Experimental particle physics

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European School of Instrumentation in Particle & Astroparticle Physics

D. Exercises on neutrino physics, detection and measurement

Mass of muon neutrino

The muon neutrino mass is constrained using the charged pion decay

$$\pi^+ \rightarrow \mu^+ + \nu_\mu$$

In order to do this, the muon momentum must be measured. Working in the rest frame of the pion:

- determine the relation between the neutrino mass and the muon momentum;
- explain why the precision on the muon momentum measurement must be very good to constrain the neutrino mass;
- If the muon neutrino mass varies between 0 and 250 keV, how much does the absolute value of the muon momentum vary?
    - m_π = 139.57MeV
    - m_μ = 105.658 MeV

Event rate in a neutrino beam

The muon neutrino ν_μ was discovered 1962 at the Brookhaven National Lab. A 15 GeV proton beam was hitting a Be target, producing mainly high energy pions (and some Kaons). From the decay $\pi^+ \rightarrow \mu^+ + \nu^\mu$, a high energy ν_μ-beam was obtained. With a detector consisting of ten 1-ton modules built from Al plates and spark chambers, it was shown, that in charged current neutrino-nucleon interactions muons were produced, but not electrons:

$$\nu_\mu + n \longrightarrow p + \mu^-$$

Neglecting the mass of the spark chambers, assume a total target mass M = 10 tons of Al (density = 2.7 g/cm3). The neutrino flux at the detector (perpendicular to the detector cross section A) was

$$\Phi_\nu = 5000/(cm^2 s)$$

the cross section for quasi-elastic ν_μ-n scattering is

$$\sigma_{\nu n} = 0.5 \cdot 10^{-38}\ cm^2$$

- Calculate the event rate *R* in the Al detector for the quasi-elastic ν_μ-n interactions.

Neutrino mass of cosmic neutrinos

- Compute the upper limit to the neutrino mass under the hypothesis of 2 simultaneous neutrino emissions from the Supernovae 1987A explosion, respectively with energies
  - ✓ 35 MeV
  - ✓ 13 MeV
- Assume that the least energetic neutrinos were observed 9 s after the most energetic ones
  - ✓ Distance Earth – SN1987A = 2 x 10^5 light years
  - ✓ *Hint: the least energetic neutrinos took longer to arrive because of their mass…*

Neutrino oscillations (2 ν approximation)

- If there are only two neutrino flavors involved in neutrino oscillations, e.g. the flavor eigen- states ν_α and ν_β and the mass eigenstates ν_1 and ν_2 respectively, then the mixing matrix is real and contains only one mixing angle θ, and there is only one mass scale $\Delta m^2 = m_2^2 - m_1^2$.
- We can get the transition probability for the 2 ν case from the one mass scale approximation by setting e.g. $\theta_{12} = \theta_{13} = 0$ (i.e. the first generation neutrinos do not participate in the neutrino mixing) and $\Delta m_{21} = 0$, thus, $\theta \equiv \theta_{23}$ and $\Delta m^2 \equiv \Delta m_{23}^2$:

✓ $\sin^2(2\theta_{12}) \sim 0.10$
✓ $\sin^2(2\theta_{23}) \sim 0.97$
✓ $\sin^2(2\theta_{13}) \sim 0.86$

$$P(\nu_\alpha \to \nu_\beta) = \sin^2(2\theta)\sin^2\left(\frac{\Delta m^2 L}{4E}\right)$$

✓ $\Delta m_{12}^2 = 7.59\times10^{-5}$ eV^2
✓ $\Delta m_{23}^2 = 2.32\times10^{-3}$ eV^2
✓ $\Delta m_{23}^2 \sim \Delta m_{13}^2$

$$\frac{\Delta m^2 L}{4E} = 1.267\left(\frac{\Delta m^2}{eV^2}\right)\cdot\left(\frac{L}{km}\right)\cdot\left(\frac{GeV}{E}\right)$$

Neutrino oscillations

Using the 2 ν approximation and assuming no CP violation, calculate the following oscillation probabilities:

- OPERA is looking for ν_τ appearance in the CNGS ν_μ beam. The average neutrino energy is 17 GeV and the baseline is about 730 km. Calculate the oscillation probability:

$$P(\nu_\mu \rightarrow \nu_\tau, L/E)$$

- The MINOS experiment in the USA (L = 735 km, E ~ 3-4 GeV) and the T2K experiment in Japan (L = 295 km, E = 0.6 GeV) measure the disappearance of muon neutrinos in a $\nu_\mu$beam. Calculate the survival probability:

$$P(\nu_\mu \rightarrow \nu_\mu, L/E)$$

- The Daya Bay experiment in China ($L_{\text{eff,far}}$ = 1648 m, E ~ few MeV) and the RENO experiment in Korea ($L_{\text{eff,far}}$ = 1383 m, E ~ few MeV) are measuring the disappearance of reactor anti-neutrinos. Calculate the survival probability:

$$P(\nu_e \rightarrow \nu_e, L/E)$$