Bruno Pontecorvo and Neutrino

S. Bilenky
JINR(Dubna)

August 20, 2012

The unified theory of the weak and electromagnetic interactions (Standard Model) perfectly describes all existing electroweak data

Existence of the scalar Higgs boson is the last unconfirmed prediction of the SM. We can hope that this most untrivial prediction of the SM also will be confirmed: a Higgs-like particle was recently discovered in LHC experiments

All other fundamental predictions of the SM (existence of NC, third type of neutrino ν_{τ}, t-quark, existence of $W^{\pm}$ and Z^{0}-bosons, prediction of their masses etc) were perfectly confirmed by experiments

The SM appeared in 1967 as a result of a long phenomenological period of the development of the theory of weak interaction

During this phenomenological period very successful phenomenological $V-A$ current$\times$ current theory of the weak interaction was created (Feynman-Gell-Mann, Marshak-Sudarshan)

The $V-A$ theory naturally became a part of the SM. Without this theory the SM could not appear

Bruno Pontecorvo was great physicists with bright, courageous ideas. He made extremely important contribution to physics of neutrino and weak interaction during phenomenological period of the development of the theory.

We all know that the SM is not the final theory of elementary particles and that it must be a beyond the SM physics.

The search for effects of physics beyond the SM is a main aim experiments at LHC and many other experiments.

The first effects of such physics were found in neutrino experiments

The idea of experiments which lead to discovery of a new, beyond the SM physics were proposed by Bruno Pontecorvo (neutrino oscillations)

Bruno Pontecorvo made the following fundamental contributions to neutrino physics

1. He proposed the first (radiochemical) method of neutrino detection (1946). Many years later this method allowed to discover solar neutrinos.

2. He was the first who came to an idea of $\mu - e$ universality of the weak interaction.

3. He proposed the experiment with accelerator neutrinos which allowed to prove that ν_μ and ν_e are different particles.

4. He was the first who came to idea of neutrino oscillations. Together with collaborators he develop a full phenomenological theory of neutrino masses and mixing and proposed solar, reactor, atmospheric and accelerator neutrino experiments.

In order to stress importance of B.P. contribution to neutrino physics I will also briefly discuss the development of the physics of neutrino and weak interaction

The neutrino physics started with Pauli hypothesis of neutrino (1930) and the Fermi theory of the β-decay (1934)

Pauli wanted to solve the problem of continuous β-spectrum

If one assume that energy and momentum is conserved there was only one possibility to solve this problem. Namely, to assume that in the β-decay together with electron additional particle was produced. Because in the β-decay experiments only electrons were observed, Pauli had to assume that a new particle had "weak interaction" (neutral and has penetration length ≥ 10 of the penetration length of the photon). Pauli also suggested that spin of a new particle was equal to 1/2 the its mass was small ($\leq m_e$)

The first theory of the β-decay was proposed by E. Fermi (1934).

Fermi assumed that the β-decay of a nuclei is due to the decay of the neutron

$$n \to p + e^- + \bar{\nu}$$

By analogy with electromagnetic interaction Fermi suggeted that the Hamiltonian of the process has the following vector form

$$\mathcal{H}^\beta(x) = G_F \ \bar{p}(x)\gamma^\alpha n(x) \ \bar{e}(x)\gamma_\alpha \nu(x) + \text{h.c.}$$

Here G_F is the interaction constant (Fermi constant) and $p(x), e(x), ...$ are fields of protons, electrons,...

The Fermi Hamiltonian allowed to describe decays of many nuclei.

Because $p(x), e(x), ...$ are quantum fields the Fermi Hamiltonian describes not only the β-decay of the neutron but also processes

$$\nu + n \to p + e^-, \quad \bar{\nu} + p \to e^+ + n \quad \text{etc}$$

In 1934, soon after the Fermi paper appeared, Bethe and Pierls estimated the cross section of the interaction of neutrino with a nucleus

At relatively small MeV energies nuclear matrix elements of the processes

$$(A,Z) \to (A,Z+1)+e^{-}+\bar{\nu}, \;\; \bar{\nu}+(A,Z+1) \to e^{+}+(A,$$

are practically the same

The β-decay width $\Gamma = \frac{1}{T_{1/2}}$ and the neutrino cross section σ are proportional to the modulus-squared of the nuclear matrix elements. Thus, we have

$$\sigma = \frac{A}{T_{1/2}}$$

A has dimension (length)$^2 \times$ time

Bethe and Pierls suggested that "the longest length and time are $\frac{\hbar}{m_e c}$ and $\frac{\hbar}{m_e c^2}$" They found the bound

$$\sigma < \frac{\hbar^3}{m_e^3 c^4 T_{1/2}}$$

At MeV energies they found the bound

$$\sigma < 10^{-44}\ \text{cm}^2$$

Bethe and Peierls concluded "*...there is no practically possible way of observing the neutrino*"

After the Bethe and Peierls paper there was a general opinion that neutrino is an undetectable particle.

Pauli during his visit to Caltech remarked:"I have done a terrible thing. I have postulated a particle that can not be detected"

The first physicist who challenged this opinion was B. Pontecorvo

In 1946 he proposed first (radiochemical) method of neutrino detection

"It has been currently stated in the literature that inverse β-processes produced by neutrinos can not be observed, due to the low yield. The object of this note is to show that experimental observation of neutrinos is not out of question and to suggest a method which might make an experimental observation feasible"

B.P. proposed a method of neutrino detection which is based on the observation of decay of a daughter nucleus produced in the reaction

$$\nu + (A, Z) \to e^- + (A, Z+1)$$

“radioactivity of the produced nucleus may be looked for as a proof of the inverse β process”

An experiment based on the reaction

$$\nu + {}^{37}\mathrm{Cl} \to e^- + {}^{37}\mathrm{Ar}$$

BP considered as the most promising

Cheap target (C_2Cl_4), convenient half-life of radioactive ^{37}Ar (34.8 days), possibility to extract a few atoms of ^{37}Ar from a large detector (Ar is a rare gas) etc

The Pontecorvo Cl – Ar method was used by R. Davis in the first experiment on the detection of the solar neutrinos.

Radiochemical Ga – Ge method based on the observation of the reaction

$$\nu + {}^{71}\mathrm{Ga} \to e^- + {}^{71}\mathrm{Ge}$$

was used in the GALLEX-GNO and SAGE solar neutrino experiments.

In 2002 R. Davis was awarded the Nobel Prize for the detection of the solar neutrinos

In the first paper on neutrino detection B. Pontecorvo paid attention on the following intensive sources of neutrinos

- The sun
- Reactors
- Radioactive materials produced in reactors

In 1948 B.P. invented low-background proportional counter with high amplification. This counter was crucial for detection of solar neutrinos in Homestake, GALLEX and SAGE experiments.

After the famous Conversi, Pancini and Piccioni experiment (1945), in which it was proved that muon is weakly interacting particle, Bruno Pontecorvo together with E. Hincks started a series of brilliant experiments on the investigation of muon decay

They proved that

1. The charged particle emitted in μ-decay is electron.

2. Muon decays into three particles.

3. Decay $\mu \to e + \gamma$ is forbidden.

Thinking about muons B.P. came to an idea that in muon capture by nuclei neutrino is emitted

He compared the probabilities of the processes

$$\mu^- + (A,Z) \to \nu + (A, Z-1)$$

and

$$e^- + (A,Z) \to \nu + (A, Z-1)$$

and concluded that these two processes are characterized by the same Fermi constant G_F(1947).

Thus, BP was the first who came to an idea that weak interaction include not only $e-\nu$ pair but also $\mu-\nu$ pair and that this general weak interaction is $\mu - e$ universal

Later to the idea $\mu - e$ universality of the weak interaction came Puppi, Klein, Tiomno and Wheeler.

The first theory of neutrino was the theory of the two-component massless neutrino

It was proposed by Landau, Lee and Yang and Salam in 1957 soon after the parity violation in the β-decay and other weak processes was discovered

Neutrino field $\nu(x)$ satisfies the Dirac equation

$$(i\gamma^{\alpha}\ \partial_{\alpha} - m_{\nu})\nu(x) = 0$$

m_{ν} is neutrino mass.

$\nu(x)$ can be presented as of the sum of left-handed and right-handed components

$$\nu(x) = \nu_L(x) + \nu_R(x) \quad \nu_{L,R}(x) = \frac{1 \mp \gamma_5}{2}\nu(x)$$

Two coupled equations

$$i\gamma^{\alpha}\partial_{\alpha}\nu_{L,R}(x) - m_{\nu}\nu_{R,L}(x) = 0$$

Landau, Lee and Yang and Salam assumed that m_{ν}

At that time from the β-decay experiments.

$$m_{\nu} \lesssim 200~\text{eV}, \quad m_{\nu} \lesssim 4 \cdot 10^{-4} m_{e}$$

(One of the first experiment was done by B. Pontecorvo)

If neutrino is massless particle

$$i\gamma^{\alpha}\partial_{\alpha}\nu_{L,R}(x) = 0$$

Neutrino field is $\nu_{L}(x)$ or $\nu_{R}(x)$

Two main consequences

- Large violation of the parity (in agreement with Wu et al and other experiments)

- Neutrino (antineutrino) helicity is equal -1 (+1) (if neutrino field is ν_L)

Notice, that under the inversion left-handed (right-handed) component of the field is transformed into right-handed (left-handed) component:

$$\nu'_L(x') = \gamma^0 \nu_R(x), \quad \nu'_R(x') = \gamma^0 \nu_L(x)$$

Thus, two-component theory corresponds to maximal violation of the parity

The neutrino helicity was measured in Goldhaber et al experiment(1958). In this experiment neutrino helicity was obtained from the measurement of the circular polarization of γ's produced in the chain of reactions

$$\begin{array}{ll} e^- + {}^{152}\mathrm{Eu} \to \nu + & {}^{152}\mathrm{Sm}^* \\ & \quad\downarrow \\ & {}^{152}\mathrm{Sm} \quad + \gamma. \end{array}$$

Goldhaber et al concluded "... our result is compatible with 100% negative helicity of neutrino emitted in orbital electron capture".

The two-component neutrino theory was perfectly confirmed

In 1958 Feynman and Gell-Mann, Marshak and Sudarshan generalized the theory of the two-component neutrino and build universal $V - A$ theory of the weak interaction

They assumed that in the Hamiltonian of the weak interaction enter not only left-handed component of the massless neutrino field but left-handed components of all all fields

It was a generalization of the idea of maximal violation of the parity

The Hamiltonian of the β-decay took the simplest possible form

$$\mathcal{H}_I^{\beta} = \frac{G_F}{\sqrt{2}} 4\, \bar{p}_L \gamma_\alpha n_L \; \bar{e}_L \gamma^\alpha \nu_L + h.c.$$

Only one interaction constant. Perfect agreement with experimental data

Feynman and Gell-Mann built theory of not only β-decay but also μ-capture $(\mu^- + p \to \nu + n)$ μ-decay $(\mu^+ \to e^+ + \nu + \bar{\nu})$ and other processes

They implemented Pontecorvo and others idea of the universaliry of the weak interaction. Namely, they introduced the universal CC

$$j_{\alpha}^{CC} = 2\ (\bar{p}_L \gamma_\alpha n_L + \bar{\nu}_L \gamma_\alpha e_L + \bar{\nu}_L \gamma_\alpha \mu_L)$$

and assumed that the Hamiltonian of the weak interaction had current × current form

$$\mathcal{H}_I = \frac{G_F}{\sqrt{2}}\ j^{\alpha}\ j_{\alpha}^{+}$$

Nondiagonal terms are Hamiltonians of the β-decay, μ-capture, μ-decay and other processes. They are characterized by the same constant G_F

Let us return back to charged current

After the $V - A$ was created there appeared a problem

Are neutrino which is produced in the β-decay (due to $\bar{\nu}_L \gamma_\alpha e_L$) and neutrino produced in μ-capture (due to $\bar{\nu}_L \gamma_\alpha \mu_L$) the same or different particles?

B. Pontecorvo remembered "....for people working with muons in the old times, the question about different types of neutrinos has always been present. True, later on many theoreticians forgot all about it and some of them "invented" again the two neutrinos...."

In 1959 Pontecorvo (and also Markov and Schwartz) came to an idea of the feasibility of experiments with accelerator neutrinos

B.P. proposed an experiment with accelerator neutrinos which could answer in a direct, model-independent way the question of existence of the second type of neutrino

This proposal was realized in the famous Brookhaven experiment in 1962. It was proved that $\nu_\mu \neq \nu_e$.

In 1988 L. Lederman, M. Schwartz and J. Steinberger were awarded the Nobel Prize "for the neutrino beam method and the demonstration of the doublet structure of the leptons through the discovery of the muon neutrino".

The discovery of the second type of neutrino meant that existed two families of leptons

$$\begin{pmatrix} \nu_e \\ e \end{pmatrix} \quad \begin{pmatrix} \nu_\mu \\ \mu \end{pmatrix}$$

which had the same weak interaction

Remark about universality

In modern theory (The Standard Model) interaction is generated by the following (gauge) change in the free Lagrangian

$$\partial_\alpha \, L_{lL}(x) \to (\partial_\alpha + i \, g_l \, \frac{1}{2} \, \vec{\tau} \cdot \vec{A}_\alpha(x)) \, L_{lL}(x)$$

$$L_{lL}(x) = \left(\begin{array}{c} \nu_{lL}(x) \\ l_L(x) \end{array} \right)$$

is lepton doublet ($l = e, \mu, \tau$),

$$W_\alpha = \frac{1}{\sqrt{2}}(A^1_\alpha + iA^2_\alpha)$$

In the nonabelian $SU(2) \times U(1)$ theory the constant g enters into the stress tensor

$$\vec{F}_{\alpha\beta} = \partial_\alpha \vec{A}_\beta - \partial_\beta \vec{A}_\alpha - g\vec{A}_\alpha \times \vec{A}_\beta$$

If exist one $W^\pm$-boson all constant g must be the same $g_e = g_\mu = g_\tau$

The universality tells us that the theory is gauge, nonabelian and only one gauge $W^\pm$-boson exists

We come now to the most brilliant idea of Bruno Pontecorvo which create a new field of neutrino research and a new era in neutrino physics

NEUTRINO OSCILLATIONS

After the two-component neutrino theory there was a general belief that neutrinos are massless particles. Neutrino oscillations (periodical transitions between different types of neutrinos in neutrino beams) are effects of small neutrino masses and neutrino mixing. They are impossible for massless neutrinos

The first idea of small neutrino masses and neutrino oscillations was suggested by B. Pontecorvo in 1957-58. At that time a Gell-Mann and Pais theory of $K^0 \rightleftarrows \bar{K}^0$ mixing and oscillations was confirmed by experiment. Pontecorvo was fascinated by the idea of particles mixing and oscillations and thought about a possibility of oscillations in the lepton world. (he believed in a similarity of the weak interaction of hadrons and leptons). In such a way he came to an idea of neutrino oscillations which was very courageous and not trivial idea at that time.

Let us consider first $K^0 - \bar{K}^0$ mixing and oscillations

K^0 and $\bar{K}^0$ are particles with $S = \pm 1$.

They are produced in hadronic processes in which the strangeness is conserved

$$H_0|K^0\rangle = m|K^0\rangle, \quad H_0|\bar{K}^0\rangle = m|\bar{K}^0\rangle$$

H_0 is the sum of the free Hamiltonian and Hamiltonians of the strong and electromagnetic interactions

$$|\bar{K}^0\rangle = CP\ |K^0\rangle$$

The weak interaction does not conserve strangeness

Let us neglect small effects of the violation of CP

Eigenstates of the total Hamiltonian are CP-even and CP-odd superpositions

$$|K_1\rangle = \frac{1}{\sqrt{2}}\left(|K^0\rangle + |\bar{K}^0\rangle\right)\ |K_2\rangle = \frac{1}{\sqrt{2}}\left(|K^0\rangle - |\bar{K}^0\rangle\right)$$

$|K_{1,2}\rangle$ are states with definite masses and widths

$$H\ |K^0_{1,2}\rangle = \lambda_{1,2}\ |K^0_{1,2}\rangle$$

$$\lambda_{1,2} = m_{1,2} - \frac{i}{2}\Gamma_{1,2}$$

We have

$$|K^0\rangle = \frac{1}{\sqrt{2}}\,(|K_1\rangle + |K_2\rangle), \quad |\bar{K}^0\rangle = \frac{1}{\sqrt{2}}\,(|K_1\rangle - |K_2\rangle)$$

The states of particles with definite strangeness K^0 and $\bar{K}^0$ are superpositions ("mixtures") of the states of particles with definite masses and widths K_1 and K_2

States with definite masses and widths are evolving in proper time t as

$$|K_{1,2}\rangle_t = e^{-i\lambda_{1,2}t}\ |K_{1,2}\rangle$$

Evolution in time of the state $|K^0\rangle$

$$|K^0\rangle_t = \frac{1}{\sqrt{2}}(e^{-i\lambda_1 t}\ |K_1^0\rangle + e^{-i\lambda_2 t}\ |K_2^0\rangle)$$

Thus, we have

$$|K^0\rangle_t = g_+(t)|K^0\rangle + g_-(t)|\bar{K}^0\rangle$$

$$g_\pm(t) = \frac{1}{2}(e^{-i\lambda_1 t} \pm e^{-i\lambda_2 t})$$

Because of the mixing at $t > 0$ *the state of K^0 become superposition of states of K^0 and $\bar{K}^0$*

The probability of the transition $K^0 \to \bar{K}^0$ during the time t

$$P = \frac{1}{4}(e^{-\Gamma_1 t} + e^{-\Gamma_2 t} - 2e^{-\frac{1}{2}(\Gamma_1+\Gamma_2)t} \cos \Delta m t)$$

$\Delta m = m_2 - m_1$. Oscillating term originates from the interference of the exponents. The study of the t-dependence in the region $\Delta m\ t \geq 1$ allows to determine Δm From experimental data

$$\Delta m = (3.483 \pm 0.006) \cdot 10^{-6}\mathrm{eV}$$

B. Pontecorvo came first to an idea of muonium$(\mu^+ - e^-)$ -antimuonum $(\mu^- - e^+)$ oscillations (1957) which are analogous to $K^0 \rightleftarrows \bar{K}^0$ oscillations. He mentioned neutrino oscillations. "If the two-component neutrino theory turn out to be incorrect and if the conservation law of neutrino charge would not apply, then in principle neutrino $\rightleftharpoons$ antineutrino transitions could take place in vacuum."

Only one type of neutrino was known at that time

According to the two-component theory there are only two neutrino states: ν_L and $\bar{\nu}_R$

Pontecorvo assumed

1. Neutrinos have small masses.
2. Lepton number is violated.
3. Exist additional neutrino states $\bar{\nu}_L$ and ν_R
4. Transitions $\nu_L \to \bar{\nu}_L$ and $\bar{\nu}_R \to \nu_R$ are possible

"If the theory of two-component neutrino theory was not valid (which is hardly probable at present) and if the conservation law for neutrino charge took no place, neutrino $\to$

antineutrino transitions in vacuum would be in principle possible.”

In analogy with $K^0 - \bar{K}^0$ mixing Pontecorvo assumed that

$$|\bar{\nu}_R\rangle = \frac{1}{\sqrt{2}}(|\nu_1\rangle + |\nu_2\rangle), \quad |\nu_R\rangle = \frac{1}{\sqrt{2}}(|\nu_1\rangle - |\nu_2\rangle)$$

$|\nu_{1,2}\rangle$ are states of Majorana neutrinos with masses $m_{1,2}$.

In contrast to $K^0_{1,2}$ neutrinos $\nu_{1,2}$ are stable particles

We find (in lab. system)

$$|\bar{\nu}_R\rangle_t = \frac{1}{\sqrt{2}}(e^{-iE_1 t}|\nu_1\rangle + e^{-iE_2 t}|\nu_2\rangle)$$

Can be rewritten

$$|\bar{\nu}_R\rangle_t = \frac{1}{2}(g_+(t)|\bar{\nu}_R\rangle + g_-(t)|\nu_R\rangle)$$

$$g_{\pm}(t) = (e^{-iE_1 t} \pm e^{-iE_2 t})$$

$$E_i = \sqrt{p^2 + m_i^2} \simeq p + \frac{m_i^2}{2p},$$

p is the neutrino momentum

The survival probability

$$P(\bar{\nu}_R \to \bar{\nu}_R) = 1 - \frac{1}{2}(1 - \cos\frac{\Delta m^2 L}{2E}),$$

$$\Delta m^2 = m_2^2 - m_1^2$$

$L \simeq t$ is the distance between neutrino source and neutrino detector

The paper on neutrino oscillations was published by B. Pontecorvo in 1958. At that time R. Davis was doing an experiment with reactor antineutrinos. He searched for production of ^{37}Ar in the process

$$\bar{\nu} + {}^{37}\text{Cl} \to \text{e}^- + {}^{37}\text{Ar}$$

A rumor reached B. Pontecorvo that R. Davis had seen such events. In the beginning B.P. thought that the "events" can be explained by $\bar{\nu}_R \to \nu_R$ oscillations. Later, when rumor was not confirmed, he continued to think that the transitions were possible but ν_R are sterile, non interacting neutrinos

Three citation from Pontecorvo first paper on neutrino oscillations(1958)

"Neutrinos in vacuum can transform themselves into antineutrinos and vice versa. This means that neutrino and antineutrino are particle mixtures , i.e., a symmetric and antisymmetric combination of two truly neutral Majorana particles ν_1 and ν_2".

" Beam of neutral leptons from a reactor which at first consists mainly of antineutrinos will change its composition and at certain distance R from the reactor will be composed of neutrino and antineutrino in equal quantities"

"...the cross section of the production of neutrons and positrons in the process of the absorption of antineutrinos from a reactor by protons would be smaller than the expected cross section. It would be extremely interesting to perform the Reins-Cowan experiment at different distances from reactor"

The program of the study of oscillations of reactor antineutrinos, which was outlined by B. Pontecorvo in the very first paper on neutrino oscillations, was realized in the KamLAND experiment in about 40 years later

In 1967 in the second paper on neutrino oscillations Pontecorvo considered $\nu_e \rightleftarrows \nu_\mu$

oscillations and applied idea of neutrino oscillations to solar neutrinos

At that time R. Davis started his famous experiment on the detection of the solar neutrinos in which the radiochemical method, proposed by B.Pontecorvo in 1946, was used.

The first Davis result was obtained in 1970. It was found that the upper bound of the observed flux of the solar ν_e's is (2-3) times smaller than the predicted flux ("the solar neutrino puzzle")

B. Pontecorvo envisaged the puzzle. In 1967 before R. Davis obtained his first result he wrote: "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." B.P. understood , however, that the prediction of the flux of high-energy ^8B neutrinos, which give the major contribution to the event rate of the Davis experiment, is a difficult problem.

It took many years of research to proof that the observed depletion of fluxes of solar neutrinos in the Davis and other experiments are effects of neutrino transitions due to neutrino masses, mixing and interaction of neutrinos with matter

In 1969 B. Pontecorvo and V. Gribov proposed the minimal scheme of neutrino mixing in which there are no sterile neutrinos, lepton number is violated and neutrino with definite masses are Majorana particles

There was a statement in the literature that if neutrino field is ν_{lL} neutrino masses are equal to zero. This is correct for Dirac neutrinos. However, if the lepton number is violated this is not the case. This was shown for the first time by Grbov and Pontecorvo.

A mass term is a sum of Lorentz-invariant products of left-handed and right-handed fields

The conjugated field $(\nu_{lL})^c = C\,\bar{\nu}_{lL}^T$ $(C\gamma_\alpha^T C^{-1} = -\gamma_\alpha, \quad C^T = -C)$ is right-handed field

A neutrino mass term in which only flavor left-handed neutrino fields enter has the form

$$\mathcal{L}^{\mathrm{M}} = -\frac{1}{2} \sum_{l',l=e,\mu,\tau} \bar{\nu}_{l'L}\, M^{\mathrm{M}}_{l'l}\, (\nu_{lL})^c + \mathrm{h.c.}$$

M^{M} is a complex, symmetric, non diagonal matrix

The matrix M^{M} can be presented in the form

$$M^{\mathsf{M}} = U\,m\,U^{T}$$

$$U^{\dagger}U = 1,\ m_{ik} = m_i\,\delta_{ik}, \quad m_i > 0$$

We have

$$\mathcal{L}^{\mathsf{M}} = -\frac{1}{2}\sum_{i=1}^{3} m_i\,\bar{\nu}_i\,\nu_i$$

The field ν_i satisfies *Majorana condition*

$$\nu_i^c(x) = \nu_i(x)$$

which means neutrino $\equiv$ antineutrino

Flavor fields ν_{lL} and Majorana fields ν_{iL} are connected by the mixing relation

$$\nu_{lL}(x) = \sum_{i=1}^{3} U_{li}\, \nu_{iL}(x)$$

In the simplest case of the two neutrino mixing

$$P(\nu_e \to \nu_e) = 1 - \frac{1}{2}\sin^2 2\theta(1 - \cos\frac{\Delta m^2 L}{2E})$$

This expression was obtained by Gribov and Pontecorvo and applied to solar neutrinos.

In 1975 and later B.Pontecvo and S.B. considered all other possibilities of neutrino mixing (Dirac mass term and the most general Dirac and Majorana mass term). All possible neutrino oscillation experiments were discussed.

In 1962 Maki, Nakagawa and Sakata suggested neutrino mixing in the framework of a Nagoya model in which proton and other barions were considered as a bound states of neutrinos and a vector boson B^+, " a new sort of matter"

The authors wrote: "We assume that there exist a representation which defines the true neutrinos ν_1 and ν_2 through orthogonal transformation"

$$\nu_1 = \cos\delta\nu_e - \sin\delta\nu_\mu, \quad \nu_2 = \sin\delta\nu_e + \cos\delta\nu_\mu$$

In contrast to Pontecorvo and others neutrino oscillations were not considered by MNS. However, they discussed possibilities of production of electrons in the Brookhaven neutrino experiment.

The 3× 3 neutrino mixing matrix is called PMNS mixing matrix in honor of the pioneers of the idea of neutrino masses and mixing

It required many years of work and heroic efforts of many experimental groups to reveal effects of tiny neutrino masses and neutrino mixing

The discovery of neutrino oscillations was real triumph of Bruno Pontecorvo who proposed neutrino oscillations and pursued the idea of oscillations for many years, when the general opinion favored massless neutrinos and no neutrino oscillations

Bruno Pontecorvo was born in Pisa (Italy) on August 22 1913 in a wealthy and intelligent family. His father was owner of a textile factory, his mother was from family of a doctor.

Bruno had four brothers and three sisters. All were talented. His brother Guido became famous biologist; Gillo Pontecorvo became famous film director.

In his autobiography Bruno P. wrote

"A scuola ero bravo ma la cosa piu' impotrante nella mia vita era il tennis, di cui mi picco a tutt'oggi di essere un profondo conoscitore"

At school I met expectations, yet the most important thing in my life was tennis, to this day I pride myself on my deep knowledge of it.

Opinion of parents about children

"Guido era il piu intelegente dei fratelli, Paolo era il piu' serio, Giuliana la piu' colta, Bruno il piu' buono ma il piu' limitato, come era demonstrato dai suoi occhi buoni ma non intelligenti...". (From autobiography of B.P.

Guido was the most intelligent among the siblings, Paolo the most serious, Giuliana the most knowledgeable, Bruno the most good-natured but also the least smart, as shown also by his eyes, which expressed kindness but not intelligence...

After the school Bruno entered the Engineer Faculty of the Pisa University

After 2 years at the Engineer Faculty Bruno decided to switch to physics

His oldest brother Guido recommended him to go to Rome, where E.Fermi and his group worked

Bruno passed an exam (Fermi, Rasetti), and was accepted to the Rome University. He became Fermi student (1932)

In Rome B.P. was one of the authors of the discovery of the effect of slow neutrons (1934). All practical applications of neutrons are based on this effect

In 1936-40 Bruno worked in Paris in Jollot Curie group. He studied in Paris nuclear isomerism.

In 1940. when German occupied Paris, B.P. with family escaped from France and immigrated to USA

In 1940-42 in USA. B.P. worked in an oil company. He invented and applied a new method of the searching for oil (neutron well logging)

In 1943-49 in Canada B.P. worked in the Chalk River Laboratory. He was scientific leader of the first research reactor in Canada, he made first experiments on the study of μ-decay, the first experiment on the measurement of neutrino mass. He proposed the first method of neutrino detection (radiochemical method), idea of $\mu - e$ universality of the weak interactions,...

In 1950-93 Dubna, JINR. B.P. performed experiments on pion production, pion-nucleon scattering,... at the Dubna synchrocyclotron. He made first proposal of accelerator neutrino experiment which allowed to establish existence of the muon neutrino. In Dubna he came to the idea of neutrino oscillations and devoted many years to the development of this idea,...

B. M. Pontecorvo was great neutrino physicist, one of the creators of modern neutrino physics. He was extremely charming, intelligent and gifted person. Physics for him was the most important. But he also liked very much tennis, literature, music, underwater fishing, ...

Bruno Pontecorvo was a true scientist in the best, classical sense of the word. When he thought about some problem he thought about it continuously from early morning till late evening

He devoted all his resources and great intellect to science, and though he was not indifferent to the recognition of his contribution to physics, his main stimulus was search for the truth

More than ten last years were for Bruno Pontecorvo years of courageous struggle against Parkinson illness. His love to physics and to neutrino helped him to overcome difficult problems of the illness. He never stopped to work, to think about neutrinos and to continue active life.