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Colloquia: The Legacy of Bruno Pontecorvo

Bruno Pontecorvo and modern neutrino physics

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Summary. — In this review, dedicated to the centenary of the birth of the great neutrino physicists Bruno Pontecorvo, I am discussing proposed by him radiochemical method of neutrino detection, his idea of the μ-e universality of the weak interaction and proposal of the accelerator neutrino experiment which allowed to proof that ν_e and ν_μ are different particles. In some details I discuss Pontecorvo's pioneer idea of neutrino masses, mixing and oscillations and the development of this idea by Pontecorvo and Gribov and Pontecorvo and myself.

1. – Introduction

Bruno Pontecorvo was great physicists with bright, courageous ideas. He made extremely important contribution to physics of neutrino and weak interaction. The idea of neutrino oscillation experiments, which led to the discovery of effects of a new, beyond the SM physics, was proposed by B. Pontecorvo.

Bruno Pontecorvo was born on August 22, 1913 in Pisa (Marina di Pisa). His father was owner of a textile factory. The factory was founded by Pellegrino Pontecorvo, Bruno grandfather. There were eight children in the family: five brothers and three sisters. All of them were very successful. Three brothers became famous: biologist Guido (the eldest brother), physicist Bruno and movie director Gillo.

From B. Pontecorvo autobiography [1]: "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"(1).

There were eight children in the Pontecorvo's family: five brothers and three sisters. All of them were very successful. Three brothers became famous: biologist Guido (the eldest brother), physicist Bruno and movie director Gillo.

Opinion of parents about children (from Bruno autobiography): Guido was the most intelligent among the siblings, Paolo the most serious, Giuliana the most knowledgeable,

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(1) "A scuola ero bravo ma la cosa più importante nella mia vita era il tennis, di cui mi picco a tutt'oggi di essere un profondo conoscitore."

Bruno the most good-natured but also the least smart, as shown also by his eyes, which expressed kindness but not intelligence. . . (2).

Bruno entered engineer faculty of the Pisa University. However, he did not like mechanical drawing and after two years he decided to switch to physics.

From Bruno's autobiography. My brother Guido declared authoritatively "Physics! I would like to say that you must go to Rome. In Rome there are Fermi and Rasetti."

Bruno passed through exam that was taken by Fermi and Rasetti and was accepted at the third year of the Faculty of Physics and Mathematics of the Rome University with specialization in experimental physics. First as a student and later as researcher from 1931 till 1936 Bruno worked in the Fermi group. He was the youngest "ragazzo di Via Panisperna".

Bruno took part in many experiments of the Fermi group. The experiment, started by E. Amaldi and B. Pontecorvo, led to the discovery of the effect of slow neutrons, the most important discovery made by the Fermi group. The effect of slow neutrons opened the road to all practical applications of neutrons (reactors, isotopes for medicine, atomic bombs, . . .). For the discovery of the effect of slow neutrons E. Fermi was awarded by the Nobel Prize.

From 1936 till 1940 Bruno Pontecorvo worked in Paris in the Joliot-Curie group. In Paris he studied nuclear isomers, metastable nuclear states with large spins. He made first experiments on the observation of electrons of the conversion in decays of isomers, on production of nuclear isomers in process of interaction of high-energy γ-quanta with nuclei etc.

For the study of the nuclear isomerism Bruno got Curie-Carnegie prize. Fermi congratulated Bruno with excellent results. Bruno was very happy and proud by Fermi‘s congratulation (as he wrote in his autobiography, he thought that Fermi, who usually called him great champion, had respect to him only as an expert in tennis).

In 1940 before Germans occupied Paris Bruno with wife and son escaped to US. From 1940 till 1942 he worked in a private oil company in Oklahoma (USA). He developed and realized a method of neutron well logging for oil (and water) prospering. This was the first practical application of the effect of slow neutrons. Nowadays, the Pontecorvo‘s method of neutron well logging is widely used method.

In 1943 B. Pontecorvo was invited to take part in the Anglo-Canadian Uranium Project in Canada. At the age of 30 Bruno became scientific leader of the project of the research reactor which was built in 1947 and was the first nuclear reactor outside of USA.

In Canada B. Pontecorvo started research in elementary particle physics which he continued the whole his life.

In Canada B. Pontecorvo started research in elementary particle physics. Soon after the famous Fermi paper on the theory of the β-decay [2] (1934) Bethe and Pierls [3] estimated the cross section of the interaction of neutrino with a nucleus. At MeV energies they found the bound

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

Bethe and Peierls concluded that ". . . there is no practically possible way of observing

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(2) "Guido era il più intelligente dei fratelli, Paolo era il più serio, Giuliana la più colta, Bruno il più buono ma il più limitato, come era dimostrato dai suoi occhi buoni ma non intelligenti. . . "

the neutrino."

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 [4]. In [4] B. Pontecorvo wrote: "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."

The method of the neutrino detection proposed by Pontecorvo was 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 observation of the reaction

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

B. Pontecorvo considered as the most promising one by the following reasons:

- C_2Cl_4 is a cheap, non-inflammable liquid;
- ^{37}Ar nuclei are unstable (K-capture) with a convenient half-life (34.8 days);
- A few atoms of ^{37}Ar(rare gas), produced during an exposition time, can be extracted from a large detector.

The Pontecorvo's Cl$-$Ar method was used by R. Davis in his first, pioneering experiment on the detection of the solar neutrinos [5]. In 2002 R. Davis was awarded the Nobel Prize "for pioneering contributions to astrophysics, in particular for the detection of cosmic neutrinos."

The Pontecorvo's radiochemical method of neutrino detection based on the observation of the reaction

$$\nu +{}^{71}\,\mathrm{Ga} \to e^- +{}^{71}\,\mathrm{Ge}, \tag{1}$$

proposed by Kuzmin [6] was used in the GALLEX-GNO [7] and SAGE [8] solar neutrino experiments in which ν_e's from all thermonuclear reactions in the sun including neutrinos from the main $p + p \to n + p + e^+ + \nu_e$ reaction were detected.

In the seminal 1946 Chalk River paper [4] B. Pontecorvo paid attention to the following intensive sources of neutrinos existing at that time

- The sun.
- Reactors.
- Radioactive materials produced in reactors.

B. Pontecorvo and his collaborators made important contribution to the solar neutrino experiments. In 1948 they invented low-background proportional counter [9] that allowed to detect very rare events. This counter was crucial for detection of neutrinos in all radiochemical solar neutrino experiments (Homestake, GALLEX-GNO and SAGE).

After the famous Conversi, Pancini and Piccioni experiment [10], in which it was proved that muon is a weakly interacting particle, Bruno Pontecorvo together with E. Hincks started a series of brilliant experiments on the investigation of the muon decay.

They proved that the charged particle emitted in the μ-decay is electron, and that muon decays into three particles. They obtained the first upper bound on the probability of the decay $\mu \to e + \gamma$.

In 1947 Bruno Pontecorvo was the first who paid attention on a deep analogy between week interaction of the electron and the muon [12].

Thinking at that time about muons Bruno Pontecorvo 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.

B.Pontecorvo suggested that the muon is a particle with spin 1/2 and in the process of capture of the muon by a nucleus neutrino is emitted. He compared the probabilities of the processes

$$\mu^- + (A, Z) \to \nu + (A, Z - 1), \quad \text{and} \quad e^- + (A, Z) \to \nu + (A, Z - 1)$$

and found that these two processes are characterized by the same Fermi constant G_F.

On the basis of this observation B. Pontecorvo came to the conclusion that exist " fundamental analogy between β-processes and processes of absorption of muons." Later the idea of $\mu - e$ universality was put forward by Puppi [13], Klein [14], Young and Tiomno [15].

Starting from 1950 Bruno Pontecorvo worked in Dubna (USSR) where at that time was the largest accelerator in the world (460 MeV later 680 MeV). B. Pontecorvo and his group performed experiments on the production of π^0 in neutron-proton and neutron-nuclei collisions, on pion-nucleon scattering and others.

Bruno always thought about neutrino. At the end of the fifties in Dubna a project of a meson factory was prepared (unfortunately the project was not realized). Thinking about future experiments at high intensity accelerators B. Pontecorvo came to the conclusion that neutrino experiments with neutrinos from decays of pions and kaons produced at high intensity accelerators were feasible [16]. Independently to the same conclusion came M.A. Markov [17] and Schwartz [18].

B. Pontecorvo always, starting from his Canadian time, had in mind that muon and electron neutrinos could be different particles (3). When he came to the conclusion that experiments with high energy accelerator neutrinos are feasible he understood that such experiments give us the best, model independent possibility to answer the question whether ν_μ and ν_e are the same or different particles [16].

Pontecorvo's proposal was realized in the famous Brookhaven experiment [19] (1962). It was proved that $\nu_e \neq \nu_\mu$. In 1988 Lederman, Schwartz and Steinberger were awarded

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(3) 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.... ".

the Nobel Prize for "the discovery of the muon neutrino leading to classification of particles in families."

2. – First ideas of neutrino masses, mixing and oscillations (1957-58)

After the two-component neutrino theory [20-22] and its confirmation in the experiment on the measurement of the neutrino helicity [23] 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. Neutrino oscillations are impossible for massless neutrinos.

Bruno Pontecorvo did not follow this common belief. He proposed an idea of neutrino oscillations in 1957-1958 [24,25] at the time of a triumph of the two-component neutrino theory.

B. Pontecorvo was impressed by a possibility of $K^0 \leftrightarrows \bar{K}^0$ oscillations suggested by Gell-Mann and Pais [26]. The phenomenon $K^0 \leftrightarrows \bar{K}^0$ oscillations is based on the following facts

1. K^0 and $\bar{K}^0$ are particles with strangeness $+1$ and -1, respectively. The strangeness is conserved in the strong interaction.
2. Weak interaction, in which strangeness is not conserved, induce transitions between K^0 and $\bar{K}^0$.
3. States of K^0 and $\bar{K}^0$, produced in processes of strong interaction, are superpositions ("mixtures") of states of K_1^0 and K_2^0, particles with definite masses and widths, eigenstates of the total Hamiltonian.

In the paper [24] B. Pontecorvo put the following question: "...wheather there exist other 'mixed' neutral particles (not necessarily elementary ones) which are not identical to corresponding antiparticles and for which particle-antiparticle transitions are not strictly forbidden."

He came to a conclusion such a system could be muonium $(\mu^+ + e^-)$ and antimuonium $(\mu^- + e^+)$.

At that time it was not known that ν_e and ν_μ are different particles. If they are the same particles transitions $(\mu^+ + e^-) \to (\mu^- + e^+)$ are allowed and are induced (in the second order of the perturbation theory) by the same weak interaction which is responsible for μ-decay. In [24] B. Pontecorvo considered $(\mu^+ + e^-) \rightleftarrows (\mu^- + e^+)$ oscillations in some details.

Let us notice that modern experiments on the search muonium-antimuonium transitions (see [27]) are considered as a sensitive way of obtaining an information about an interaction in which flavor lepton numbers are changed by two.

In the paper [24] B. Pontecorvo made the following remark about neutrino: "If the theory of two-component neutrino was not valid (which is hardly probable at present) and if the conservation law for neutrino charge took no place, neutrino → antineutrino transitions in vacuum would be in principle possible."

The problem was that according to the two-component neutrino theory for one neutrino type exist only left-handed neutrino ν_L and right-handed antineutrino $\bar{\nu}_R$. Transitions between them are forbidden by the conservation of the angular momentum.

Some rumor helped B.Pontecorvo to realize the idea of neutrino oscillations in the case of one neutrino.

In 1957 R. Davis made an reactor experiment on the search for the process

$$\bar{\nu} + ^{37}\mathrm{Cl} \to e^- + ^{37}\mathrm{Cl} \tag{2}$$

in which the lepton number is violated [28]. A rumor reached Pontecorvo that Davis observed such events. He suggested that these "events" could be due to transitions of reactor antineutrinos into right-handed neutrinos on the way from the reactor to the detector [25].

This was a very courageous idea. Let us stress again that in at that time only one type of neutrinos was known. B. Pontecorvo assumed that there are transition $\bar{\nu}_R \to \nu_R$ (and $\nu_L \to \bar{\nu}_L$). Thus, he had to assume that not only the lepton number is not conserved but also in addition to the standard right-handed antineutrino $\bar{\nu}_R$ and left-handed neutrino ν_L (quanta of the left-handed field $\nu_L(x)$) existed also right-handed neutrino ν_R and left-handed antineutrino $\bar{\nu}_L$, quanta of right-handed field $\nu_R(x)$.

In [25] B. Pontecorvo wrote: "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."

In order to explain Davis "events", B. Pontecorvo had to assume that "a definite fraction of particles (ν_R) can induce the Cl − Ar reaction." Later, when such anomalous "events" disappeared and only upper bound for the cross section of the reaction (2) was found in the Davis experiment, B. Pontecorvo understood that there is no need in such assumption. The terminology "sterile neutrino", which is standard nowadays, was introduced by him in the next neutrino oscillations paper [29].

In the very first paper on neutrino oscillations B. Pontecorvo considered possible disappearance of reactor antineutrinos in the Reines and Cowan type experiment [30]. He wrote in [25]: "The cross section of the process $\bar{\nu} + p \to e + +n$ with $\bar{\nu}$ from reactor must be smaller than expected. 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."

Starting from the paper [25] all his life Bruno believed in existence of neutrino oscillations. 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."

3. – The second Pontecorvo's paper on neutrino oscillations (1967)

Next paper on neutrino oscillations was written by B. Pontecorvo in 1967 [29]. At that time phenomenological $V - A$ theory was established, $K^0 \leftrightarrows \bar{K}^0$ oscillations were observed and it was proved that (at least) two types on neutrinos ν_e and ν_μ existed in nature.

It was easy for Pontecorvo to generalize his idea of neutrino oscillations for the case of two types of neutrinos ν_e and ν_μ. He wrote: "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."

In the paper [29] Pontecorvo considered oscillations between active neutrinos $\nu_\mu \leftrightarrows \nu_e$ and also between active and sterile neutrinos $\nu_\mu \leftrightarrows \bar{\nu}_{eL}$ etc.

In the 1967 paper B.Pontecorvo for the first time discussed the effect of neutrino oscillations for the solar neutrinos: "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 that the flux of observable sun neutrinos must be two times smaller than the total neutrino flux."

It was written at the time when R. Davis prepared his famous solar neutrino experiment. When in 1970 the first results of the experiment were obtained [31] it occurred that the detected flux of the solar neutrinos was about 2–3 times smaller than the predicted flux. This result created so called solar neutrino problem. It was soon commonly accepted that among different astrophysical explanations of the problem proposed by Pontecorvo effect of oscillations of the solar neutrinos was the most natural explanation.

4. – Gribov-Pontecorvo paper on neutrino oscillations (1969)

Gribov and Pontecorvo [32] considered a scheme of neutrino mixing and oscillations with four neutrino and antineutrino states: the left-handed neutrinos ν_e and ν_μ and right-handed antineutrinos $\bar{\nu}_e$ and $\bar{\nu}_\mu$. They assumed that there are no sterile neutrino states.

It was assumed in the paper [32] that in addition to the standard charged current $V - A$ interaction with the lepton current

$$j_\alpha = 2(\bar{\nu}_{eL}\gamma_\alpha e_L + \bar{\nu}_{\mu L}\gamma_\alpha \mu_L) \tag{3}$$

in the total Lagrangian enters an effective superweak interaction which violate L_e and L_μ.

After the diagonalization of the most general effective Lagrangian of this type the following mixing relations were found

$$\nu_{eL} = \cos\theta \nu_{1L} + \sin\theta \nu_{2L}, \quad \nu_{\mu L} = -\sin\theta \nu_{1L} + \cos\theta \nu_{2L}\,. \tag{4}$$

Here $\nu_{1,2} = \nu^c_{1,2}$ are fields of the Majorana neutrinos with masses $m_{1,2}$ (4) and θ is a mixing angle. Neutrino masses and the mixing angle are determined by parameters of the effective Lagrangian.

The authors obtained the following expression for the $\nu_e \to \nu_e$ survival probability in vacuum (in modern notations):

$$P(\nu_e \to \nu_e) = 1 - \frac{1}{2}\sin^2 2\theta(1 - \cos\frac{\Delta m^2 L}{2E}), \quad \Delta m^2 = m_2^2 - m_1^2 \tag{5}$$

and applied the developed formalism to the solar neutrino oscillations. They considered a possibility of the maximal mixing $\theta = \pi/4$. as the most simple and attractive one. In this case the averaged observed flux of the solar neutrinos was equal to 1/2 of the predicted flux.

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(4) Because the effective Lagrangian violate L_e and L_μ there are no quantum numbers which can distinguish neutrinos and antineutrinos. This is the reason why fields of neutrinos with definite masses are Majorana fields.

Fig. 1. – Bruno Pontecorvo and the author in 1983, in Dubna (photo by Yurii Tumanov; courtesy of JINR, Dubna).

5. – General phenomenological theory of neutrino mixing and oscillations (Dubna, 1975-1987)

B. Pontecorvo and my work on neutrino masses, mixing and oscillations started in 1975 [33]. The first paper was based on the idea of quark-lepton analogy.

It was established at that time that the charged current of quarks has the form (in the case of four quarks)

$$j_{\alpha}^{CC(quark}(x) = 2(u_L(x)\gamma_{\alpha}d_L^c(x) + \bar{c}_L(x)\gamma_{\alpha}s_L^c(x)). \tag{6}$$

Here

$$d^c_L(x) = \cos\theta_C d_L(x) + \sin\theta_C s_L(x), \quad s^c_L(x) = -\sin\theta_C d_L(x) + \cos\theta_C s_L(x) \tag{7}$$

are Cabibbo-GIM mixtures of d and s quarks with masses m_d and m_s and θ_C is the Cabibbo angle.

The lepton charged current

$$j^{CC(lept)}_\alpha(x) = 2(\bar{\nu}_{eL}(x)\gamma_\alpha e_L(x) + \bar{\nu}_{\mu L}(x)\gamma_\alpha \mu_L)(x)\,. \tag{8}$$

has the same form as the quark charged current (same coefficients, left-handed components of the fields).

In order to make an analogy between quarks and leptons complete it was natural to assume that $\nu_{eL}(x)$ and $\nu_{\mu L}(x)$ are also mixed fields:

$$\nu_{eL}(x) = \cos\theta\nu_{1L}(x) + \sin\theta\nu_{2L}(x), \quad \nu_{\mu L}(x) = -\sin\theta\nu_{1L}(x) + \cos\theta\nu_{2L}(x). \tag{9}$$

Here $\nu_1(x)$ and $\nu_2(x)$ are Dirac fields of neutrinos with masses m_1 and m_2 and θ is the leptonic mixing angle. We wrote in the paper [33]: "...in our scheme ν_1 and ν_2 are just as leptons and quarks (which, may be, is an attractive feature) while in Gribov-Pontecorvo scheme the two neutrinos have a special position among the other fundamental particles."

If the mixing (9) takes place, the total lepton number $L = L_e + L_\mu$ is con- served and neutrinos with definite masses ν_i (i=1,2) differ from antineutrinos $\bar{\nu}_i$ by the lepton number $(L(\nu_i) = -L(\bar{\nu}_i) = 1)$.

After the great success of the two-component theory in 1975 there was still a general belief than neutrinos are massless nonoscillating particles. Our main arguments for neutrino masses were at that time the following

1. There was no principle (like gauge invariance in the case of γ-quanta) which required that masses of neutrinos must be equal to zero.
2. In the framework of the two-component neutrino theory massless of neutrinos was an argument in favor of the left-handed neutrino fields. It occurred, however, that in the weak Hamiltonian enter *left-handed components of all fields* (the $V-A$ theory). In the framework of the $V-A$ theory it was more natural consider neutrinos not as a special massless particles but as a particles with some masses.

In the paper [33] we discussed in a possible value of the mixing angle θ. We argued that

- there is no reason for lepton and Cabibbo mixing angles be the same;
- "the special values of the mixing angles $\theta = 0$ and $\theta = \pi/4$ (maximum mixing) are of the greatest interest."

For probabilities of the two-neutrino transitions we obtain the following expressions

$$P(\nu_l \to \nu_{l'}) = \frac{1}{2}\sin^2 2\theta\left(1 - \cos\frac{\Delta m^2 L}{2E}\right) \quad (l' \neq l) \tag{10}$$

and

$$P(\nu_l \to \nu_l) = 1 - \frac{1}{2}\sin^2 2\theta\left(1 - \cos\frac{\Delta m^2 L}{2E}\right), \tag{11}$$

the same as in the case of the mixing of two Majorana neutrinos (^{5}).

In the paper [35] we considered the most general neutrino mixing. In accordance with modern gauge theories we started to characterize neutrino mixing by the neutrino mass term. In 1977 B. Pontecorvo and me wrote first review on neutrino oscillations [36] in which we summarized the situation with neutrino masses, mixing and oscillations at the time when special experiments on the search for neutrino oscillations yet were not started. This review attracted attention of many physicists to the problem of neutrino mass and oscillations.

I will briefly summarize our papers and our understanding of neutrino oscillations (^{6}). Three types of the neutrino mass terms and, correspondingly, neutrino mixing are possible (^{7}).

1. Majorana neutrino mixing

$$\nu_{lL} = \sum_{i=1}^{3} U_{li}\nu_{iL} \quad l = e, \mu, \tau. \tag{12}$$

   Here ν_i is the field of the Majorana neutrino with mass m_i, U is a unitary 3×3 mixing matrix which is characterized by three mixing angles and three CP phases. Transitions only between flavor neutrinos $\nu_l \leftrightarrows \nu_{l'}$ are possible.

2. Dirac neutrino mixing

$$\nu_{lL} = \sum_{i=1}^{3} U_{li}\nu_{iL} \quad l = e, \mu, \tau\ . \tag{13}$$

   Here ν_i is the field of the Dirac neutrino with mass m_i, U is a 3×3 unitary mixing matrix which is characterized by three mixing angles and one CP phases. Transitions only between flavor neutrinos $\nu_l \leftrightarrows \nu_{l'}$ are possible.

3. Majorana and Dirac mixing

$$\nu_{\alpha L} = \sum_{i=1}^{3+n} U_{\alpha i}\nu_{iL} \quad \alpha = e, \mu, \tau, s_1, ..., s_n. \tag{14}$$

   Here ν_i is the field of the Majorana neutrino with mass m_i and U is an unitary $(3+n) \times (3+n)$ mixing matrix. Transitions between flavor neutrinos $\nu_l \leftrightarrows \nu_{l'}$ and flavor and sterile neutrinos $\nu_l \leftrightarrows \nu_{s_i}$ are possible.

(^{5}) Later it was shown [34] that in the general case of n massive neutrinos probabilities of neutrino transitions have the same form in the case of mixing of neutrinos with Dirac and Majorana masses

(^{6}) Notice that there are still many debates in the literature about the basics of neutrino oscillations (see [37, 38])

(^{7}) See reviews [36, 39].

We developed non stationary picture of neutrino oscillations. In CC weak processes together with lepton l^+ flavor neutrino ν_l is produced ($l = e, \mu, \tau$). The flavor neutrino ν_l is described by the mixed state

$$|\nu_l\rangle = \sum_i U^*_{li} |\nu_i\rangle. \tag{15}$$

Here $|\nu_i\rangle$ is the state of neutrinos with mass m_i, momentum $\vec{p}$ and energy $E_i = \sqrt{p^2 + m_i^2} \simeq E + \frac{m_i^2}{2E}$.

In accordance with QFT we assumed that the evolution of states is determined by the Schrödinger equation

$$i\frac{\partial|\Psi(t)\rangle}{\partial t} = H_0\ |\Psi(t)\rangle, \tag{16}$$

where H_0 is the free Hamiltonian. From (16) it follows that if at $t = 0$ a flavor neutrino ν_l is produced at the time t for the neutrino state we have

$$|\nu_l\rangle_t = \ e^{-iH_0\,t}\ |\nu_l\rangle = \sum_i U^*_{\alpha i}\, e^{-iE_i t}\, |i\rangle. \tag{17}$$

Neutrinos are detected through the observation of CC and NC weak processes. From (15) and (17) for the probability of the transition $\nu_l \to \nu_{l'}$ during the time t we find the expression

$$\mathrm{P}(\nu_l \to \nu_{l'}) = |\sum_i U_{l'i} e^{-iE_i t} U^*_{li}|^2 = |\delta_{l'l} + \sum_{i\geq 2} U_{l'i} U^*_{li}\ (e^{-i\Delta m^2_{1i}\frac{L}{2E}} - 1)|^2. \tag{18}$$

Here $\Delta m^2_{1i} = m_i^2 - m_1^2$, $L \simeq t$ is the distance between a neutrino source and a neutrino detector. The expression (18) became the standard one. It is commonly used in analysis of data of experiments on the investigation of neutrino oscillations.

In 1998 after many years of heroic efforts oscillations of atmospheric neutrinos were discovered in the Super-Kamiokande experiment [40]. This was the beginning of the golden years of neutrino oscillations. In 2001 existence of oscillations of solar neutrinos was proved in a model independent way in the SNO experiment [41]. In 2002 oscillations of reactor neutrinos were discovered in the reactor KamLAND experiment [42]. Several recent accelerator [43-45] and reactor [46-48] neutrino oscillation experiments confirmed this discovery.

Discovery of neutrino oscillations was a great triumph of Bruno Pontecorvo who came to the idea of neutrino oscillations at a time when common opinion favored massless neutrinos and no neutrino oscillations and pursued and developed the idea of massive, mixed and oscillating neutrinos during many years.

From my point of view the history of the neutrino oscillations is an illustration of an 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.

Independently on Pontecorvo in 1962 Maki, Nakagawa and Sakata [49] came to an idea of neutrino masses and mixing. Their arguments were based on Nagoya model in which neutrinos were considered as constituents of barions. In the paper [49] a possibility of the transition ("virtual transmutation") $\nu_\mu \to \nu_e$ was considered. To acknowledge the pioneer ideas of Pontecorvo and Maki, Nakagawa and Sakata the neutrino mixing matrix is usually called the PMNS matrix.

6. – Conclusion

Bruno Pontecorvo was one of the first who understood importance of neutrinos for elementary particle physics and astrophysics. He felt and understood neutrinos probably better than anybody else in the world. Starting from his Canadian time he thought about neutrino the whole his life. He was never confined by narrow theoretical frameworks. He was completely open-minded, without any prejudices, very courageous and with very good intuition and scientific taste.

Bruno Pontecorvo was very bright, wise, exceptionally interesting and very friendly personality. People liked him and he had many friends in Italy, Russia, France, Canada and many other countries. He participated in many conferences, seminars and discussions. His clear laconic questions and remarks were very important for clarification of many problems.

The name of Bruno Pontecorvo, who was the founder and father of modern neutrino physics, will be forever connected with neutrino. He will remain with us in our memory and our hearts as a great outstanding physicist, as a man of great impact and humanity.

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