Neutrino Oscillations. Nobel Prize 2015

S. Bilenky
JINR(Dubna)

February 10, 2016

The award of the Nobel Prize to T. Kajita and A. McDonald "for the discovery of neutrino oscillations, which shows that neutrinos have mass" was a result of more than fifty years efforts of many theoreticians and experimentalists

First ideas of neutrino oscillations were pioneered in 1957-58

First model independent evidence in favor of disappearance of atmospheric ν_μ's was obtained in 1998 by the Super-Kamiokande collaboration

First model independent evidence of the disappearance of solar ν_e's was obtained by the SNO collaboration in 2001

First model independent evidence of the disappearance of reactor $\bar{\nu}_e$'s was obtained by the KamLAND collaboration in 2002

The discovery of neutrino oscillations was confirmed by the accelerator K2K, MINOS, K2K neutrino experiments

With the accelerator T2K and the reactor Daya Bay, RENO and Double Chooze experiments the study of the neutrino oscillations enter into high precision era

There is a general belief that with the discovery of neutrino oscillations, driven by small neutrino masses, a first evidence in the particle physics in favor of a new, beyond the Standard Model Physics was obtained

First ideas of neutrino masses, mixing and oscillations was put forward by B. Pontecorvo in 1957-58

B. Pontecorvo came to an idea of neutrino oscillations searching for analogy (in the lepton world) of famous $K^0 \leftrightarrows \bar{K}^0$ oscillations

$K^0 \leftrightarrows \bar{K}^0$ oscillations are based on the assumption that states of K^0 and $\bar{K}^0$, particles produced in strong interactions, are mixtures of the states of K^0_1 and K^0_2, particles with definite masses and widths

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

When Pontecorvo proposed neutrino oscillations only one type of neutrino was known (ν_L and $\bar{\nu}_R$ according to the two-component theory). He assumed existence of ν_R and $\bar{\nu}_L$ (later he called such neutrino states sterile) and analogous to $K^0 - \bar{K}^0$ mixing

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

ν_1 and ν_2 are Majorana neutrinos with masses m_1 and m_2

If at $t = 0$ $\bar{\nu}$ is produced, at the time t we have

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

$$\frac{1}{2}(e^{-iE_1 t} + e^{-iE_2 t})|\bar{\nu}_R\rangle + \frac{1}{2}(e^{-iE_1 t} - e^{-iE_2 t})|\nu_R\rangle$$

$$E_{1,2} = \sqrt{p^2 + m_{1,2}^2} \simeq E + \frac{m_{1,2}^2}{2E}, \quad E = p$$

The probability of the transition $\bar{\nu}_R \to \bar{\nu}_R$ at the distance $L \simeq t$

$$P(\bar{\nu}_R \to \bar{\nu}_R) = \frac{1}{2}(1 + \cos\frac{\Delta m^2 L}{2E}), \quad \Delta m^2 = m_2^2 - m_1^2$$

Pontecorvo proposed to search for neutrino oscillations by detecting reactor $\bar{\nu}$ ($\bar{\nu}_e$) at different distances from reactors and by measuring the flux of ν (ν_e) from the sun

In 1962 Maki, Nakagawa and Sakata came to an idea of neutrino masses and mixing on the bases of the Nagoya model in which baryons were considered as bound states of neutrinos and a vector boson B^+

MNS assumed "that there exists a representation which defines the true neutrinos ν_1 and ν_2 through orthogonal transformation"

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

Neutrino oscillations was not considered by MNS. They wrote "Weak neutrinos ν_e and ν_μ are not stable due to the occurrence of virtual transition $\nu_e \rightleftarrows \nu_\mu$"

MNS estimated transition time ($\tau \simeq \frac{1}{\Delta m}$) and in connection with the Brookhaven experiment noticed "the absence of e^- will be able not only to verify the two-neutrino hypothesis but also to provide an upper limit of the mass difference Δm"

In the seventies it was established that the weak charged current has a form

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

$$d^{\rm mix}_L = \cos\theta_C d_L + \sin\theta_C s_L, \quad s^{\rm mix}_L = -\sin\theta_C d_L + \cos\theta_C s_L$$

fields of d and s quarks enter in charged current in the mixed form

In 1975 it was suggested (by B.Pontecorvo and S.B.) that there is an analogy of the weak interaction of quarks and leptons, neutrinos have small masses and neutrino fields enter into CC in the mixed form

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

ν_1 and ν_2 are Dirac fields with masses m_1 and m_2 (like quark fields) and θ is a neutrino mixing angle (not the same as Cabibbo angle)

This was a beginning of investigation of the problem of neutrino masses, mixing and oscillations continued during many years in Dubna (B. Pontecorvo and S.B.)

We considered all possible neutrino mixing, neutrino oscillations and different experiments on the search for neutrino oscillations

In accordance with spontaneously broken gauge theories we assumed that the source of the neutrino masses and mixing is a neutrino mass term, a Lorenz-invariant product of left-handed and right-handed components of neutrino fields

What types of neutrino mass terms are possible?

The leptonic charged current $j^{CC}_{\alpha} = 2 \sum_{l=e,\mu,\tau} \nu_{lL} \gamma_{\alpha} l_L$

$\nu_{lL} \quad (l = e, \mu, \tau)$ is the left-handed field

Conjugated field $(\nu_{lL})^c = C \bar{\nu}^T_{lL}$ is a right-handed component

$C \gamma^T_{\alpha} C^{-1} = -\gamma_{\alpha} \quad , C^T = -C$

Majorana mass term

$$\mathcal{L}^{\mathrm{L}} = -\frac{1}{2} \sum_{l',l} \bar{\nu}_{l'L} \, M_{l'l} (\nu_{lL})^c + \mathrm{h.c.}, \quad M = M^T$$

After the diagonalization

$\mathcal{L}^{\mathrm{L}} = -\frac{1}{2} \sum_{i=1}^{3} m_i \bar{\nu}_i \nu_i, \quad \nu^c_i = C \bar{\nu}^T_i = \nu_i$

ν_i is the Majorana field with mass m_i $(\nu_i \equiv \bar{\nu}_i)$

Mixing $\nu_{lL} = \sum_{i=1}^{3} U_{li} \nu_{iL}$

1. Majorana mass term in the simplest case of two neutrinos was considered first by Gribov and Pontecorvo (1969)
2. Only left-handed fields ν_{lL} enter in the total Lagrangian

If there are also right-handed fields ν_{lR} it will be two additional possibilities for the neutrino mass term

Dirac mass term

$$\mathcal{L}^{\mathrm{D}} = -\sum_{l'l} \bar{\nu}_{l'L}\, M^{\mathrm{D}}_{l'l}\, \nu_{lR} + \mathrm{h.c.} = -\sum_{\mathrm{i}=1}^{3} \mathrm{m_i} \bar{\nu}_{\mathrm{i}} \nu_{\mathrm{i}}$$

- The total lepton number $L = L_e + L_\mu + L_\tau$ is conserved
- ν_i are Dirac neutrinos with mass m_i, $L(\nu_i) = 1; \quad L(\nu_i) = -1$
- Mixing $\nu_{lL} = \sum_{i=1}^{3} U_{li} \nu_{iL}$

Dirac and Majorana mass term

$$\mathcal{L}^{\mathrm{D+M}} = \mathcal{L}^{\mathrm{L}} + \mathcal{L}^{\mathrm{D}} + \mathcal{L}^{\mathrm{R}} = -\frac{1}{6}\sum_{i=1}^{6} m_i \bar{\nu}_i \nu_i$$

$$\mathcal{L}^{\mathrm{R}} = -\tfrac{1}{2} \sum_{l',l} \overline{(\nu_{l'R})^c} \, M^R_{l'l} \, \nu_{lR} + \mathrm{h.c.}$$

- Lepton number is not conserved. ν_i $(i = 1, 2...6)$ is the Majorana field with mass m_i
- $\nu_{lL} = \sum_{i=1}^{6} U_{li} \, \nu_{iL}, \quad (\nu_{lR})^c = \sum_{i=1}^{6} U_{\bar{l}i} \, \nu_{iL}$
- If $m_1, m_2, m_3, m_4, ...$ are small, transition of flavor neutrinos into sterile states are possible
- $M^L = 0, M^D \ll M^R$ - seesaw mechanism of the neutrino mass generation explaining the smallness of neutrino masses

In 70's-80's in Dubna we discussed neutrino oscillations taking into account all these possibilities for neutrino mixing

Our general conclusions

We do not know neutrino masses. Because reactor, accelerator, solar and atmospheric neutrino experiments are sensitive to different values of neutrino mass-squared differences neutrino oscillations must be searched for at all neutrino facilities. As we know this strategy brought success.

NEUTRINO OSCILLATIONS

We call flavor neutrinos ν_μ, $\bar\nu_e$,... particles which are produced together with μ^+ (in the decay $\pi^+ \to \mu^+ + \nu_\mu$), with e^- (in the decay $(A,Z) \to (A,Z+1) + e^- + \bar\nu_e$) etc

In the case of the neutrino mixing

$$\nu_{lL} = \sum_i U_{li}\, \nu_{iL}$$

what are the states of flavor neutrinos?

The standard phenomenology is based on the assumption that state of flavor neutrino ν_l is given

$|\nu_l\rangle = \sum_i U^*_{li}\ |\nu_i\rangle \quad (l = e, \mu, \tau)$

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

The state of flavor neutrino is a coherent superposition of states of neutrinos with different masses

It means that in weak decays it is impossible to resolve production of neutrinos with small mass-squared differences (Heisenberg uncertainty relation)

A possibility to reveal Δm^2_{ik} is based on the time-energy uncertainty relation $\Delta E \Delta t \geq 1$

In the case of the mixed neutrinos $\frac{\Delta m^2_{ki}}{2E}\ L \geq 1$

If at $t = 0$ flavor neutrino ν_l is produced, at the time t we have

$|\nu_l\rangle_t = e^{-iH_0 t}|\nu_l\rangle = \sum_i e^{-iE_i t} U^*_{li}\ |\nu_i\rangle = \sum_{l'} |\nu_{l'}\rangle (\sum_i U_{l'i} e^{-iE_i t} U^*_{li})$

Using the unitarity $\sum_i U_{\alpha' i} U^*_{\alpha i} = \delta_{\alpha' \alpha}$ we have for the probability

$$P(\nu_l \to \nu_{l'}) = |\delta_{l'l} - 2i \sum_i U_{l'i} U^*_{li} e^{-i\Delta_{pi}} \sin \Delta_{pi}|^2$$

$$\Delta_{pi} = \frac{\Delta m^2_{pi} L}{4E}, \quad i \neq p$$

In the case of three-neutrino oscillations there are two mass-squared differences: small (solar) and large (atmospheric); ratio $\sim 3 \cdot 10^{-2}$

Two possible mass spectrum

Neutrino masses are labeled in such a way that $m_2 > m_1$ and $\Delta m^2_{12} = \Delta m^2_S > 0$ for both mass spectra

Possible neutrino mass spectra are determined by the mass m_3

1. Normal ordering (NO) $m_3 > m_2 > m_1$
2. Inverted ordering (IO) $m_2 > m_1 > m_3$

$$\Delta m^2_{23} = \Delta m^2_A \text{ (NO)}, \quad |\Delta m^2_{13}| = \Delta m^2_A \text{ (IO)}$$

Notice that other definitions of the atmospheric mass-squared difference are used

Transition probabilities is the sum of atmospheric, solar and interference terms

$$P^{NO}(\overset{(-)}{\nu}_l \to \overset{(-)}{\nu}_{l'}) = \delta_{l'l} - 4|U_{l3}|^2(\delta_{l'l} - |U_{l'3}|^2)\sin^2\Delta_A -$$
$$4|U_{l1}|^2(\delta_{l'l} - |U_{l'1}|^2)\sin^2\Delta_S - 8\ [\mathrm{Re}\ (U_{l'3}U^*_{l3}U^*_{l'1}U_{l1})\cos(\Delta_A + \Delta_S)$$
$$\pm\ \mathrm{Im}\ (U_{l'3}U^*_{l3}U^*_{l'1}U_{l1})\sin(\Delta_A + \Delta_S)]\sin\Delta_A\sin\Delta_S$$

$$P^{IO}(\overset{(-)}{\nu}_l \to \overset{(-)}{\nu}_{l'}) = \delta_{l'l} - 4|U_{l3}|^2(\delta_{l'l} - |U_{l'3}|^2)\sin^2\Delta_A -$$
$$4|U_{l2}|^2(\delta_{l'l} - |U_{l'2}|^2)\sin^2\Delta_S - 8\ [\mathrm{Re}\ (U_{l'3}U^*_{l3}U^*_{l'2}U_{l2})\cos(\Delta_A + \Delta_S)$$
$$\mp\ \mathrm{Im}\ (U_{l'3}U^*_{l3}U^*_{l'2}U_{l2})\sin(\Delta_A + \Delta_S)]\sin\Delta_A\sin\Delta_S$$

Expressions for NO and IO differ by the change $U_{l(l')1} \leftrightarrows U_{l(l')2}$ and $(\pm) \leftrightarrows (\mp)$

Basic feature of the three-neutrino oscillations (the leading approximation)

Two neutrino oscillation parameters are small:

$$\frac{\Delta m_S^2}{\Delta m_A^2} \simeq 3 \cdot 10^{-2}, \quad \sin^2 2\theta_{13} = 0.084 \pm 0.005$$

Let us neglect contribution of these parameters and consider $\overset{(-)}{\nu}_\mu \to \overset{(-)}{\nu}_\mu$ transition in the atmospheric range of $\frac{L}{E}$. In this region $\Delta_A \simeq 1, \quad \Delta_S \ll 1$, solar and interference terms can be neglected. For NO and IO we have

$$P(\overset{(-)}{\nu}_\mu \to \overset{(-)}{\nu}_\mu) \simeq 1 - \sin^2 2\theta_{23}\ \sin^2 \frac{\Delta m_A^2 L}{4E}$$

In this approximation $P(\nu_\mu \to \nu_e) \simeq 0$. Oscillations in the atmospheric region are $\nu_\mu \leftrightarrows \nu_\tau$

$\bar{\nu}_e \to \bar{\nu}_e$ transitions in the solar range of $\frac{L}{E}$ (KamLAND experiment)

In this region $\Delta_S \simeq 1$ and $\Delta_A \gg 1$. The contribution of Δm_A^2 is averaged out. For NO and IO we have

$$P(\bar{\nu}_e \to \bar{\nu}_e) \simeq 1 - \sin^2 2\theta_{12}\ \sin^2 \frac{\Delta m_S^2 L}{4E}$$

At present beyond the leading approximation effects were observed ($\overset{(-)}{\nu}_\mu \to \overset{(-)}{\nu}_e$ transitions were observed in T2K and MINOS accelerator experiments, the parameter $\sin^2 2\theta_{13}$ was measured in the reactor Daya Bay, RENO and Double Chooze experiments). Exact three-neutrino formulas must be used in analysis of data

Results of a global analysis of the data (NuFit)

Parameter	Normal Ordering	Inverted Ordering
$\sin^2\theta_{12}$	$0.304^{+0.013}_{-0.012}$	$0.304^{+0.013}_{-0.012}$
$\sin^2\theta_{23}$	$0.452^{+0.052}_{-0.028}$	$0.579^{+0.025}_{-0.037}$
$\sin^2\theta_{13}$	$0.0218^{+0.0010}_{-0.0010}$	$0.0219^{+0.0011}_{-0.0010}$
δ (in $^\circ$)	(306^{+39}_{-70})	(254^{+63}_{-62})
Δm^2_S	$(7.50^{+0.19}_{-0.17}) \cdot 10^{-5}\ \mathrm{eV}^2$	$(7.50^{+0.19}_{-0.17}) \cdot 10^{-5}\ \mathrm{eV}^2$
Δm^2_A	$(2.457^{+0.047}_{-0.047}) \cdot 10^{-3}\ \mathrm{eV}^2$	$(2.449^{+0.048}_{-0.047}) \cdot 10^{-3}\ \mathrm{eV}^2$

Parameters are known with accuracies from ~ 3 % ($\Delta m^2_{S,A}$) to $\sim$ 10% ($\sin^2\theta_{23}$)

The study of neutrino oscillations does not allow to establish the nature of ν_i (Dirac or Majorana?).

To reveal the nature of ν_i we need to study L-violating neutrinoless double β-decay of some even-even nuclei

$(A, Z) \to (A, Z+2) + e^- + e^-$. The probability of the process

$$\frac{1}{T^{0\nu}_{1/2}} = |m_{\beta\beta}|^2 \; |M^{0\nu}|^2 \; G^{0\nu}(Q, Z)$$

$M^{0\nu}$ is nuclear matrix element and $G^{0\nu}(Q, Z)$ is known phase factor

The process was not observed. Very large lower bounds for half-lives were obtained

EXO-200.

$T^{0\nu}_{1/2}(^{136}\mathrm{Xe}) > 1.1 \cdot 10^{25}$ y (90% CL) $|m_{\beta\beta}| < (1.9 - 4.5) \cdot 10^{-1}$ eV

KamLAND-Zen

$T^{0\nu}_{1/2}(^{136}\mathrm{Xe}) > 2.6 \cdot 10^{25}$ y (90% CL) $|m_{\beta\beta}| < (1.4 - 2.8) \cdot 10^{-1}$ eV

GERDA, Heidelberg-Moscow, IGEX

$T^{0\nu}_{1/2}(^{76}\mathrm{Ge}) > 3.0 \cdot 10^{25}$ y (90% CL) $|m_{\beta\beta}| < (2 - 4) \cdot 10^{-1}$ eV

Future experiments will be sensitive to (probe of IO)

$|m_{\beta\beta}| \simeq$ a few $\cdot\, 10^{-2}$ eV

Problems for future

- Are ν_i Majorana or Dirac particles? (neutrinoless double β-decay)
- Is neutrino mass ordering normal or inverted ? (High precision neutrino oscillation experiments)
- What is the value of the CP phase δ?(High precision neutrino oscillation experiments)
- Are there transitions of flavor neutrinos ν_l into sterile states? (short baseline oscillations)
- What are the absolute values of neutrino masses? (β-decay, cosmology)
- ...

What is the origin of small neutrino masses and mixing? What new physics was discovered? Implications?

We will discuss the most economical (natural?) mechanism of neutrino mass generation

After the discovery of the Higgs boson at LHC the Standard Model acquire a status of a theory of elementary particles in the electroweak range (up to $\sim$ 300 GeV) What the Standard Model teaches us?

The Standard Model is based on the following principles

- Local gauge invariance
- Unification of electromagnetic and weak interactions
- Spontaneous breaking of the electroweak symmetry

In the framework of these principles nature choose the simplest, most economical possibilities

The two-component massless Weyl neutrino ν_{lL} is the simplest possibility for particle with spin 1/2 (2 dof)

The simplest local symmetry group which allow to include Weyl neutrinos, leptons and quarks is $SU_L(2)$

The electromagnetic currents of leptons and quarks are sums of L and R terms

Neutrinos have no electromagnetic interaction. Unification of the weak and electromagnetic interactions does not require right-handed neutrino fields. No right-handed neutrino fields in the Standard Model Lagrangian is the most economical possibility

The simplest group which allow to unify the weak and electromagnetic interactions is $SU_L(2) \times U_Y(1)$

The SM interactions of fermions and vector bosons are minimal ones

In the framework of Brout-Englert-Higgs mechanism of the mass generation Higgs doublet with one physical neutral, scalar Higgs boson (discovered at LHC) is the minimal possibility

Let us apply an idea of minimality to neutrinos

Neutrino masses and mixing can be generated only by a beyond the SM mechanism

The method of the effective Lagrangian is a powerful, general method which allows to describe beyond the SM effects

The effective Lagrangian is a nonrenormalizable, dimension five or more $SU_L(2) \times U_Y(1)$ invariant Lagrangian built from Standard Model fields

The neutrino mass term is a Lorenz-invariant product of left-handed and right-handed components

Consider $\bar{\psi}^{lep}_{lL}\tilde{\phi}, \quad \tilde{\phi} = i\tau_2\phi^*, \ \mathrm{doublet}, Y = -1$

$$\psi^{lep}_{eL} = \left(\begin{array}{c} \nu'_{lL} \\ l'_L \end{array} \right) \quad \phi = \left(\begin{array}{c} \phi_+ \\ \phi_0 \end{array} \right)$$

- It is $SU_L(2) \times U_Y(1)$ invariant
- After spontaneous symmetry breaking $\to \bar{\nu}_{lL}\frac{v}{\sqrt{2}}$
- It has dimension $M^{5/2}$

The only possible effective Lagrangian which generate the neutrino mass term (Weinberg)

$$\mathcal{L}^{\mathrm{eff}}_I = -\frac{1}{\Lambda} \sum_{l_1,l_2} (\bar{\psi}^{lep}_{l_1L}\tilde{\phi}) \ Y_{l_1l_2} \ (\tilde{\phi}^T(\psi^{lep}_{l_2L})^c) + \mathrm{h.c.}$$

A parameter Λ (dimension M) characterizes a scale of a beyond the SM physics, $\Lambda \gg v$.

After spontaneous symmetry breaking we come to the Majorana mass term

$$\mathcal{L}^{\rm M} = -\frac{1}{2}\,\frac{v^2}{\Lambda}\sum_{l_1,l_2}\bar{\nu}'_{l_1 L}\,Y_{l_1 l_2}(\nu'_{l_2 L})^c + \text{h.c.} = -\frac{1}{2}\sum_{i=1}^{3} m_i\bar{\nu}_i\nu_i$$

$$v = (\sqrt{2}G_F)^{-1/2} \simeq 246 \ \ \text{GeV}$$

$\nu_i = \nu_i^c$ is the field of the neutrino Majorana with the mass m_i

$$m_i = \frac{v^2}{\Lambda} y_i = \frac{v}{\Lambda}(y_i v)$$

$(y_i v)$ is a "typical" fermion mass in Standard Model

$$\frac{v}{\Lambda} = \frac{\text{scale of SM}}{\text{scale of a new physics}} \ll 1$$

is a suppression factor

Neutrino masses are (naturally) much less that lepton and quark masses.

To estimate Λ assume hierarchy of neutrino masses $m_1 \ll m_2 \ll m_3$. In this case $m_3 \simeq \sqrt{\Delta m_A^2} \simeq 5\cdot 10^{-2}\text{eV}$. Assume also that $y_3 \simeq 1$

$$\Lambda \simeq 10^{15} \ \text{GeV}$$

General consequences of the effective Lagrangian mechanism of the neutrino mass generation

- Neutrino with definite masses ν_i must be Majorana particles(neutrinoless double β-decay)
- The number of neutrinos with definite masses must be equal to the number of lepton-quark generations (no transitions into sterile neutrinos)

Sterile neutrinos have no standard weak interaction and can not be detected directly. In order to reveal existence of the sterile neutrinos

- Detect flavor neutrinos and prove that transition (survival) probabilities depend on additional large Δm^2
- Detect neutrinos via NC processes. The probability of the transition into all flavor neutrinos is measured
  $\sum_{l'=e,\mu,\tau} P(\nu_l \to \nu_{l'}) = 1 - \sum_{s=s_1,s_2,\dots} P(\nu_l \to \nu_s)$
  If there are no transitions into sterile neutrinos no oscillations

Indications in favor of existence of sterile neutrinos were obtained in short baseline LSND $\bar{\nu}_\mu \to \bar{\nu}_e$ experiment, MiniBooNE experiment, searching for $\overset{(-)}{\nu}_\mu \to \overset{(-)}{\nu}_e$ transitions, reactor $\bar{\nu}_e \to \bar{\nu}_e$ experiments and source $\nu_e \to \nu_e$ experiments.

Existing data can be explained by neutrino oscillations with $\Delta m^2 \simeq 1\ \mathrm{eV}^2$ much larger than Δm^2_A

There exist ,however, a tension between data

Many new accelerator, reactor, source experiments on the search for sterile neutrinos are in preparation

Conclusion

The Standard Model teaches us that the simplest possibilities are more likely to be correct. Massless two-component left-handed Weyl neutrinos and absence of the right-handed neutrino fields in the Standard Model is the simplest, most elegant and most economical possibility

Majorana neutrino mass term generated by the beyond the SM dimension 5 effective Lagrangian is the simplest possibility for neutrinos to be massive, naturally light and mixed

Nobel Prize 2015 was awarded to T.Kajita and A. McDonald

T.Kajita made major contribution to the Super-Kamiokande atmospheric neutrino experiment in which first model independent evidence of neutrino oscillations was obtained (1998)

S-K is 50 kilotons water-Cherenkov detector (fiducial mass 22.5 kilotons)

located in the Kamioka mine (about 1 km underground)

Atmospheric $\overset{(-)}{\nu}_\mu$ and $\overset{(-)}{\nu}_e$ are detected

Zenith-angle θ dependence of the electron and muon events was measured

Span the whole region of distances from about 20 km (downward going neutrinos $\theta = 0$) to about 13000 km (upward going neutrinos $\theta = \pi$)

Significant deficit of upward-going muons was observed

For high-energy electron and muon events

$$\left(\frac{U}{D}\right)_e = 0.961^{+0.086}_{-0.079} \pm 0.016, \quad \left(\frac{U}{D}\right)_\mu = 0.551^{+0.035}_{-0.033} \pm 0.004$$

U (D) is the total number of upward (downward) going leptons

From analysis of the SK data

$$1.9\ (1.7) \cdot 10^{-3}\ \mathrm{eV}^2 \leq \Delta m^2_A \leq 2.6\ (2.7) \cdot 10^{-3}\ \mathrm{eV}^2$$
$$0.407 \leq \sin^2\theta_{23} \leq 0.583$$

In 1978 B. Pontecorvo and me wrote first review on neutrino oscillations (Phys. Reports, 41(1978)225)

Apparently for the first time we discussed oscillations of atmospheric neutrinos

"...The average neutrino momentum in atmospheric neutrino experiments 5-10 GeV and distance from neutrino source to detector is 10^4 km for neutrino coming from the Earth opposite face....The sensitivity of those experiments for testing neutrino mixing is $\Delta m^2 \simeq 10^{-3}\ \mathrm{eV}^2$

In this estimate we assumed maximal mixing ($\theta \simeq \frac{\pi}{4}$)

From our first paper on neutrino oscillations (1975)

"...it seems to us that the special values of mixing angle $\theta = 0$ (the usual scheme in which muonic charge is strictly conserved) and $\theta = \pi/4$ are of the greatest interest"

A. McDonald made major contribution to the SNO solar neutrino experiment in which first model independent evidence of disappearance of the solar ν_e's was obtained (2001)

Solar neutrinos were detected by a large heavy-water detector (1000 tons of D_2O)

The SNO experiment was performed in the Creighton mine (Canada, depth 2092 m)

The high-energy ^8B neutrinos were detected in the SNO experiment via observation

1. The CC process $\nu_e + d \to e^- + p + p$
2. The NC process $\nu_x + d \to \nu_x + p + n \quad (x = e, \mu, \tau)$
3. Elastic neutrino-electron scattering $\nu_x + e \to \nu_x + e$

The detection of solar neutrinos via observation of the NC reaction allows to determine the total flux of ν_e, ν_μ and ν_τ

It was found

$$\Phi^{NC}_{\nu_{e,\mu,\tau}} = (5.25 \pm 16(\mathrm{stat})^{+0.11}_{-0.13}(\mathrm{syst})) \cdot 10^6 \ \mathrm{cm}^{-2}\ \mathrm{s}^{-1}$$

Compatible with prediction of the SSM

$$\Phi^{SSM}_{\nu_e} = (4.85 \pm 0.58) \cdot 10^6 \ \mathrm{cm}^{-2}\ \mathrm{s}^{-1}$$

The flux of ν_e is about three times smaller than the total flux of all active neutrinos

$$\frac{\Phi^{CC}_{\nu_e}}{\Phi^{NC}_{\nu_{e,\mu,\tau}}} = P(\nu_e \to \nu_e) = 0.317 \pm 0.016 \pm 0.009$$

Thus, it was proved in a direct, model independent way that solar ν_e on the way to the earth are transferred into ν_μ and ν_τ

From the three-neutrino analysis of the results of the SNO and other solar and KamLAND neutrino experiments

$$\Delta m^2_S = (7.41^{+0.21}_{-0.19}) \cdot 10^{-5}\ \mathrm{eV}^2$$

$$\tan^2\theta_{12} = 0.427^{+0.033}_{-0.029}, \quad \sin^2\theta_{13} = (2.5^{+1.8}_{-1.5}) \cdot 10^{-2}$$

In 1967 (a few years before R. Davis publish first results of the observation of solar neutrinos) B. Pontecorvo predicted suppression of the flux of the solar ν_e's due to neutrino oscillations

"From observational point of view the ideal object is 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 suffice would be that the flux of observable solar neutrinos must be two times smaller than the total neutrino flux"