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Colloquia: Pontecorvo100

# Bruno Pontecorvo — pioneer of neutrino oscillations

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**Summary.** — In this brief review, dedicated to the centenary of the birth of the great neutrino physicist Bruno Pontecorvo, I am discussing his major contribution to neutrino physics, mainly to the physics of neutrino oscillations.

## 1. – Introduction

Bruno Pontecorvo was born on August 22, 1913 in Pisa (Marina di Pisa). He entered the Faculty of Engineering of the Pisa University. However, after two years he decided to switch to physics. His elder brother Giudo recommended him to go to Rome where at that time was the famous Fermi group. Bruno passed through an exam, taken by Fermi and Rasetti, and was accepted at the third year of the Faculty of Physics and Mathematics of the Rome University. Thus, Bruno Pontecorvo started his scientific work in 1932 in Rome, first as a student of E. Fermi and later as a member of the Fermi group. He was the youngest "ragazzo di Via Panisperna".

Bruno took part in many experiments of the Fermi group including the experiment in which the effect of slow neutrons was discovered.

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 the first experiments on the observation of electrons of the conversion in decays of isomers, on production of nuclear isomers in process of the irradiation of nuclei by high-energy $\gamma$-quanta etc.

From 1940 till 1942 B. Pontecorvo worked in a private oil company in Oklahoma (USA). He developed and realized a method of neutron well logging for oil prospering. This was the first practical application of the effect of slow neutrons. The Pontecorvo's method of neutron well logging is widely used nowadays.

In 1943 B. Pontecorvo was invited to take part in the Anglo-Canadian Uranium Project in Canada. He was 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.

After the Bethe and Pierls paper [1], in which it was shown that the cross section of the interaction of neutrino with nuclei was extremely small($\sigma < 10^{-44}\text{cm}^2$), the neutrino was considered as an "undetectable particle".

B. Pontecorvo was the first who challenged this opinion. In 1946 he proposed the radiochemical method of neutrino detection [2]. The method was based on the observation of decay of daughter nucleus produced in the reaction $\nu + (A, Z) \to e^- + (A, Z + 1)$.

He considered as most promising the reaction ([1])

$$\nu +^{37} \text{Cl} \to e^- +^{37} \text{Ar}. \tag{1}$$

The Pontecorvo's Cl−Ar method was used by R. Davis in his first, pioneering experiment on the detection of the solar neutrinos [3] for which R. Davis was awarded the Nobel Prize in 2002.

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

$$\nu +^{71} \text{Ga} \to e^- +^{71} \text{Ge}, \tag{2}$$

was used in the GALLEX-GNO [4] and SAGE [5] solar neutrino experiments in which $\nu_e$'s from all thermonuclear reactions in the sun including neutrinos from the main reaction $p + p \to n + p + e^+ + \nu_e$ were detected.

In the seminal Chalk River paper [2] B. Pontecorvo paid attention to the following intensive sources of neutrinos

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

In Canada B. Pontecorvo and E. Hincks [6] performed a series of pioneer experiments on the investigation of fundamental properties of muon. They proved that the charged particle emitted in $\mu$-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 to a deep analogy between week interaction of the electron and the muon [7]. 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 the constants which characterize these two processes were of the same order of magnitude. On the basis of this observation B. Pontecorvo came to the conclusion that a " fundamental analogy between $\beta$-processes and processes of absorption of muons" exists.

Later the idea of $\mu - e$ universality was put forward by Puppi [8], Klein [9], Young and Tiomno [10].

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([1]) $C_2Cl_4$ is a cheap, non-flammable liquid, $^{37}$Ar nuclei are unstable with a convenient half-life (34.8 days), a few atoms of $^{37}$Ar(rare gas) can be extracted from a large detector ...

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 $\pi^0$ in neutron-proton and neutron-nuclei collisions, on pion-nucleon scattering and others.

Bruno always thought about neutrino. At the end of the fifties he came to the conclusion that experiments with neutrinos from decays of pions and kaons produced at high intensity accelerators are feasible [11]. Independently to the same conclusion came M.A. Markov [12] and Schwartz [13]. B. Pontecorvo, however, was the first who understood that experiments with high-energy neutrinos gave us the best possibility to answer in a model independent way the fundamental question whether $\nu_\mu$ and $\nu_e$ are the same or different particles [11]. Pontecorvo's proposal was realized in 1962 in the famous Brookhaven experiment [14]. It was proved that $\nu_e \neq \nu_\mu$. In 1988 Lederman, Schwartz and Steinberger were awarded 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)

We come now to the most important idea of Bruno Pontecorvo, idea of neutrino masses, mixing and oscillations. He came to the idea of neutrino oscillations in 1957-1958 [15, 16] soon after the two-component neutrino theory [17-19] was proposed and confirmed in Goldhaber et al experiment [20].

B. Pontecorvo was impressed by a possibility of $K^0 \leftrightarrows \bar{K}^0$ oscillations suggested by Gell-Mann and Pais [21]. 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 $K^0_1$ and $K^0_2$, particles with definite masses and widths.

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 that such a system could be muonium $(\mu^+ + e^-)$ and antimuonium $(\mu^- + e^+)$ [15].

In the paper [15] he 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 $\to$ antineutrino transitions in vacuum would be in principle possible."

Only one type of neutrino was known at that time. According to the two-component neutrino theory in this case only left-handed neutrino $\nu_L$ and right-handed antineutrino $\bar{\nu}_R$ exist. Transitions between them are forbidden by the conservation of the angular momentum.

Some rumor helped B. Pontecorvo to realize idea of neutrino oscillations in the case of one neutrino. In 1957 R.Davis made an experiment on the search for $^{37}$Ar production in the process of interaction of reactor antineutrino with $^{37}$Cl [22]. 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 [16](1958).

B. Pontecorvo assumed that there are transitions $\bar{\nu}_R \to \nu_R$ (and $\nu_L \to \bar{\nu}_L$). Thus, he had to assume that not only the lepton number is not conserved but also that in addition to the standard right-handed antineutrino $\bar{\nu}_R$ and left-handed neutrino $\nu_L$ (quanta of the left-handed field $\nu_L(x)$) also right-handed neutrino $\nu_R$ and left-handed antineutrino $\bar{\nu}_L$, quanta of right-handed field $\nu_R(x)$ existed.

In order to explain Davis "events" B. Pontecorvo had to assume that "a definite fraction of particles ($\nu_R$ ) can induce the Cl − Ar reaction". Later, when such anomalous "events" disappeared and only upper bound for the cross section of the reaction $\bar{\nu} +^{37}$ Cl $\to e^- +^{37}$ Ar was found in the Davis experiment, B. Pontecorvo understood that there is no need in such assumption and that $\nu_R$ (and $\bar{\nu}_l$) are sterile neutrinos. The terminology "sterile neutrino", which is standard nowadays, was introduced by B. Pontecorvo in his next neutrino oscillations paper [23].

In the very first paper on neutrino oscillations [16] B. Pontecorvo pointed out that in the experiment of Reines and Cowan [24], in which antineutrinos from reactor were detected, a deficit of antineutrino events could be observed. He wrote: "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."

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

The next paper on neutrino oscillations was written by B. Pontecorvo in 1967 [23] at the time when it was proved that (at least) two types on neutrinos $\nu_e$ and $\nu_\mu$ existed in nature.

In [23] Pontecorvo 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". 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 paper [23] 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 solar neutrinos must be two times smaller than the total neutrino flux."

Three years later R. Davis obtained results of his solar neutrino experiment. It occurred that the detected flux of the solar neutrinos was about 2- 3 times smaller than the predicted flux [25]. This result created the so called solar neutrino problem. It was soon commonly accepted that, among the different astrophysical explanations of the problem, the solar neutrinos oscillations proposed by Pontecorvo was the most natural explanation.

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

V. Gribov and B. Pontecorvo [26] considered a scheme of neutrino mixing and oscillations with four neutrino and antineutrino states: the left-handed neutrinos $\nu_e$ and

$\nu_\mu$ and right-handed antineutrinos $\bar{\nu}_e$ and $\bar{\nu}_\mu$. They assumed that there are no sterile neutrino states.

It was assumed in [26] that in addition to the standard charged current $V - A$ interaction in the total Lagrangian enters an effective interaction which violate $L_e$ and $L_\mu$ . After the diagonalization of the effective Lagrangian the following mixing relations were found

$$\nu_{eL} = \cos\theta\nu_{1L} + \sin\theta\nu_{2L}, \quad \nu_{\mu L} = -\sin\theta\nu_{1L} + \cos\theta\nu_{2L}. \tag{3}$$

Here $\nu_{1,2}$ are fields of the Majorana neutrinos with masses $m_{1,2}$ and $\theta$ is a mixing angle.

For the $\nu_e \to \nu_e$ survival probability in vacuum the following expression was found

$$P(\nu_e \to \nu_e) = 1 - \frac{1}{2}\sin^2 2\theta(1 - \cos\frac{\Delta m^2 L}{2E}), \tag{4}$$

where $\Delta m^2 = m_1^2 - m_2^2$, $E$ is the neutrino energy and $L$ is the distance between neutrino source and detector.

The developed formalism was applied in [26] to the solar neutrino oscillations. The maximal mixing $\theta = \pi/4$ was considered as the most simple and attractive possibility. In this case the averaged observed flux of the solar neutrinos is equal to 1/2 of the predicted flux.

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

B. Pontecorvo and myself started working together on neutrino masses, mixing and oscillations in 1975 [27]. The first paper was based on the idea of quark-lepton analogy.

Cabibbo-GIM mixing of quarks was established at that time . The lepton charged current has the same form as the quark charged current. In order to make a complete analogy between quarks and leptons it was natural to assume that $\nu_{eL}(x)$ and $\nu_{\mu L}(x)$ are also mixed fields:

$$\nu_{eL}(x) = \cos\theta\nu_{1L}(x) = +\sin\theta\nu_{2L}(x), \quad \nu_{\mu L}(x) = -\sin\theta\nu_{1L}(x) + \cos\theta\nu_{2L}(x) \tag{5}$$

Here $\nu_1(x)$ and $\nu_2(x)$ are Dirac fields of neutrinos with masses $m_1$ and $m_2$ and $\theta$ is the leptonic mixing angle. We wrote in [27]: "...in our scheme $\nu_1$ and $\nu_2$ are just as leptons and quarks (which, may be, is an attractive feature) while in the Gribov-Pontecorvo scheme the two neutrinos have a special position among the other fundamental particles".

We discussed in [27] a possible value of the mixing angle $\theta$. 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".

In the paper [28] we considered the most general neutrino mixing. In accordance with modern gauge theories we started to characterize neutrino mixing by the neutrino mass term. Three types of the neutrino mass terms are possible : Majorana mass term, Dirac mass term and Dirac and Majorana mass term [29,30]. Correspondingly, there are three types of the neutrino mixing:

1. Majorana neutrino mixing

$$\nu_{lL} = \sum_{i=1}^{3} U_{li} \nu_{iL}^{M} \quad l = e, \mu, \tau, \tag{6}$$

where $\nu_i^M$ is the field of the Majorana neutrinos ($(\nu_i^M)^c = \nu_i^M$) with mass $m_i$, $U$ is a unitary $3 \times 3$ Pontecorvo-Maki-Nakagawa-Sakata mixing matrix

2. Dirac neutrino mixing

$$\nu_{lL} = \sum_{i=1}^{3} U_{li} \nu_{iL} \quad l = e, \mu, \tau, \tag{7}$$

where $\nu_i$ is the field of the Dirac neutrinos and antineutrinos ($L(\nu_i) = -L(\bar{\nu}_i) = -1$) with mass $m_i$.

3. Majorana and Dirac mixing

$$\nu_{\alpha L} = \sum_{i=1}^{3+n} U_{\alpha i} \nu_{iL}^{M} \quad \alpha = e, \mu, \tau, s_1, ... s_n, \tag{8}$$

$\nu_i^M$ is the field of the Majorana neutrinos with mass $m_i$, $U$ is a unitary $(3+n) \times (3+n)$ mixing matrix.

We considered a non stationary picture of neutrino oscillations. The state of the flavor neutrino $\nu_l$ which is produced in a weak decay together with $l^+$ is given by the relation

$$|\nu_l\rangle = \sum_i U_{li}^* \ |\nu_i\rangle. \tag{9}$$

Here $|\nu_i\rangle$ is the state of neutrino with momentum $\vec{p}$ and energy

$$E_i = \sqrt{p^2 + m_i^2} \simeq E + \frac{m_i^2}{2E}, \tag{10}$$

For the probability of the transition $\nu_l \to \nu_{l'}$ during the time $t$ we have the following the expression

$$\mathrm{P}(\nu_l \to \nu_{l'}) = |\sum_i U_{l'i} \ e^{-iE_i t} \ U_{li}^*|^2 = |\delta_{l'l} + \sum_{i \geq 2} U_{l'i} U_{li}^* \ (e^{-i \Delta m_{i1}^2 \frac{L}{2E}} - 1)|^2. \tag{11}$$

Here $L \simeq t$ is the distance between a neutrino source and a neutrino detector. Nowadays (11) became the standard expression for the transition probability. 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 [31]. This was the beginning of the golden years of neutrino oscillations. In 2001 oscillations of solar neutrinos were proved in a model independent way in the SNO experiment [32]. In 2002 oscillations of reactor neutrinos were discovered in the reactor KamLAND experiment [33]. Several recent accelerator [34-36] and reactor [37-39] neutrino oscillation experiments confirmed this discovery.

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

## 6. – Conclusion

Bruno Pontecorvo was one of the first who understood the 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 for his whole 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. The name of Bruno Pontecorvo will be forever connected with neutrino as the name of the founder and father of modern neutrino physics

Bruno Pontecorvo was very bright, wise, exceptionally interesting and had a very friendly personality. People liked him and he had many friends in Italy, Russia, France, Canada and many other countries. He will remain with us in our memory and our hearts as a great outstanding physicist, as a man of of great impact and humanity.

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REFERENCES


[1] H. Bethe and R.Peierls, *Nature* **133** (1934) 532.
[2] B. Pontecorvo,*Report PD-205, Chalk River Laboratory* 1946.
[3] J. N. Bahcall and R. Davis, Jr. *Science* **191**, 264 (1976); B.T. Cleveland et al. *Astrophysical Journal* **496** (1998) 505.
[4] W. Hampel et al. (GALLEX Collaboration), *Phys. Lett.* **B447** (1999) 127; M. Altmann et al. (GNO), *Phys. Lett.* **B616** (2005) 174.
[5] J.N. Abdurashitov (SAGE Collaboration), *J. Exp. Theor. Phys.* **95** (2002) 181, arXiv:astro-ph/0204245.
[6] E.P. Hincks and B. Pontecorvo, *Can. J. Res.* **28A** (1950) 29; Phys. Rev. **77** (1950) 102.
[7] B. Pontecorvo, *Phys. Rev.***72** (1947) 246.
[8] G. Puppi, *Nuovo Cimento* **5** (1948) 587.
[9] O. Klein, *Nature* **161** (1948) 897.
[10] C. N. Yang and J. Tiomno, *Phys. Rev.* **79** (1950) 495.
[11] B. Pontecorvo, *Sov. Phys. JETP* **10** (1960) 1236.
[12] M. A . Markov, *Neutrino,(1964) NAUKA (in Russian)*, preprint JINR- D577 (1960).
[13] M. Schwartz, *Phys. Rev. Lett.***4** (1960) 306.
[14] G. Danby, J.-M. Gaillard, K. Goulianos, L.M. Lederman, N. Mistry, M. Schwartz and J. Steinberger, *Phys. Rev. Lett.* **9** (1962) 36.
[15] B. Pontecorvo, *Zh. Eksp. Teor. Fiz.* **33** (1957) 549 (*Sov. Phys. JETP* **6** (1958) 429.)
[16] B. Pontecorvo, *Zh. Eksp. Teor. Fiz.* **34** (1958) 247(*Sov. Phys. JETP* **7** (1958) 172.)
[17] L. D. Landau, *Nucl. Phys.* **3** (1957) 127.
[18] T. D. Lee and C. N. Yang, *Phys. Rev.* **105** (1957) 1671.

[19] A. Salam, *Nuovo Cim.* **5** (1957) 299.
[20] M. Goldhaber, L. Grodzins and A.W. Sunyar, *Phys. Rev.* **109** (1958) 1015.
[21] M. Gell-Mann and A. Pais, *Phys. Rev.* **97** (1955) 1387.
[22] R. Davis, *Bull. Am. Phys. Soc. (Washington meeting)* 1959.
[23] B. Pontecorvo, *Zh. Eksp. Teor. Fiz.* **53** (1967) 1717 (Sov. Phys. JETP **26** (1968) 984).
[24] C.L. Cowan, Jr., F. Reines, F.B. Harrison, H.W. Kruse and A.D. McGuire, *Science* **124** (1956) 103; F. Reines and C. L. Cowan, *Nature* **178** (1956) 446; F. Reines and C. Cowan, *Phys.Rev.* **113** (1959) 273.
[25] R. Davis and J. M. Evans, Proc. *13th Int. Cosmic Ray Conf.* **178** (1973) 2001.
[26] V. Gribov and B. Pontecorvo, *Phys. Lett.* **B28** (1969) 493.
[27] S.M. Bilenky and B. Pontecorvo, *Phys. Lett.* **B61** (1976) 248; *Yad. Fiz.* **3** (1976) 603 .
[28] S.M. Bilenky and B. Pontecorvo, *Lett. Nuovo Cim.* **17** (1976) 569.
[29] S.M. Bilenky and B. Pontecorvo, *Phys. Rep.* **41** (1978) 225 .
[30] S. M. Bilenky and S.T. Petcov, *Rev. Mod. Phys.***59** (1987) 671.
[31] R. Wendell et al. (Super-Kamiokande Collaboration), *Phys. Rev.* **D 81** (2010) 09200 ; Y. Takeuchi et al. (Super-Kamiokande Collaboration), arXiv:1112.3425.
[32] B. Aharmim et al. (SNO Collaboration), *Phys. Rev.* **C 81** (2010) 055504.
[33] A. Gando et al. (KamLAND Collaboration), *Phys. Rev.* **D 83** (2011) 052002.
[34] M.H.Ahn et al. (K2K Collaboration), *Phys. Rev.* **D74** (2006) 072003.
[35] P. Adamson et al. (MINOS Collaboration), *Phys. Rev. Lett.* **107** (2011) 181802; J.J. Evans et al. (MINOS Collaboration), arXiv: 1307.0721.
[36] K. Abe et al. (T2K Collaboration), *Phys. Rev. Lett.* **107** (2011) 041801; T. Nakaya et al. (T2K Collaboration), *Nucl. Phys. B, Proc. Suppl.* **(235-236)** (2013) 97.
[37] F.P. An et al. (Daya Bay Collaboration), *Phys. Rev. Lett.* **108** (2012) 171803.
[38] J.K. Ahn et al. (RENO Collaboration), *Phys. Rev. Lett.* **108** (2012) 191802.
[39] Y. Abe et al. (Double CHOOZ Collaboration ), *Phys. Lett.* **B723** (2013) 66.