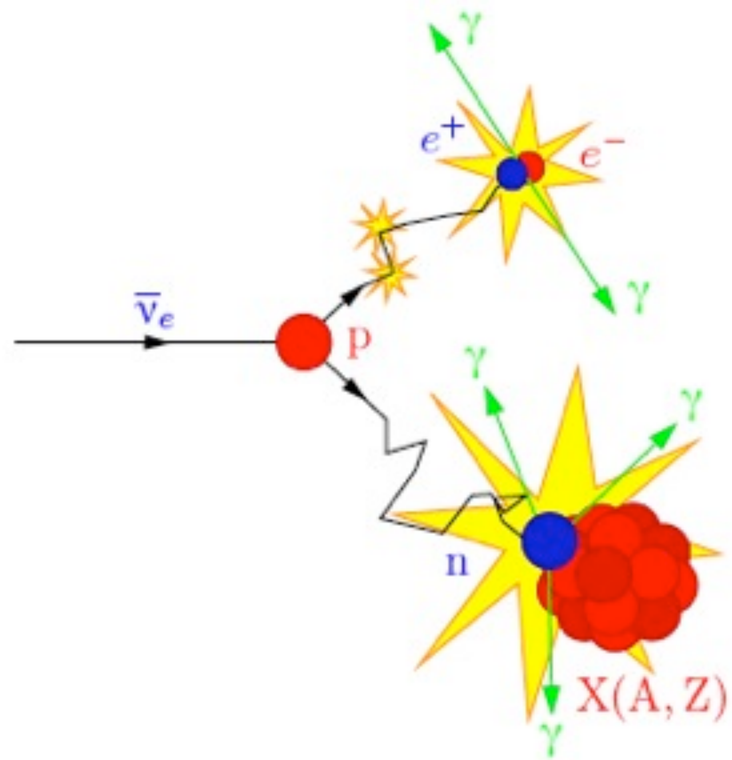

What is the energy threshold if we have muon anti-neutrinos?

$$\bar{\nu}_\mu + p \rightarrow n + \mu^+$$