Measurement of Neutrino Properties

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TeV Particle Astrophysics 2009
SLAC, 13 Jul 2009
Neutrinos at *TeV Particle Astrophysics 2009*

Three points of view:

- **Intrinsic properties of the neutrino** *(this talk)*
- **Neutrinos as tools to relay information on astrophysical phenomena** *(several talks on Wed)*
- **Neutrinos in cosmology**, this can also be used to constrain neutrino properties connecting together very different threads, worlds, scales,... *(see Wendy Freedman’s talk tomorrow)*
Last 15 yrs in particle physics: the age of $\nu$

**Discovery of $\nu$ flavor change**

- **Solar neutrinos** (MSW effect)
- **Reactor neutrinos** (vacuum oscillation)
- **Atmospheric neutrinos** (vacuum oscillation)
- **Accelerator neutrinos** (vacuum oscillation)

- $\nu$ masses are non-zero
- Lepton mixing matrix very different from that of quarks
- There are $2.984 \pm 0.008 \, \nu$ (Z lineshape, PDG Phys Lett. B667 (08) 1)
- 3 $\nu$ flavors were active in Big Bang Nucleosynthesis
- The Sun emits neutrinos as expected
- Supernovae emit neutrinos
Our knowledge of the lepton mixing matrix

\[ U = \begin{pmatrix}
U_{e1} & U_{e2} & U_{e3} \\
U_{\mu1} & U_{\mu2} & U_{\mu3} \\
U_{\tau1} & U_{\tau2} & U_{\tau3}
\end{pmatrix} = \]

\[ \begin{pmatrix}
1 & 0 & 0 \\
0 & \cos\theta_{23} & \sin\theta_{23} \\
0 & -\sin\theta_{23} & \cos\theta_{23}
\end{pmatrix} \begin{pmatrix}
\cos\theta_{13} & 0 & e^{-i\delta_{CP}} \sin\theta_{13} \\
0 & 1 & 0 \\
-e^{-i\delta_{CP}} \sin\theta_{13} & 0 & \cos\theta_{13}
\end{pmatrix} \begin{pmatrix}
\cos\theta_{12} & \sin\theta_{12} & 0 \\
-sin\theta_{12} & \cos\theta_{12} & 0 \\
0 & 0 & 1
\end{pmatrix} \begin{pmatrix}
1 & 0 & 0 \\
0 & e^{-i\alpha/2} & 0 \\
0 & 0 & e^{-i\alpha/2+i\beta}
\end{pmatrix} \]

- Atmospheric v K2K
- Chooz/Palo Verde Off axis
- Solar v KamLAND Future solar v exp.

\[ \theta_{23} \sim 45^\circ \]
\[ \theta_{13} < 7^\circ \text{ @ } 90\% \text{CL} \]
\[ \theta_{12} \sim 34^\circ \]

Neutrinoless double beta decay
Nuclear reactors are very intense sources of $\bar{\nu}_e$ deriving from beta-decay of the neutron-rich fission fragments.

Yield: 
200 MeV / fission
6$\bar{\nu}_e$ / fission

Look for a deficit of $\bar{\nu}_e$ and/or spectral distortions at a distance $L$.
The KamLAND detector

Until now only liquid Scintillators used
- Low threshold
- Neutron sensitivity (2.2MeV)
- Large quantity
  (KamLAND is 1kton)

Reactor $\bar{\nu}_e$ spectrum

Observable spectrum using $\bar{\nu}_e + p \rightarrow n + e^+$ (a.u.)
Over 50 reactors cores contribute to the signal in KamLAND

~1 km high Mt. Ikenoyama

See K. Nakamura this afternoon
The spectrum observed by KamLAND clearly reveals oscillations.

S. Abe, et al. PRL 100 (2008) 021101
Different look at the same spectrum
(unfortunately cannot point to source, so the baseline $L_0$ is the most probable value of 180km):
The “oscillatory behavior” of neutrino oscillations!
Different look at the same spectrum
(unfortunately cannot point to source, so the baseline $L_0$ is the most probable value of 180km):

The “oscillatory behavior” of neutrino oscillations!
Solar Neutrinos

Borexino

Neutrino Flux

Neutrino Energy (MeV)

Gallium | Chlorine | SuperK, SNO

pp $\pm 1\%$

$^7$Be $\pm 10\%$

$^7$Be $\pm 1.5\%$

pp $\pm 20\%$

$^8$B $-16\%$

$^{12}$C $\pm ?$

hep

TeV Particle AP, SLAC Jul 09

Giorgio Gratta -- Neutrino Properties
SNO: Neutrino interactions in D$_2$O

**Charged Current (CC):**
\[ \nu_e + d \rightarrow p + p + e^- \]  
*Electron neutrinos only*

**Elastic Scattering (ES):**
\[ \nu_x + e^- \rightarrow \nu_x + e^- \]
\[ 0.154 \cdot \sigma(\nu_e) = \sigma(\nu_\mu) = \sigma(\nu_\tau) \]
*this is all SuperK sees*

**Neutral Current (NC):**
\[ \nu_x + d \rightarrow p + n + \nu_x \]  
*Same for all neutrino flavors!*
...and, indeed, SNO sees disappearance of $\nu_e$ but also appearance of $\nu_\mu$ and $\nu_\tau$

\[
\phi(e) = (1.76 \pm 0.05) \times 10^6 \text{ cm}^{-2}\text{s}^{-1}
\]

\[
\phi(\mu, \tau) = (3.41 \pm 0.45) \times 10^6 \text{ cm}^{-2}\text{s}^{-1} \neq 0 \text{ at a } 7.5\sigma \text{ level}
\]

B. Aharmim et al. PRC 75 (2007) 045502
Solar neutrinos meet reactor anti-neutrinos

The fact that there is overlap between the two regions requires that:

- CPT is valid ($\nu$ mixing is same as $\bar{\nu}$ mixing)
- The phenomenology of MSW uses the same parameters as vacuum oscillations

$$\Delta m^2_{12} = 7.59^{+0.19}_{-0.21} \times 10^{-5} \text{eV}^2$$

$$\theta_{12} = 34.4^{+1.3}_{-1.2} \text{deg}$$

S. Abe, et al.
PRL 100 (2008) 021101

Atmospheric and accelerator neutrinos

Accelerators measurements have the advantage of high energy and the possibility to shoot and detect different flavors and polarities (note: I did not say this is easy...
SuperK atm ν ~3000 d of data (180 kton-yr)
MINOS: clear energy-dependent $\nu_\mu$ deficit

848 CC $\nu_\mu$ candidate events detected
1065±60 (syst) expected for no oscillations

Again, there is good agreement between different Phenomena -atmospheric and accelerator neutrinos- (although in the case this is maybe less surprising -both are vacuum oscillations).

\[ \Delta m_{23}^2 = (2.43 \pm 0.13) \times 10^{-3} \text{eV}^2 \]

\[ \sin^2 2\theta_{23} > 0.92 \quad @ \, 90\% \, CL \]

\[ U = \begin{pmatrix}
U_{e1} & U_{e2} & U_{e3} \\
U_{\mu1} & U_{\mu2} & U_{\mu3} \\
U_{\tau1} & U_{\tau2} & U_{\tau3}
\end{pmatrix} = \theta_{13} \]

\[
\begin{pmatrix}
1 & 0 & 0 \\
0 & \cos \theta_{23} & \sin \theta_{23} \\
0 & -\sin \theta_{23} & \cos \theta_{23}
\end{pmatrix}
\begin{pmatrix}
\cos \theta_{13} & 0 & e^{-i\delta_{CP}} \sin \theta_{13} \\
0 & 1 & 0 \\
-e^{-i\delta_{CP}} \sin \theta_{13} & 0 & \cos \theta_{13}
\end{pmatrix}
\begin{pmatrix}
\cos \theta_{12} & \sin \theta_{12} & 0 \\
-\sin \theta_{12} & \cos \theta_{12} & 0 \\
0 & 0 & 1
\end{pmatrix}
\]

\( U \) contains the CP-violating phase \( \delta_{CP} \) with coefficients of the type
\[ \sin \theta_{12} \sin \theta_{23} \sin \theta_{13} \]

...so it is important to understand if \( \theta_{13} \approx 0 \)

Present best limit is from reactors (Chooz and Palo Verde)
\[ \sin^2(2\theta_{13}) < 0.19 \text{ @90\% CL} \]

PDG Phys Lett B667 (2008) 1
Future: mixing parameters

High precision (near/far detectors) reactor experiments dedicated to $\theta_{13}$:

- Daya Bay (China, near Hong Kong)
- Double Chooz (France)
- RENO (Korea)

Runs expected to start in 2011 (but will take time to accumulate statistics and start the far detectors)

Expected sensitivities to $\theta_{13}$:

- $<10^{-2}$ (Daya Bay)
- $3\times10^{-2}$ (Double Chooz)

see D. McKee this afternoon

Off-axis, long baseline experiments:

- T2K (Japan, 2009-...)
- NOvA (US, 2013-...)

Sensitivity to $\theta_{13}$ as low as $3\times10^{-3}$ but this depends also on $\delta_{CP}$ and the hierarchy (so, if lucky get more than $\theta_{13}$...
The ν mass pattern/magnitude

The ν mass pattern/magnitude

- \( \nu_e \)
- \( \nu_\mu \)
- \( \nu_\tau \)

\[ m^2 \]

\[ m_1^2 \]
\[ m_2^2 \]
\[ m_3^2 \]

- \( \approx 2.8 \text{ eV} \) From tritium endpoint (Mantz and Troitsk)
- \( \approx 0.3 \text{ eV} \) From \( O\nu\beta\beta \) if \( \nu \) is Majorana
- \( \approx 1 \text{ eV} \) From Cosmology
- \( 23 \text{ eV} \) Time of flight from SN1987A (PDG 2002)

\[ \approx 2.4 \times 10^{-3} \text{ eV}^2 \]
\[ \approx 7.7 \times 10^{-5} \text{ eV}^2 \]

\[ \nu \text{ mass pattern/magnitude} \]
Endpoint mass measurements

Study the spectral shape near the endpoint of a $\beta$ decay (note that the end-point value is generally not known well enough to use its absolute position)

Measure the quantity:

$$m_{\nu e}^2(\text{eff}) = \sum_i \left| U_{ei} \right|^2 m_i^2$$

If the experimental resolution is smaller than $m_i^2 - m_j^2$ then one should see a separate kink in the spectrum for each of the states $i$ and $j$.
Modern experiments use mainly
\[ _3^1T \rightarrow _2^3He + e^- + \bar{\nu}_e \]
a super-allowed transition with rather good combination of low end point \((E_0 = 18.6 \text{ keV})\) and short half life \((T_{1/2} = 12.3 \text{ yr})\)

Spectrometer requirements
1) very high resolution
2) very high luminosity (endpoint has no rate…)

Present limit \(m_{\nu_e}^{\text{eff}} < 2 \text{ eV}\) \((\text{PDG estimate based on Mainz and Troisk results})\)
New, very large electrostatic, integrating spectrometer being built in Karlsruhe: “KATRIN”

Expected sensitivity
0.20 - 0.25 eV

(assuming systematics are understood)
Double-beta decay: a second-order process only detectable if first order beta decay is energetically forbidden

Candidate nuclei with $Q > 2$ MeV

<table>
<thead>
<tr>
<th>Candidate</th>
<th>$Q$ (MeV)</th>
<th>Abund. (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>$^{48}\text{Ca} \rightarrow ^{48}\text{Ti}$</td>
<td>4.271</td>
<td>0.187</td>
</tr>
<tr>
<td>$^{76}\text{Ge} \rightarrow ^{76}\text{Se}$</td>
<td>2.040</td>
<td>7.8</td>
</tr>
<tr>
<td>$^{82}\text{Se} \rightarrow ^{82}\text{Kr}$</td>
<td>2.995</td>
<td>9.2</td>
</tr>
<tr>
<td>$^{96}\text{Zr} \rightarrow ^{96}\text{Mo}$</td>
<td>3.350</td>
<td>2.8</td>
</tr>
<tr>
<td>$^{100}\text{Mo} \rightarrow ^{100}\text{Ru}$</td>
<td>3.034</td>
<td>9.6</td>
</tr>
<tr>
<td>$^{110}\text{Pd} \rightarrow ^{110}\text{Cd}$</td>
<td>2.013</td>
<td>11.8</td>
</tr>
<tr>
<td>$^{116}\text{Cd} \rightarrow ^{116}\text{Sn}$</td>
<td>2.802</td>
<td>7.5</td>
</tr>
<tr>
<td>$^{124}\text{Sn} \rightarrow ^{124}\text{Te}$</td>
<td>2.228</td>
<td>5.64</td>
</tr>
<tr>
<td>$^{130}\text{Te} \rightarrow ^{130}\text{Xe}$</td>
<td>2.533</td>
<td>34.5</td>
</tr>
<tr>
<td>$^{136}\text{Xe} \rightarrow ^{136}\text{Ba}$</td>
<td>2.479</td>
<td>8.9</td>
</tr>
<tr>
<td>$^{150}\text{Nd} \rightarrow ^{150}\text{Sm}$</td>
<td>3.367</td>
<td>5.6</td>
</tr>
</tbody>
</table>
2 neutrino and neutrino-less $\beta\beta$ decay

$2\nu$ mode: a conventional 2nd order process in nuclear physics

$0\nu$ mode: a hypothetical process can happen only if:

\[
M_{\nu} \neq 0
\]
\[
\nu = \bar{\nu}
\]
\[
|\Delta L| = 2
\]
\[
|\Delta (B-L)| = 2
\]

Since helicity has to "flip"
In the last 10 years there has been a transition

1) From a few kg detectors to 100s or 1000s kg detectors
   → Think big: qualitative transition from cottage industry
even to large experiments

2) From “random shooting” to the knowledge that at least the
   inverted hierarchy will be tested

Discovering 0νββ decay:
→ Discovery of the neutrino mass scale
→ Discovery of Majorana particles
→ Discovery of lepton number violation
Background due to the Standard Model $2\nu\beta\beta$ decay

The two can be separated in a detector with good energy resolution
If $0\nu\beta\beta$ is due to light $\nu$ Majorana masses

$$\langle m_\nu \rangle^2 = \left( T_{1/2}^{0\nu\beta\beta} G^{0\nu\beta\beta}(E_0, Z) \left| M^{0\nu\beta\beta}_{GT} - \frac{g_V^2}{g_A^2} M^{0\nu\beta\beta}_F \right| \right)^{-1}$$

$M^{0\nu\beta\beta}_F$ and $M^{0\nu\beta\beta}_{GT}$ can be calculated within particular nuclear models

$G^{0\nu\beta\beta}$ is a known phasespace factor

$T_{1/2}^{0\nu\beta\beta}$ is the quantity to be measured

$$\langle m_\nu \rangle = \sum_{i=1}^{3} \left| U_{e,i} \right|^2 m_i \varepsilon_i$$

effective Majorana $\nu$ mass ($\varepsilon_i = \pm 1$ if CP is conserved)
Much progress made recently in accuracy of nuclear matrix elements. (e.g. was found that the main uncertainly in (R)QRPA calculations comes from the single particle space around the Fermi surface. → Can use the measured $2\nu\beta\beta$ $T_{1/2}$ to make a correction.)

Still, if/once $0\nu\beta\beta$ decay is discovered, the $T_{1/2}$ in more than one nucleus will be needed to pin down neutrino masses

F. Simkovic et al.
### Present Limits for $0\nu$ double beta decay

<table>
<thead>
<tr>
<th>Candidate nucleus</th>
<th>Detector type</th>
<th>(kg yr)</th>
<th>Present $T_{1/2}^{0\nu\beta\beta}$ (yr)</th>
<th>$\langle m \rangle$ (eV)</th>
</tr>
</thead>
<tbody>
<tr>
<td>$^{48}$Ca</td>
<td>Ge diode</td>
<td>~47.7</td>
<td>&gt;$1.4 \times 10^{22}$ (90%CL)</td>
<td>&lt;0.35</td>
</tr>
<tr>
<td>$^{76}$Ge</td>
<td>Ge diode</td>
<td>~47.7</td>
<td>&gt;$1.9 \times 10^{25}$ (90%CL)</td>
<td></td>
</tr>
<tr>
<td>$^{82}$Se</td>
<td>Ge diode</td>
<td>~47.7</td>
<td>&gt;$2.1 \times 10^{23}$ (90%CL)</td>
<td></td>
</tr>
<tr>
<td>$^{100}$Mo</td>
<td>Ge diode</td>
<td>~47.7</td>
<td>&gt;$5.8 \times 10^{23}$ (90%CL)</td>
<td></td>
</tr>
<tr>
<td>$^{116}$Cd</td>
<td>Ge diode</td>
<td>~47.7</td>
<td>&gt;$1.7 \times 10^{23}$ (90%CL)</td>
<td></td>
</tr>
<tr>
<td>$^{128}$Te</td>
<td>TeO$_2$ cryo</td>
<td>~12</td>
<td>&gt;$1.1 \times 10^{23}$ (90%CL)</td>
<td>&lt;0.19 – 0.68</td>
</tr>
<tr>
<td>$^{130}$Te</td>
<td>TeO$_2$ cryo</td>
<td>~12</td>
<td>&gt;$3 \times 10^{24}$ (90%CL)</td>
<td>&lt;1.1 – 2.9</td>
</tr>
<tr>
<td>$^{136}$Xe</td>
<td>Xe scint</td>
<td>~4.5</td>
<td>&gt;$1.2 \times 10^{24}$ (90%CL)</td>
<td></td>
</tr>
<tr>
<td>$^{150}$Nd</td>
<td></td>
<td></td>
<td>&gt;$1.2 \times 10^{21}$ (90%CL)</td>
<td></td>
</tr>
<tr>
<td>$^{160}$Gd</td>
<td></td>
<td></td>
<td>&gt;$1.3 \times 10^{21}$ (90%CL)</td>
<td></td>
</tr>
</tbody>
</table>
There is also a discovery claim (using $^{76}\text{Ge}$)

EVIDENCE FOR NEUTRINOLESS DOUBLE BETA DECAY

H.V. KLAPDOR-KLEINGROTHAUSEN, A. DIETZ, H.L. HARNEY, I.V. KRIVOSHEINA

1 Max-Planck-Institut für Kernphysik, Postfach 10 89 80, D-69029 Heidelberg, Germany
2 Radiophysical-Research Institute, Nishni-Novgorod, Russia
3 Spokesman of the GENIUS and HEIDELBERG-MOSCOW Collaborations,

With the values $T_{1/2}^{0
\nu\beta\beta} = 2.23^{+0.44}_{-0.31}$ $m_{\nu}^{\text{eff}} = 0.32 \pm 0.03$

…but this is a controversial matter (see details in)

A.M. Bakalyarov et al. hep-ex/0309016
H.V. Klapdor-Kleingrothaus et al. Mod. Phys. Lett. 21 (2006) 1547
## Future experiments (a very broad brush, personal view)

<table>
<thead>
<tr>
<th>Isotope</th>
<th>Experiment</th>
<th>Main principle</th>
<th>Fid mass</th>
<th>Lab</th>
</tr>
</thead>
<tbody>
<tr>
<td>$^{76}\text{Ge}$</td>
<td>Majorana$^\dagger$</td>
<td>Eres, 2site tag, Cu shield</td>
<td>30-60kg</td>
<td>SUSEL</td>
</tr>
<tr>
<td></td>
<td>Gerda$^\dagger$</td>
<td>Eres, 2site tag, LAr shield</td>
<td>34.3 kg</td>
<td>G Sasso</td>
</tr>
<tr>
<td></td>
<td>MaGe/GeMa</td>
<td>See above</td>
<td>~1ton</td>
<td>DUSEL? GS?</td>
</tr>
<tr>
<td>$^{150}\text{Nd}$</td>
<td>SNO+</td>
<td>Size/shielding</td>
<td>56 kg</td>
<td>SNOlab</td>
</tr>
<tr>
<td>$^{150}\text{Nd}$ or $^{82}\text{Se}$</td>
<td>SuperNEMO$^\ddagger$</td>
<td>Tracking</td>
<td>100 kg</td>
<td>Canfranc Frejus</td>
</tr>
<tr>
<td>$^{130}\text{Te}$*</td>
<td>CUORE</td>
<td>E Res.</td>
<td>204 kg</td>
<td>G Sasso</td>
</tr>
<tr>
<td>$^{136}\text{Xe}$</td>
<td>EXO</td>
<td>Tracking/Eres</td>
<td>150 kg</td>
<td>WIPP</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Ba tag, Track/Eres</td>
<td>1-10ton</td>
<td>DUSEL?</td>
</tr>
</tbody>
</table>

* No isotopic enrichment in baseline design
$^\dagger$ Plan to merge efforts for ton-scale experiment
$^\ddagger$ Non-homogeneous detector

See this J. Loach and K. O'Sullivan
Sensitivity of future $0\nu\beta\beta$ decay experiments

- **Degenerate**: Klapdor et al. 0.24 - 0.58 eV
- **100 kg-scale exps**: >100 kg-scale experiments
- **Inverted**
- **Normal**

Plot from Avignone, Elliott, Engel; Rev Mod Phys 80 (2008) 481
Conclusions

Last 15 years:
• discovery of neutrino oscillations
• confirm that MSW is the dominant mechanism for flavor conversion in the Sun
• begin precision measurements of mixing parameters
• begin the study of geological neutrinos

Next 15 years:
• discover the neutrino mass scale
• measure/bound $\theta_{13}$ to <1% 
• observe SN neutrinos with SK, KamLAND, Ice$^3$, Borexino, LVD, SNO+, LIGO?, ...
• study solar physics with neutrinos

Further out in the future...:
• precision geophysics with neutrinos
• CP violation in the lepton sector
• observe relic neutrinos