Bruno Pontecorvo-pioneer of neutrino oscillations

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Bruno Pontecorvo came to an idea of neutrino oscillations in 1957 soon after parity violation in β-decay and μ-decay was discovered and the two-component theory of massless neutrino was proposed by Landau, Lee and Yang and Salam and confirmed in the the classical Goldhaber et al experiment on the measurement of the neutrino helicity

At that time only one type of neutrino was known

According to the two-component theory only massless ν_L and $\bar{\nu}_R$ exist. No possibility of transitions between different neutrinos, no neutrino oscillations

What was B. Pontecorvo motivations?

B. Pontecorvo believed in a similarity (analogy) of weak interactions of hadrons and leptons, very popular at that time idea He was impressed by $K^0 \rightleftarrows \bar{K}^0$ oscillations, suggested by Gell-Mann and Pais, and looked for a similar phenomenon in the lepton world

Basics of $K^0 \rightleftarrows \bar{K}^0$ oscillations

1. K^0 and $\bar{K}^0$ are particles with the strangeness $S = 1$ and $S = -1$. Strangeness is conserved in the strong interaction.
2. Weak interaction, in which S is not conserved, induce transitions between K^0 and $\bar{K}^0$.
3. Particles with definite masses and life-times, eigenstates of the total Hamiltonian, are K_1, K_2. K^0, $\bar{K}^0$ are "mixed particles"

$$|K^0(\bar{K}^0)\rangle = \frac{1}{\sqrt{2}}(|K_1^0\rangle \pm |\bar{K}_2^0\rangle)$$

$$|K^0(\bar{K}^0)\rangle_t = \frac{1}{\sqrt{2}}(|K_1^0\rangle e^{-im_1 t - \frac{1}{2}\Gamma_1 t} \pm |\bar{K}_2^0\rangle e^{-im_2 t - \frac{1}{2}\Gamma_2 t})$$

B. Pontecorvo (1957) raised the following question "...whether there exist other "mixed" neutral particles (not necessarily elementary ones) which are not identical to their corresponding antiparticles and for which particle $\leftrightarrows$ antiparticle transitions are not strictly forbidden".

B. Pontecorvo (1957) found such "neutral particles" : muonium ($\mu^+ - e^-$) and antimuonium ($\mu^- - e^+$)

He wrote: "muonium $\leftrightarrows$ antimuonium transitions are allowed and are induced by the same interaction which is responsible for μ-decay":

$$(\mu^+ - e^-) \to \nu + \bar{\nu} \to (\mu^- - e^+)$$

It was unknown at that time that ν_e and ν_μ are different particles and $(\mu^+ - e^-) \leftrightarrows (\mu^- - e^+)$ transition is allowed if exist an interaction which conserve the total lepton number and $|\Delta L_e| = 2$ and $|\Delta L_\mu| = 2$

In the 1957 paper Pontecorvo made the following remark about neutrino oscillations: "If the theory of the two-component neutrino is not valid (which is hardly probable at present) and if the conservation law for the neutrino charge does not hold, neutrino $\to$ antineutrino transitions in vacuum in principle be possible."

He had in mind $\nu_L \to \bar{\nu}_L$ ($\bar{\nu}_R \to \nu_R$) transition

It was not easy for him to publish a paper on neutrino oscillations at that time, BUT

In 1957-58 R. Davis performed a reactor experiment in which he searched for

$$\bar{\nu}_R(\mathrm{reactor}) +^{37}\mathrm{Cl} \to \mathrm{e}^- +^{37}\mathrm{Ar}$$

A rumor reached B.Pontecorvo that R.Davis observed $^{37}\mathrm{Ar}$ production in the reactor experiment

B.Pontecorvo (1958) assumed that these "events" could be due to neutrino oscillations: transitions of reactor antineutrinos into right-handed neutrinos: $\bar{\nu}_R \to \nu_R$

He wrote: "...neutrino may be a particle mixture and consequently there is a possibility of real transitions neutrino $\to$ antineutrino in vacuum, provided that the lepton (neutrino) charge is not conserved.

"This means that the neutrino and antineutrino are *mixed* particles, i.e., a symmetric and antisymmetric combination of two truly neutral Majorana particles ν_1 and ν_2 "

$$|\bar{\nu}_R\rangle = \frac{1}{\sqrt{2}}(|\nu_{1R}\rangle + |\nu_{2R}\rangle) \quad |\nu_R\rangle = \frac{1}{\sqrt{2}}(|\nu_{1R}\rangle - |\nu_{2R}\rangle)$$

B. Pontecorvo: "...this possibility became of some interest in connection with new investigations of inverse β-processes."

At a later stage of the Davis experiment the anomalous "events" disappeared. Only upper bound on the lepton number violation was obtained

B. Pontecorvo later understood that ν_R is a sterile particle. The terminology "sterile neutrino", which is standard nowadays, was introduced by him in the next publication on neutrino oscillations

In the 1958 paper B. Pontecorvo discussed possibilities to search for neutrino oscillations in $\bar{\nu}_R \to \bar{\nu}_R$ transition

"...the cross section of the process $\bar{\nu} + p \to e^{+} + n$ would be smaller than the expected cross section. This is due to the fact that the neutral lepton beam which at the source is capable of inducing the reaction changes its composition on the way from the reactor to the detector."

"It would be extremely interesting to perform the Reins-Cowan experiment at different distances from reactor"

Notice that the Reines and Cowan reactor experiment, in which neutrino was discovered in the process $\bar{\nu} + p \to e^{+} + n$, was going on at that time.

Search for oscillations which was proposed by B. Pontecorvo in 1958 (search for transition of reactor $\bar{\nu}_e$'s into sterile states) is very actual problem today

To resolve the problem of the reactor neutrino anomaly and the problem of sterile neutrinos many short baseline reactor experiments are going on

Nucifer (France), NEOS (Korea), DANSS (Russia), Neutrino-4 (Russia), Stereo (France), SoLid (Belgium), PROSPECT (USA)...

In 1958 B. Pontecorvo could not know the values of neutrino masses and Δm^2 driving neutrino oscillations but he believed that phenomenon of neutrino oscillations exist

In the 1958 paper he wrote

"Effects of transformation of neutrino into antineutrino and vice versa may be unobservable in the laboratory but will certainly occur, at least, on an astronomical scale."

He had in mind solar neutrinos

Solar neutrinos were discussed in the second Pontecorvo paper on neutrino oscillations (1967) written after ν_μ was discovered (Brookhaven, 1962)

He continued to think in terms of analogy with $K^0 \rightleftarrows \bar{K}^0$ oscillations which were observed at that time

"If the lepton charge is not an exactly conserved quantum number, and the neutrino mass is different from zero, oscillations similar to those in K^0 beams become possible in neutrino beams"

B. Pontecorvo considered oscillations $\nu_\mu \rightleftarrows \nu_e$ and also transitions $\nu_\mu \rightleftarrows \bar{\nu}_{\mu L}$ etc."which transform active particles into particles, which from the point of view of ordinary weak processes, are sterile"

"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, 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 neutrino flux."

Two types of neutrinos ν_e and ν_μ were known at that time. $\frac{1}{2}$ corresponds to maximal mixing

In 1970 the first result of the Davis solar experiment was obtained. It occurred that the detected flux of solar neutrinos was (2-3) times smaller than the flux predicted by the SSM ("the solar neutrino problem")

Pontecorvo neutrino oscillations, based on neutrino masses and mixing, was accepted as a explanation of the problem. Later it was discovered that combination of of neutrino masses and mixing and coherent neutrino-electron scattering in matter (MSW effect) provides natural explanation of the suppression of the solar neutrino flux observed first in the Homestake experiment and later in Kamiokande, GALLEX, SAGE, Super-Kamiokande, SNO and BOREXINO experiments. The MSW effect was studied in detail by the BOREXINO collaboration.

Next B. Pontecorvo paper (1969) was also dedicated to solar neutrinos and was done together with V. Gribov

In this paper two-neutrino oscillation formula (in vacuum) was derived and the factor $\frac{1}{2}$ was justified

The most interesting is theoretical part of the paper

G-P put the following question

Can we have neutrino masses and mixing if we use as a basis only left-handed flavor fields ν_{eL} and $\nu_{\mu L}$ (no right-handed fields)?

Their answer: yes, if neutrino mass term (which they interpreted as additional interaction) does not conserve the total lepton number

$$L = L_e + L_\mu$$

It is Majorana mass term. In modern form for any number of flavors (SB,Petcov)

$$\mathcal{L}_M = -\frac{1}{2}\sum_{l',l}\bar{\nu}_{l'L}M_{l'l}(\nu_{lL})^c + h.c$$

$(\nu_{lL})^c = C(\bar{\nu}_{lL})^T$, C is the charge-conjugated matrix.

From the Fermi-Dirac statistics $M^T = M$

After the diagonalization of the Majorana mass term

$$\mathcal{L}_M = -\frac{1}{2}\sum_i m_i \bar{\nu}_i \nu_i$$

$\nu_i = \nu_i^c$ is the Majorana field (neutrino≡ antineutrino) with mass m_i

Mixing $\nu_{lL} = \sum_i U_{li}\nu_{iL} \quad U^\dagger U = 1$

U is Pontecorvo-MNS mixing matrix. Only $\nu_l \rightleftarrows \nu_{l'}$ oscillations are possible

Summarizing

Majorana mass term is the most economical possibility (only ν_{lL} in the Lagrangian) to generate neutrino masses and mixing

by the prize of the total lepton number L nonconservation

In the G-P approach neutrino masses m_i are parameters, no physical reasons why neutrino masses are so small

The most plausible modern effective Lagrangian approach to neutrino masses (Weinberg) is based on the same principle of economy and on the nonconservation of L

It generates the same Majorana mass term, but it gives us a possibility to explain the smallness of neutrino masses

After the discovery of the Higgs boson at LHC the Standard Model acquired the status of the theory of elementary particles in the electroweak range (up to $\sim$ 300 GeV)

The Standard Model is based on the following principles

- Local gauge symmetry
- Unification of the weak and electromagnetic interactions.
- Brout-Englert-Higgs mechanism of the spontaneous breaking of the electroweak symmetry

From the success of the SM we can conclude that in the framework of these principles the nature chooses the simplest possibilities

Let us start with neutrinos. Two-component massless Weil fields ν_{lL} is the simplest possibility (2 dof)

$SU(2)_L$ is the simplest nonabelian group, which allows to unify neutrinos and leptons (up and down quarks)

$SU(2)_L \times U_Y(1)$ is the simplest group, which allows to unify weak and electromagnetic interactions

The Standard Model CC +NC+EM interaction is the minimal gauge interaction

One Higgs doublet is the minimal possibility to generate masses of $W^{\pm}$ and Z^0

In order to generate fermion masses by the Yukawa interaction we need right-handed singlets l_R etc

Right-handed fields enter into electromagnetic interaction

Neutrino has no direct electromagnetic interaction

The most economical (and natural) possibility: there are no right-handed neutrino fields ν_{lR} in SM

In the SM neutrinos are massless, left-handed Weil particles

The method of the effective Lagrangian is a general method which allows to describe effects of a beyond the Standard Model physics

The effective Lagrangian is a nonrenormalizable dimension five or more operator invariant under the $SU(2)_L \times U(1)_Y$ transformations and built from the Standard Model fields

The only effective Lagrangian which generate neutrino mass term (Weinberg)

$$\mathcal{L}_I^{\rm eff} = -\frac{1}{\Lambda}\ \sum_{l',l}(\bar{\psi}^{lep}_{l'L}\tilde{\phi})\ X_{l'l}\ (\bar{\psi}^{lep}_{lL}\tilde{\phi})^c + \mathrm{h.c.}$$

$$\psi^{lep}_{lL} = \left(\begin{array}{c} \nu_{lL} \\ l_L \end{array}\right), \quad \phi = \left(\begin{array}{c} \phi_+ \\ \phi_0 \end{array}\right)$$

$\mathcal{L}_I^{\rm eff}$ does not conserve the total lepton number L

The constant Λ characterizes a scale of a beyond the SM physics

After the spontaneous symmetry breaking we come to the Majorana mass term

$$\mathcal{L}^{\rm M} = -\frac{1}{2}\,\frac{v^2}{\Lambda}\sum_{l',l}\bar{\nu}_{l'L}\,X_{l'l}(\nu_{lL})^c + \mathrm{h.c.} = -\frac{1}{2}\,\sum_{i=1}^{3} m_i\bar{\nu}_i\nu_i$$

$$m_i = \frac{v^2}{\Lambda}\ x_i = \frac{v}{\Lambda}\ (x_i v) \quad v = (\sqrt{2}G_F)^{-1/2} \simeq 246\ \mathrm{GeV}$$

x_i is the eigenvalue of the matrix X, $(x_i v)$ is a "typical SM mass"

v — scale of SM

$\nu_i = \nu_i^c$, ν_i is the field of the Majorana neutrino with mass m_i

$$m_i = \frac{v^2}{\Lambda}\, x_i = \frac{v}{\Lambda}\, (x_i v)$$

x_i is the eigenvalue of the matrix X (unknown). If similar to Yukawa couplings $(x_i v)$ is a "typical SM mass"

$$\frac{v}{\Lambda} = \frac{\text{scale of SM}}{\text{scale of a new physics}}$$

Smallness of neutrino masses with respect to masses of leptons and quarks can be ensured if we assume that $\Lambda \gg v$

The Weinberg Lagrangian is the only effective Lagrangian of the dimension 5 ($\frac{1}{\Lambda}$)

Neutrinos are the most sensitive probe of a new physics

Main implications of this most economical mechanism of neutrino mass generation

1. Neutrinos with definite masses ν_i are Majorana particles. Investigation of $0\nu\beta\beta$-decay is the first priority problem
2. The number of neutrinos with definite masses must be equal to the number of the flavor neutrinos (three). No transitions of flavor neutrinos into sterile states are allowed. Experiments on the search for sterile neutrinos are extremely important

In 1975 we B. Pontecorvo and me started our collaboration on neutrino oscillations

We published many papers. The last one ("Neutrino Today") for Italian Encyclopedia in 1989.

We considered all possible neutrino mass terms Dirac, Majorana and the most general Dirac and Majorana and all possible experiments on the search for neutrino oscillations.

We proposed to search for neutrino oscillations in atmospheric neutrino experiments and estimated sensitivity of such experiments ($\Delta m^2 \simeq 10^{-3}\ \mathrm{eV}^2$)

After the success of the two-component theory during many years there was a general opinion that $m_i = 0$. We always believed that neutrino masses are small but different from zero:

1. There is no principle (like gauge invariance for γ-quanta) which requires neutrino masses to be equal to zero
2. After $V - A$ theory (in the weak Hamiltonian enter left-handed components of *all fields*) it was natural to consider neutrinos not as a special massless particles but as a particles with some masses

It was widespread belief that neutrino mixing angle is small (like Cabibbo angle)

Our opinion

- there is no reason for the lepton and Cabibbo mixing angles to be the same.
- "it seems to us that the special values of the mixing angles $\theta = 0$ and $\theta = \frac{\pi}{4}$ (maximum mixing) are of the greatest interest."

In 1977 we wrote first review on neutrino oscillations which attracted attention of many physicists to the problem

The history of neutrino oscillations is an illustration of the importance of analogy in physics. It is also an illustration of the importance of new courageous ideas which are not always in agreement with general opinion

The discovery of neutrino oscillations was a great triumph of Bruno Pontecorvo. He came to the idea of neutrino oscillations at a time when the common opinion favored massless neutrinos and no neutrino oscillations. He pursued the idea of neutrino oscillations over decades.