Determining the sign of Δ_{31} at long baseline experiments

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Prelimenaries

Assume oscillations between three active neutrino flavours which can explain solar and atmospheric neutrino problems.

Since $\Delta m^2_{atm} \gg \Delta m^2_{sol}$, one of the mass-squared differences is much smaller than the other two.

$$\Delta m^2_{sol} = \Delta_{21} \ll |\Delta_{31}| \simeq |\Delta_{32}| = \Delta m^2_{atm}$$

Two different mass patterns can lead to this

- $m_1 < m_2 << m_3$ where all Δ's are positive (called natural hierarchy)

- $m_1 > m_2 >> m_3$ where all Δ's are negative (called inverted hierarchy)

Use Kuo-Pantaleone parametrization for mixing matrix

$$U = U_{23}(\theta_{23})U_{13}(\theta_{13})U_{12}(\theta_{12})$$

Then

- Solar neutrino problem depends only Δ_{21}, θ_{12} and θ_{13}
- Atmospheric neutrino problem depends only Δ_{31}, θ_{13} and θ_{23}

CHOOZ places a strong bound
$\sin^2(2\theta_{13}) \leq 0.1$ implying $\theta_{13} \leq 9^\circ$.

Then $\theta_{12} \simeq \theta_{sol}$ and $\theta_{23} \simeq \theta_{atm} = \pi/4$.

Which mass mattern is realized in nature?
To put it another way
Is Δ_{31} positive or negative?

Need matter effects to answer this question. They boost $\nu_\mu \to \nu_e$ oscillation probability if Δ_{31} is positive and suppress it if Δ_{31} is negative.

The situation is reversed for anti-neutrinos. Neutrino factories, with ν_μ and $\bar{\nu}_\mu$ beams, can measure the difference between $\nu_\mu \to \nu_e$ and $\bar{\nu}_\mu \to \bar{\nu}_e$ oscillations to determine the sign of Δ_{31}. But the energies of the beams will be very high (tens of GeV) and one needs extremely long baselines ($5 - 10$ thousand km) to have appreciable $\nu_\mu \to \nu_e$ oscillation signal.

At Long Baseline experiments, with baselines of 730 km, matter effects are significant. These can be observed if the experiment is sensitive to small values of θ_{13}.

Three flavor $\nu_\mu \to \nu_e$ oscillation probability, including matter effects, is

$$P^m_{\mu e} = \sin^2\theta_{23}\sin^2(2\theta^m_{13})\sin^2\left(1.27\frac{\Delta^m_{31}L}{E}\right)$$

Matter effects do not change θ_{23} because it mixes ν_μ and ν_τ.

In the above equation,

$$\Delta^m_{31} = \sqrt{(\Delta_{31}\cos 2\theta_{13} - A)^2 + (\Delta_{31}\sin 2\theta_{13})^2}$$

$$\sin 2\theta^m_{13} = \sin 2\theta_{13}\frac{\Delta_{31}}{\Delta^m_{31}}$$

$$A = 0.76 \times 10^{-4}\rho \text{ (in gm/cc) } E \text{ (in GeV)}$$

No advantage in tuning the energy to $E_{res} \simeq 15$ GeV. At this energy $\sin^2(2\theta^m_{13}) = 1$ but Δ^m_{31} is minimum. This leads to $P^m(\nu_\mu \to \nu_e) \simeq P(\nu_\mu \to \nu_e)$ around $E \sim E_{res}$.

Which energy is best suited for observing matter effects?

$P(\nu_\mu \to \nu_e)$ is maximum when the phase $1.27\Delta_{31}L/E = \pi/2$. To maximize the $\nu_\mu \to \nu_e$ oscillation signal, it is best to tune the energy of the neutrino beam to $E = E_{\pi/2}$.

Matter effects are also maximum at $E = E_{\pi/2}$. Hence tuning the beam energy to $E_{\pi/2}$ confers the double benefit of maximizing the signal and maximizing the sensitivity to matter effects.

For $\Delta_{31} = 3.5 \times 10^{-3}$ eV^2 and $L = 730$ km, $E_{\pi/2} = 2$ GeV.

Two points from the figure:

- For $E > 2E_{\pi/2}$, matter effects have negligible effect on $P_{\mu e}$. Hence the higher energy range $E > 2E_{\pi/2}$ can be used to determine the vacuum value of θ_{13}.

- In the neighbourhood of $E_{\pi/2}$, we have $P^m_{\mu e} = 1.25 P_{\mu e}$ if Δ_{31} is positive and $P^m_{\mu e} = 0.8 P_{\mu e}$ if Δ_{31} is negative.

Using the vacuum value of θ_{13} one can predict the number of events expected in the lower energy range $0 < E < 2E_{\pi/2}$ for Δ_{31} positive and for Δ_{31} negative. Measuring electron events in this energy range will tell us which prediction is correct.

How about backgrounds?

Two major sources

- Electron events coming from the ν_e component of the beam (about 1%).

- Neutral Current events of ν_μ (very large).

To study the relative effects of the signal to background, we consider a neutrino beam spectrum similar to MINOS low energy beam, which peaks around 3.5 GeV.

In case of vacuum oscillations, the signal events are split in the ratio $3 : 1$ between the lower energy ($0 < E < 2E_{\pi/2}$) region and the higher energy ($E > 2E_{\pi/2}$) region, for a baseline of $L = 730$ Km. The background events, which are proportional to the ν_μ CC events, are split in the ratio $4 : 6$ between the same energy regions.

Suppose the minimum value of θ_{13} an experiment can measure is ε. To do this, we suppose that, it is capable of detecting N signal electron events above the background.

If θ_{13} is equal to 2ε, then the number of signal events is $4N$. Of these, N will be in the higher energy region. This number is larger than the background and can determine the vacuum value of θ_{13}.

In case of vacuum oscillations, the number of events in the lower energy range will be $3N$. Matter effects will boost this number to $3.75N$ if Δ_{31} is positive and suppress it to $2.4N$ if Δ_{31} is negative.

In each case, the change induced by the matter effects in the lower energy range is larger than the number of background events in the lower energy range, which is less than half the total background.

Hence, if an experiment is sensitive to θ_{13} at a level ε, then it is automatically sensitive to the sign of Δ_{31} if θ_{13} is as large as 2ε.

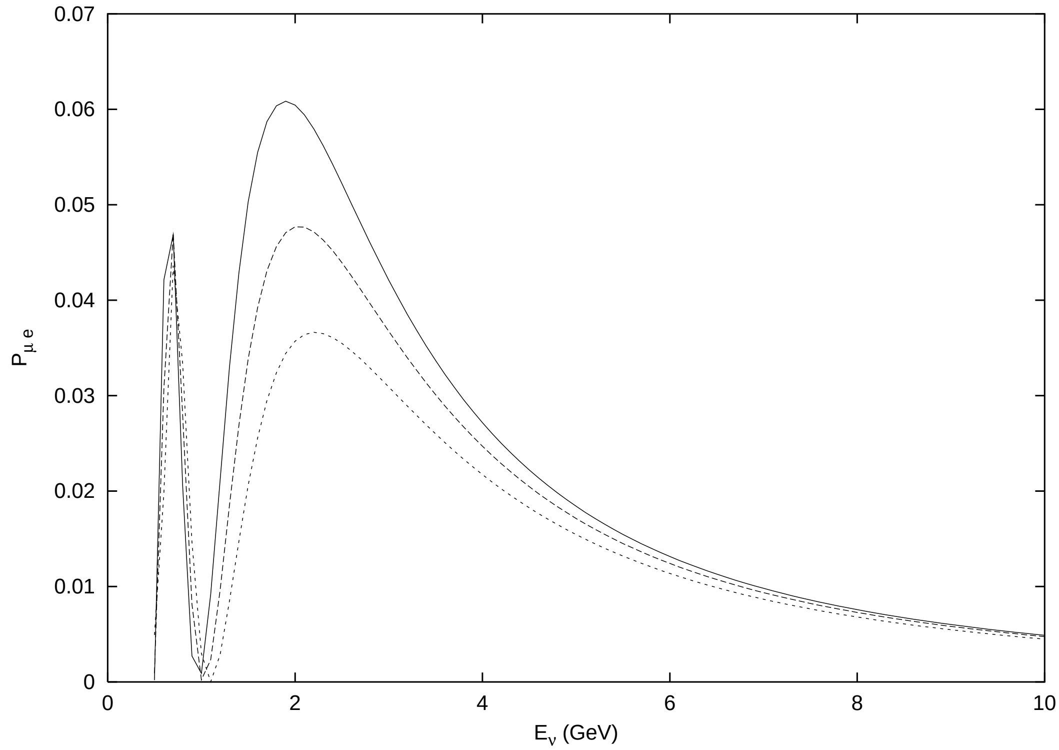

FIG. 1. $\nu_\mu \to \nu_e$ oscillation probabilities vs E for $|\Delta_{31}| = 3.5 \times 10^{-3}$ eV^2, $\sin^2 2\phi = 0.1$ and $L = 730$ km. The middle line is $P_{\mu e}$, the upper line is $P^m_{\mu e}$ with Δ_{31} positive and the lower line is $P^m_{\mu e}$ with Δ_{31} negative.