Status of neutrino masses and mixings and future perspectives

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In the last years clear model independent evidence for neutrino oscillations were obtained in the Super Kamiokande, SNO, KamLAND, K2K, MINOS and other neutrino oscillation experiments

These findings mean that neutrinos have small masses and are mixed

- Basics of neutrino mixing and oscillations
- Evidence for neutrino oscillations
- Open problems, future experiments

BASICS

I. NEUTRINO INTERACTION

Standard Model charged and neutral current interaction

$$\mathcal{L}_I^{\text{CC}} = -\frac{g}{2\sqrt{2}}\, j^{\text{CC}}_{\alpha}\, W^{\alpha} + \text{h.c.}$$

$$j^{\text{CC}}_{\alpha} = 2\sum_{l=e,\mu,\tau} \bar{\nu}_{lL}\gamma_{\alpha} l_L$$

$$\mathcal{L}_I^{\text{NC}} = -\frac{g}{2\cos\theta_W}\, j^{\text{NC}}_{\alpha}\, Z^{\alpha}$$

$$j^{\text{NC}}_{\alpha} = \sum_{l=e,\mu,\tau} \bar{\nu}_{lL}\gamma_{\alpha} \nu_{lL}$$

Confirmed by numerous experiments on investigations of weak decays and neutrino processes

2. NEUTRINO MIXING

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

$U^\dagger U = 1$, $\nu_i(x)$ is the field of neutrino with mass m_i

For neutrinos, particles with electric charge equal to zero, two possibilities

I. $\nu_i(x)$ can be four-component Dirac field of neutrinos and antineutrinos

Total lepton number L is conserved

$$L(\nu_i) = 1; \quad L(\bar{\nu}_i) = -1$$

II. $\nu_i(x)$ can be two component Majorana field of neutrinos

$$\nu_i^c(x) = C\bar{\nu}_i^T(x) = \nu_i(x)$$

No conserved lepton numbers

$$\nu_i \equiv \bar{\nu}_i$$

The number of the flavor neutrinos ν_e, ν_μ, ν_τ is equal to three

From analysis of the data of the LEP experiments on the measurement of the width of the decay $Z^0 \to \nu_l + \bar{\nu}_l$ it was found

$$n_\nu = 2.994 \pm 0.012$$

The number n of neutrinos with definite masses ν_i can be larger than three. If $n > 3$ sterile neutrinos must exist (no SM interaction)

For the mixing we have in this case

$$\nu_{lL}(x) = \sum_{i=1}^{n} U_{li}\, \nu_{iL}(x) \quad l = e, \mu, \tau$$

$$\nu_{sL}(x) = \sum_{i=1}^{n} U_{si}\, \nu_{iL}(x) \quad s = s_1, s_2, ... s_{n-3}$$

3. NEUTRINO OSCILLATIONS

State of flavor neutrino ν_l produced and detected in weak processes

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

Coherent superposition of states of neutrinos with different masses $|\nu_i\rangle$

Conditions for coherent states to be produced: small neutrino mass-squared differences, energies much larger than neutrino masses

After time t neutrino state

$$|\nu_l\rangle_t = \sum_i e^{-iE_it}U_{li}^*|\nu_i\rangle = e^{-iEt}\sum_i e^{-i\frac{m_i^2}{2E}t}U_{li}^*|\nu_i\rangle$$

At the time t different $|\nu_i\rangle$ have different phases.

Superposition of different flavor states

$$|\nu_l\rangle_t = e^{-iEt} \sum_{l'} |\nu_{l'}\rangle \ \sum_i U_{l'i} \ e^{-i\frac{m_i^2}{2E}t} U_{li}^*$$

Transition probability

$$\text{P}(\nu_l \to \nu_{l'}) =$$
$$|\delta_{l'l} + \sum_{i>1} U_{l'i} \ (e^{-i\Delta m_{1i}^2 \frac{L}{2E}} - 1) \ U_{li}^* |^2$$

$$t \simeq L; \qquad \Delta m_{ik}^2 = m_k^2 - m_i^2$$

All existing neutrino oscillation data, with the exception of the LSND data, are described by the minimal scheme of the three-neutrino mixing

Transition probabilities depend on six parameters (Δm_{12}^2, Δm_{23}^2, θ_{12},θ_{23}, θ_{13}, δ) and have complicated form

However, in the leading approximation neutrino oscillations are described by simple two-neutrino expressions

There are two small parameters

$$\frac{\Delta m^2_{12}}{\Delta m^2_{23}} \simeq \frac{1}{30}; \qquad \sin^2\theta_{13} \leq 5\cdot 10^{-2}$$

Consider atmospheric and LBL accelerator experiments with $\Delta m^2_{23}\frac{L}{2E} \gtrsim 1$

Contribution of $\Delta m^2_{12}\frac{L}{2E} \ll 1$ can be neglected

Neglecting also terms proportional to $\sin^2\theta_{13}$ we come to the conclusion that dominant oscillations in atmospheric region of $\frac{L}{E}$ are $\nu_\mu \leftrightarrows \nu_\tau$

Survival probability

$$\mathrm{P}(\nu_\mu \to \nu_\mu) = 1 - \mathrm{P}(\nu_\mu \to \nu_\tau) =$$
$$1 - \frac{1}{2}\sin^2 2\theta_{23}(1 - \cos\Delta m^2_{23}\frac{L}{2E})$$

Two parameters. Perfectly describes data

Consider reactor KamLAND and solar neutrino experiments for which Δm^2_{12} is relevant

In this region the contribution of "large" Δm^2_{23} is averaged

Neglecting $\sin^2\theta_{13}$ for $\bar{\nu}_e \to \bar{\nu}_e$ survival probability in the KamLAND experiment we have

$$\mathrm{P}(\bar{\nu}_e \to \bar{\nu}_e) = 1 - \frac{1}{2}\sin^2 2\theta_{12}(1 - \cos\Delta m^2_{12}\frac{L}{2E})$$

For solar neutrinos effect of matter must be taken into account. In the leading approximation

$$\mathrm{P}(\nu_e \to \nu_e) = \mathrm{P}^{(1,2)}_{\mathrm{mat}}(\sin^2\theta_{12}, \Delta m^2_{12}, \rho_e)$$

Two-neutrino survival probability in matter

In the leading approximation decoupling of oscillations in atmospheric-LBL and solar-KamLAND regions

3. EVIDENCE FOR NEUTRINO OSCILLATIONS

Super-Kamiokande atmospheric neutrino experiment

e and μ are observed in the large 50 kt water Cherenkov detector

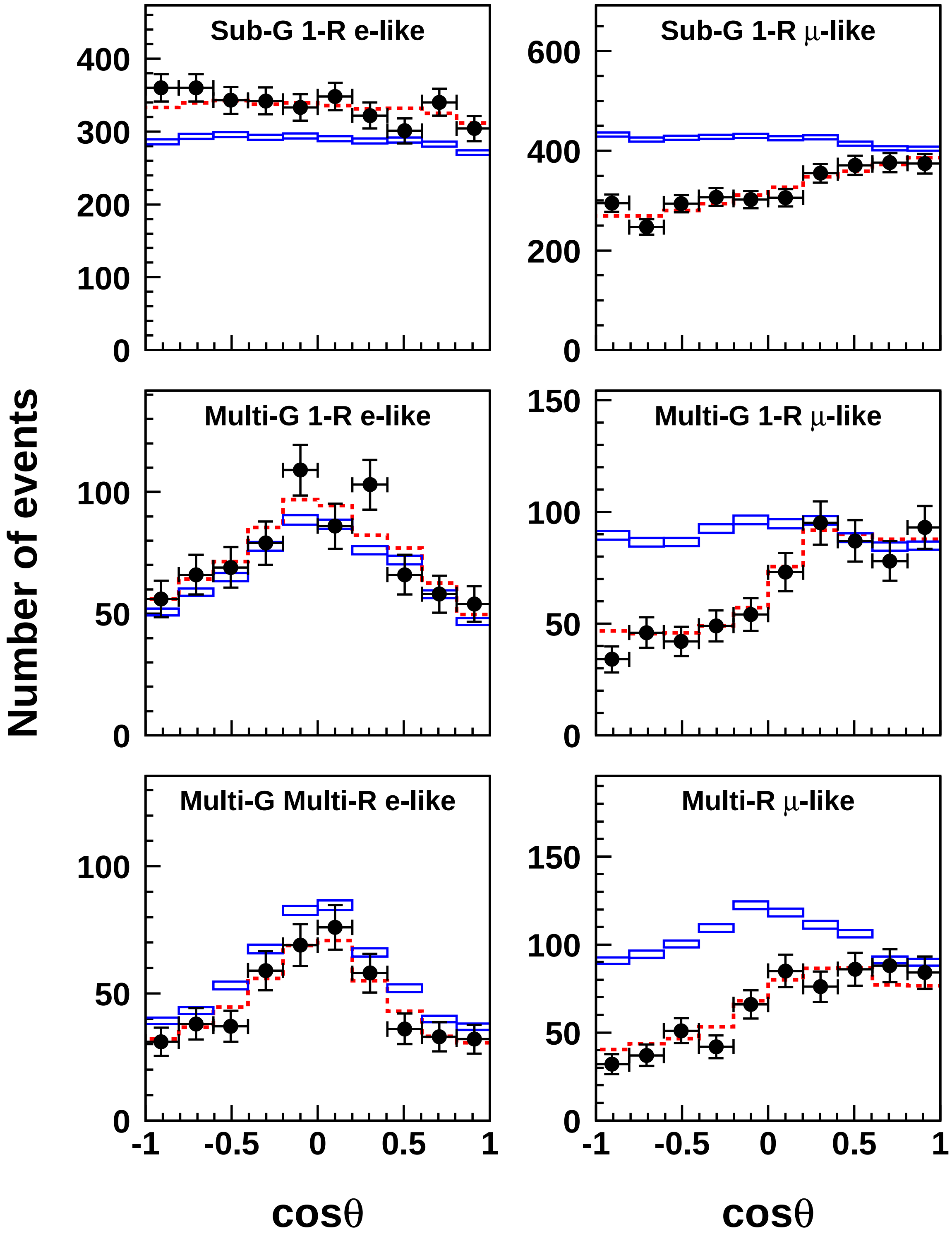
Large up-down asymmetry of muon events was discovered

$$\left(\frac{U}{D}\right)_{\mu} = 0.551 \pm 0.035 \pm 0.004$$

U is the the total number of the up-going muons (13000 -500 km); D is the the total number of the down-going muons (20 - 500 km)

If there is no neutrino oscillations

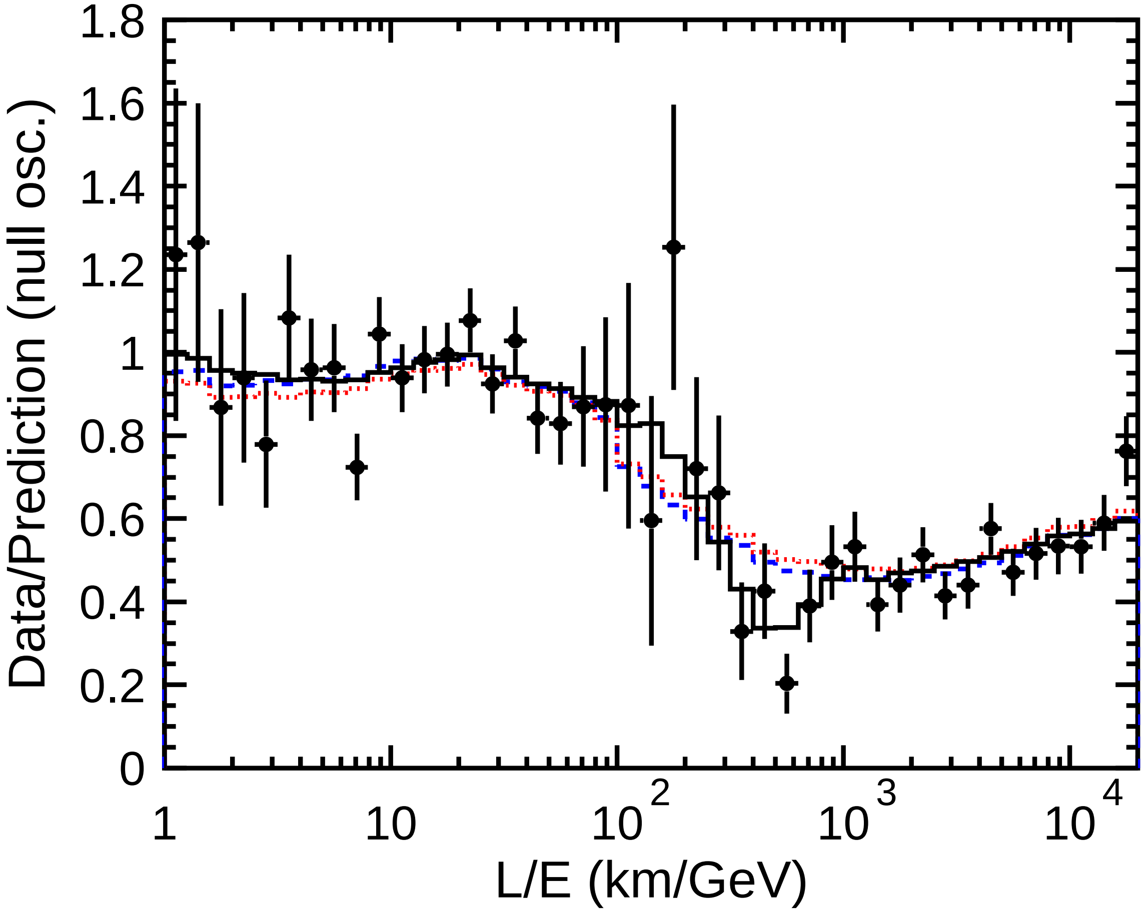
$N_l(\cos\theta) = N_l(-\cos\theta) \quad (l = e, \mu)$ θ is zenith angle


Sub-G 1-R e-like
Sub-G 1-R μ-like
Multi-G 1-R e-like
Multi-G 1-R μ-like
Multi-G Multi-R e-like
Multi-R μ-like
Number of events
cosθ
cosθ
0
100
200
300
400
600
50
150
-1
-0.5
0
0.5
1

$\frac{L}{E}$ dependence of the ν_μ survival probability was measured in the SK experiment

First minimum of P$(\nu_\mu \to \nu_\mu)$ at $\Delta m^2_{23}\frac{L}{2E} = \pi$

First oscillation minimum was observed



All Super-Kamiokande data are described by two- neutrino $\nu_\mu \rightleftarrows \nu_\tau$ oscillations

$$1.9 \cdot 10^{-3} \leq \Delta m^2_{23} \leq 3.1 \cdot 10^{-3} \mathrm{eV}^2$$

$\sin^2 2\theta_{23} > 0.9$ (90 % CL)

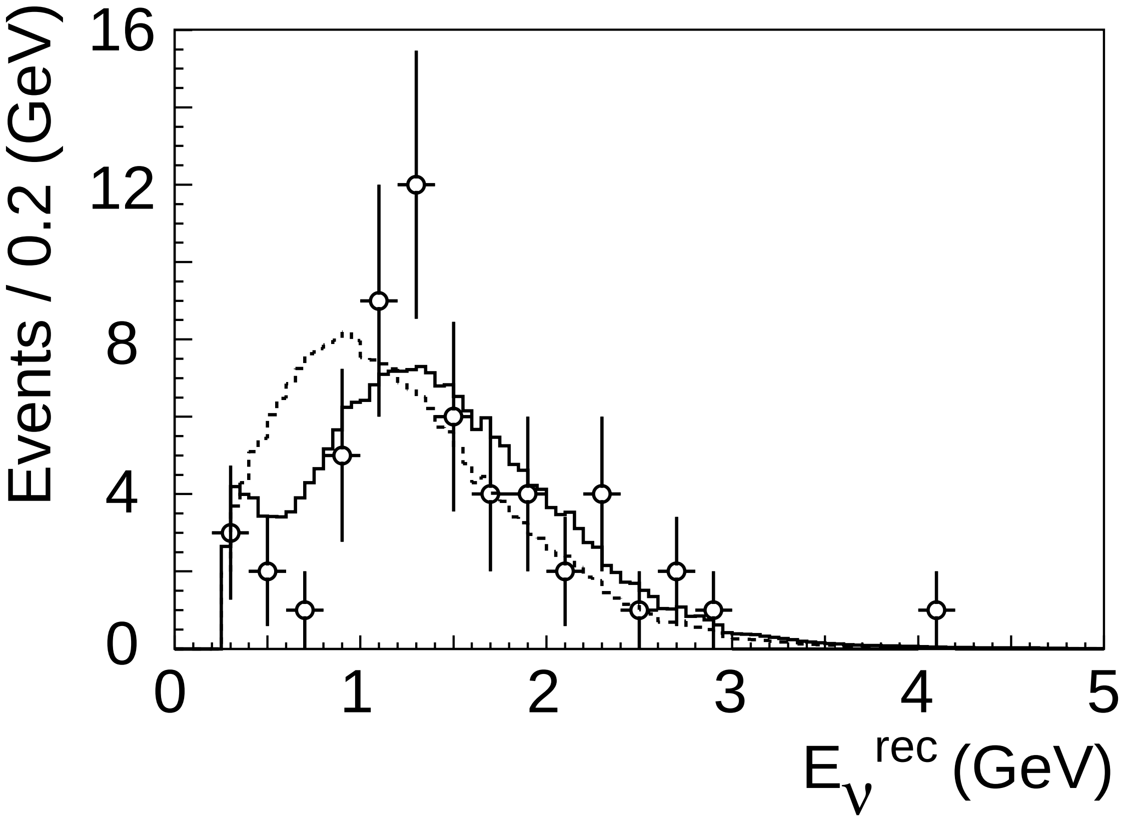
Best fit:

$$\Delta m^2_{23} = 2.5 \cdot 10^{-3} \mathrm{eV}^2; \quad \sin^2 2\theta_{23} = 1$$

$$(\chi^2/\mathrm{dof} = 839.7/755)$$

Super-Kamiokande atmospheric neutrino evidence for neutrino oscillations were confirmed by accelerator K2K and MINOS experiments

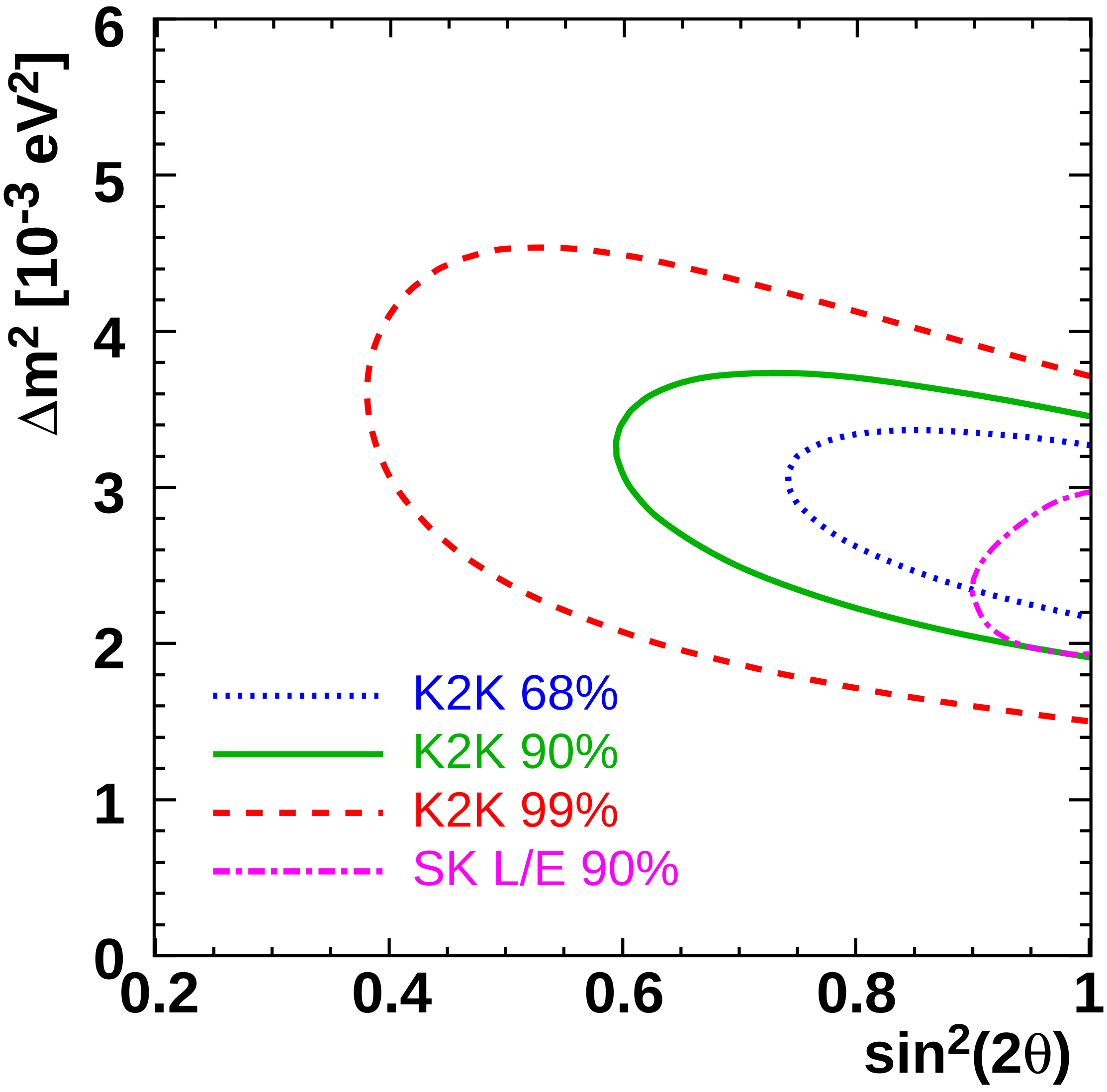
Spectrum distortion in K2K experiment



The K2K result is compatible with SK

The best fit values

$$\Delta m^2_{23} = 2.64 \cdot 10^{-3} \mathrm{eV}^2; \quad \sin^2 2\theta_{23} = 1$$



In the MINOS LBL accelerator experiment (Fermilab-Soudan, 730 km) the number of expected $\nu_\mu + \bar{\nu}_\mu$ events is 298 ± 15. The number of observed events is 204 (5 σ effect)

$$\Delta m^2_{23} = (3.05 \pm 0.60 \pm 012)\ 10^{-3}\mathrm{eV}^2$$

$$\sin^2 2\theta_{23} = 0.88 \pm 0.15 \pm 0.06$$

Solar neutrinos

Produced mainly in the following reactions of the solar p-p cycle

$$
\begin{aligned}
p+p \to d+e^{+}+\nu_e; &\quad E \leq 0.42\,\mathrm{MeV}\\
e^{-}+^{7}\mathrm{Be} \to \nu_{\mathrm{e}}+^{7}\mathrm{Li}; &\quad \mathrm{E}=0.86\,\mathrm{MeV}\\
^{8}\mathrm{B} \to ^{8}\mathrm{Be}+\mathrm{e}^{+}+\nu_{\mathrm{e}}; &\quad \mathrm{E} \leq 15\,\mathrm{MeV}
\end{aligned}
$$

Different experiments are sensitive to different parts of the solar neutrino spectrum: Homestake (^{8}B and ^{7}Be), GALLEX-GNO and SAGE ($p-p$, ^{7}Be and ^{8}B), SNO and SK (^{8}B)
In all experiments observed rates smaller (2-3 times) than expected rates

Model independent evidence for neutrino oscillations was obtained in the SNO experiment

In this experiment solar neutrinos are detected via the observation of three reactions

$$\text{CC} \quad \nu_e + d \to e^- + p + p$$

$$\text{NC} \quad \nu_{\text{x}} + \text{d} \to \nu_{\text{x}} + \text{n} + \text{p}$$

$$\text{ES} \quad \nu_{\text{x}} + \text{e} \to \nu_{\text{x}} + \text{e}$$

From CC the flux of ν_e can be inferred. From NC the flux of all active neutrinos ν_e, ν_μ and ν_τ can be determined. It was obtained

$$\Phi^{\text{SNO}}_{\nu_e} = (1.68 \pm 0.06 \pm 0.09) \cdot 10^6 \ \ cm^{-2} s^{-1}$$

$$\Phi^{\text{SNO}}_{\nu_{e,\mu,\tau}} = (4.94 \pm 0.21 \pm 0.38) \cdot 10^6 \ \ cm^{-2} s^{-1}$$

The total flux of ν_e, ν_μ and ν_τ is about three times larger than the flux of ν_e

$$\frac{\Phi^{\text{SNO}}_{\nu_e}}{\Phi^{\text{SNO}}_{\nu_{e,\mu,\tau}}} = 0.340 \pm 0.023 \pm 0.031$$

The total flux measured by SNO is in agreement with the flux predicted by SSM

$$\Phi^{\text{SSM}}_{\nu_e} = (5.69 \pm 0.91) \cdot 10^6 \ cm^{-2} s^{-1}$$

From global analysis of all solar data

$$\Delta m^2_{21} = 6.5^{+4.4}_{-2.3} \cdot 10^{-5}\text{eV}^2; \quad \tan^2\theta_{12} = 0.45 \pm 0.09$$

KamLAND reactor experiment

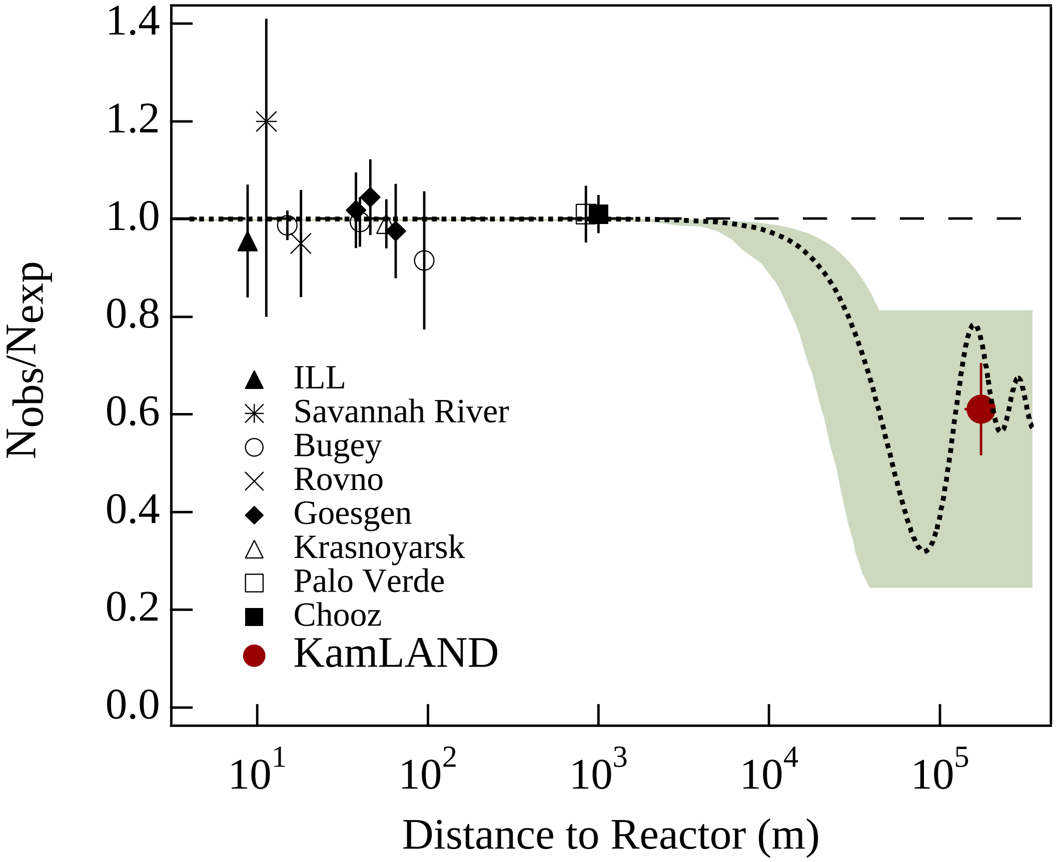
$\bar{\nu}_e$'s from 53 reactors in Japan are detected via the observation of the reaction

$$\bar{\nu}_e + p \to e^+ + n$$

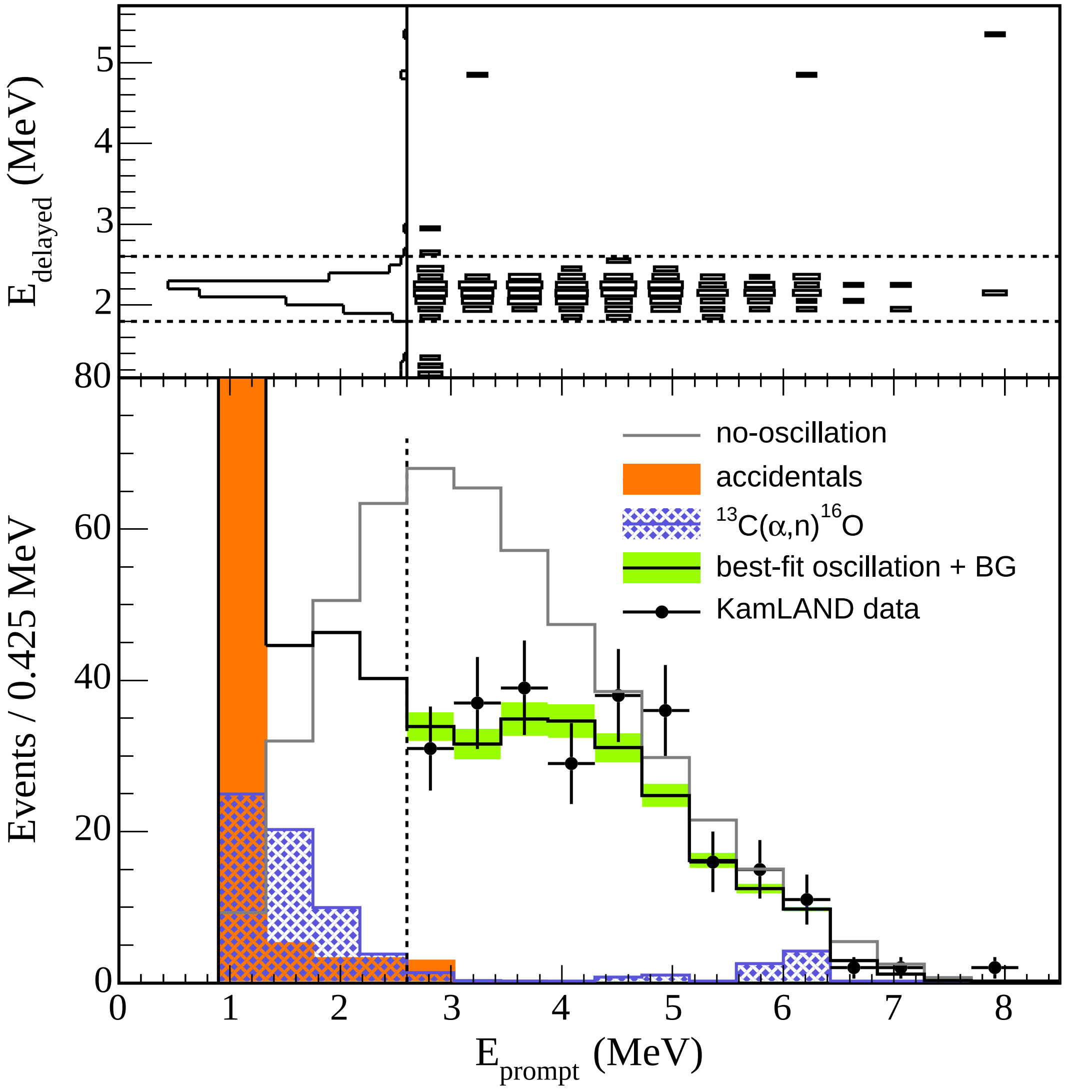
Average distance from reactors about 170 km

Sensitive to Δm^2_{12} and $\sin^2\theta_{12}$

The expected number of the events (without oscillations) 365.2 ± 23.7. The observed number 258 events. The ratio of the observed and expected events $R = 0.658 \pm 0.044 \pm 0.047$



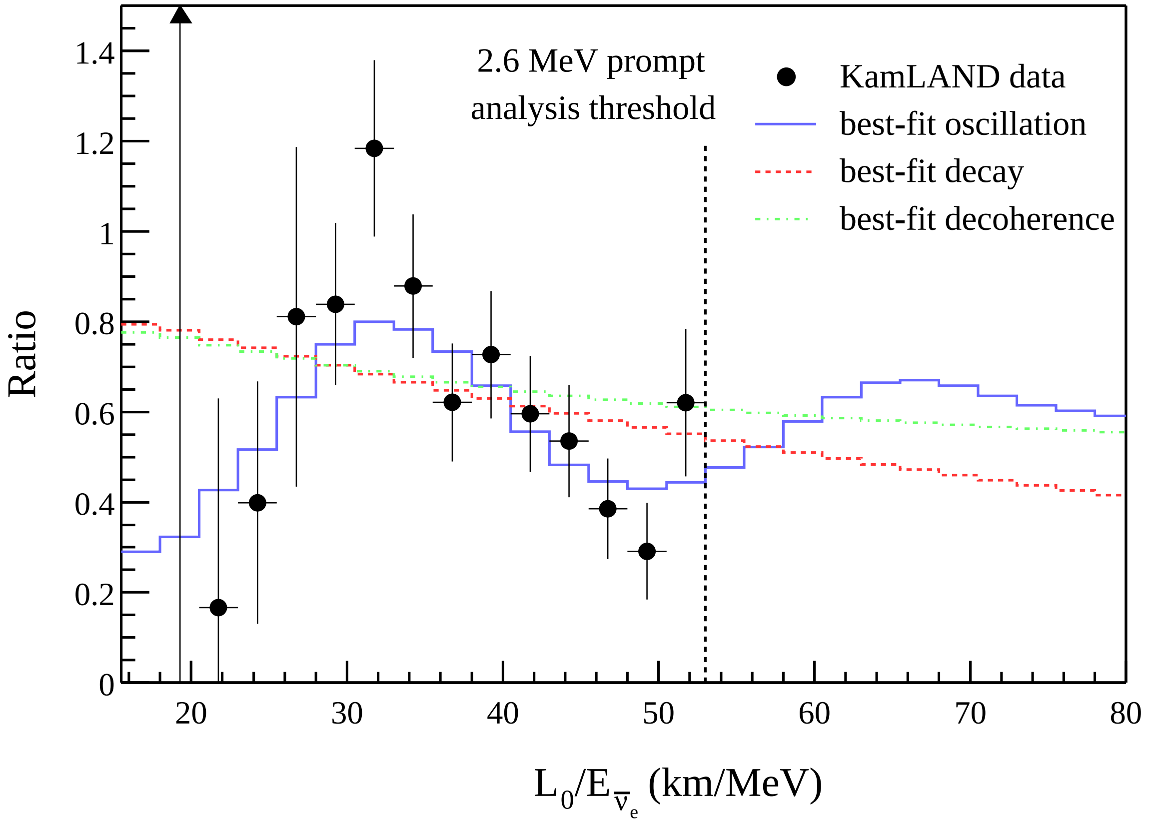
Distortion of the spectrum of positrons produced in the reaction $\bar{\nu}_e + p \to e^+ + n$ was observed in the KamLAND experiment



From global analysis of all solar and KamLAND data

$$\Delta m^2_{12} = 8.0^{+0.6}_{-0.4}\ 10^{-5}\ \mathrm{eV}^2$$
$$\tan^2\theta_{12} = 0.45^{+0.09}_{-0.07}$$

Dependence of the survival probability on $\frac{L}{E}$.
Clear oscillatory behavior



Summarizing

Model independent evidence for neutrino oscillations driven by small neutrino masses and neutrino mixing

Agreement with three-neutrino mixing

Except LSND. Indications in favor $\bar{\nu}_\mu \to \bar{\nu}_e$ $\Delta m^2 \simeq 1\text{eV}^2$ $\sin^2 2\theta \simeq 4 \cdot 10^{-2}$ Will be checked soon (?) by the MiniBooNE experiment.

We know values of four neutrino oscillation parameters

$$\Delta m^2_{12}(\sim 10\%); \tan^2\theta_{12}(\sim 20\%)$$
$$\Delta m^2_{23}; \sin^2 2\theta_{23}(\sim 30\%)$$

WE DO NOT KNOW

I. The lightest neutrino neutrino mass m_0

From the measurement of the high-energy part of the β-spectrum of ^{3}H

$$m_0 < 2.3 \text{ eV}$$

In the future KATRIN experiment the sensitivity $m_0 \simeq 0.2$ is planned to be reached

From cosmological data

$$\sum_i m_i < (02. - 0.7) \text{ eV}$$

Gravitational lensing will be sensitive to $\sum_i m_i \simeq 5 \cdot 10^{-2}$ eV

II. Nature of neutrinos with definite masses ν_i

Investigation of neutrino oscillations can not reveal the nature of ν_i. Necessary to study processes in which total lepton number L is violated

Probabilities of such processes are proportional to m_i^2 and are strongly suppressed (in the limit $m_i \to 0$ Dirac and Majorana are equivalent)

The most sensitive way to look for the Majorana nature of massive neutrinos is the search for neutrinoless double β decay

$$(\mathrm{A}, \mathrm{Z}) \to (\mathrm{A}, \mathrm{Z}+2) + \mathrm{e}^- + \mathrm{e}^-$$

of some even-even nuclei like ^{76}Ge, ^{130}Te, ^{136}Xe, ^{100}Mo,...

$0\nu\beta\beta$ is the second order in G_F process with virtual neutrinos

The matrix element of $0\nu\beta\beta$-decay is proportional to the effective Majorana mass

$$m_{\beta\beta} = \sum_i U_{ei}^2 m_i$$

The half-life of $0\nu\beta\beta$ decay

$$\frac{1}{T_{1/2}^{0\,\nu}(A,Z)} = |m_{ee}|^2 \, |M^{0\,\nu}(A,Z)|^2 \, G^{0\,\nu}(E_0,Z)$$

$G^{0\,\nu}(E_0,Z)$ known phase-space factor , $M^{0\,\nu}(A,Z)$ is NME.

NME includes propagator of massless neutrinos, many intermediate nuclear states must be taken into account; large uncertainties

The results of many experiments on the search for $0\nu\beta\beta$-decay of different nuclei are available

Best lower bounds

Heidelberg-Moscow (^{76}Ge)

$$T^{0\nu}_{1/2} \geq 1.9 \cdot 10^{25} \,\text{years}; \;\; |\mathrm{m}_{\beta\beta}| \leq (0.3 - 1.2) \;\; \mathrm{eV}$$

Cuoricino (^{130}Te)

$$T^{0\nu}_{1/2} \geq 5.5 \cdot 10^{23} \,\text{years}; \;\; |\mathrm{m}_{\beta\beta}| \leq (0.37 - 1.9) \;\; \mathrm{eV}$$

Many new experiments on the search for $0\nu\beta\beta$-decay are in preparation

CUORE (TeO_2, 750 kg), GERDA (^{76}Ge, 40 kg), EXO (^{136}Xe, 1 ton), MAJORANA (^{76}Ge, 180 kg), etc.

Future goal : $|m_{\beta\beta}| \simeq$ a few 10^{-2}eV

The expected value of $|m_{\beta\beta}|$ strongly depends on the character of neutrino mass spectrum and the lightest neutrino mass

Existing data are compatible with two neutrino mass spectra

I. Normal spectrum

$$m_1 < m_2 < m_3; \;\; \Delta m^2_{12} \ll \Delta m^2_{23}$$

II. Inverted spectrum

$$m_3 < m_1 < m_2; \;\; \Delta m^2_{12} \ll |\Delta m^2_{13}|$$

In the case of the normal spectrum and $m_1 \ll \sqrt{\Delta m^2_{12}}$ we have

$m_1 \ll m_2 \ll m_3$ (Neutrino mass hierarchy)

$$|m_{\beta\beta}| \leq 6.4 \cdot 10^{-3}\text{eV}$$

Smaller than the anticipated sensitivity of the future experiments

In the case of the inverted spectrum and $m_1 \ll \sqrt{|\Delta m^2_{13}|}$ we have

$m_3 \ll m_1 < m_2$ (Inverted hierarchy of neutrino masses)

Effective Majorana mass

$$|m_{\beta\beta}| \simeq \sqrt{|\Delta m^2_{31}|}\; (1 - \sin^2 2\,\theta_{12} \sin^2 \alpha_{12})^{\frac{1}{2}}$$

One unknown parameter $\sin^2 \alpha_{12}$, α_{12} is Majorana phase difference

From oscillation data the following 90 % CL range can be obtained

$$1.0 \cdot 10^{-2} \leq |m_{\beta\beta}| \leq 5.5 \cdot 10^{-2}\ \text{eV}$$

The values within reach of future $0\nu\beta\beta$-decay experiments

III. The value of the parameter $\sin\theta_{13}$

New reactor experiments DOUBLE CHOOZ, Daya Bay and others are in preparation. Factor 10-20 improvement in the sensitivity to $\sin^2\theta_{13}$ is expected. In the accelerator T2K experiment sensitivity to $\sin^2\theta_{13}$ will be about 25 times better than in CHOOZ experiment

$$U_{e3} = \sin\theta_{13}\; e^{-i\delta}$$

If parameter $\sin^2\theta_{13}$ is not too small it will be possible to study

1. CP violation in the lepton sector

2. To reveal the character of neutrino mass spectrum

Comparison of $\nu_\mu \to \nu_e$ and $\bar\nu_\mu \to \bar\nu_e$ (T2K, Super beam, β -beam, Neutrino factory)

There exist general consensus that neutrino masses and mixing is evidence of a new physics

We have no theory of neutrino (and quark) masses and mixing

Exist different strategies

The most natural and viable assumption see-saw mechanism of neutrino mass generation

Based on the assumption that in addition to the Dirac mass term generated by the standard Higgs mechanism and characterized by elecroweak $v \sim 250$ Gev exist a new mechanism which generate right-handed Majorana mass term characterizing by a large scale $M \sim 10^{15}$ GeV

Total lepton number L is violated, neutrinos with definite masses are Majorana particles

neutrino mass matrix has the form

$$m_\nu = -m_{\mathrm{D}}^T\, M_R^{-1}\, m_{\mathrm{D}}$$

and neutrino masses are much smaller than quark and lepton masses

Heavy Majorana particles, see-saw partners of light Majorana neutrinos, must exist. CP-violating decays of these particles in the early Universe is a probable source of the barion asymmetry of the Universe

Light Dirac neutrino masses can be generated in the framework of models with large extra dimentions

Further progress in understanding of the origin of small neutrino masses and neutrino mixing requires further theoretical efforts and NEW EXPERIMENTAL DATA