Monoenergetic Neutrino Beam for Long Baseline Experiments

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In an electron capture process by a nucleus, emitted neutrinos are monoenergetic. By making use of this, we study how to get a completely monoenergetic neutrino beam in a long baseline experiment. This is based on [1]

Numerous observations on neutrinos from the sun[2], the atmosphere[3], reactors[4], and the accelerator[5] suggest that neutrinos are massive and hence there is mixing in the lepton sector. To determine these mixing parameters much more precisely, there were several ideas proposed for next generation neutrino oscillation experiments.[6–9]

For a precision measurement, it is obviously better to have an experiment using neutrinos with controllable and precisely known energy. To achieve this we consider making use of a nucleus which absorbs an electron and emits a neutrino:

$$(Z, A) + e^- \to (Z-1, A) + \nu_e, \tag{1}$$

where Z is the electric charge of the mother nucleus and A is its mass number. In this case neutrinos have a line spectrum and their energy is precisely known. Therefore by accelerating the mother nuclei appropriately with the Lorenz boost factor γ_m, we can control the neutrino energy and make use of monoenergetic neutrinos in an oscillation experiment.

We examine the theoretical aspects of this idea in detail.

Case (i) Purely monoenergetic neutrinos:

As one of the first candidates we study here ${}^{110}_{50}\mathrm{Sn}$. Since it decays into the excited state of ${}^{110}_{49}\mathrm{In}$, emitted neutrino energy in the rest frame of Sn, $Q_{\mathrm{Sn}} = \Delta_{\mathrm{Sn}} - E^K_{\mathrm{In}}$[?] is 267 keV.

Then the appropriate acceleration of ${}^{110}_{50}\mathrm{Sn}$ to get the oscillation maximum energy is

$$\gamma_{\mathrm{Sn}} = 378 \left(\frac{\delta m^2}{2.5\times 10^{-3}\mathrm{eV}^2}\right)\left(\frac{L}{100\mathrm{km}}\right). \tag{2}$$

Furthermore there is an interesting feature for sufficiently high γ_m. Since γ_m is extremely high, almost all neutrinos go through the detector. Therefore we have a wide range of neutrino energies and by measuring the interaction point the neutrino energy can be "measured" precisely. The energy of a neutrino, which is detected at a distance R from the center of the beam, is easily calculated (in the large γ_m limit):

$$E_\nu(R) = \frac{2\gamma_m Q}{1 + R^2/L'^2}, \quad L' \equiv L/\gamma_m. \tag{3}$$

The neutrino energy range is determined by eq.(3) ,

$$\frac{2\gamma_m Q}{1 + D^2/L'^2} < E_\nu < 2\gamma_m Q, \tag{4}$$

where D is the "fiducial" detector diameter. For example, if $D = L'$, then half of the emitted neutrinos hit the detector and their energy range is $\gamma_m Q \le E_\nu \le 2\gamma_m Q$. The range of the oscillation phase varies from $\pi/3$ to $2\pi/3$, from which we can explore the oscillation shape around the oscillation maximum very precisely.

For the position resolution $\delta R(\delta R^2 = 2R\delta R)$, the energy resolution is given by

$$|\delta E_\nu| = \frac{2\gamma_m Q \delta R^2/L'^2}{(1 + R^2/L'^2)^2} \quad \Rightarrow \quad \left|\frac{\delta E_\nu}{E_\nu}\right| = \frac{\delta R^2/L'^2}{(1 + R^2/L'^2)}. \tag{5}$$

In the rest frame of the mother nucleus, monoenergetic neutrinos are emitted isotropically. In a solid angle $d\Omega$ in the rest frame, the number of neutrinos is distributed uniformly. The solid angle $d\Omega = 2\pi \sin\theta d\theta$ corresponds to

$$2\pi \sin\theta d\theta = \frac{4\pi}{(1+R^2/L'^2)^2}\frac{dR^2}{L'^2} \tag{6}$$

and in terms of the neutrino energy

$$d\Omega = 2\pi \sin\theta d\theta = \frac{2\pi}{\gamma_m Q}\, dE_\nu. \tag{7}$$

Thus we have a neutrino beam uniformly distributed in its energy. As a detector can measure the energy and the interaction point, by combining these two measurement, we can determine the neutrino energy very precisely. This specific feature in a beta-capture beam arises from the fact that neutrinos are monoenergetic in the rest frame of the mother nucleus.

Another candidate for this perpose is $^{111}_{49}$In .

case (ii) Monoenergetic neutrino and Continuous energy neutrino:

Next we consider the nucleus $^{48}_{24}$Cr. It decays into an excited state of $^{48}_{23}$V and $Q_{\rm Cr}$ is 1233 KeV. Since $Q_{\rm Cr}$ is larger than $2m_e$, twice of the electron mass, it can not only capture an electron but also emit a positron:

$$^{48}_{24}{\rm Cr} + e^- \rightarrow^{48}_{23} {\rm V} + \nu_e \;\&\; ^{48}_{24}{\rm Cr} \rightarrow^{48}_{23} {\rm V} + e^+ + \nu_e. \tag{8}$$

Assuming that there are 2 K shell electrons in the mother nucleus $^{48}_{24}$Cr, we can conclude that electron capture process is dominant (98.0%) and hence a neutrino beam with well-controlled energy is available.

Since $Q_{\rm Cr}$ is higher than in the previous case, the appropriate $\gamma_{\rm Cr}$ is lower and hence the quality factor is worse than in the previous case. Therefore, we need to store much more $^{48}_{24}$Cr nuclei than $^{110}_{50}$Sn. Assuming the oscillation maximum energy at the detector,

$$\gamma_{\rm Cr} = 82\left(\frac{\delta m^2}{2.50\times 10^{-3}{\rm eV}^2}\right)\left(\frac{L}{100{\rm km}}\right)\left(\frac{\pi/2}{P}\right), \tag{9}$$

which means that the neutrinos at the detector are completely monoenergetic as can be seen from eq.(4). There is essentially no position dependence of neutrino energy at the detector.

Therefore we cannot explore the energy dependence of the oscillation without changing the beam energy as previously discussed. However, this problem may be solved by the use of continuous neutrino associated with positron emission. We can control the boost factor γ_m very well and hence the highest neutrino energy at a detector is completely determined by it.

Other candidates are $^{18}_{9}$F , $^{111}_{50}$Sn , and $^{113}_{50}$Sn*[77] .

We have studied how the neutrino energy in oscillation experiments can be controlled better than with other ideas that are currently discussed. By electron capture, a nucleus emits a monoenergetic neutrino. Therefore by accelerating the mother nuclei, we can get a well-controlled neutrino beam.

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