

Experimental particle. physics

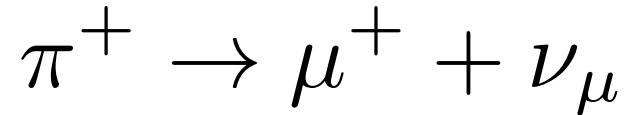
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European School of Instrumentation
in Particle & Astroparticle Physics

D.

Exercises on neutrino
physics, detection and
measurement

Mass of muon neutrino

The muon neutrino mass is constrained using the charged pion decay

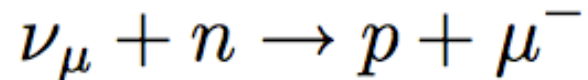


In order to do this, the muon momentum must be measured. Working in the rest frame of the pion:

- 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?
 - $m_\pi = 139.57 \text{ MeV}$
 - $m_\mu = 105.658 \text{ MeV}$

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:



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 – SNI987A = 2×10^5 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 eigenstates 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 $\Delta m^2 \equiv \Delta m_{23}^2$:

✓ $\sin^2(2\theta_{12}) \sim 0.10$

✓ $\sin^2(2\theta_{23}) \sim 0.97$

✓ $\sin^2(2\theta_{13}) \sim 0.86$

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

✓ $\Delta m_{12}^2 = 7.59 \times 10^{-5} \text{ eV}^2$

✓ $\Delta m_{23}^2 = 2.32 \times 10^{-3} \text{ eV}^2$

✓ $\Delta m_{23}^2 \sim \Delta m_{13}^2$

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

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, $E \sim 3\text{-}4$ GeV) and the T2K experiment in Japan ($L = 295$ km, $E = 0.6$ GeV) measure the disappearance of muon neutrinos in a ν_μ 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, $E \sim \text{few MeV}$) and the RENO experiment in Korea ($L_{\text{eff, far}} = 1383$ m, $E \sim \text{few MeV}$) are measuring the disappearance of reactor anti-neutrinos. Calculate the survival probability:

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