Prehistory of Neutrino Oscillations

S. Bilenky
JINR(Dubna)

September 5, 2018

Two remarks

I. It took about 40 years to discover neutrino oscillations (it took about 25 years to discover neutrino) **Inspite of that Nature was kind to us**

Two conditions to observe neutrino oscillations

- **Appropriate L and E must be available** for the condition $\Delta m^2(\mathrm{eV}^2) \simeq \frac{E(\mathrm{GeV})}{L(\mathrm{km})}$ will be satisfied

  Atmospheric neutrino experiments are optimal to reveal $\Delta m^2_A \simeq 2.5 \cdot 10^{-3}\mathrm{eV}^2$

- **Mixing must be large** for neutrino oscillations to be large and observable

  In the atmospheric neutrino case mixing is maximal ($\sin^2 2\theta_{23} \simeq 1$)

Same with reactor antineutrinos in the KamLAND experiment

Future experiments will be very challenging: mass ordering and CP require measurement of small effects (smallness of $\sin^2\theta_{13}$). $0\nu\beta\beta$-decay is very strongly suppressed (second order in G_F, probability is proportional to small $m_{\beta\beta}$, possible quenching of g_A)

II. **From the very beginning it was generally correct, quantum-mechanical understanding of the phenomenon of neutrino oscillations** (inspite of of all subtleties)

Correct formulas for transition probabilities were derived and used in first papers

1957-58 was a great time in physics

- Large violation of parity and C was discovered in β-decay (Wu et al) and μ-decay (Garwin, Lederman and Weinrich, Friedman and Telegdi).
- Two-component theory of massless neutrino was proposed by Landau, Lee and Yang, Salam.
- In the experiment on the measurement of neutrino helicity (Goldhaber et al) the two-component theory was confirmed "... our result is compatible with 100% negative helicity of neutrino"
- Feynman and Gell-Mann, Marshak and Sudarshan proposed universal current$\times$current weak interaction theory which was in agreement with existed data

There was a general belief that neutrino was massless particle. According to the two-component theory only ν_L and $\bar{\nu}_R$ existed (one type of neutrino was known at that time). Transitions $\nu_L \rightleftarrows \bar{\nu}_R$ are obviously forbidden

In 1957-58 Bruno Pontecorvo put forward an idea of neutrino oscillations.

Bruno P. was impressed by an idea of $K^0 \rightleftarrows \bar{K}^0$ oscillations proposed by Gell-Mann and Pais. The basics

I. K^0 and $\bar{K}^0$ have different strangeness ($\pm$). These particles are produced (and detected) in strong interaction processes in which strangeness is conserved

II. Weak interaction does not not conserve strangeness.

Eigenstates of the total Hamiltonian (states with definite masses and widths) are coherent superpositions

$$|K^0_1\rangle (|K^0_2\rangle) = \frac{1}{\sqrt{2}}(|K^0\rangle \pm |\bar{K}^0\rangle)$$

$|K^0\rangle (|\bar{K}^0\rangle) = \frac{1}{\sqrt{2}}(|K^0_1\rangle \pm |K^0_2\rangle)$ are "mixed" states

This is the reason for $K^0 \rightleftarrows \bar{K}^0$ oscillations

In 1957 Bruno P. 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 $\leftrightarrows$ antiparticle transitions are not strictly forbidden"

He came to the conclusion that such "mixed" systems 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. This gave Bruno. P a possibility to suggest that transitions

$$(\mu^+ - e^-) \leftrightarrows (\mu^- - e^+)$$

"are induced by the same interaction which is responsible for μ-decay"

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

In 1957 paper Bruno P. considered muonium $\to$ antimuonium oscillations in some details. He made in this paper 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."

In 1957 R.Davis searched for $^{37}\mathrm{Ar}$ production in the process

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

A rumor reached B.Pontecorvo that Davis observed such "events"

Bruno P. suggested (1958) that these "events" could be due to transitions of reactor antineutrinos into neutrinos on the way from the reactor to the detector (neutrino oscillations)

"Recently the question was discussed whether there exist other *mixed* neutral particles beside the K^0 mesons, i.e., particles that differ from the corresponding antiparticles, with the transitions between particle and antiparticle states not being strictly forbidden. It was noted that the neutrino might be such a mixed particle, and consequently there exists the possibility of real neutrino $\leftrightarrows$ antineutrino transitions in vacuum, provided that lepton (neutrino) charge is not conserved. This means that the neutrino and antineutrino are *mixed* particles, i.e., a symmetric and antisymmetric combination of two truly neutral Majorana particles ν_1 and ν_2 of different combined parity"

In other words Bruno P. assumed (by analogy with K^0)

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

Thus, he had to assume that $\bar{\nu}_R$ and ν_L (antineutrino and neutrino of the two-component theory) could be transferred into ν_R and $\bar{\nu}_L$, correspondingly

In order to explain Davis "events" B.P. had to assume that "a definite fraction of particles (ν_R) can induce the ($^{37}\mathrm{Cl} -^{37}\mathrm{Ar}$) reaction"

In 1958 paper (and this is the most important) Bruno P. pointed out that in the Reines and Cowan experiment, in which reactor $\bar{\nu}$'s were detected, a deficit of antineutrino events could be observed. "...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"

And further It will be extremely interesting to perform C.L. Cowan and F. Reines experiment at different distances from reactor"

Bruno P. concluded his 1958 paper with the following remark "Effects of transformation of neutrino into antineutrino and vice versa may be unobservable in the laboratory, but it will certainly occur, at least, on an astronomical scale."

At the later stage of the Davis experiment the anomalous candidate "events" disappeared and only an upper bound of the cross section of the reaction $\bar{\nu} +^{37}\mathrm{Cl} \to \mathrm{e}^- +^{37}\mathrm{Ar}$ was obtained

B. Pontecorvo soon came to conclusion that ν_R and $\bar{\nu}_L$, quanta of right-handed field $\nu_R(x)$, could be noninteracting, sterile particles.

The terminology "sterile neutrino", which is standard nowadays, was introduced by him in the next paper on neutrino oscillations

Next paper on neutrino oscillations was written by Bruno Pontecorvo in 1967

At that time it was proved that (at least) two types on neutrinos ν_e and ν_μ existed in nature

He discussed in this paper not only neutrino oscillations but $0\nu\beta\beta$-decay, $\mu \to e + \gamma$ and other lepton number violating processes

In 1967 paper Bruno P. considered $\nu_{eL} \to \bar{\nu}_{eL}$ and $\nu_{\mu L} \to \bar{\nu}_{\mu L}$ transitions which "transform potentially active particles into particles, which from the point of view of ordinary weak processes are sterile, i.e. practically undetectable"

"The only way of observing the effects in question consists in measuring the intensity and time variation of intensity of original active particles"

He considered in this paper also oscillations between active (flavor) neutrinos: "...there will take place oscillations $\nu_\mu \leftrightarrows \nu_e$ which in principle are detectable not only by measuring the intensity and time variation of intensity of original particles, but also by observing the appearance of new particles"

In the 1967 paper Bruno P. 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 flux of observable sun neutrinos must be two times smaller than the total (active and sterile) neutrino flux."

When the first results of the Davis experiment were obtained (1970) it occurred that the detected flux of the solar neutrinos was (2- 3) times smaller than the predicted flux (solar neutrino problem)

It was commonly accepted that the proposed by Pontecorvo neutrino mixing and oscillations could be a natural explanation of the solar neutrino problem

As we know today real explantation of the solar neutrino problem requires to take into account not only neutrino mixing but also effect of coherent scattering of neutrino in matter (MSW effect)

In Gribov and Pontecorvo paper (1969) first model of neutrino mixing was developed. They considered $\nu_e \rightleftarrows \nu_\mu$ oscillations

Oscillations into sterile states "should not be considered if it is required that in nature there are only four neutrino states" (left-handed $\nu_e,\ \nu_\mu$ and right-handed $\bar\nu_e,\ \bar\nu_\mu$)

"Lepton nonconservation leads to transitions between neutrino states. All possible transitions may be described with the help of an interaction Lagrangian"

$$\mathcal{L}_I = -\frac{1}{2}(m_{e\bar e}\bar\nu_{eL}(\nu_{eL})^c + m_{\mu\bar\mu}\bar\nu_{\mu L}(\nu_{\mu L})^c + m_{\mu\bar e}\bar\nu_{\mu L}(\nu_{eL})^c + m_{e\bar\mu}\bar\nu_{eL}(\nu_{\mu L})^c) + \mathrm{h.c.}$$

$(\nu_{lL})^c = C\bar\nu_{lL}^T, \quad (l = e, \mu)$ is the conjugated field and

$m_{e\bar e}, m_{\mu\bar\mu}, m_{\mu\bar e} = m_{e\bar\mu}$ are real parameters

After diagonalization of Lagrangian, the mixing relations

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

$\nu_{1,2} = C\bar\nu_{1,2}^T$ are fields of Majorana neutrinos with masses

$$m_{1,2} = \frac{1}{2}\left[m_{e\bar e} + m_{\mu\bar\mu} \mp \sqrt{(m_{e\bar e} - m_{\mu\bar\mu})^2 + 4m_{e\bar\mu}^2}\right]$$

The mixing angle

$$\tan 2\theta = \frac{2m_{e\bar\mu}}{m_{e\bar e} - m_{\mu\bar\mu}}$$

Gribov-Pontecorvo applied the developed formalism to the solar neutrinos

The cases $m_{e\bar{e}}, m_{\mu\bar{\mu}} \ll m_{e\bar{\mu}}$ and $m_{e\bar{e}} = m_{\mu\bar{\mu}}$ they considered as the most attractive

In these cases $\theta = \frac{\pi}{4}$ (maximal mixing) and "neutrino oscillations are similar to the oscillations in the K^0 beams"

If the mixing is maximal "the flux of observable neutrino must be two times smaller than the total sun neutrino flux"

Analogy with $K^0 \rightleftarrows \bar{K}^0$ oscillations apparently was important for the authors: strong interaction conserves S and weak interaction violates S and induce $K^0 - \bar{K}^0$ mixing

Analogously, weak interaction conserves L_e and L_μ and neutrino mixing is induced by some superweak interaction changing lepton numbers

Connection between history and modern physics

Gribov-Pontecorvo scheme (generalized by Petcov and S.B) is based on **the Majorana mass term**

$$\mathcal{L}^{Mj} = -\frac{1}{2}\bar{\nu}_L M (\nu_L)^c + \text{h.c.} = -\frac{1}{2}\sum_i m_i \bar{\nu}_i \nu_i$$

$\nu_i = \nu_i^c$ is the Majorana field

The most economical mass term. Only flavor fields enter into Lagrangian

Main conclusions

- ν_i are Majorana neutrinos
- $\nu_{lL} = \sum_{i=1}^{3} U_{li}\nu_{iL}$, no sterile neutrinos
- **However, masses m_i are parameters.** No any reasons for their smallness

The most plausible modern approach is based on the Weinberg effective Lagrangian

$$\mathcal{L}^{\text{eff}} = -\frac{1}{\Lambda}\,(\bar{\psi}_L\tilde{\phi})\;X\;(\tilde{\phi}^{\dagger}\;\psi_L)^c + \text{h.c.}$$

The only possible effective Lagrangian which generates neutrino mass term

After spontaneous symmetry breaking generates Majorana mass term BUT

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

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

if $\Lambda \gg v$ **natural smallness of neutrino masses**

"...non-renormilazible interaction that produces the neutrino masses is probably also accompanied with non-renormalizable interactions that produce proton decay...We don't know anything about the details of those terms, but I'll swear they are there" Weinberg interview to "CERN Courier" (November 2017)

Development of the idea of neutrino mixing and oscillations in Dubna (1975-1985)

I started long-term collaboration with Bruno P. in 1975. The title of our first paper was "Quark-lepton analogy and neutrino oscillations"

At that time it was established that Charged Current of leptons and quarks had the form

$$j^{CC}_{\alpha} = 2(\bar{\nu}_{eL}\gamma_{\alpha}e_L + \bar{\nu}_{\mu L}\gamma_{\alpha}\mu_L + \bar{u}_L\gamma_{\alpha}d'_L + \bar{c}_L\gamma_{\alpha}s'_L)$$

with mixed d and s quarks

$$d'_L = \cos\theta_C d_L + \sin\theta_C s_L, \quad s'_L = -\sin\theta_C d_L + \cos\theta_C s_L$$

It was natural to assume that neutrinos are also mixed

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

$\nu_{1,2}$ are fields of Dirac neutrinos with masses $m_{1,2}$

Thinking in terms of quark-lepton analogy we wrote

"In this scheme the neutrinos ν_1 and ν_2 are described in the same way as the other leptons and quarks (which is perhaps an advantage of this scheme), whereas in the Gribov-Pontecorvo theory the neutrinos (Majorana) play a special role among the fundamental particles"

We saw no any reasons for the mixing angle θ to be the same as the Cabibbo angle θ_C. Moreover, "... the maximal mixing ($\theta = \frac{\pi}{4}$) seems to us the most fruitful hypothesis"

Our next step (Pontecorvo, SB 1976) was a scheme of neutrino masses and mixing with the most general "interaction" which included left-handed Gribov-Pontecorvo Majorana term, Dirac term and right-handed Majorana term

In this case (for two neutrino flavors) ν_{eL} and $\nu_{\mu L}$ are mixture of four left-handed components of massive Majorana fields

Neutrino oscillations in flavor and sterile states were discussed

In 1978 we wrote the first review on neutrino oscillations (S. Bilenky and B.Pontecorvo, Lepton Mixing and Neutrino Oscillations, Physics Report 41(1978)225)

This review attracted attention of many physicists to the problem of neutrino masses, mixing, oscillations and lepton number violation (neutrinoless double β-decay)

We discussed possible experiments on the search for neutrino oscillations

As an example, on the search for neutrino oscillations in atmospheric neutrino experiments

"The averaged neutrino momentum in such experiments is 5-10 Gev and the distance from the neutrino source to the detector is $\simeq 10^4$ km for neutrinos coming from the Earth opposite site. Making use of formula (66) it is possible to test neutrino mixing hypothesis by comparing the measured and expected ν_μ intensities. The sensitivities of such experiments is rather high

$$\Delta m^2 \simeq 10^{-3}\ \mathrm{eV}^2"$$

At that time from experiments on the measurement of the β-spectrum of ^3H it was known that neutrino mass is much smaller than electron mass (original Pauli suggestion) :

$$m_\beta < 60\ \mathrm{eV} \simeq 10^{-4}\ m_e$$

Our main question was: do neutrinos have small, nonzero masses?

Our main reference theory was the theory of massless, two-component neutrino

It was confirmed by Goldhaber et al experiment but, of course, small neutrino masses were not excluded by this data

We had different arguments in favor of neutrino masses

1.there is no principle which requires that neutrino masses are equal to zero

2. After $V - A$ theory it was more natural to assume that neutrinos like charged leptons are particles with mass, etc

But the most important was the understanding that due to interference nature of the neutrino oscillations and a possibility to perform experiments at large values of $\frac{L}{E}$ the investigation of neutrino oscillations is the most sensitive way to search for small neutrino masses (Δm^2)

A condition to observe neutrino oscillations in vacuum

$$\frac{\Delta m^2(\mathrm{eV})^2 L(\mathrm{m})}{2E(\mathrm{MeV})} \geq 1$$

Different experiments (reactor, accelerator, atmospheric) are sensitive to different Δm^2

Necessary to search for neutrino oscillations at all neutrino facilities

This strategy finally brought success

When we were writing a review on neutrino oscillations our attention was drown to the paper of Z. Maki, M. Nakagawa and S. Sakata (1962) in which neutrino mixing was discussed

Their approach was based on Nagoya model in which p,n and Λ were considered as a bound state of leptons and a vector boson B^{+} ("a new sort of matter"): $p = \langle \nu B^{+} \rangle$, etc

At that time there were an indication that $\nu_e \neq \nu_\mu$ (from the limit on $\Gamma(\mu \to e + \gamma)$) but the Brookhaven experiment was not finished

MNS "introduced the weak neutrinos ν_e and ν_μ trough a standard leptonic weak current"

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

"...neutrinos from which a corresponding barion (say p) should be constructed are not necessary the weak neutrinos themselves; there may be a possibility that the true neutrinos are different from ν_e and ν_μ but defined by their linear combination"

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

"...ν_1 and ν_2 are regarded as the basic particles"

..weak neutrinos are not stable due to occurrence of virtual transitions $\nu_e \leftrightarrows \nu_\mu$. Therefore, a chain of reactions $\pi^+ \to \mu^+ + \nu_\mu$, $\nu_\mu + A \to (\mu^- \ and/or \ e^-) + X$ is useful to check the two-neutrino hypothesis if $|m_{\nu_1} - m_{\nu_2}| < 10^{-6}$ MeV under the conventional geometry of the experiments.

Conversely, the absence of e^- will be able not only to verify two-neutrino hypothesis but also to provide an upper limit of the mass of the second neutrino ν_2...

Returning to neutrino oscillations in vacuum

Starting from our first papers we considered states of flavor neutrinos ν_l, produced together with charged lepton l^+ $(l = e, \mu, \tau)$ in CC decays, as a superposition of states with the same momentum and different energies (non stationary state)

$$|\nu_l\rangle = \sum_{i=1}^{3} U_{li}^* \ |\nu_i\rangle$$

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

Coherence of the flavor states is ensured by the Heisenberg uncertainty relation and is based on the smallness of neutrino mass-squared differences

Applying to the flavor states the standard evolution equation for the neutrino state at the time t we have (assuming that initial state is $|\nu_l\rangle$)

$$|\nu_l\rangle_t = \sum_{i=1}^{3} U_{li}^{*} e^{-iE_i t}\,|\nu_i\rangle = \sum_{l'} |\nu_{l'}\rangle (\sum_{i=1}^{3} U_{l'i} e^{-iE_i t} U_{li}^{*})$$

The standard expression for $\nu_l \to \nu_{l'}$ transition probability

$$P(\nu_l \to \nu_{l'}) = |\sum_{i=1}^{3} U_{l'i} e^{-iE_i t} U_{li}^{*}|^2 =$$

$$|\delta_{l'l} - 2i \sum_{i \neq p} U_{l'i} U_{li}^{*} e^{-i\Delta_{pi}} \sin\Delta_{pi}|^2$$

$\Delta_{pi} = \frac{\Delta m_{pi}^2 L}{4E}$, $\Delta m_{pi}^2 = m_i^2 - m_p^2$ $L \simeq t$ is the source-detector distance

All possible neutrino mass terms, neutrino oscillations, neutrinoless double β -decay, electromagnetic properties of neutrinos and many other problems were discussed in many details in our review with S. Petcov (S. M. Bilenky, S.T. Petcov "Massive Neutrinos and Neutrino Oscillations", Rev.Mod.Phys. 59 (1987) 671) which, apparently, plaid an important role in the propaganda of initial ideas of neutrino masses, mixing and oscillations

From the history of neutrino oscillations we can CONCLUDE

- Analogy is important guiding principle (Fermi-analogy of weak and electromagnetic interactions, B. Pontecorvo-analogy with $K^0 - \bar{K}^0$ oscillations, etc
- Courageous general ideas (not always in agreement with common opinion) have good chances to be correct (B. Pontecorvo -inspite beautiful two-component theory neutrinos could have small masses)
- The history of neutrino oscillations is an illustration of a complicated and thorny way of science: correct pioneer ideas could be inspired by wrong preliminary data (Pontecorvo) or are based on wrong models (MNS)

Origin of neutrino masses and mixing is still unknown

There is a plausible scenario but we need additional data (first of all observation of $0\nu\beta\beta$-decay)

The most important

different original and later arguments in favor of neutrino masses and mixing convinced experimentalists to perform special (very difficult and expensive) experiments on the search for neutrino oscillations...

The aim of the first Kamiokande and IMB experiments was to search for the proton decay

Atmospheric neutrinos was as an important background

They studied atmospheric neutrinos and discovered anomaly which was strong indication in favor of neutrino oscillations...

First long baseline experiment MINOS became possible after the atmospheric neutrino anomaly was found...

Neutrino mixing matrix is called PMNS mixing matrix to honor four neutrino visionaries Pontecorvo, Maki, Nakagawa, Sakata

In 1988 there were difficulties with financial support of the SNO solar neutrino experiment (2015 Nobel Prize to Art McDonald).

Bruno wrote a strong letter of support

Dr. Walter F. Davidson

High Energy Physics Section, National Research Council of Canada

Dear Dr. Davidson,

Thank you very much for sending me the SNO proposal. Below I am writing a short comment on SNO in the hope that opinion of a person who already in 1946 worked in Canada on neutrinos may be of some value. The SNO proposal (1000 tons of D_2O immersed in H_2O in a mine 2 km deep) in my opinion is a wonderful proposal for several reasons.

First it is new, in the sense that with the help of large D_2O detector immersed in H_2O there become possible the investigation of reactions

$$1.\ \nu_e d \to e^- pp, \quad 2.\ \nu_x e \to \nu_x e, \quad 3.\ \nu_x d \to \nu_x np$$
$$4.\ \bar{\nu}_e d \to e^+ nn, \quad 5.\ \bar{\nu}_e p \to e^+ n$$

with main application to solar and star collapse neutrinos (1,2,3) and star collapse antineutrinos (4,5)

Second, the proposal is realistic, in the sense that at least one large Cerenkov counter filled with H_2O is known to work properly (Kamiokande)

Third, the proposal can be realized only in Canada, where for historical reasons large quantities of D_2O are available during a period of several years.

Finally, in my opinion the neural current reaction (3) yielding the total number of neutrinos of all flavors, can be investigated in spite of serious difficulties of registration of neutrons.

In conclusion the SNO proposal is progressive and should be supported by all means.

Yours sincerely.

Bruno Pontecorvo, Dubna August 18, 1988