Lecture 11 : Neutrinos -1

- Role of the neutrinos in elementary particle physics
- Flavors of neutrinos : Electron, muon and tau neutrinos and their antiparticles
- The historical development of the discoveries in neutrino physics
- Solar neutrinos : Fusion chain reactions in the Sun produce neutrinos

<u>PP chain</u>	<u>Energy in MeV</u>
(pp)	
$p + p \rightarrow ^2 H + e^+ + \nu_e$	≤ 0.42
(pep)	
$p + e^- + p \rightarrow ^2 H + \nu_e$	1.552
(^{7}Be)	
$^7 Be + e^- \rightarrow ^7 Li + \nu_e$	$0.862(90\%)$ 0.384 (10%)
(hep)	
$^2 He + p \rightarrow ^4 He + e^+ + \nu_e$	≤ 18.77
(^{8}B)	
$^8 B \rightarrow ^8 Be^* + e^+ + \nu_e$	≤ 15

CNO chain	**Energy in MeV**
(^{13}N)	
$^{13} N \rightarrow ^{13} C + e^+ + \nu_e$	≤ 1.199
(^{15}O)	
$^{15} O \rightarrow ^{15} N + e^+ + \nu_e$	≤ 1.732
(^{17}F)	
$^{17} F \rightarrow ^{17} O + e^+ + \nu_e$	≤ 1.74

Energy spectra of solar neutrinos :
Study of the Figure 11.2 in the D.Griffiths's book. Source J.N.Bachall and A.M.Serenelli and S.Basu Astrophysical Journal, 621, **L85,** 2005

The great discover by J.Davis in 1968 to measure solar neutrino flux using a huge tank of chlorine in the Homestake Mine at South Dakota. Nobel Prize of the year 2002 is later awarded to J.Davis.

Two different languages :

- Flavor eigenstates of the neutrinos : ν_e , ν_μ , ν_τ

- Mass eigenstates of the neutrinos : ν_1 , ν_2 , ν_3

Mixing matrix of flavor and mass eigenstates of the neutrinos

a) Two flavor case

$$\begin{pmatrix} \nu_1 \\ \nu_2 \end{pmatrix} = \begin{pmatrix} \cos\theta_{12} & -\sin\theta_{12} \\ \sin\theta_{12} & \cos\theta_{12} \end{pmatrix},$$

b) Three flavor case : U_{PMNS} mixing matrix

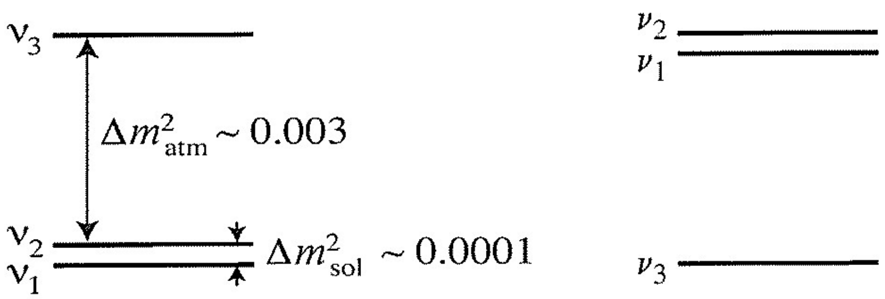
$$\begin{pmatrix} \nu_1 \\ \nu_2 \\ \nu_3 \end{pmatrix} = \begin{pmatrix} U_{e1} & U_{e2} & U_{e3} \\ U_{\mu 1} & U_{\mu 2} & U_{\mu 3} \\ U_{\tau 1} & U_{\tau 2} & U_{\tau 3} \end{pmatrix} \begin{pmatrix} \nu_e \\ \nu_\mu \\ \nu_\tau \end{pmatrix}$$

The above U_{PMNS} mixing matrix contains thee mixing angles θ_{12} , θ_{23} , θ_{13} and CP violating Dirac phase factor δ and Majorana phases α_1 *and* α_2

$$U_{\text{PMNS}} = \begin{pmatrix} 1 & 0 & 0 \\ 0 & c_{23} & s_{23} \\ 0 & -s_{23} & c_{23} \end{pmatrix} \begin{pmatrix} c_{13} & 0 & s_{13}e^{i\delta} \\ 0 & 1 & 0 \\ -s_{13}e^{i\delta} & 0 & c_{13} \end{pmatrix} \begin{pmatrix} c_{12} & s_{12} & 0 \\ -s_{12} & c_{12} & 0 \\ 0 & 0 & 1 \end{pmatrix} \begin{pmatrix} 1 & 0 & 0 \\ 0 & e^{i\alpha_1} & 0 \\ 0 & 0 & e^{i\alpha_2} \end{pmatrix}$$

The phases are not acessible by the neutrino oscillations.

The absolute values of the neutrino masses are not known; only the differencs of the their squares are measured via experiment. Two possible ordering of the masses are :



Normal hierarchy Inverted hierarchy

Transition probability between the flavors ν_α *and* ν_β :

$$P(\nu_\alpha \to \nu_\beta) = |\langle \nu_\beta | \nu_\alpha(t) \rangle|^2 = \left| \sum_{j=1}^{n} \sum_{k=1}^{n} U_{\alpha j}^* U_{\beta k} \langle \nu_k | \nu_j(t) \rangle \right|^2$$

$$\approx \sum_{j,k} U_{\alpha j}^* U_{\beta j} U_{\alpha k} U_{\beta k}^* \, \mathrm{e}^{-\mathrm{i}\Delta m_{jk}^2 L/2E}$$

In the simple case of two flavors the above formula reduces to

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

- Solve the following problems at the end of the Chapter XI of the textbook "Intr. to Elementary Particle Physics by D.Griffiths 2nd Ed. J.Wiley."

Solve Problem 11.1

Solve Problem 11.2

Solve Problem 11.3

Solve Problem 11.4