Bruno Pontecorvo-pioneer of neutrino oscillations

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- 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.
- After the war during many years the factory was closed and the building was not used. Now the Pisa department of INFN is in the building of the Pontecorvo's factory. The square before the building is called Largo Bruno Pontecorvo
- There were 8 children in the family: 5 brothers and 3 sisters All of them were very successful
- Three brothers became famous:
  - Biologist Guido (the eldest brother)
  - Physicist Bruno
  - Movie director Gillo

- Bruno entered engineer faculty of Pisa University. However, after two years he decided to switch to physics
- From his 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
- The experiment performed by Amaldi and Pontecorvo lead to the discovery of the effect of slow neutrons, the most important discovery made by the Fermi‘s group
  At that time Bruno was 21
- For the discovery of the effect of slow neutrons Fermi was awarded the Nobel Prize.
  This effect opened the road to all applications of neutrons (reactors, isotopes for medicine,... and atomic bombs)

- In 1936 Bruno received a premium of the Italian Ministry of Education and went to Paris to work with F. Joliot-Curie
- 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 the irradiation of nuclei by high-energy -quanta etc
- For the study of the nuclear isomerism Bruno got Curie-Carnegie premium. Fermi congratulated Bruno on 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. 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. 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. Bruno (30) was scientific leader of the project of the research reactor which was built in 1945 and was the first nuclear reactor outside of USA

- In Canada Pontecorvo started research in elementary particle physics
- After famous Conversi, Pancini and Piccioni experiment (1947) from which it followed that muon weakly interact with nuclei Bruno Pontecorvo and E. Hincks performed a series of pioneer experiments on the investigation of fundamental properties of muon
- They proved that
  - The charged particle emitted in μ-decay is electron.
  - Muon decays into three particles.
  - Muon does not decay into electron and γ-quantum.

- Pontecorvo suggested that the muon is a particle with spin $1/2$ and in the process of muon capture by a nucleus neutrino is emitted.
- He compared the probabilities of the processes
  - $\mu^- + (A, Z) \to \nu + (A, Z - 1)$
  - $e^- + (A, Z) \to \nu + (A, Z - 1)$

  and found that the constants which characterize these two processes were of the same order of magnitude
- He came to the conclusion that exist " fundamental analogy between β-processes and processes of absorption of muons". Thus, in 1947 Pontecorvo came to the idea of the existence of an universal weak interaction which include $e\nu$ and $\mu\nu$ pairs. Later the idea of $\mu - e$ universality was put forward by Puppi, Klein, Tiomno and Wheeler.

- Soon after famous Fermi paper on the theory of the β-decay (1934) Bethe and Pierls estimated cross section of the interaction of postulated by Pauli neutrino with a nucleus
- The estimated cross section was extremely small. At $\sim$ MeV energies $\sigma < 10^{-44} cm^2$
- At that time did not existed methods of detection of processes with such small cross section. During many years neutrino was considered as an "undetectable particle"
- The first physicist who challenged this opinion and proposed a method of neutrino detection was Pontecorvo (Canada, 1946)

- Pontecorvo's 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 the most promising the reaction $\nu +^{37} Cl \to e^{-} +^{37} Ar$
- many reasons: C_2Cl_4 is a cheap, non-flammable liquid, ^{37}Ar is unstable nucleus 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, etc
- The Pontecorvo $Cl - Ar$ radiochemical method was realized by R. Davis in his first experiment on the detection of the solar neutrinos
- In 2002 R. Davis was awarded the Nobel Prize for the discovery of the solar neutrinos

- Radiochemical method of neutrino detection based on the observation of the reaction $\nu +^{71} Ga \to e^{-} +^{71} Ge$, proposed by V. Kuzmin, was used in the GALLEX-GNO and SAGE solar neutrino experiments in which main $p-p$ neutrinos were detected
- In the seminal Chalk River paper (1946) Pontecorvo paid attention to the following intensive sources of neutrinos
  - The sun
  - Reactors
  - Radioactive materials produced in reactors
- In 1948 Pontecorvo invented low-background proportional counter with high amplification. This counter was crucial for detection of solar neutrinos in Homestake , GALLEX and SAGE experiments

- In 1950 Bruno with family (wife and three sons) moved from England to USSR
- He started to work in Dubna where at that time was the largest accelerator in the world (460 MeV later 680 MeV)
- 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
- In the end of the fifties in Dubna a project of a meson factory was developed (unfortunately the project was not realized). In connection with this project Pontecorvo thought about a feasibility of neutrino experiments with neutrinos from decays of pions and kaons produced at high intensity accelerators
- Bruno came to the conclusion that experiments with accelerator neutrinos are possible (independently M.A. Markov and Schwartz came to the same conclusion)

- Bruno understood that experiments with high energy accelerator neutrinos give perfect possibility to answer the fundamental question
- Are ν_e and ν_μ the same or different particles?
- In 1959 he published a paper on accelerator neutrinos.
- Pontecorvo's proposal was realized in the famous Brookhaven neutrino experiment (1962). 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

- NEUTRINO MASSES, MIXING AND OSCILLATIONS
  This bright and courageous idea of Bruno Pontecorvo created a new era in neutrino physics
- Bruno came to idea of neutrino oscillations in 1957-58 soon after the two-component neutrino theory appeared. He was very much impressed by a possibility of $K^0 \leftrightarrows \bar{K}^0$ oscillations suggested by Gell-Mann and Pais
- The $K^0 \leftrightarrows \bar{K}^0$ oscillations are based on the following facts
  - K^0 and $\bar{K}^0$ are different particles with strangeness -1 and +1, respectively. The strangeness is conserved in the strong interaction
  - Weak interaction does not conserve the strangeness. As a result states of K^0 and $\bar{K}^0$ are "mixed" states, superpositions of states of K^0_1 and K^0_2, particles with definite masses and transitions between them in vacuum are possible
- In 1957 Pontecorvo put the following question: "...whether 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 $(\mu^- - e^+)$ and wrote a paper on that (1957).
- In this paper he mentioned neutrino. The problem was two-component neutrino theory established at that time. According to this theory only ν_L and $\bar{\nu}_R$ exist (one neutrino type was known at that time). Transitions between them are forbidden
- Some rumor helped Pontecorvo to realize idea of neutrino oscillations in the case of one neutrino
- In 1957 R.Davis searched for ^{37}Ar production in the process of interaction of reactor antineutrino with ^{37}Cl. 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 and published a first paper dedicated to neutrino oscillations (1958)

- Pontecorvo considered 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 in addition to $\bar{\nu}_R$ and ν_L, quanta of $\nu_L(x)$, existed also ν_R and $\bar{\nu}_L$, quanta of $\nu_R(x)$
- In order to explain Davis "events" Pontecorvo had to assume that "a definite fraction of particles (ν_R) can induce the $Cl - Ar$ reaction"
- In the 1958 paper (and this is the most important) Pontecorvo pointed out that in reactor experiments a deficit of antineutrino events will be observed " due to the fact that the neutral lepton beam which at the source is capable of inducing the reaction $\bar{\nu} + p \to e^+ + n$ changes its composition on the way from the reactor to the detector"
- Later the anomalous events disappeared and B. Pontecorvo understood that ν_R and $\bar{\nu}_R$ must be noninteracting, sterile particles. The terminology sterile neutrino, which is standard nowadays, was introduced by B. Pontecorvo

- Starting from this first paper 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.“
- In the next paper on neutrino oscillations, written in 1967 after the second type of neutrino was discovered, Pontecorvo considered oscillations between active neutrinos $\nu_\mu \to \nu_e$ and also between active and sterile $\nu_\mu \to \bar{\nu}_{eL}$ etc.
- He discussed in this paper the effect of neutrino oscillations for the solar neutrinos and came to the conclusion that “the flux of observable sun neutrinos must be two times smaller than the expected neutrino flux.“
- In 1970 R. Davis obtained the first result of the detection of the solar neutrinos.
- It occurred that the detected flux of the solar neutrinos was 2-3 times smaller than the predicted flux
- This created so called solar neutrino problem
- Bruno Pontecorvo anticipated the solar neutrino problem

- In Pontecorvo and Gribov paper (1969) neutrino oscillations between ν_e and ν_μ (no sterile neutrinos) were considered
- For the mixing they found

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

- ν_1 and ν_2 are fields of truly neutral Majorana neutrinos with masses m_1 and m_2
- ν_e survival probability in vacuum in such a scheme

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

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

- Oscillations of the solar neutrinos were considered in some details

- In 1975 Pontecorvo and me started a long term collaboration (about 15 years) on the study and development of the idea of neutrino masses, mixing and oscillations
- Our first paper was based on the idea of quark-lepton analogy
- In this case for two neutrinos we have the same mixing as in the Majorana case but ν_1 and ν_2 are fields of Dirac neutrinos and antineutrinos with masses m_1 and m_2
- There is no conserved total lepton number L in the Majorana case. In the Dirac case L is conserved
- We published many papers

Summarizing

- There are three types of neutrino mixing
  - Majorana neutrino mixing

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

ν_i is the field of the Majorana neutrino with mass m_i, U is a unitary 3×3 mixing matrix

Transitions only between flavor neutrinos $\nu_l \leftrightarrows \nu_{l'}$

  - Dirac neutrino mixing

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

ν_i is the field of the Dirac neutrino with mass m_i, U is a 3×3 unitary mixing matrix

Transitions only between flavor neutrinos $\nu_l \leftrightarrows \nu_{l'}$

- Majorana and Dirac mixing

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

ν_i is the field of the Majorana neutrino with mass m_i, U is a unitary $(3+n)\times(3+n)$ mixing matrix

Transitions between flavor neutrinos $\nu_l \leftrightarrows \nu_{l'}$ and flavor and sterile neutrinos $\nu_l \leftrightarrows \nu_{s_i}$

- We considered non stationary picture of neutrino oscillations
- In CC weak processes together with lepton e^+, μ^+, τ^+ flavor neutrinos ν_e, ν_μ, ν_τ are produced
  - Mixed states of flavor neutrinos

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

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

- If at $t = 0$ flavor neutrinos ν_l is produced

$$|\nu_l\rangle_t = \sum_i U^*_{li} e^{-E_i t} |\nu_i\rangle$$

- Flavor neutrino transition probability

$$P(\nu_l \to \nu_{l'}) = |\sum_i U_{l' i} e^{-\frac{\Delta m^2_{2i} L}{2E}} U^*_{li}|^2$$

$L \simeq t$ (OPERA and other experiments)
L is the distance between neutrino production and detection points
If there are no sterile neutrinos, six parameters : Δm^2_{23} and Δm^2_{12}, θ_{12}, θ_{23}, θ_{13}, δ

- In 1998 after many years of heroic efforts oscillations of atmospheric neutrinos were discovered in the Super-Kamiokande experiment
- Golden years of neutrino oscillations started
- In 2001 oscillations of solar neutrinos were discovered in the SNO experiment
- In 2002 oscillations of reactor neutrinos were discovered in the KamLAND experiment
- Many recent neutrino oscillation experiments confirm this discovery

- Discovery of neutrino oscillations was a great triumph of ideas of Pontecorvo who came to idea of neutrino oscillations at a time when common opinion favored massless neutrinos and no neutrino oscillations

  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

- The situation with neutrino oscillations today
- Neutrino oscillation data are perfectly described by the three neutrino mixing

$$\Delta m^2_{23} = (2.41 \pm 0.10) \cdot 10^{-3}\,\mathrm{eV}^2, \;\; \Delta m^2_{12} = (7.53 \pm 0.18) \cdot 10^{-5}\,\mathrm{eV}^2$$

$$0.407 < \sin^2\theta_{23} < 0.585, \quad \tan^2\theta_{12} = 0.436^{+0.029}_{-0.023}$$

$$\sin^2 2\theta_{13} = 0.090 \pm 0.009$$

- The CP phase δ is unknown

For absolute values of neutrino mass upper bound

$$m_\beta < 2.3\ \mathrm{eV}$$

- Small neutrino masses and neutrino mixing is the only signature in the particle physics of a NEW BEYOND THE STANDARD MODEL PHYSICS

- Future very challenging problems

- Are ν_i Majorana or Dirac particles? ($0\nu\beta\beta$-decay)
- Character of neutrino mass spectrum (Normal or inverted?)
- What is the value of the CP phase δ?
- Are there transitions into sterile states? (at the moment exist some indications)
- ...

- The years of work and friendship with Bruno Pontecorvo were the happiest and unforgettable years in my life. His wide and profound knowledge of physics, his love of physics, his ingenious intuition and his ability to understand complicated problems in a clear and simple way were gifts of God. 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 and help of family and friends helped him to overcome difficult problems of the illness. He never stopped to work, to think about neutrinos and to continue active life. Two days before his death Bruno came to his office at the second floor of the Laboratory of Nuclear Problem in Dubna, where he worked 43 years When he was leaving the Laboratory he looked into window at golden and yellow birches and said to his secretary Irina Pokrovskaya: Look how beautiful are these colors... It was nice Russian Golden Autumn, September 22d 1993.

- 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. The name of Bruno Pontecorvo will be forever connected with neutrino as the name of the founder and father of modern neutrino physics
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