Early years of neutrino oscillations

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Abstract

The first papers on neutrino oscillations are shortly reviewed

I. B. PONTECORVO 1957

The idea of neutrino oscillations was put forward in Dubna by B. Pontecorvo. He came to this idea as early as 1957, soon after parity violation in $\beta$-decay was discovered by Wu et. al. and the theory of two-component neutrino was proposed by Landau, Lee and Yang, and Salam. Only one type of neutrinos was known at that time.

B. Pontecorvo mentioned the possibility of $\nu \leftrightarrow \bar{\nu}$ transitions in vacuum for the first time in his paper on muonium $\leftrightarrow$ antimuonium transitions ($\mu^- e^+ \leftrightarrow \mu^+ e^-$). He looked in the lepton world for a phenomenon that would be analogous to $K^0 \leftrightarrow \bar{K^0}$ oscillations:

“The possible $K^0$ and $\bar{K^0}$ transition, which is due to the weak interactions, leads to the necessity of considering neutral $K$-mesons as a superposition of particles $K^0_1$ and $K^0_2$ having a different combined parity. In the present note the question is treated whether there exist other mixed neutral particles (not necessarily elementary) besides the $K^0$-mesons, which differ from their anti-particles and for which the particle $\rightarrow$ antiparticle transitions are not strictly forbidden.”

At that time (and for many years later) neutrino was generally believed to be a massless particle. This belief was grounded on the experimental upper limit of the neutrino mass which was known to be much smaller than the mass of the electron (about 250 eV at that time) and on the success of the theory of the two-component neutrino that was based on the assumption of a massless neutrino. In the paper B. Pontecorvo wrote:

“If the two-component neutrino theory should turn out to be incorrect (which at present seems to be rather improbable) and if the conservation law of neutrino charge would not apply, then in principle $\nu \leftrightarrow \bar{\nu}$ transitions could take place in vacuo.”
B. Pontecorvo wrote his first paper on neutrino oscillations later in 1957 [6]. At that time F. Reines and C. Cowan [7] were doing the famous experiment which led them to discover the neutrino through the observation of the inverse $\beta$-process

$$\bar{\nu}_e + p \rightarrow e^+ + n$$

induced by reactor antineutrinos.

At the same time R. Davis was also doing an experiment on reactor antineutrino beam [8]. R. Davis searched for production of $^{37}$Ar in the process

$$\bar{\nu}_e + ^{37}Cl \rightarrow e^- + ^{37}Ar$$

that is allowed only if lepton number is not conserved. A rumour reached B. Pontecorvo that Davis had seen some events (2). B. Pontecorvo who had earlier been thinking about possible antineutrino $\rightarrow$ neutrino transitions decided to study this possibility in details in connection with reactor experiments:

“Recently the question was discussed [5] whether there exist other mixed neutral particles beside the $K^0$ mesons, i.e., particles that differ from the corresponding antiparticles, with the transitions between particle and antiparticle states not being strictly forbidden. It was noted that the neutrino might be such a mixed particle, and consequently there exists the possibility of real $\nu \leftrightarrow \bar{\nu}$ transitions in vacuum, provided that lepton (neutrino) charge is not conserved. In the present note we make a more detailed study of this possibility, in which interest has been renewed owing to recent experiments dealing with inverse beta processes.”

B. Pontecorvo assumed that

(a) the neutrino ($\nu$) and antineutrino ($\bar{\nu}$) that are produced in the processes $p \rightarrow n + \beta^+ + \nu$ and $n \rightarrow p + \beta^- + \bar{\nu}$ are not identical particles;

(b) lepton number is not strictly conserved

and went on:

“It follows from the above assumptions that in vacuum a neutrino can be transformed into an antineutrino and vice versa. This means that the neutrino and antineutrino are mixed particles, i.e., a symmetric and antisymmetric combination of two truly neutral Majorana particles $\nu_1$ and $\nu_2$ of different combined parity$^1$.”

B. Pontecorvo wrote in the paper [6] that he has considered this possibility

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$^1$i.e. CP values
“... since it leads to consequences which, in principle, can be tested experimentally. Thus, for example, a beam of neutral leptons consisting mainly of antineutrinos when emitted from a nuclear reactor, will consist at some distance $R$ from the reactor of half neutrinos and half antineutrinos. Under the condition that $R \leq 1m$ neutrino experiments, reminiscent of the Pais-Piccioni experiments with $K^0$ mesons, become possible. Thus, in the experiment of Cowan and Reines, if $R \leq 1m$, when the neutral particles from the reactor are captured by hydrogen, the cross section for formation of neutrons and positrons should be smaller than the cross section expected on simple thermodynamic grounds. This is due to the fact that the beam of neutral leptons, which at creation has a known probability for initiating the reaction, changes its composition on the way from the reactor to the detector.”

In this first paper, that was written at the time the two-component neutrino theory had just appeared and the Davis reactor experiment was not yet finished, B. Pontecorvo discussed a possible explanation of the Davis events:

“On the other hand, it is difficult to anticipate the effect of real $\text{antineutrino} \rightarrow \text{neutrino}$ transitions in the Davis experiment, since in this case one deals with non-strictly inverse $\beta$ process ...”

Later B. Pontecorvo understood that in the framework of the two-component neutrino theory, fully established after the M. Goldhaber et al. experiment [9], right-handed antineutrinos can be transferred in vacuum only into sterile right-handed neutrinos that do not take part in weak interaction processes and cannot induce the process (2). B. Pontecorvo was in fact the first who introduced in 1967 the notion of sterile neutrinos so popular nowadays (see later).

II. Z. MAKI, M. NAKAGAWA, S. SAKATA 1962

The mixing of two neutrinos was introduced by Maki, Nakagawa and Sakata in 1962 [10] in the framework of the Nagoya model. In this model nucleons were considered as bound states of a new sort of matter $B^+$ and leptons. In addition to usual neutrinos $\nu_e$ and $\nu_\mu$, that they called weak neutrinos, the authors introduced massive neutrinos $\nu_1$ and $\nu_2$, that they called true neutrinos (the proton was considered as a bound state of a $B^+$ and a true neutrino $\nu_1$ etc.). They assumed that the fields of weak neutrinos and true neutrinos were connected by an orthogonal transformation:

\[ \begin{pmatrix} 
\nu_e \\
\nu_\mu 
\end{pmatrix} = \begin{pmatrix} 
C_{1e} & C_{1\mu} \\
C_{2e} & C_{2\mu}
\end{pmatrix} \begin{pmatrix} 
\nu_1 \\
\nu_2
\end{pmatrix} \]

\[ \begin{pmatrix} 
C_{1e} & C_{1\mu} \\
C_{2e} & C_{2\mu}
\end{pmatrix} \]

2 This inequality was based on B. Pontecorvo’s first estimate of the oscillation length of reactor antineutrinos

3 B. Pontecorvo had in mind thermodynamic and dimensional arguments by Bethe and Peierls that allowed to connect the cross section of the inverse $\beta$-decay processes with the probability of $\beta$-decay.
“It should be stressed at this stage that the definition of the particle state of the neutrino is quite arbitrary; we can speak of neutrinos which are different from weak neutrinos but are expressed by a linear combination of the latter. We assume that there exists a representation which defines the true neutrinos through some orthogonal transformation applied to the representation of weak neutrinos:

\[
\nu_1 = +\nu_e \cos \delta + \nu_\mu \sin \delta \\
\nu_2 = -\nu_e \sin \delta + \nu_\mu \cos \delta
\]  

The authors introduced an interaction non-diagonal in \(\nu_e\) and \(\nu_\mu\) (if mixing is assumed):

\[
\mathcal{L} = g\nu_2 \nu_2 X^+ X
\]  

where \(g\) is a constant and \(X\) is the field of heavy particles.

Different effects of neutrino masses and mixing including \(\nu_\mu \rightarrow \nu_e\) transitions were considered in the paper [10].

The authors shortly discussed the possibility to see effects of \(\nu_\mu \rightarrow \nu_e\) transitions in Brookhaven neutrino experiment [11], aiming to check whether \(\nu_e\) and \(\nu_\mu\) were identical or different particles, that at that time was going on.

I report below the part of the paper [10] dedicated to the consideration of \(\nu_\mu \rightarrow \nu_e\) transitions:

“In the present case, however, weak neutrinos are not stable due to occurrence of virtual transmutation \(\nu_\mu \rightarrow \nu_e\) induced by the interaction (4). If the mass difference between \(\nu_1\) and \(\nu_2\), i.e. \(|m_{\nu_2} - m_{\nu_1}| = m_{\nu_2}\), is assumed to be a few MeV the transmutation time \(T(\nu_e \leftrightarrow \nu_\mu)^2\) becomes \(\sim 10^{-18}\) sec for fast neutrinos with momentum \(\sim \text{BeV}/c\).

Therefore a chain of reactions such as

\[
\pi^+ \rightarrow \mu^+ \nu_\mu \\
\nu_\mu + Z \text{ (nucleus)} \rightarrow Z' + \left(\mu^- / e^-\right)
\]  

is useful to check the two-neutrino hypothesis only when \(|m_{\nu_2} - m_{\nu_3}| \leq 10^{-6}\) MeV under the conventional geometry of the experiments. Conversely, the absence of \(e^-\) in the reaction (5) will be able not only to verify two-neutrino hypothesis but also to provide an upper limit of the mass of the second neutrino \(\nu_2\) if the present scheme should be accepted.”

III. B. PONTECORVO 1967

B. Pontecorvo discussed all the possibilities of neutrino oscillations in the case of two flavour neutrinos \(\nu_e\) and \(\nu_\mu\) in the paper [12]. In this paper he introduced the notion of sterile neutrino:
“If there are two different additive lepton charges, the transitions $\nu_e \leftrightarrow \bar{\nu}_e$ and $\nu_\mu \leftrightarrow \bar{\nu}_\mu$ transform potentially active particles into particles, which from the point of view of ordinary weak processes, are sterile, i.e. practically undetectable, inasmuch as they have wrong spirality. In such a case the only way of observing the effects in question consists in measuring the intensity and the time variation of the intensity of original active particles, but not in detecting the appearance of the corresponding (sterile) antiparticles.”

B. Pontecorvo considered as a very favourable the Zeldovich-Konopinsky-Mahmoud scheme with one lepton number for $e$ and $\mu$ and one four-component neutrino. In this scheme $\nu_L = \nu_e$, $\bar{\nu}_L = \nu_\mu$, $\nu_R = \bar{\nu}_e$ and $\bar{\nu}_R = \nu_\mu$ and there are no sterile neutrinos:

“Let us consider now the case when there is only one additive leptonic charge the sign of which differs for $\mu^-$ and $e^-$. The proper notation for the four neutral objects in such a case is $\nu_{\text{left}}, \bar{\nu}_{\text{left}}, \nu_{\text{right}}, \bar{\nu}_{\text{right}}$. Then the transitions $\nu_{\text{left}} \rightarrow \bar{\nu}_{\text{left}}, \bar{\nu}_{\text{right}} \rightarrow \nu_{\text{right}}$ generate nonsterile particles.

Returning to the usual notations, there will take place oscillations $e\nu_e \leftrightarrow \mu\nu_\mu$, which, in principle are detectable not only by measuring the intensity and the time variation of the intensity of original particles, but also by observing the appearance of new particles.”

In the same paper [12] oscillations of solar neutrinos were considered for the first time. Before the first results of Davis experiment appeared, B. Pontecorvo pointed out that due to neutrino oscillations the observed flux of solar neutrinos could be twice smaller than the expected flux. He anticipated the solar neutrino problem:

“From an observational point of view the ideal object is the sun. If the oscillation length is smaller than the radius of the sun region effectively producing neutrinos, (let us say one tenth of the sun radius $R_\odot$ or 0.1 million km for $^8B$ neutrinos, which will give the main contribution in the experiments being planned now), direct oscillations will be smeared out and unobservable. The only effect on the earth’s surface would be that the flux of observable sun neutrinos must be two times smaller than the total (active and sterile) neutrino flux.”

In this paper B. Pontecorvo discussed also the possible seasonal variation of the flux of solar neutrinos that could appear in the case if oscillation length is larger than the region of the sun where neutrinos are produced. This possibility was pointed out to him by I. Pomeranchuk.

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4 At that time Neutral Current processes were not known

5 Old notations for $\nu_e$ and $\nu_\mu$.  

In the paper \cite{13} it was pointed out that

“solar neutrino oscillations is the most sensitive way of investigating the question of lepton charge conservation.”

In this paper the Majorana mass term, in which only left-handed fields $\nu_{eL}$ and $\nu_{\mu L}$ enter, was for the first time considered, and a scheme of neutrino mixing in which there are no transitions of $\nu_e$ and $\nu_\mu$ into sterile states was proposed. Neutrinos with definite masses $m_1$ and $m_2$ are in this scheme Majorana particles:

“The two component spinors $\nu_e$ and $\nu_\mu$ are not describing anymore particles with zero mass but must be expressed in terms of four-component Majorana spinors $\phi_1$ and $\phi_2$

$$
\nu_e = \frac{1}{2} (1 + \gamma_5) (\phi_1 \cos \xi + \phi_2 \sin \xi)
$$

$$
\nu_\mu = \frac{1}{2} (1 + \gamma_5) (-\phi_1 \sin \xi + \phi_2 \cos \xi)
$$

(6)

Here

$$
\tan 2\xi = \frac{2m_e\pi}{m_\mu\pi - m_e\pi}
$$

(7)

where $m_e\pi$, $m_\mu\pi$ and $m_e\pi$ are parameters that characterise the neutrino mass matrix.

In the paper \cite{13} neutrino oscillations were considered:

“The mass difference between Majorana neutrinos described by $\phi_1$ and $\phi_2$ leads to oscillations $\nu_e \leftrightarrow \nu_\mu$, $\bar{\nu}_e \leftrightarrow \bar{\nu}_\mu$. If at the time $t = 0$, one electron neutrino is generated, the probability of observing it at the time $t$ is

$$
|\nu_e (t)|^2 = |\nu_e (0)|^2 \left\{ \frac{m_1^2 + 2m_e^2\pi}{m_1^2 + 4m_e^2\pi} + \frac{2m_e^2\pi}{m_1^2 + 4m_e^2\pi} \cos \Delta t \right\}
$$

(8)

where

$$
m_- = m_e\pi - m_\mu\pi
$$

(9)

$$
\Delta = \frac{1}{2p} \left( m_1^2 - m_2^2 \right) = \frac{m_e\pi + m_\mu\pi}{2p} \sqrt{m_1^2 + 4m_e^2\pi}
$$

(10)

and $p$ is the neutrino momentum.”

If $m_e\pi$, $m_\mu\pi$, $\ll m_e\pi$, or $m_e\pi = m_\mu\pi$ the mixing is maximal ($\xi = \pi/4$) and neutrino oscillations are analogous to $K^0 \leftrightarrow \bar{K}^0$ oscillations. The authors consider this possibility as the most simple and attractive one.

In the paper \cite{14} written soon after the V.Gribov and B.Pontecorvo paper appeared, J.Bahcall and S.Frautschi considered vacuum oscillations of solar neutrinos in details. In this paper the importance of averaging over the solar neutrino energy spectrum was demonstrated and stressed.
V. QUARK-LEPTON ANALOGY AND NEUTRINO OSCILLATIONS

After the Cabibbo-GIM quark mixing was established in the beginning of the seventies the main arguments for neutrino mixing were based on quark-lepton analogy [15], [16]. In the Gribov-Pontecorvo scheme massive neutrinos are very different from other fundamental fermions: whereas charged leptons and quarks are four-component Dirac particles, massive neutrinos are two-component Majorana particles. In the paper [13]

“...we consider neutrino mixing starting from a different point of view suggested by an analogy between leptons and quarks. We assume that each neutrino is described by a four-component spinor.”

We stressed in [15] that the value of the lepton mixing angle and the value of the Cabibbo angle could be completely different. We tried to present different quantitative arguments that maximal mixing is the most plausible and fruitful assumption. In the paper [17] we wrote:

“...it seems to us that the special values of mixing angle \( \theta = 0 \) (the usual scheme in which muonic charge is strictly conserved) and \( \theta = \pi/4 \) are of the greatest interest."

For arbitrary angle \( \theta \) the formulas for the oscillation of two types of neutrinos, that are now standard, were presented in [18] and [19]:

\[
I_{\nu_{\ell}}(R, p) = \left[ 1 - \frac{1}{2} \sin^2 2 \theta \left( 1 - \cos \frac{2 \pi R}{L} \right) \right] I_{\nu_{\ell}}^0(R, p) \quad \ell = e, \mu
\]

\[
I_{\nu_{\ell'}}(R, p) = \left[ \frac{1}{2} \sin^2 2 \theta \left( 1 - \cos \frac{2 \pi R}{L} \right) \right] I_{\nu_{\ell'}}^0(R, p) \quad \ell \neq \ell', \quad \ell, \ell' = e, \mu
\]

(11)

Here \( I_{\nu_{\ell}}(R, p) \), \( I_{\nu_{\ell'}}(R, p) \) are the intensities of \( \nu_{\ell} \), \( \nu_{\ell'} \) respectively, with momentum \( p \) at a distance \( R \) from a source of \( \nu_{\ell} \) neutrinos. \( I_{\nu_{\ell}}^0(R, p) \) is the intensity of \( \nu_{\ell} \) neutrinos which would be expected in the absence of oscillations and

\[
L = \frac{4 \pi p}{|m_2^2 - m_1^2|}
\]

(12)

is the oscillation length.

The list of papers on neutrino oscillations published before 1977 is very short: [6,10,12] - [21]. In our review [22] where we summarised the status of neutrino oscillations and of other processes in which neutrino masses and mixing can be revealed there

\[\text{6Today it looks like small and } \pi/4 \text{ values of neutrino mixing angles are really the preferable ones. Indeed in the framework of the mixing of three massive neutrinos with three mixing angles } \theta_{12}, \theta_{13}, \theta_{23} \text{ from CHOOZ and atmospheric neutrino experiments it follows that } \theta_{13} \text{ is small. From Super-Kamiokande atmospheric neutrino experiments it follows that } \theta_{23} \simeq \pi/4. \text{ The best fit of the latest Super-Kamiokande solar neutrino data was obtained for vacuum solution and large mixing angle MSW solution with } \theta_{12} \simeq \pi/4.\]
are about seventy references. At that time the idea of massless strictly two-component neutrinos still prevailed.

The situation drastically changed after the appearance of Grand Unification models and of the famous see-saw mechanism \[23\] that connect the smallness of neutrino masses with the violation of the lepton numbers at very large scale. From the point of view of the Grand Unification models it is natural and plausible that neutrinos have a mass and the investigation of the neutrino masses and mixing can provide a probe for a new scale in physics. At the end of the seventies new experiments specially dedicated to search for neutrino oscillations were started. In our review on neutrino masses and oscillations \[24\], written in 1986, there are about 230 references.

The real massive neutrino boom started after the Super-Kamiokande result was announced at the Neutrino 98 conference at Takayama. More than 450 papers on the neutrino mass, mixing and oscillations appeared in the HEP archive in less than one year.

VI. CONCLUSION

There is at present a convincing evidence that neutrinos are massive and mixed particles. This evidence has been obtained from atmospheric neutrino experiments (Kamiokande \[25\], IMB \[26\], Soudan 2 \[27\] and MACRO \[28\]), and first of all from the Super-Kamiokande experiment \[29\] and from all solar neutrino experiments (Homestake \[30\], Gallex \[31\], Sage \[32\], Kamiokande \[33\] and Super-Kamiokande \[34\]). From the theoretical point of view it is very plausible that neutrinos have a mass possibly connected with a new scale in physics.

It required many years of work and heroic efforts of many experimental groups to reveal effects of tiny neutrino masses. It is difficult not to give tribute to the great intuition of B. Pontecorvo who pursued the idea of neutrino oscillations for many years at a time when the general opinion, mainly based on the success of the two-component neutrino theory, favoured massless neutrinos.\[7\]

From my own point of view the history of the neutrino oscillations is an illustration of the importance of analogy in physics. It is also an illustration of the importance of new courageous ideas not always in agreement with the general opinion.

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\[7\] For a collection of the papers of B. Pontecorvo see \[35\].
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