<u>Neutrino oscillation</u>

Neutrino oscillation was first proposed by B. Pontecorvo in analogy to the $K^0 - \bar{K}^0$ regeneration. Recall that when produced in the strong interaction, we have either K^0 or $\bar{K}^0$ depending on the strangeness quantum number of the other particles in the production. However, in the weak interaction it is the combinations $K^0 \pm \bar{K}^0$ have the definite lifetimes. Neglecting the CP violation, the weak eigenstates are

$$K_S = \frac{1}{\sqrt{2}}\left(K^0 + \bar{K}^0\right), \qquad K_L = \frac{1}{\sqrt{2}}\left(K^0 - \bar{K}^0\right)$$

Here K_S has shorter lifetime while K_L has longer lifetime because of the different final states in the decays, $K_S \to 2\pi$ while $K_L \to 3\pi$. Pontecorvo suggested that ν_e, ν_μ produced from the weak interaction are not mass eigenstates but a linear combinations of mass eigenstates ν_1,and ν_2. These mass eigenstates propagate differently in time and change the cofficients of the linear combinations and causes the changes of the neutrino flavors and this phenomena is called the **neutrino oscillations.** Note that Pontecorvo was an experimentalist working for Fermi in his early career. In 1950 he defected to Soviet Union because like many young people in those days he was attracted to idea of the communism. Nevertheless he had made many useful contributions to high energy physics, including neutrino oscillation.

Ever since the suggestion by Pontecorvo the neutrino oscillations have been serach for from time to time. However due to the very small probability and the difficulty of detection neutrinos this phenomena is very difficult to observe. In 1960's neutrino oscillation was applied to the solar neutrino problem to try to explain the deficiency of ν_e coming from the sun. The mechanism is attractive but not completely satisfactory due to lack of a complete theory and crudeness in the experimental measurements.

Note that the mechanism of neutrino oscillation requires i) masses for the neustrinos and ii) mixing between neutnio flavors. In mid 1970,as a result of discussion with some experimentalists, Wolfenstein proposed a different mechanism of changing the flavors of neutrinos. He called it "oscillation for massless neutrinos". The idea is that the difference between the coherent forward-scattering amplitudes for different neutrinos can be expressed phenomenogically in term of **index of refraction,** n in analogy to index of refaction in the standard optics. Forward scattering of $\nu' s$ is possible through neutral current interactions. Consider a simple model with 2 types of massless neutrinos for which the effective neutral-current Hamiltonian is

$$H_w = \frac{G_F}{\sqrt{2}} L_\lambda J^\lambda$$

where

$$L_\lambda = \cos^2\alpha\left[\bar{\nu}_a \gamma_\lambda \nu_{L\alpha} + \bar{\nu}_b \gamma_\lambda \nu_{Lb}\right] + \sin^2\alpha\left[\bar{\nu}_a \gamma_\lambda \nu_{Lb} + \bar{\nu}_b \gamma_\lambda \nu_{La}\right]$$

$$J^\lambda = g_p \bar{p}\gamma^\lambda p + g_n \bar{n}\gamma^\lambda n + g_e \bar{e}\gamma^\lambda e + \cdots$$

The essential term in $H_w is$ the off-diagonal term proportional to $\sin^2\alpha$, where ν_a and ν_b are the neutino types defined by the charged-current interactions. If we take neutral current interactions for ν_e and ν_μ to be of the same strength then it is not hard to see that the eigenstates are

$$|\nu_1\rangle = \frac{1}{\sqrt{2}}\left(|\nu_e\rangle + |\nu_\mu\rangle\right), \qquad |\nu_2\rangle = \frac{1}{\sqrt{2}}\left(|\nu_e\rangle - |\nu_\mu\rangle\right)$$

It can be used to in the solar neutrino case to get the reduction of ν_e flux by the right order of magnitude. Wofenstein got all excited about this amazing result and wrote it up imediatelly and sent it to Physical Review Letters. Many people were impressed by this result and the paper was accepted in a record short time. Unfortunately, shortly after the acceptance, Daniel Wyler a former student of Wolfenstein called and pointed out that for the electron neutrino ν_e there is additional contribution coming from the charged current interaction the form

$$\frac{G}{\sqrt{2}}\bar{\nu}_e\gamma_\lambda\left(1-\gamma_5\right)\nu_e\left(\bar{e}\gamma^\lambda e + \cdots\right)$$

This breaks ν_μ ν_e symmetry and mixing is no longer 45^0 and the situation is much more complicate. From this feature it is clear that the electrons play an important role in this type of neutrino oscillation. Wolfenstein turned his attention to the propagation in a big object where there are plenty of electrons to see whether he can find some significant effects. But it turns out that all the effects he looked at are really small until it was discovered by Mikheyev and Smirnov that under some favorable condition a resonant amplification of oscillations may occur. This is now known as MSW effect.