BIRTH OF NEUTRINO OSCILLATION *

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Abstract
This is a brief presentation of historical introduction to the theoretical concept of neutrino oscillation during the early stage of the studies up to 60’s.

1 Prediction of $\mu$ and $\nu_\mu$ (1942) and Critiques by Sakata

Let me begin with Sakata, that would concern with the theme of this talk. In 1942, Sakata and Inoue proposed the so-called "two-meson theory" [1]. Their theory was to claim the existence of another pair of leptons:

$$m^- (= \mu^-), \quad n (= \nu_\mu)$$

in addition to $e^-$ and $\nu_e$. Original meaning of the two-meson theory was the introduction of $\mu$ (called as mu-meson) in addition to the Yukawa meson (pi-meson). It is to be noted that the 'neutrino' $n$ was assumed as a particle different from $\nu(= \nu_e)$, and was not necessarily considered as a massless particle. However, the masses of the neutrinos were found to be very small, and afterwards the neutrinos were taken practically as massless particles and more-over as identical each other ($\nu_e = \nu_\mu$) from the convenience and economy principles.

Sakata had been always sceptical to these conventional assumptions and repeatedly warned us that the principles of convenience and economy were dangerous and often mislead physics.

I would like to present another critique by Sakata. In 1955, Sakata wrote a paper in Japanese with a shocking title 'Superstition around Majorana Neutrino' [2]. His claim is that it is not adequate to ask whether a neutrino be a Dirac or Majorana particle in alternatives, and it will be nothing but a superstition to believe that the

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answer be obtained by the experiment of the double beta decay and so on. His point is that such a question arises from choosing the interactions within unnecessarily small variety. Two sorts of interactions for the beta decay are introduced with a Dirac neutrino $\nu$ as

$$ H = \sum_i G_i (\bar{\Psi}_p O_i \Psi_n)(\bar{\Psi}_e O_i \Psi_\nu) + h.c., $$

(2)

and

$$ H^c = \sum_i G_i'(\bar{\Psi}_p O_i \Psi_n)(\bar{\Psi}_e O_i \Psi_\nu^c) + h.c., $$

(3)

where $\Psi_\nu^c$ means a charge conjugated field of $\Psi_\nu$. As far as the neutrino is massless, these interactions are completely equivalent each other, and a Dirac neutrino can be defined from either of interactions just as a matter of naming. If, however, the beta interaction consists generally of both interactions as

$$ H_\beta = H + H^c = \sum_i (\bar{\Psi}_p O_i \Psi_n)\{\bar{\Psi}_e O_i (G_i \Psi_\nu + G_i' \Psi_\nu^c)\} + h.c., $$

(4)

the physical situation gets a drastic change. When the coupling constants satisfy

$$ G_i = G'_i, $$

(5)

the interaction can be transferred to the one defining a Majorana field. However as a matter of experimental accuracy, a confirmation of neutrinoless double beta decay, if it is, would yield only a constraint on the coupling constants, say, to the extent as

$$ G_i \simeq G'_i. $$

(6)

Conversely, eq.(6) leads to the result almost equivalent to the one of the Majorana theory on the phenomenological level. Furthermore, to confirm the Majorana theory literally, one must establish the equality eq.(5) strictly for all the processes involving the neutrino.

Sakata had on many occasions noted that people is used to believe in a simple idea on ‘neutral’ particles because of the difficulties of their detection, but exactly by this property the neutral particles would be gifted an unexpected nature. His point is that the Majorana theory is equivalent to a specific choice of the neutrino interactions of the Dirac theory violating the lepton number conservation, and is to choose a specific (convenient and economical) type for the neutrino field beyond the accuracy of experimental confirmation. He, of course, did not deny the theoretical significance of the Majorana particle. We see such a case in an example of the two-component neutrino theory with only one chirality for the V-A weak interactions, which seems to have long been preventing people from considering the possibility of massive neutrinos.
2 Proposal of Neutrino Oscillation of a $\nu \leftrightarrow \bar{\nu}$ Transition (1957)

B.Pontecorvo (1957) [2]

We have another great physicist Pontecorvo, who had posed a strong question on the lepton number conservation. In 1957, Pontecorvo has indicated that if the two-component neutrino theory should turn out to be incorrect and if the conservation law of neutrino charge would not apply, then in principle neutrino $\rightarrow$ antineutrino transitions could take place in vacuo just on the analogy to the $K^0 \rightarrow \bar{K}^0$ transition of Gell-Mann and Pais [3].

In a subsequent paper (1958) [2], Pontecorvo has put forth the idea to define the mixed particles as

$$\nu = \frac{1}{\sqrt{2}}(\nu_1 + \nu_2),$$

$$\bar{\nu} = \frac{1}{\sqrt{2}}(\nu_1 - \nu_2),$$

where $\nu_1$ and $\nu_2$ are, he called, truly neutral Majorana particles which are mass eigenstates. As important physical consequences, he pointed out that a stream of neutral leptons consisting mainly of antineutrinos when emitted from a nuclear reactor, will consists at some distance R from the reactor of

$$\bar{\nu} \rightarrow \nu (50\%) + \nu (50\%),$$

provided that either of $\nu_1$ or $\nu_2$ ceases out of the coherence leaving the other to survive. So, this effect will cause a decrease of the capture cross-section of the antineutrinos to the half of the simple $\beta$ interaction, and the detection at different distances from the reactor will be needed. And it was first pointed out the possibility of the observation of the oscillation effect on an astronomical scale, which has long been a key concept to solve the solar neutrino problem.

3 Proposal of Flavor Mixing and Flavor Oscillation of Neutrinos (1962)

Z.Maki, M.Nakagawa and S.Sakata (1962) [4]
M.Nakagawa, H.Okonogi, S.Sakata and A.Toyoda (1963) [4]

The flavor mixing of neutrinos was proposed from a quite different line of thought than Pontecorvo’s approach. It was based on an attempt at a unified understanding of leptons and hadrons. After the proposal of the Sakata model of hadrons
(1955) [1], it came to our attention that the weak interactions of the Sakata model (Okun’(1958) [2]) with a current,
\[ J_\lambda = (\bar{e}\nu)_\lambda + (\bar{\mu}\nu)_\lambda + (\bar{p}p)_\lambda + \epsilon(\bar{\Lambda}p)_\lambda, \] (10)
have a lepton-baryon symmetry as follows;
\[ \nu, \ e, \ \mu \leftrightarrow p, \ n, \ \Lambda \ (\text{Sakata fundamental particles}), \] (11)
provided the factor $\epsilon$ is assumed to be unit, which was pointed out by Gamba, Marshak and Okubo (1959) [3]. On the basis of this symmetry, the Sakata fundamental baryons were assumed as composite particles of leptons and a charged boson responsible for the strong interaction [4].

After the confirmation of the two-neutrino hypothesis [1], we proposed a new model (Maki, Nakagawa and Sakata (1962)) [4] of the fundamental baryons modifying the above lepton-baryon symmetry to the correspondence of four leptons including two kinds of neutrinos. In the model building we have assumed the following basic properties:
(1) Neutrinos should be of 4-component spinors in order to be seeds of the massive baryons. Consequently, the neutrinos $\nu_1$ and $\nu_2$ to be bound in the baryons should have naturally their own masses. We called these neutrinos as true neutrinos.
(2) $\nu_e$ and $\nu_\mu$ coupled to $e$ and $\mu$ in the weak current should be mixing states of $\nu_1$ and $\nu_2$. We called the neutrinos $\nu_e$ and $\nu_\mu$ as weak neutrinos.

The mixing is expressed as
\[ \begin{align*}
\nu_e &= \cos \theta \nu_1 - \sin \theta \nu_2, \\
\nu_\mu &= \sin \theta \nu_1 + \cos \theta \nu_2,
\end{align*} \] (12)
where we expressed the angle $\theta$ as $\delta$ in the paper, and the lepton-baryon correspondence [4] are as follows:
\[ \begin{align*}
\nu_1 &\leftrightarrow p \\
\nu_2 &\leftrightarrow X \\
e^- &\leftrightarrow n \\
\mu^- &\leftrightarrow \Lambda.
\end{align*} \] (13)

In terms of the true neutrinos, the leptonic charged weak current is written as
\[ j_\lambda = \cos \theta(\bar{e}\nu_1)_\lambda + \sin \theta(\bar{\mu}\nu_1)_\lambda - \sin \theta(\bar{e}\nu_2)_\lambda + \cos \theta(\bar{\mu}\nu_2)_\lambda, \] (14)
and the baryonic charged weak current is obtained as
\[ J_\lambda = \cos \theta(\bar{p}p)_\lambda + \sin \theta(\bar{\Lambda}p)_\lambda - \sin \theta(\bar{p}X)_\lambda + \cos \theta(\bar{\Lambda}X)_\lambda, \] (15)
\[ ^1\text{The correspondence was also proposed by Y.Katayama, K.Matumoto, S.Tanaka and E.Yamada,} \]
\[ Prog.Theor.Phys. \ 25, \ 675 \ (1962) \text{from a different point of view on neutrinos.} \]
which reproduced the current suggested by Gell-Mann and Lévy modifying eq.(10) as
\[
\frac{1}{\sqrt{1 + \epsilon^2}}(\bar{\nu}p)_{\lambda} + \frac{\epsilon}{\sqrt{1 + \epsilon^2}}(\bar{\Lambda}p)_{\lambda}.
\] (16)

A few remarks should be added here:
(1) Sakata fundamental baryons are now taken to be quarks.
(2) The structure of the baryonic weak charged current including mixing angle \(\theta\) that we obtained is, when read in terms of the quarks, identical with the present quark current involving the Cabbibo angle that is transfered from the mixing angle of neutrinos. The proposal of the Cabibbo angle was made in 1963 [11].
(3) As regards the origin of the mixing angle, we considered it as a realization of a mechanism making \(e\) and \(\mu\) different, and attempted a simple model diagonalizing \(e\) and \(\mu\) into the observed masses. However, the origin will be still one of the largest problems beyond the standard model.
(4) The fourth baryon \(X\) came also naturally into the above correspondence. But this particle was considered as having no seat in the weak current from unknown reason or as being a very large mass particle not yet discovered. Later on, this particle became a candidate for the fourth quark, and was discovered as the charm [13].

3.1 Upper bound on the neutrino mass from the high energy neutrinos

Because of the particle mixing states of \(\nu_1\) and \(\nu_2\) with masses, the weak neutrinos \(\nu_e\) and \(\nu_\mu\) are not stable due to the the transmutation \(\nu_e \leftrightarrow \nu_\mu\). Therefore, we noted that a chain of reactions such as
\[
\begin{align*}
\pi^+ \to & \mu^+ + \nu_\mu, \\
\nu_\mu + Z(\text{nucleus}) \to & Z' + (\mu^- / e^-)
\end{align*}
\] (17)
will take place as a consequence of oscillation and will be only useful to check the two-neutrino hypothesis depending on the mass difference of \(m_1, m_2\) which denote the masses of \(\nu_1\) and \(\nu_2\). We defined the (half) oscillation time as
\[
T = \frac{\pi}{|E_1 - E_2|} \simeq 2\pi \frac{pc}{m_2c^2} \cdot \frac{M_p}{m_2} \cdot 0.7 \times 10^{-24}\text{sec},
\] (18)
where assumed as \(m_1 = 0\).

We have analyzed neutrinos of the famous experiment by Danby et al.(1962) which confirmed the two-neutrino hypothesis. Geometry of the neutrino path was

\footnote{Here I present the formulas of the oscillation that we calculated at that time. The calculation followed as a simple exercise to the \(K_1\) and \(K_2\) scheme of Gell-Mann and Pais(1955) but involving an arbitrary mixing angle as follows.}
taken as 100m, the flight time is

\[ t_G = \frac{1}{3} \times 10^{-6} \text{sec}. \]  \hfill (19)

Assume for the neutrino beam as

\[ pc = 1 \text{ BeV}, \]
\[ m_1 c^2 = 0, \]
\[ m_2 c^2 = x \text{ MeV}. \] \hfill (20)

Then no observation of \( \nu_e \) would mean \( T \geq t_G \), which gives an upper bound

\[ m_2 c^2 \leq 3 \times 10^{-6} \text{ MeV}. \] \hfill (21)

**Time development of \( \nu_\mu \) from pion decay:**

\[ |\nu_\mu, t\rangle = \left\{ e^{-iE_1 t} \sin^2 \theta + e^{-iE_2 t} \cos^2 \theta \right\} |\nu_\mu\rangle + \frac{1}{2} \left\{ e^{-iE_1 t} - e^{-iE_2 t} \right\} \sin 2\theta |\nu_e\rangle. \]

Detection probability of \( \nu_e \) at t :

\[ |\langle \nu_e | \nu_\mu, t\rangle|^2 = \frac{1}{2} \sin^2 2\theta \{1 - \cos(E_1 - E_2)t\}. \]

Detection probability of \( \nu_\mu \) at t :

\[ |\langle \nu_\mu | \nu_\mu, t\rangle|^2 = \sin^4 \theta + \cos^4 \theta + \frac{1}{2} \sin^2 2\theta \cos(E_1 - E_2)t. \]

A half oscillation time of the detection probability of \( \nu_e \) :

\[ T = \pi \frac{1}{|E_1 - E_2|}. \]

At relativistic limit, under an assumption \( m_2 \neq 0 \), and \( m_1 \simeq 0 \),

\[ |E_1 - E_2| = \left| \sqrt{p^2 + m_1^2} - \sqrt{p^2 + m_2^2} \right| \]
\[ \simeq p(1 + \frac{m_2^2}{2p^2}) - p \]
\[ = \frac{m_2^2}{2p}. \]

Thus

\[ T \simeq \frac{2\pi p}{m_2^2} \]
\[ = 2\pi \frac{pc}{m_2 c^2} \cdot \frac{M_p}{m_2} \cdot 0.7 \times 10^{-24} \text{sec}, \]

where \( M_p \) means the proton mass.

See also, for example, A.K.Mann and H.Primakoff, *Phys.Rev.* D15, 655 (1977); S.M.Bilenky and B.Pontecorvo, *Physics Reports*, 41, 225 (1978).
3.2 Observation of electrons does not disprove the two-neutrino hypothesis in $\pi \rightarrow \mu + \nu_\mu$ chain

We have also remarked an emission of a massive neutrino together with a massless neutrino would cause an apparent change in the magnitudes of the effective $\beta$ coupling constants depending on the Q-values and also would show an anomalous kink in the Kurie-plots as the threshold effect of massive neutrino. The $\beta$ interaction is now given from eqs.\((14), (13)\) as

$$-L_\beta = \frac{G_F}{\sqrt{2}}(\overline{m}_1)_{\lambda}\{\cos^2\theta(\overline{\nu}_1)_{\lambda} - \cos\theta\sin\theta(\overline{\nu}_2)_{\lambda}\} + h.c. \quad (22)$$

This means that the $\beta$-transition emitting $\nu_1$ is determined by an effective coupling constant $G_F\cos^2\theta$, but the $\nu_2$-emitting transition by that of $-G_F\cos\theta\sin\theta$. Then when the Q-value is so small, the $\beta$ decay emits only the $\nu_1$ (in this analysis, we assumed $m_1 \simeq 0$), whereas the Q-value is large, the decay emits both of neutrinos $^3$.

To get the real information of the masses and mixing angle of neutrinos, we studied the data of nuclear $\beta$ decays. Just in those times, there were reported an anomalous kink in the Kurie-plots by Langer group (we called this effect as "Langer effect") and also an increase of the magnitudes of the coupling constants with increase of the Q-values after subtraction of the radiative corrections $^{[14]}$. These suggested

$$m_2c^2 \simeq 1 \text{ MeV},$$
$$\sin \theta \simeq 0.16 \sim 0.25. \quad (23)$$

Under this mass condition, the $\cos(E_1 - E_2)t$ term vanishes in the probability oscillations of $\nu_e$ and $\nu_\mu$, thus the ratio of $N_e$ to $N_\mu$ to be observed in the two-neutrino experiment initiating from $\pi \rightarrow \mu + \nu_\mu$ is given in terms of only the mixing angle $\theta$ as

$$\frac{N_e}{N_\mu} = \frac{2\sin^2\theta\cos^2\theta}{\cos^4\theta + \sin^4\theta}$$
$$\simeq \frac{1}{20} \sim \frac{1}{8}. \quad (24)$$

We heard Brookhaven had 29 $\mu^-$ with 8 showers found at that time.

$^3$We have used the following formula for the Kurie-plot analysis as

$$\sqrt{\frac{N(E)}{G_F \cdot (G - T)pE}} = \left\{(E_0 - E)^2 + \epsilon[(E_0 - E)^2 - m_2^2]^2(E_0 - E)^2\right\}^{\frac{1}{2}},$$

where

$$\epsilon = 0 \quad \text{for the emission of only } \nu_1,$$
$$= \frac{\sin^2\theta}{\cos^2\theta} \quad \text{for the emission of } \nu_1 \text{ and } \nu_2.$$
3.3 Other processes

We also computed the decay processes \( \mu \rightarrow e + \gamma \) and \( \nu_2 \rightarrow \nu_1 + \gamma \) with diagrams involving the weak boson; these can take place only through the muon-number non-conservation. And we realized these diagrams can be given in terms of mass (squared) differences of virtual leptons on account of cancellations of divergent terms due to the rotation caused by the mixing angle (later on, this was called as G.I.M. mechanism \([12]\)). The decay amplitudes are controlled by factors \((m_1^2 - m_2^2)/M_W^2\) for \( \mu \rightarrow e + \gamma \), and \((m_\nu^2 - m_\nu^2)/M_W^2\) for \( \nu_2 \rightarrow \nu_1 + \gamma \) up to the Feynman integral factors \([4]\). The numerical results were

\[
Br(\mu \rightarrow e + \gamma) \simeq 10^{-17}, \\
\tau(\nu_2 \rightarrow \nu_1 + \gamma) \simeq 10^{10} \text{ sec},
\]

under the same parameters \( m_1 = 0, m_2 = 1\text{MeV}, \sin \theta \simeq 0.16 \sim 0.25, M_W = 1\text{BeV} \).

4 Flavor Oscillation of Majorana Neutrino (1967)

B.Pontecorvo (1967) \([15]\)  
V.Gribov and B.Pontecorvo (1969) \([15]\)

In 1967 \([15]\), Pontecorvo proposed the violation of the muon charge together with the violation of the leptonic charge conservation of the following type as

\[
\nu \leftrightarrow \bar{\nu} \quad \text{and} \quad \nu_e \leftrightarrow \nu_\mu.
\]  

(26)

Again the transition of an active particle to a sterile particle takes place here as a transition el-neutrino \( \leftrightarrow \) mu-neutrino, that is, physically as the flavor oscillation.

The above concept has been given a beautiful formulation by Gribov and Pontecorvo in 1969 \([15]\), which may be a first formulation, to my knowledge, of the Majorana mass terms of the Dirac neutrinos. Assumed neutrinos are the massless two-component Dirac neutrinos \( \nu_{eL} \) and \( \nu_{\mu L} \), which construct the weak interactions. The mass term of the Lagrangean is assumed as

\[
L_{\text{int}} = m_e \bar{\nu}_{eL} \nu_{eL} + m_\mu \bar{\nu}_{\mu L} \nu_{\mu L} + m_\nu \bar{\nu}_{eL} \nu_{eL} + \text{h.c.},
\]

(27)

where e.g. \( \nu_{eL}^c \) means a charge conjugated spinor. Diagonalization of this Lagrangean leads to the Majorana particles \( \phi_1 \) and \( \phi_2 \) which have each eigenmass, and the original weak left-handed neutrinos are expressed as

\[
\nu_{eL} = \frac{1}{2}(1 + \gamma_5)(\phi_1 \cos \xi + \phi_2 \sin \xi),
\]

(28)

\[
\nu_{\mu L} = \frac{1}{2}(1 + \gamma_5)(\phi_1 \sin \xi - \phi_2 \cos \xi),
\]

(29)

\footnote{For the Feynman integral factor of the \( \mu \rightarrow e + \gamma \) process, we followed the work of M.E.Ebel and F.J.Ernst, \textit{Nuovo Cimento} 15, 173 (1960) by noting that \( m_2 \) plays their cutoff under \( m_1 = 0 \). And for the \( \nu_2 \rightarrow \nu_1 + \gamma \), we calculated it keeping only the leading term.}
where the mixing angle $\xi$ is determined in terms of $m_{e\mu}$, $m_{e\tau}$ and $m_{\mu\tau}$.

5 Summary

I have presented a brief historical introduction on the neutrino theory carried out in early stage up to 60’s where the concept of the neutrino oscillation has born. The developments of the theory after this stage are well known so that I would apologize for skipping the other many important contributions.

The motivation to the concept of the neutrino oscillation seems, to me, to consist in two main streams. One of them may be of a strong question on the conservation laws concerning leptonic charges either or both of the lepton number and the muon charge that would be violated just in analogy with the established evidence of $K^0$ to $\bar{K}^0$ transition. The other is in the attempt at model building for a unified understanding of the leptons and the fundamental entities of hadrons. A unification of four leptons and the fundamental baryons at that time suggested the mixing scheme for neutrinos that explained successfully the structure of the baryonic weak current; the universality of the weak interaction and the smallness of strangeness changing interaction.

The above features of intentions are, I would like to say, in principle still alive in the present stage of neutrino study as the quests for the origin of the mixing and for the true nature of the neutrinos. I would hope the physics of leptons will be much deepened over every generation of flavors to open the new realm beyond the standard model, and indeed this workshop will remain as a great milestone for the future progress.

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