Neutrino Oscillation and CP violation

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1.

- Completely Unkown Parameters for lepton Sector :

$\sin \theta_{13}$: last mixing

$\sin \delta$: $\not{CP}$

How can we see ?

- $\not{CP}$ is essentially 3 generation phenomenon

$\Rightarrow$ We have to see "3 generation"

$\Rightarrow$ Not too "high" & Not too "low" energy

- What "high & "low" energy in oscillation experiment.

2 energy scale $E \sim \begin{cases} \delta m_{31}^2 L \\ \delta m_{21} L \end{cases}$

☆ In high energy, the first two lightest states seem degenerate

$\Longleftrightarrow \quad \delta m_{21}^2 \sim 0$

☆ In low energy, the heaviest (two) state(s) "decouple(s)"

$\Longleftrightarrow \quad \sin\Delta_{21} + \sin\Delta_{32} + \sin\Delta_{13} \sim 0$

(within finite resolution and statics)

○ $\delta m_{21}^2 L \lesssim E \lesssim \delta m_{31}^2 L$ will be the best energy range.

cf $L \sim 300\,\mathrm{km}$. $\delta m_{31}^2 \sim 3\times10^{-3}\,\mathrm{eV}^2$

$\delta m_{21}^2 \sim 10^{-4}\,\mathrm{eV}^2$

$0.1\,\mathrm{GeV} \lesssim E \lesssim 2\,\mathrm{GeV}$.

◦ Can we see such low $E\nu$'s !?

(partially) Yes ⇒ Konaka-san

Here we consider this possibility theoretically.

2 Oscillation probability

for $\delta m_{21}^2 L < E < \delta m_{31}^2 L$ & $L \ll 3000$ km

(Ignoring matter effect)

$$P(\nu_\mu \to \nu_e) = 4|U_{e3}U_{\mu3}|^2 \sin^2\Delta_{31}$$

$$+ 4\,\mathrm{Re}(U_{e3}^* U_{\mu3} U_{e2}^* U_{\mu2})\, \Delta_{31} \times \frac{\delta m_{21}^2}{\delta m_{31}^2} \sin 2\Delta_{31}$$

~~CP~~ ☆ $\underbrace{+ 8\,\mathrm{Im}(U_{e3}^* U_{\mu3} U_{e2}^* U_{\mu2}) \frac{\delta m_{21}^2}{\delta m_{31}^2} \Delta_{31} \sin^2\Delta_{31}}$

$$- 4\,\mathrm{Re}(U_{e2}^* U_{\mu2} U_{e1}^* U_{\mu1}) \left(\frac{\delta m_{21}^2}{\delta m_{31}^2}\right)^2 \Delta_{31}^2$$

up to the leading order of small values, U_{e3}, $\frac{\delta m_{21}^2}{\delta m_{31}^2}$.

Bound on coefficients

$$4|U_{e3}U_{\mu3}|^2 \lesssim 0.05 \times \left|\frac{U_{e3}}{0.15}\right|^2 \qquad \underbrace{\left(\frac{U_{e3}}{0.15}\right)}$$

$$8\,\mathrm{Re}\, U_{e3}^* U_{\mu3} U_{e2}^* U_{\mu2} \cdot \frac{\delta m_{21}^2}{\delta m_{31}^2} \lesssim 0.006 \left(\frac{\delta m_{21}^2/10^{-4}}{\delta m_{31}^2/3\times10^{-3}}\right) \cos\delta\, \underbrace{\left(\frac{U_{e3}}{0.15}\right)}$$

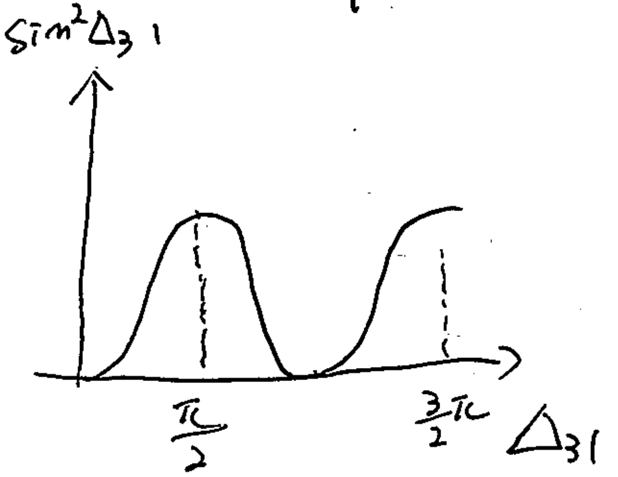
$$8\,\mathrm{Im}\, U_{e3}^* U_{\mu3} U_{e2}^* U_{\mu2} \frac{\delta m_{21}^2}{\delta m_{31}^2} \lesssim 0.006 \left(\frac{\delta m_{21}^2/10^{-4}}{\delta m_{31}^2/3\times10^{-3}}\right) \sin\delta$$

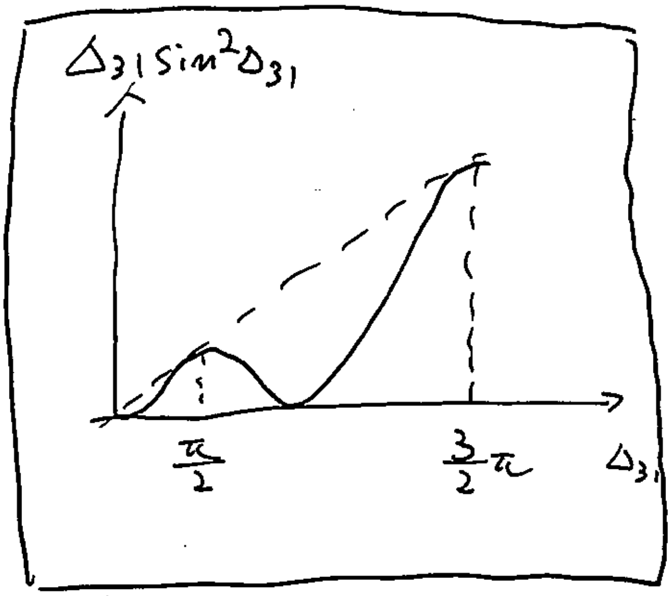
$$4\,\mathrm{Re}(U_{e2}^* U_{\mu2} U_{e1}^* U_{\mu1}) \left(\frac{\delta m_{21}^2}{\delta m_{31}^2}\right)^2 \lesssim 0.001 \left(\quad\right)^2$$

Base fn's

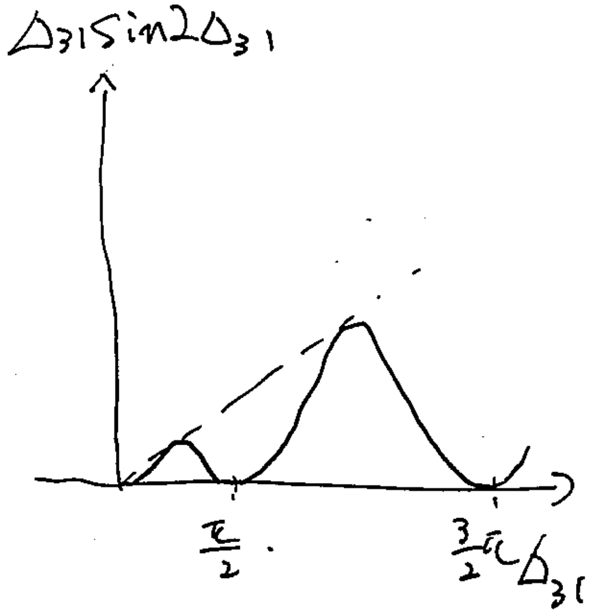
$\sin^2\Delta_{31}$, $\Delta_{31}\sin 2\Delta_{31}$, $\Delta_{31}\sin^2\Delta_{31}$, Δ_{31}^2

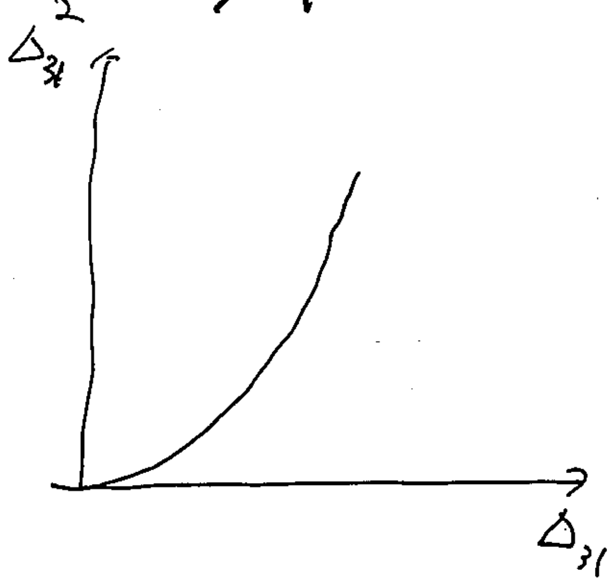
are independent.





$\cancel{CP}$





$$\begin{cases} L = 300\,\mathrm{km} \\ \delta m_{31}^2 = 3\times10^{-3}\,\mathrm{eV}^2 \end{cases} \Longleftrightarrow \Delta_{31} = \begin{array}{l} \frac{\pi}{2} \text{ at } E\sim 700\,\mathrm{MeV} \\ \frac{3}{2}\pi \text{ at } E\sim 250\,\mathrm{MeV} \end{array}$$

$$P(\nu_\mu \to \nu_\mu) = 1 - (1 - |U_{\mu 3}|^2)|U_{\mu 3}|^2 \sin^2 \Delta_{31}$$

$\begin{cases} \text{no } \delta \\ \text{almost no infomation on } \theta_{13} \end{cases}$

$\Rightarrow \begin{cases} \delta m_{31}^2 \\ \theta_{23} \end{cases}$ can be determined precisely

4 Discussion

- Much richer information on ν's can be obtained in $\delta m_{21}^2 L < E < \delta m_{31}^2 L$.
- We can see not only transition but also Oscillation.

How to $\begin{cases} \text{measure} \\ \text{produce} \end{cases}$ such low ν's ? ?

$\bar{\nu}_e$ ν_e : OK !! Konaka

? ν_μ, $\bar{\nu}_\mu$?

$\begin{cases} \text{Speacies} \\ \text{Charge} \end{cases}$