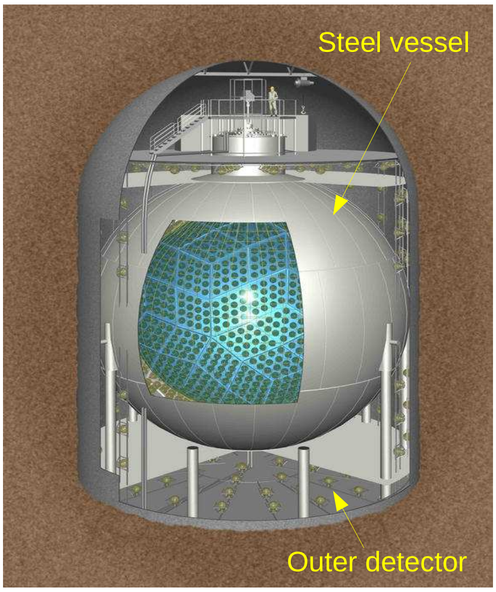
4. Reactor Experiments – Example KamLAND

Kamioka Liquid scintillator Anti-Neutrino Detector located in the original KamiokaNDE cavity

- Site is surrounded by 53 Japanese commercial power reactors at an average distance *L* = 180 km
- 9 m radius stainless steel vessel
- 1879 photomultipliers on the inner surface to measure scintillator light
- 6.5 m radius nylon balloon inside filled with 1000 t liquid scintillator (mineral oil, benzene and fluorescent chemicals)
- Balloon surrounded by non-scintillating oil shielding external radiation and supporting (nylon film is too thin to support 1000t)
- Steel vessel is surrounded by ultrapure water + Cerenkov counters – further shielding and veto against muons



Disappearance experiment:
$\bar{\nu}_e$ produced in reactors are detected via inverse β-decay with threshold *E* > 1.8 MeV

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

Prompt scintillation light from e^+ gives E_ν – study *E* spectrum

$$E_\nu = E_{\text{prompt}} + \langle E_{n\,\text{recoil}} \rangle + 0.8\,\text{MeV}$$

n capture by proton produces another 2.2 MeV γ-ray delayed by 200 μs
- allows good background control

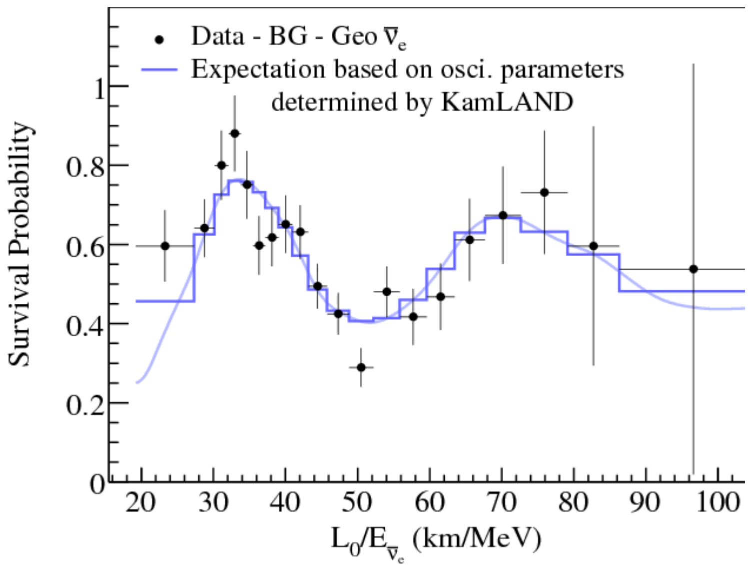
Very good sensitivity to Δm^2 due to rather large *L* = 180 km

$$P(\nu_\alpha \rightarrow \nu_\beta, t) = \sin^2 2\theta \sin^2\left(\frac{\Delta m^2}{4E} L\right)$$

Note: solar neutrino are ν_e, reactor neutrinos are $\bar{\nu}_e$. Different signature:
for ν_e there is no combination of prompt and delayed light.

KamLAND Results

- Big deficit observed – in 1st study (2004) 258 ν_e w. E > 3.4 MeV out of 365 expected
- Newest result for ratio (signal – geo bg) / expectation w/o oscillations



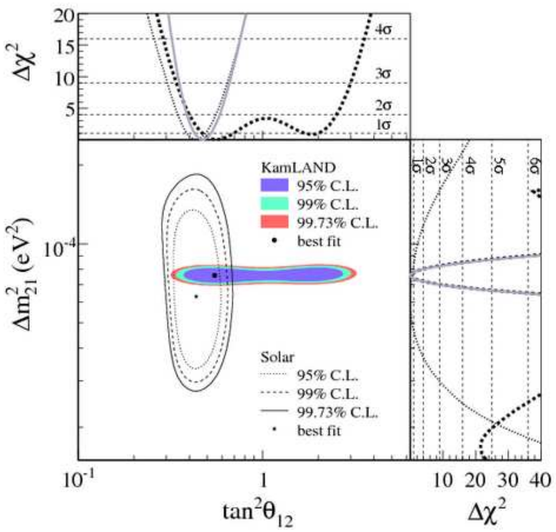
Using average L_0 = 180 km

KamLAND Results

Two-flavour analysis $P(\nu_\alpha \rightarrow \nu_\beta, t) = \sin^2 2\theta \sin^2\left(\frac{\Delta m^2}{4E} L\right)$

$\Delta m^2 = (8.2 \pm 0.6) \times 10^{-5}\,\mathrm{eV}$

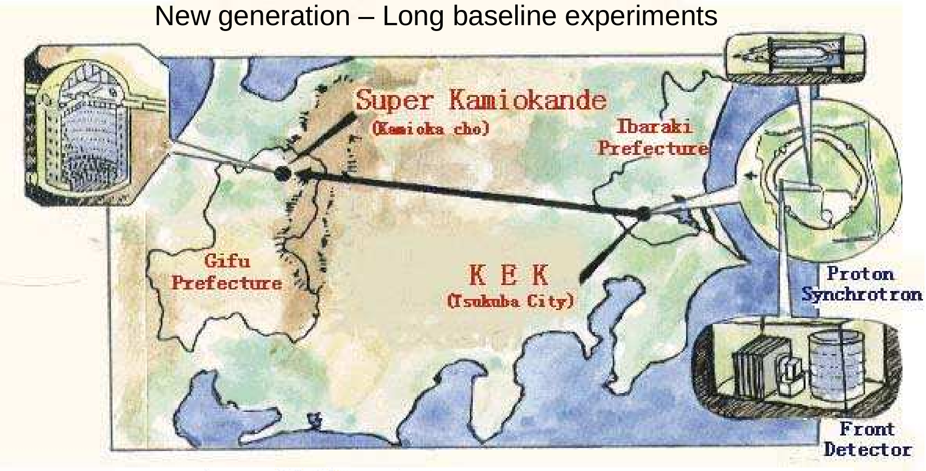
$\sin^2 2\theta \approx 0.83$

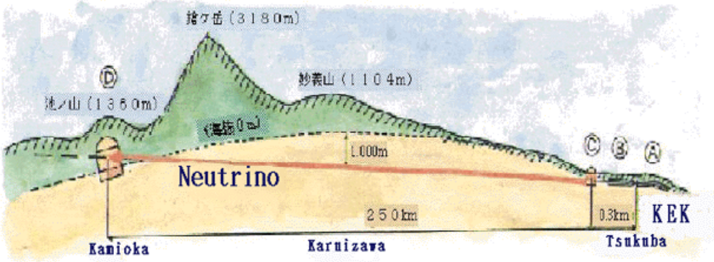


LMA = large mixing angle:
MSW effect necessary for solar ν

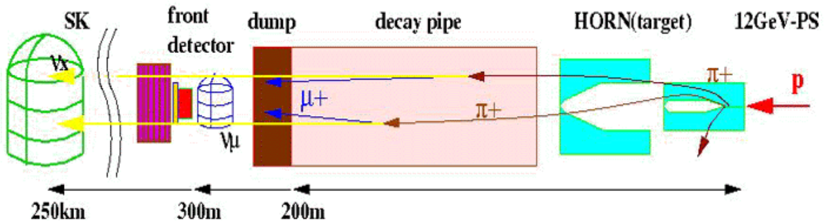
5. Accelerator Experiments – Example K2K

New generation – Long baseline experiments





Scheme of the experiment



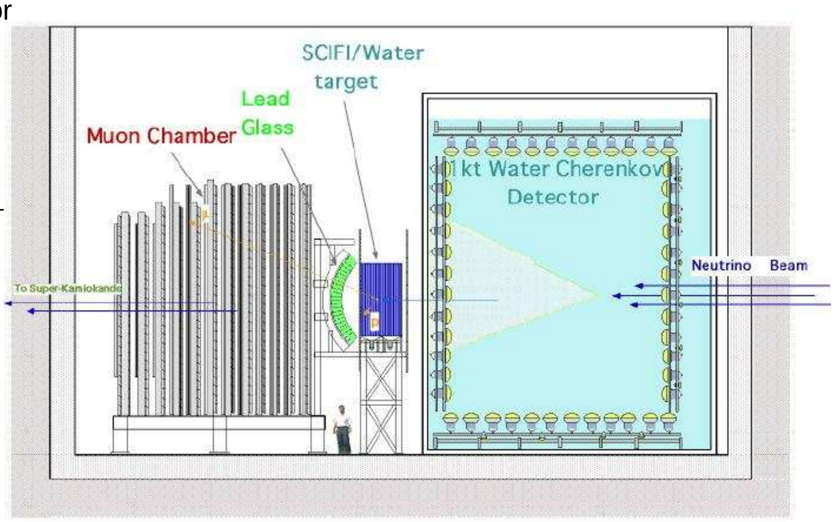
Front detector

measure CC

$\nu_\mu + n \rightarrow \mu^- + p$

and pion production

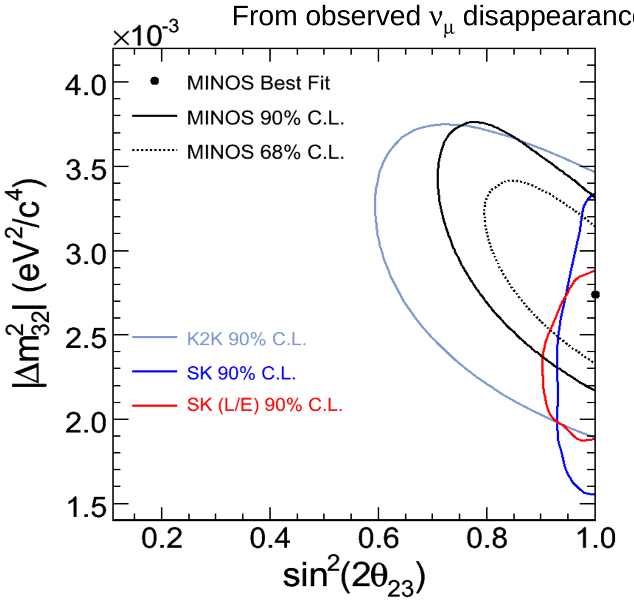
$\nu_\mu + p \rightarrow \mu^- + p + \pi^+$



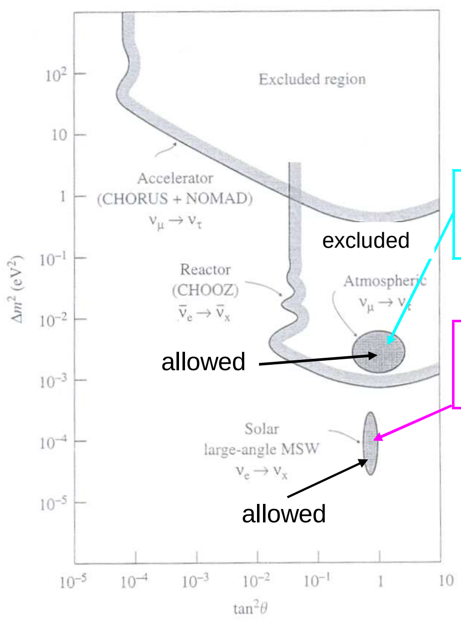
Similar experiment in the USA:
NuMI(Neutrinos at the Main Injector) at Fermilab + MINOS (Main Injector Neutrino Oscillation Search) in Soudan mine
Distance: 735 km, 120 GeV protons

In Europe: CERN beam to Gran Sasso ICARUS and OPERA experiments
Distance: 730 km

From observed ν_μ disappearance



Status of oscillation measurements



Atmos
$\nu_\mu \to \nu_x$

$\Delta m^2 = (2.4 \pm 0.4) \times 10^{-3}\,\mathrm{eV}$
$\sin^2 2\theta > 0.92\ @\,90\ C.L.$

+ accelerator (not on this plot)

Solar+KamLAND
$\nu_e \to \nu_x$

$\Delta m^2 = (8.2 \pm 0.6) \times 10^{-5}\,\mathrm{eV}$
$\sin^2 2\theta \approx 0.83$

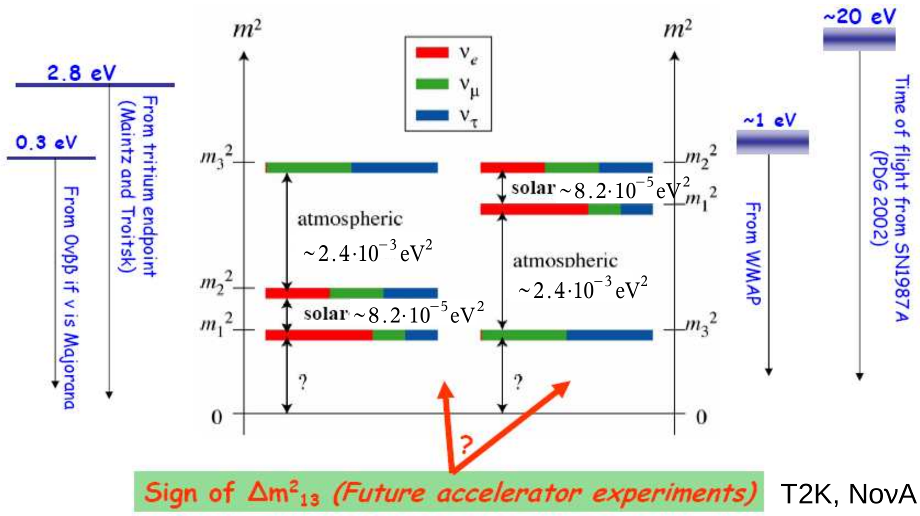
Different oscillation pattern for different neutrinos – what can we learn about the masses ??

6. Neutrino masses

$$U=\begin{pmatrix} c_{12}c_{13} & s_{12}c_{13} & s_{13} \\ -s_{12}c_{23}-c_{12}s_{23}s_{13} & c_{12}c_{23}-s_{12}s_{23}s_{13} & s_{23}c_{13} \\ s_{12}s_{23}-c_{12}c_{23}s_{13} & -c_{12}s_{23}-s_{12}c_{23}s_{13} & c_{23}c_{13} \end{pmatrix}$$

where $c_{ij}=\cos\theta_{ij}$, $s_{ij}=\sin\theta_{ij}$

$\theta_{12}\equiv\theta_{sol}$ $\theta_{23}\equiv\theta_{atm}$ $\theta_{13}\approx 0$



T2K, NovA also measure θ_{13}

Absolute neutrino masses are not known !

Neutrino masses added to the Standard Model

- Mass term in the Lagrangian of a free massive Dirac field

$$L(\vec{x},t)=i\bar{\psi}(\vec{x},t)\gamma^{\mu}\partial_{\mu}\psi(\vec{x},t)-\boxed{m\bar{\psi}(\vec{x},t)\psi(\vec{x},t)}$$

(Using Euler-Lagrange formalism *L* leads to the Dirac equation)

- Using chirality projection operators:

$$\bar{\psi}_L=\bar{\psi}\frac{1}{2}(1+\gamma^5) \qquad \psi_L=\frac{1}{2}(1-\gamma^5)\psi$$

$$\bar{\psi}_R=\bar{\psi}\frac{1}{2}(1-\gamma^5) \qquad \psi_R=\frac{1}{2}(1+\gamma^5)\psi$$

we get

$$m\bar{\psi}\psi=m\bar{\psi}[\frac{1}{2}(1-\gamma^5)+\frac{1}{2}(1+\gamma^5)]\psi=$$

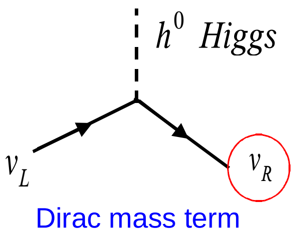
$$=m\bar{\psi}[\frac{1}{2}(1-\gamma^5)+\frac{1}{2}(1+\gamma^5)][\frac{1}{2}(1-\gamma^5)+\frac{1}{2}(1+\gamma^5)]\psi=$$

$$\boxed{=m\bar{\psi}_R\psi_L+m\bar{\psi}_L\psi_R}$$

because $\gamma^5\gamma^5=1 \longrightarrow (1-\gamma^5)(1+\gamma^5)=1-\gamma^5\gamma^5=0$

Neutrino masses added to the Standard Model

- Neutrino Mass term: the same as for charged leptons: $\sim m\bar{\psi}_R \psi_L$



Dirac mass term

$$\langle m \rangle = m_D(\bar{L}_\nu R_\nu + \bar{R}_\nu L_\nu)$$

Masses of neutrinos through Yukawa coupling to Higgs:

$$m_\nu = \frac{\lambda_\nu v}{\sqrt{2}}$$

From the vacuum expectation value of the Higgs, υ≈246 GeV, follows that the Yukawa coupling must be extremely small ($<10^{-11}$) to generate the small neutrino masses.

→ unnatural

- Dirac mass terms imply existence of right (left) -handed (anti) neutrinos.

  Minimal extension of the Standard Model:

  Introduce singlets of right (left)-handed (anti)neutrinos which do not couple to charged and neutral currents.

- Lepton numbers: L_e L_μ and L_τ are not conserved. L is conserved !!
- But why are the neutrino masses so small ?

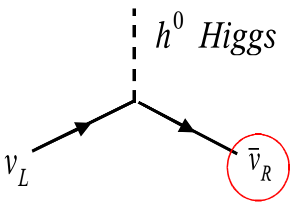
Majorana Neutrinos

- Unlike the charged leptons, neutrinos could be their own anti-particles:

Majorana Neutrinos

$$\nu = \bar{\nu} \quad \begin{cases} \bar{\nu}_L = \nu_L \\ \nu_R = \bar{\nu}_R \end{cases}$$

- Majorana-mass terms in addition to Dirac mass terms possible:

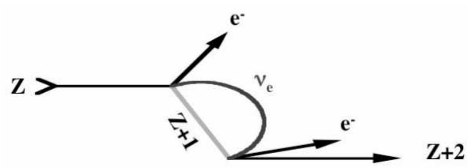


Majorana mass term

$$\langle m \rangle = (\bar{L}_\nu, \bar{L}_{\bar{\nu}}) \begin{pmatrix} m_{M,L} & 0 \\ 0 & m_{M,R} \end{pmatrix} \begin{pmatrix} R_{\bar{\nu}} \\ R_\nu \end{pmatrix} + c.c.$$

Mass term violates Lepton flavor conservation: ΔL = ± 2

- Majorana character can be checked in neutrinoless double beta decay (0ν2β):

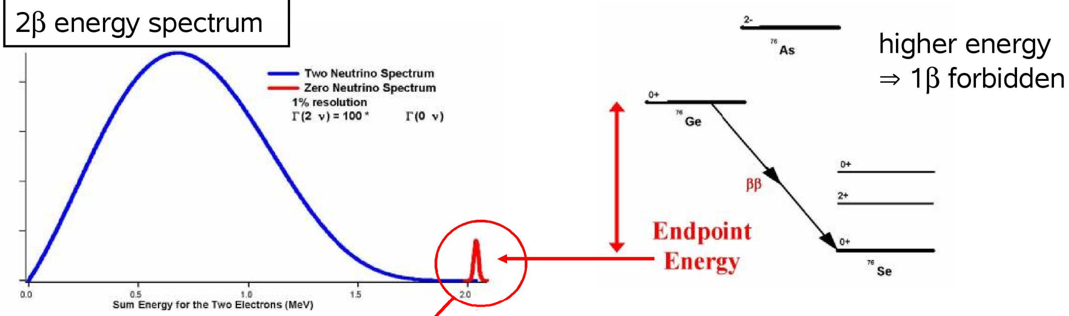


- Can we prove that neutrino is a Dirac particle

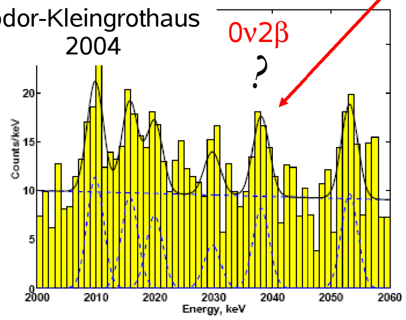
Search for 0ν2β

Germanium decay (example)

2β energy spectrum



Klapdor-Kleingrothaus 2004



Isotope	Half-life (years)	$m_{\beta\beta}$ (meV)	Reference
^{48}Ca	$>1.4 \times 10^{22}$	<7200-44700	[7]
^{76}Ge	$>1.9 \times 10^{25}$	<350	[8]
^{76}Ge	$>1.6 \times 10^{25}$	<330-1350	[9]
^{76}Ge	$=1.2 \times 10^{25}$	=440	[10]
^{82}Se	$>2.7 \times 10^{22}$ (68%)	<5000	[11]
^{100}Mo	$>5.5 \times 10^{22}$	<2100	[12]
^{116}Cd	$>1.7 \times 10^{23}$	<1700	[13]
^{128}Te	$>7.7 \times 10^{24}$ (geochem)	<1100-1500	[14]
^{130}Te	$>5.5 \times 10^{23}$	<370-1900	[15]
^{136}Xe	$>4.4 \times 10^{23}$	<1800-5200	[16]
^{150}Nd	$>1.2 \times 10^{21}$	<3000	[17]

Seesaw mechanism to generate light neutrinos

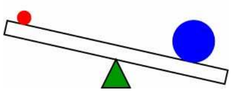
- If neutrinos are Majorana particles:

  Introduce in addition to the Dirac mass term also a Majorana mass term for the right-handed neutrino singlet:

$$\langle m \rangle = \left(\bar{L}_\nu , \bar{L}_{\bar{\nu}} \right) \begin{pmatrix} m_{M,L} & m_D \\ m_D & m_{M,R} \end{pmatrix} \begin{pmatrix} R_{\bar{\nu}} \\ R_\nu \end{pmatrix} + c.c.$$

Seesaw Model: Assume Higgs mechanism gives Dirac mases at EW scale, and very high (GUT) Majorana mass M_R of the right-handed neutrino, and zero Majorana mass M_L of left handed neutrino = 0. The eigenstates for weak interaction are eigenstates of this matrix. Diagonalising gives:

$$m_\nu = \frac{m_D^2}{M_R}$$



- Small neutrino masses can be explained … but how large is M_R ($10^{10} \ldots 10^{15}$ GeV) ?