

# Hands-on Neutrinos

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# A bit of Quantum Mechanics

- Quantum systems can be described by a superposition of states  $|\psi\rangle$
- Consider a neutrino of a given flavor  $\alpha = e, \mu, \tau$  as being represented by the state  $|\nu_\alpha\rangle$
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- Consider in what follows only 2 flavours,  $\nu_e$  and  $\nu_\mu$ , associated to the quantum states  $|\nu_e\rangle$  and  $|\nu_\mu\rangle$
- Assume also that these are not **mass eigenstates**...

**What does this mean???**

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- Assume also that these are not **mass eigenstates**...
  
- It means they are not eigenstates of the free particle Hamiltonian.  
Recall that a free particle of mass  $m_i$  has energy  $E_i = \sqrt{p_i^2 c^2 + m_i^2 c^4}$
- The true mass eigenstates  $|\nu_1\rangle$  and  $|\nu_2\rangle$  must be related to the flavour eigenstates  $|\nu_e\rangle$  and  $|\nu_\mu\rangle$ . **How?**

## Problem 1

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

*Hints:*

- *Think of the simplest parameterisation*
- *Each superposition should obey the probability conservation law of quantum dynamics*
- *The two flavour states should be orthogonal (assume the mass states are)*

# A bit of Quantum Mechanics: the neutrino over time

- Suppose now that an electron neutrino described by the state  $|\nu_e\rangle$  is produced in the sun as a result of a nuclear reaction, at  $t = 0$
- Recall that the propagation of a **mass eigenstate** follows the time-dependent Schrödinger equation

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

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## Problem 2

Obtain  $|\nu_e(t)\rangle$ , i.e. the state that started as  $|\nu_e(0)\rangle = |\nu_e\rangle$  at any instant of time  $t > 0$

*Hints:*

- *Use natural units ( $c = \hbar = 1$ )*
- *Express it in terms of the mass eigenstates at  $t = 0$ ,  $|\nu_i(0)\rangle$*

# A bit of Quantum Mechanics: the $\nu$ flavour over time

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## Problem 3

What is the probability that, at a time  $t_1 > 0$ , your electron neutrino  $\nu_e$  has oscillated into a muon neutrino  $\nu_\mu$ ?

*Hints:*

- *The probability is defined as*

$$P(\nu_e \rightarrow \nu_\mu) = |A(\nu_e \rightarrow \nu_\mu)|^2 = |\langle \nu_\mu | \nu_e(t_1) \rangle|^2$$

- *Remember that  $E_i^2 = p_i^2 + m_i^2$  and use the fact that neutrinos are ultra-relativistic, i.e.  $m_i \ll p_i$*



## Problem 4

You found in the previous problem that **neutrinos can oscillate!**  
What are the necessary conditions for neutrino oscillations to occur?

## Problem 5

What is the probability that, at a distance  $L$  from the source, the neutrinos of energy  $E$  are detected in the same flavour they were produced ( $\nu_e$ )?

*Hint: recall that we are dealing only with 2 flavours...*

Congratulations! You have just done Nobel Prize Physics...



# Experimental $\nu$ physics: reactor antineutrinos

- Electron antineutrinos from a nuclear reactor were the first to be detected
- Their detection is extremely challenging since they have an extremely small interaction cross section with matter,  $\sigma \sim 10^{-42} \text{ cm}^2$
- In order to detect them we therefore need a large target mass. One of the most common and cheap materials is **water!** ( $\rho = 1 \text{ g/cm}^3$ )

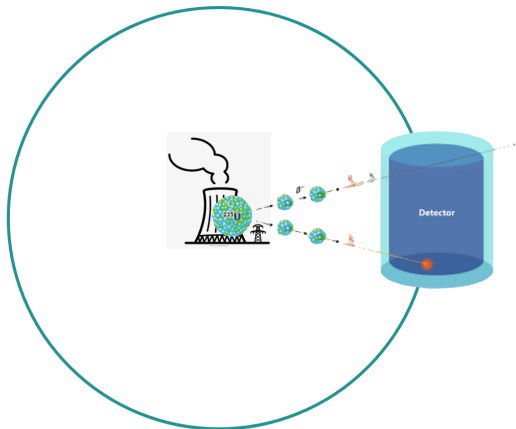
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- Finally we need a large neutrino flux. A nuclear reactor has generally 10 GW of power. The energy is given by uranium and plutonium fission chains, each releasing around 200 MeV of energy and 2 electron-flavour antineutrinos. The energy spectrum of the emitted (anti)neutrinos peaks at 4 MeV.

## Problem 6

How many antineutrinos are produced per second?

# Experimental $\nu$ physics: reactor antineutrinos



## Problem 7

How many  $\bar{\nu}$  will reach a detector 100 m away? (i.e. what is the flux there?)

## Experimental $\nu$ physics: reactor $\bar{\nu}$ , near detector

- A detector at such a distance from this source (100 m, 4 MeV) is called the **near detector**. It is generally used to study the characteristics of the **original**, emitted (anti)neutrino flux. *Can you guess why?*

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- Recall that the oscillation probability is proportional to  $\sin^2 \left( 1.27 \Delta m^2 [\text{eV}^2] \frac{L [m]}{E [\text{MeV}]} \right)$  (Problem 5) and use  $\Delta m^2 = 8 \times 10^{-5} \text{ eV}^2$ , known as the “solar mass-squared difference”



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- You should find that up to the near detector **no oscillations are expected!**

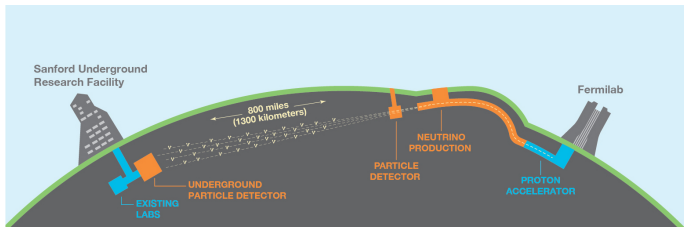
## Problem 8

How many  $\bar{\nu}_e$  will produce signals in a  $10 \text{ m}^3$  near detector, per unit time?

*Hint: Assume the interaction is with protons (use  $\sigma = 10^{-42} \text{ cm}^2$ )*

# Experimental $\nu$ physics: reactor $\bar{\nu}$ , far detector

- To study if neutrinos actually oscillate, another detector is needed...
- This is called the **far detector**: it is placed at a larger distance



DUNE setup with near and far detectors (here however  $\nu_\mu$  are produced from accelerated protons, there is no reactor)

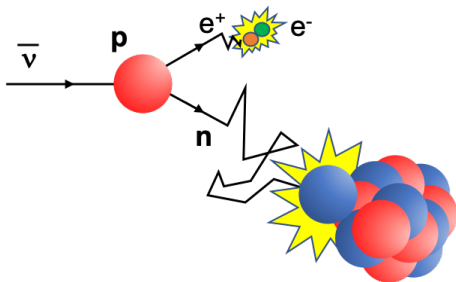
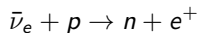
## Problem 9

What is the best distance  $L$  at which to place the far detector, in order to measure oscillations of the 4 MeV reactor antineutrinos?

*Hint: Use the "solar" parameters  $\Delta m^2 = 8 \times 10^{-5} \text{ eV}^2$  and  $\theta = 33^\circ$*

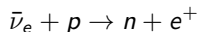
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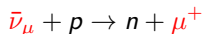
- The neutron is produced almost at rest. It is captured about 250  $\mu\text{s}$  later, providing a clear signal that *tags* the interaction
- The positron carries most of the leftover energy. Its kinetic energy  $T_{e^+}$  is used to measure the antineutrino kinetic energy  $T_{\bar{\nu}_e}$ . They are related by

$$T_{\bar{\nu}_e} = T_{e^+} + \Delta$$

## Problem 10

What is the threshold  $\Delta$ , i.e. the minimum  $\bar{\nu}_e$  energy for this interaction to occur?

- Antineutrinos react with water and are detected via **inverse beta decay**



## Problem 11

What is the energy threshold  $\Delta$  if we have **muon** antineutrinos?

# Playing with ROOT

It is now time to **start using the macro** (.C files attached).

It will allow you to simulate the energy spectra as measured in the two detectors (near and far), 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.

*Note: For this part you need to have ROOT installed!*

- 1 Open the macro file `Neutrino_2023.C` with your preferred editor
- 2 Start ROOT by typing `root` in a terminal shell
- 3 Once in the ROOT environment, run the macro by typing  
`.x Neutrino_2023.C`
- 4 To proceed follow the instructions given in the macro
- 5 Ask if unsure what to do!

# Playing with ROOT: $\bar{\nu}_e$ energy spectrum

- The reactor antineutrino energy spectrum can be described by a normalised Gaussian, having a mean value of 4 MeV and a standard deviation of 2 MeV

## Step 1

Plot the energy spectrum using ROOT

# Playing with ROOT: $\bar{\nu}_e$ survival probability

- Recall what you obtained for the neutrino oscillation probabilities
- Recall your result for the optimal far detector distance
- Consider the “solar” values for the neutrino parameters  $\Delta m^2$  and  $\theta$

## Step 2

Plot the survival probability  $P(\nu_e \rightarrow \nu_e)$  at the far detector, as a function of the antineutrino energy



# Playing with ROOT: events at near and far detectors

- The actual survival probability determining **how many events we see** is defined as the product:

$$\begin{array}{c} \text{reactor antineutrino energy spectrum} \\ \times \\ \text{survival probability function} \end{array}$$

- Recall also that only events above a certain *threshold* can be seen

## Step 3

Plot the actual survival probabilities for the near and the far detector  
Compute the fraction of events seen in each detector

# Playing with ROOT: histograms

- In the macro file, the `FillDetection` function is provided
- It simulates a detector, for a certain number of events and energy resolution (for a liquid scintillator, it is  $\sim 5\%/\sqrt{E}$  [MeV])
- Recall how many events/second are expected in the near detector. How about after a year of operation?
- How does the flux scale for a 40 kton far detector?

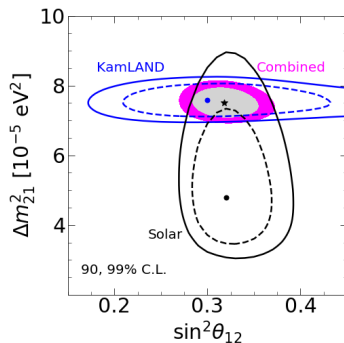
## Step 4

Obtain simulated histograms for the near and far detectors

# Playing with ROOT: fit

## Step 5

Extract the fundamental parameters  $\Delta m^2$  and  $\sin^2 2\theta$  by fitting the data!



Reactor data (here KamLAND) are complementary to solar data in extracting the solar neutrino mass and mixing parameters!