Neutrinoless double β-decay

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Model independent evidence of neutrino masses and mixing

I. S-K ATMOSPHERIC NEUTRINO EVIDENCE

Zenith angle dependence

If there are no oscillations

$$N(\cos\theta_z) = N(-\cos\theta_z)$$

Deficit of the up-going high energy ν_μ (Fig.)

Clear demonstration of the dependence of the number of ν_μ on distance

Perfectly described by $\nu_\mu \to \nu_\tau$ oscillations

Best-fit values of the oscillation parameters

$$\Delta m^2_{\rm atm} = 2\cdot 10^{-3}{\rm eV}^2;\quad \sin^2 2\theta_{\rm atm} = 1.0$$

$$(\chi^2_{\rm min} = 170.8/170\,{\rm d.o.f.})$$

II. SNO SOLAR NEUTRINO EVIDENCE

Neutrinos from the decay $^8\mathrm{B} \to ^8\mathrm{Be} + \mathrm{e}^+ + \nu_\mathrm{e}$ are detected via the observation

$$\nu_e + d \to e^- + p + p$$

$$\nu_l + d \to \nu_l + n + p \quad (l = e, \mu, \tau)$$

The total flux of the detected ν_e (CC)

$$\Phi^{\mathrm{SNO}}_{\nu_e} = (1.59^{+0.09}_{-0.07}(\mathrm{stat.})^{+0.06}_{-0.08}\,(\mathrm{syst.}))\cdot 10^6 \;\; cm^{-2}s^{-1}$$

The total flux of the detected ν_e, ν_μ, ν_τ (NC)

$$\sum_{l=e,\mu,\tau}\Phi^{\mathrm{SNO}}_{\nu_l} = (5.21 \pm 0.27 \pm 0.38)\cdot 10^6 \;\; cm^{-2}s^{-1}$$

Clear demonstration of the transitions of the solar ν_e into ν_μ and ν_τ

III. KamLAND REACTOR ANTINEUTRINO EVIDENCE

The reactor $\bar{\nu}_e$ are detected via observation of e^+ and n in $\bar{\nu}_e + p \to e^+ + n$

Average distance is 180 km

$\frac{N_{obs}}{N_{exp}} = 0.611 \pm 0.085 \pm 0.041$

clear demonstration of the disappearance of the reactor $\bar{\nu}_e$ (Fig)

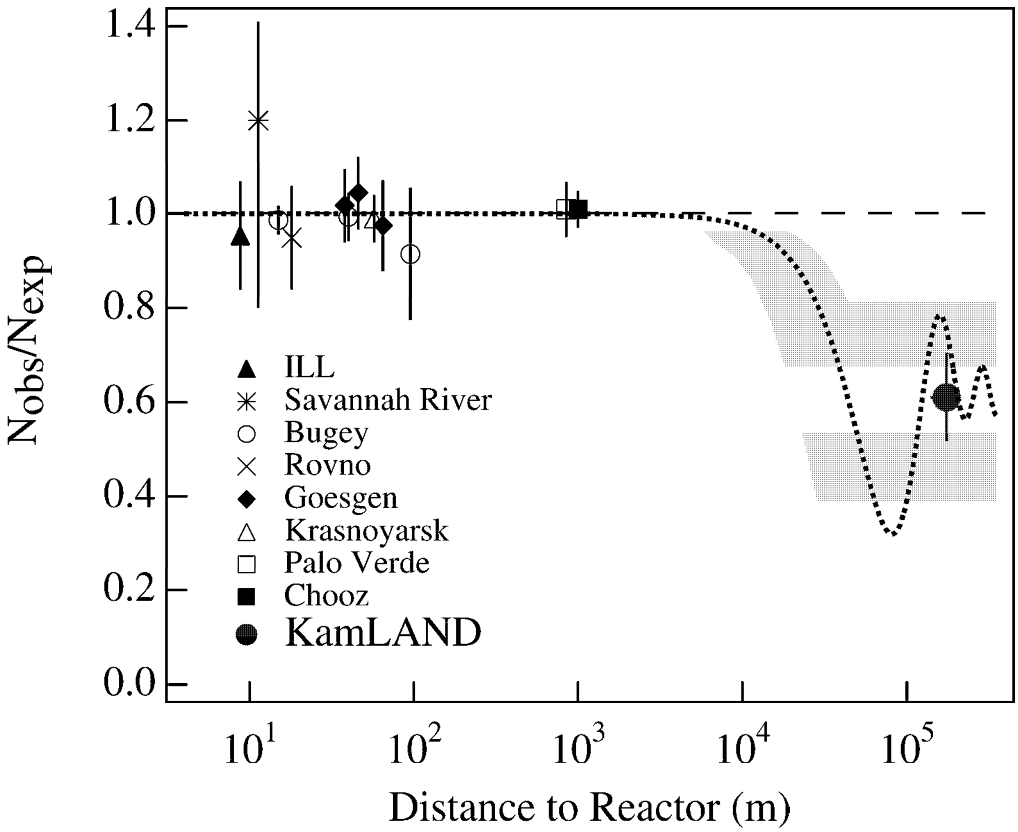
All solar neutrino data are described by the two-neutrino ν_e survival probability in matter

KamLAND data are described by the two-neutrino $\bar{\nu}_e$ survival probability in vacuum.

The values of the oscillation parameters found from analysis of the solar and KamLAND data are compatible

From joint analysis of the solar and KamLAND data (assuming CPT) best fit values of the parameters

$\Delta m^2_{\rm sol} = 7.1 \cdot 10^{-5}{\rm eV}^2;\ \tan^2\theta_{\rm sol} = 0.41$


1.4
1.2
1.0
0.8
0.6
0.4
0.2
0.0
Nobs/Nexp
ILL
Savannah River
Bugey
Rovno
Goesgen
Krasnoyarsk
Palo Verde
Chooz
KamLAND
10^1
10^2
10^3
10^4
10^5
Distance to Reactor (m)

Atmospheric neutrino evidence of neutrino oscillations was confirmed by the accelerator K2K experiment

Average ν_μ energy 1.3 Gev. Distance 250 km.

56 ν_μ observed events; $80.1^{+6.2}_{-5.4}$ expected.

best-fit values

$$\sin^2 2\,\theta_{K2K} = 1 : \quad \Delta m^2_{K2K} = 2.8 \;\; 10^{-3} \;\; \mathrm{eV}^2$$

agreement with $\sin^2 2\,\theta_{\rm atm}, \Delta m^2_{\rm atm}$

Negative result of the CHOOZ experiment is very important

$\bar\nu_e$ detected via $\bar\nu_e + p \to e^+ + n$

Distance about 1 km

$$\frac{N_{obs}}{N_{exp}} = 1.01 \pm 2.4\% \pm 2.7\%$$

From CHOOZ exclusion curve

$$\sin^2 2\theta_{\rm CHOOZ} \leq 2 \cdot 10^{-1}$$

BASICS

I. The Standard CC and NC Lagrangian

$$j_\alpha^{\rm CC} = 2 \sum_{l=e,\mu,\tau} \bar\nu_{lL}\gamma_\alpha l_L; \quad j_\alpha^{\rm NC} = \sum_{l=e,\mu,\tau} \bar\nu_{lL}\gamma_\alpha \nu_{lL}$$

II. Three flavor neutrinos ν_e, ν_μ ,ν_τ

III. Neutrino mixing

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

$U^+ U = 1$ ν_i is the field with the mass m_i

Two basic facts

1. $\Delta m^2_{\rm sol} \ll \Delta m^2_{\rm atm}$
2. $|U_{e3}|^2 \ll 1$

Leading transitions

$\nu_\mu \to \nu_\tau$ in the atmospheric range of L/E

Transitions of solar ν_e in matter and reactor $\bar\nu_e$ in the KamLAND range of L/E are

$\nu_e \to \nu_{\mu,\tau}$ and $\bar\nu_e \to \bar\nu_{\mu,\tau}$

After neutrino masses and mixing were established one of the most fundamental problem

Are ν_i Dirac or Majorana particles?

The solution of this problem will have important impact on our understanding of the origin of neutrino masses

It is impossible to distinguish D and Mj in neutrino oscillations

$U^{Mj} = U^D\, S(\beta)$; $\quad S(\beta)$ is a diagonal phase matrix

$$\mathrm{P}(\nu_\alpha \to \nu_{\alpha'}) = |\sum_i U_{\alpha' i}\ e^{-i\Delta m^2_{i1}\frac{L}{2E}}\ U^*_{\alpha i}|^2$$

$$\mathrm{P}^{Mj}(\nu_\alpha \to \nu_{\alpha'}) = \mathrm{P}^{D}(\nu_\alpha \to \nu_{\alpha'})$$

$0\nu\beta\beta$- *decay*

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

The most sensitive way to search for small Majorana masses

The half-life

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

The effective Majorana mass

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

$M^{0\,\nu}(A,Z)$ nuclear matrix element, $G^{0\,\nu}(E_0,Z)$ phase-space factor

- Experimental data, future experiments
- Possible values of $|m_{ee}|$
- The problem of nuclear matrix elements

Experimental data

$0\nu\beta\beta$- decay possible for even-even nuclei for which usual β-decay is forbidden

^{76}Ge(2.040 MeV), ^{130}Te(2.533 MeV), ^{136}Xe(2.479 MeV), ^{150}Nd(3.367 MeV), ...

The probability is proportional to E_0^5

The results of many experiments are available

Some data (90 % CL bounds)

Hedelberg-Moscow ^{76}Ge crystals, 86% enreached (11 kg)

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

MIBETA ^{130}Te, cryogenic detector (6.8 kg)

$$T^{0\nu}_{1/2} \geq 2.1 \cdot 10^{23}\,\text{years}; \;\; |\mathrm{m_{ee}}| \leq (1.1 - 2.6) \;\; \text{eV}$$

ranges due to NME uncertainties

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

Can be reached with $\simeq 1$ ton detectors (now $\simeq 10$ kg), low background, good energy resolution, efficient signature for real events

15 proposals

CUORE Cryogenic detector, 800 kg TeO_2 crystals, resolution 5 keV

$T^{0\nu}_{1/2} \simeq 9.5 \cdot 10^{26}$ years; $|\mathrm{m_{ee}}| \simeq (2-5.2)\, 10^{-2}$ eV

EXO 60-80 % enreached ^{136}Xe , $\simeq 10$ tons; additional signature: Ba^{+} atoms from the decay $^{136}\mathrm{Xe} \rightarrow ^{136}\mathrm{Ba}^{++} + e^{-} + e^{-}$ will be optically tagged with lasers. Background only from $2\nu\beta\beta$ decay.

$T^{0\nu}_{1/2} \simeq 1 \cdot 10^{28}$ years; $|\mathrm{m_{ee}}| \simeq (1.3-3.7)\, 10^{-2}$ eV

GENIUS 1 ton 86 % enreached ^{76}Ge in liquid nitrogen (creostat and shielding)

$T^{0\nu}_{1/2} \simeq 1 \cdot 10^{28}$ years; $|\mathrm{m_{ee}}| \simeq (1.3-5.0)\, 10^{-2}$ eV

MAJORANA 500 kg of 86 % enreached ^{76}Ge background from $^{68}\mathrm{Ge} \to \mathrm{e}^+ + \nu_\mathrm{e} +^{68}\mathrm{Ga}$.

can be suppressed by the segmentation and pulse shape analysis

$T^{0\nu}_{1/2} \simeq 4 \cdot 10^{27}$ years; $|\mathrm{m_{ee}}| \simeq (2.1 - 7.0)\, 10^{-2}$ eV

Effective Majorana mass $|m_{ee}|$

THREE-NEUTRINO MIXING

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

LSND ? will be checked by the MiniBooNE

$$m_{ee} = \sum_{i=1}^{3} U_{ei}^2\, m_i$$

I. Neutrino masses

From neutrino oscillations

$$\Delta m^2_{21} \simeq \Delta m^2_{\mathrm{sol}} \quad |\Delta m^2_{32}| \simeq \Delta m^2_{\mathrm{atm}}$$

For the minimal mass upper bounds

From Troitsk and Mainz tritium experiments

$$m_{\min} \leq 2.05 \;\; (2.3)\, \mathrm{eV}$$

From WMAP and Sloan Digital Survey data

$$m_{\rm min} \leq 0.6\,{\rm eV}$$

II. 1-2 and 1-3 mixing angles

$$U^2_{e1} = \cos^2\theta_{13}\,\cos^2\theta_{12}\,e^{2\,i\alpha_1}$$

$$U^2_{e2} = \cos^2\theta_{13}\,\sin^2\theta_{12}\,e^{2\,i\alpha_2}$$

$$U^2_{e3} = \sin^2\theta_{13}\,e^{2\,i\alpha_3}$$

$$\sin^2\theta_{12} \simeq \sin^2\theta_{\rm sol}\quad \sin^2\theta_{13} \leq 5\cdot 10^{-2}$$

III. Majorana phases

In the case of CP invariance

$$U_{ei} = U^*_{ei}\,\eta_i$$

$\eta_i = i\,\rho_i \quad \rho_i = \pm 1$ is CP-parity of ν_i

$$|m_{ee}| = |\sum_{i=1}^{3} |U_{ei}|^2\,\rho_i\,m_i|$$

Cancellations take place for different CP parities

$|m_{ee}|$ *strongly depends*

on pattern of neutrino mass spectrum and the minimal neutrino mass

Three "standard" spectra

I. Hierarchy of masses $m_1 \ll m_2 \ll m_3$

Neutrino masses are known from oscillation data

$$m_2 \simeq \sqrt{\Delta m^2_{\rm sol}} \simeq 8.4 \cdot 10^{-3} {\rm eV}.$$

$$m_3 \simeq \sqrt{\Delta m^2_{\rm atm}} \simeq 4.5 \cdot 10^{-2} {\rm eV}.$$

$$|m_{ee}| \simeq \left| \sin^2\theta_{\rm sol} \sqrt{\Delta m^2_{\rm sol}} + e^{i\,\alpha_{32}} \sin^2\theta_{13} \sqrt{\Delta m^2_{\rm atm}} \right|$$

The first term is small. Contribution of "large" $\sqrt{\Delta m^2_{\rm atm}}$ is suppressed by the smallness of $\sin^2\theta_{13}$

Upper bound

$$|m_{ee}| \leq 4.6 \cdot 10^{-3} {\rm eV}$$

significantly smaller than the sensitivity of the future experiments

II. Inverted hierarchy of masses $m_3 \ll m_1 < m_1$

$$m_2 \simeq m_1 \simeq \sqrt{\Delta m^2_{\rm atm}};\, m_3 \ll \sqrt{\Delta m^2_{\rm atm}}$$

Effective Majorana mass

$$|m_{ee}| \simeq \sqrt{\Delta m^2_{\rm atm}}\ (1 - \sin^2 2\,\theta_{\rm sol}\, \sin^2 \alpha_{21})^{\frac{1}{2}}$$

$\alpha_{21} = \alpha_2 - \alpha_1; \alpha_{21} = 0, \pm\frac{\pi}{2}$ in the CP case

Important: $\sin^2 2\,\theta_{\rm sol} < 1$ $(5.4\ \sigma)$

$|m_{ee}|_{\rm min}$ can not be equal to zero

$$\cos 2\,\theta_{\rm sol} \sqrt{\Delta m^2_{\rm atm}} \leq |m_{ee}| \leq \sqrt{\Delta m^2_{\rm atm}}$$

Using solar data

$$0.4 \sqrt{\Delta m^2_{\rm atm}} \leq |m_{ee}| \leq \sqrt{\Delta m^2_{\rm atm}}$$

Scale of $|m_{ee}|$ is determined by $\sqrt{\Delta m^2_{\rm atm}}$

For the best-fit values of the parameters

$$0.8 \cdot 10^{-2}{\rm eV} \leq |{\rm m_{ee}}| \leq 5.5 \cdot 10^{-2}{\rm eV}$$

Can be reached in the future experiments

III. Practically degenerate neutrino masses

In two previous cases $m_{\rm min}$ was small and neutrino masses were determined by $\sqrt{\Delta m^2_{\rm atm}}$ $\sqrt{\Delta m^2_{\rm sol}}$

If $m_{\rm min} \gg \sqrt{\Delta m^2_{\rm atm}}$

$m_1 \simeq m_2 \simeq m_3$ and $m_{\rm min}$ unknown

Effective Majorana mass

$$|m_{ee}| \simeq m_{\rm min}\ (1 - \sin^2 2\,\theta_{\rm sol}\, \sin^2 \alpha)^{\frac{1}{2}}$$

From the solar data

$$0.42\ m_{\rm min} \leq |m_{ee}| \leq m_{\rm min}$$

The scale of $|m_{ee}|$ is determined by $m_{\rm min}$

The sensitivity of the future tritium KATRIN experiment

$$m_{\rm min} \simeq 0.2\,{\rm eV}$$

From the measurement $|m_{ee}|$ an information on $m_{\rm min}$ can be inferred

$$|m_{ee}| \leq m_{\rm min} \leq 2.38\,|m_{ee}|$$

$|m_{ee}|$ for arbitrary $m_{\rm min}$ Fig.

Nuclear Matrix elements

Complicated nuclear problem

two methods: QRPA and shell model

The results of different calculations differ by factor ≥ 3

$$6.8 \cdot 10^{26}\text{y} \leq T^{0\nu}_{1/2}(^{76}\text{Ge}) \leq 70.8 \cdot 10^{26}\text{y}$$

at $|m_{ee}| = 5 \cdot 10^{-2}\text{eV}$

Recently important progress in QRPA

(V.A. Rodin et al Phys. Rev. C 68 (2003) 044302)

For ^{76}Ge, ^{100}Mo, ^{130}Te and ^{136}Xe $0\nu\beta\beta$ NME were calculated

the constant g_{pp} (particle-particle interaction) was fixed by measured half-life of the $2\nu\beta\beta$-decay.

NME are stable under the change of the nuclear potential and the number of single particle states

A POSSIBLE TEST OF NME CALCULATIONS

NME of the $0\nu\beta\beta$- decay can not be connected with other measurable

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

Assume $0\nu\beta\beta$- decay of several nuclei is observed

A model is compatible with the data if

$$|m_{ee}|_{A_1,Z_1} \simeq |m_{ee}|_{A_2,Z_2}$$

For models m_1 and m_2

$$|m_{\beta\beta}|^{m_2}_{A,Z} = |m_{\beta\beta}|^{m_1}_{A,Z}\, \eta_{A,Z}(m_2/m_1)$$

$$\eta_{A,Z}(m_2/m_1) = \frac{|M^{0\,\nu}(A,Z)|_{m_2}}{|M^{0\,\nu}(A,Z)|_{m_1}}$$

Using existing calculations we can see that $\eta^{A}_{A,Z}$ depends on (A,Z)

However, observation of the $0\nu\beta\beta$- decay of two nuclei can be not enough to distinguish models

Nucleus	$\eta(NSM/QRPA)$
^{76}Ge	1.75
^{130}Te	1.45
^{136}Xe	2.54

The latest NSM and QRPA calculations were used

If $0\nu\beta\beta$-decay of ^{76}Ge and ^{130}Te is observed and the same $|m_{ee}|$ will be obtained with QRPA nuclear matrix elements, it will be difficult to exclude NSM

Observation of $0\nu\beta\beta$-decay of more that two nuclei is needed

Conclusion

- The establishment of the nature of ν_i (Majorana or Dirac?) will have a profound importance for the understanding of small neutrino mass and mixing physics
- Far the most sensitive process is $0\nu\beta\beta$-decay
- Today's limit $|m_{ee}| \leq (0.3 - 1.2)$ eV
- Goal of future experiments (15 proposals) $|m_{ee}| \simeq$ a few 10^{-2}eV
- If $0\nu\beta\beta$-decay is observed, the pattern of the neutrino mass spectrum can be revealed.
- Calculation of the nuclear matrix elements is a complicated nuclear problem and is a theoretical challenge
- Observation of $0\nu\beta\beta$-decay of several nuclei the only possibility to test calculations