Reach of future non-accelerator neutrino efforts

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Overview

• Current knowledge of neutrino properties
• Non-accelerator based experimental reaches:
  – Neutrinoless double beta-decay
  – Direct mass measurements
  – Limits from cosmology
  – Reactor neutrinos
  – Solar neutrinos
  – Cosmic-rays neutrinos
  – Others
• Conclusion & Open Issues
Neutrino Flavor Mixing

Compelling evidence propagating neutrinos undergo flavor oscillations.

In 3-neutrino mixing model:

Mass to flavor relationship described by PMNS neutrino mixing matrix with 5 parameters:

\[
U = \begin{pmatrix}
1 & 0 & 0 \\
0 & c_{23} & s_{23} \\
0 & -s_{23} & c_{23}
\end{pmatrix}
\begin{pmatrix}
c_{13} & 0 & e^{i\delta} s_{13} \\
0 & 1 & 0 \\
- e^{i\delta} s_{13} & 0 & c_{13}
\end{pmatrix}
\begin{pmatrix}
c_{12} & s_{12} & 0 \\
-s_{12} & c_{12} & 0 \\
0 & 0 & 1
\end{pmatrix}
\begin{pmatrix}
e^{i\alpha_1} & 0 & 0 \\
0 & e^{i\alpha_2} & 0 \\
0 & 0 & 1
\end{pmatrix}
\]

\[
c_{ij} = \cos \theta_{ij} \quad s_{ij} = \sin \theta_{ij}
\]

Majorana Phases
Neutrino Masses

Absolute masses weakly constrained.
Relative mass-squared differences known.
Three possible scenarios: Quasi-degenerate, also:

\[ \Delta m_{23}^2 \approx 2 \times 10^{-3} \text{ eV}^2 \]

\[ \Delta m_{12}^2 = 8.0 \times 10^{-5} \text{ eV}^2 \]

"Normal"

\[ \nu_e \]
\[ \nu_\mu \]
\[ \nu_\tau \]

"Inverted"

\[ \Delta m_{12}^2 \]

\[ \Delta m_{23}^2 \]

Needs to be resolved

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# Current Best Values

(PDG 2007)

| Parameter       | Value                  | Method               |
|-----------------|------------------------|----------------------|
| $\sin^2(2\theta_{12})$ | $0.86^{+0.03}_{-0.04}$ | Solar+ KamLAND       |
| $\sin^2(2\theta_{23})$ | $>0.92$                | Atmospheric $\nu$    |
| $\sin^2(2\theta_{13})$ | $<0.19$                | Reactor (CHOOZ)      |
| $|\Delta m^2_{32}|$      | $1.9-3.0 \times 10^{-3}$ eV$^2$ | Super-K+MINOS        |
| $|\Delta m^2_{21}|$      | $8.0 \pm 0.3 \times 10^{-5}$ eV$^2$ | Solar+ KamLAND       |
| $\alpha_1, \alpha_2$ | ?                     | DBD?                 |
| $\delta$         | ?                     | Future LBL?          |
Neutrinoless double-beta decay ($0\nu\beta\beta$)

$$Z^A \Rightarrow Z^{+2}A + 2e^-$$

Violates Total Lepton Number Conservation

Existence implies Neutrino is Majorana fermion*

Also ECEC, $e^+e^+$, E$Ce^+$

$2\nu\beta\beta$: Observed 2nd order weak weak process.

$$Z^A \Rightarrow Z^{+2}A + 2e^- + 2\bar{\nu}_e$$

*Schechter et al, Phys. Rev. D25, 2951 (1982)

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Majorana vs. Dirac

DBD implies Majorana mass term in Lagrangian that mixes $\nu$ and $\bar{\nu}$.

No good QM # to distinguish between $\nu$ and $\bar{\nu}$.

Experimental evidence consistent with both Majorana or Dirac neutrinos.

Verification difficult due to small neutrino masses.

The observation of neutrinoless double-beta decay is the only practical way to show that the neutrino is Majorana.
0νββ Rate and Neutrino Mass

\[
\left[ T_{1/2}^{0\nu} \right]^{-1} = G^{0\nu}(E_0, Z) \left| \langle m_{\beta\beta} \rangle \right|^2 \left| M^{0\nu} \right|^2
\]

\( T_{1/2}^{0\nu} \): Half-life
\( G^{0\nu} \): Phase Space (Known)
\( M^{0\nu} \): Nuclear Matrix Element (large uncertainty)

\[
\left| \langle m_{\beta\beta} \rangle \right| = \left| \sum_i U_{ei}^2 m_{\nu_i} e^{i\alpha_i} \right| \quad \text{Effective Majorana electron neutrino mass*}
\]

0νββ decay can probe absolute neutrino mass scale and mixing.

Current neutrino experiments measure mass squared differences: \( \Delta m^2 \). * Assumes \( \nu_m \) exchange
Upcoming Experimental Program and Reach

• Experiments require extreme reduction in radioactive backgrounds (underground sites, materials, analysis, etc…)

• Current generation:
  • 10s of kg of enriched isotope
  • $T_{1/2} \sim 10^{26}-10^{27}$ years
  • $m_{\beta\beta} \sim 100$ meV
  • ~$10-20M$

• Next Generation (~10 years from now):
  • ~ 1 tonne of enriched isotope
  • $T_{1/2} \sim 10^{28}$ years
  • $m_{\beta\beta} \sim 20$ meV (atmospheric mass-scale)
  • ~$100-200M$

Majorana?
### Selected Current and Future Experiments

Many different technologies…

| Technology Type                  | Examples                                      |
|----------------------------------|-----------------------------------------------|
| **Cryogenic Bolometry**          | CUORE/Cuoricino-^{130}Te                      |
| **Scintillation**                | CAMEO-^{116}Cd, CANDLES-^{48}Ca, EXO-^{136}Xe, SNO+^{150}Nd, XMASS-^{136}Xe |
| **Ionization**                   | COBRA-CdTe, GERDA-^{76}Ge (MAJORANA-^{76}Ge) |
| **Time Projection and Tracking** | MOON-^{100}Mo, Nemo/Super-Nemo (many), HPXeTPC-^{136}Xe, DCBA-^{150}Nd |

Possible Discovery Requires Confirmation with Different Isotope(s)
Direct Mass Measurements

- Tritium beta decay endpoint measurements
- Current: $m_\beta < 2\text{eV}$
- New Generation: KATRIN (Karlsruhe Tritium Neutrino Experiment)
  - Massive spectrometer
  - Sensitivity to $m_\beta = 0.2\text{eV}$
  - Anticipated Start in 2009, 5 year run.
- Cryogenic bolometers promising future alternative.

\[ < m_\beta > = \sum_i |U_{ei}|^2 m_i^2 \]
KATRIN Main Spectrometer
(world’s largest beer keg)
Indirect Limits from Cosmology

• Relic Big Bang Neutrinos
  – $T = 1.7K$
  – $\rho \sim 300 \text{ cm}^{-3}$

• $m_1 + m_2 + m_3 < 0.17\text{eV}$
  – JCAP 0610:014, 2006. Recent CMB, large scale structure, Lyman-$\alpha$ forest, and SN1a data.

• Model-dependent
• Possible improvement with better understanding of systematics.
• Factor of 2 improvement probes inverted hierarchy.
$|\langle m_{\beta\beta} \rangle| = \sum_i |U_{ei}|^2 m_{\nu_i} e^{i\alpha_i}$

*IGEX & KKDC Limits, excluding controversial discovery claim

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Combined Mass Limits

Estimated KATRIN Sensitivity

\[ \sim 100 \text{ kg isotope} \]

\[ \sim 1 \text{ ton} \]

\[ \sim 100 \text{ ton} \]
Solar Neutrinos

- First evidence of oscillations
- Constrain $\theta_{12}$ via $\nu_e \rightarrow \nu_x$
- Measurements of $^8$B flux described by Large Mixing Angle with matter (MSW) effects.
- Lower energy (<2 MeV) solar neutrinos insensitive to MSW effect.
  - Probe vacuum oscillations

[Diagram showing neutrino flux and reactions with error bars and labels]
Solar Neutrino Status

• SNO will present results of final NCD phase soon.
• Borexino and KamLAND-solar running
  – Measure $^7$Be flux
  – Some published early results
  – Verify Solar model
• CLEAN, LENS, others in proposal phase.
  – Measure pp flux, the dominant source of neutrinos from sun.
  – Verify solar model
  – 10 year timescale
Other Probes

• Cosmic-rays:
  – Atmospheric: Verify LBL results
  – UHECR: Astrophysical Applications

• Coherent neutrino scattering:
  – Unobserved SM process.
  – Magnetic dipole moment - Probe for NP.

• Supernovae (prompt and relic)

• Geoneutrinos

• Neutrino-induced nuclear decays: zero-threshold

• Neutron-antineutron oscillations
Conclusion and Current Projects

• Current emphasis on
  – Neutrinoless DBD
  – $\theta_{13}$

• Probe degenerate mass scale with current generation of DBD experiments.

• Improve direct mass measurements to 0.2eV.

• Cosmology a sensitive probe.

• Verify solar neutrino results.
Backups
$0\nu\beta\beta$–decay and Majorana Neutrinos

Schechter et al, Phys. Rev. D25, 2951 (1982)

Majorana nature verification independent of process that mediates $0\nu\beta\beta$ decay!
A Recent Claim

KKDC used five $^{76}\text{Ge}$ crystals, with a total of 10.96 kg of mass, and 71 kg-years of data.

$$T_{1/2} = 1.2 \times 10^{25} \text{ y}$$

$$0.24 < m_\nu < 0.58 \text{ eV (3 sigma)}$$

Background level depends on intensity fit to other peaks.

A More Recent Claim

6.8 sigma

Neural Net Analysis
## Current Limits
~40 years of work

| Isotope     | Half-life Limit (y) | $|m_\nu|\text{ limit (eV)}$ |
|-------------|---------------------|--------------------------|
| Ca-48       | $>9.5\times10^{21}$ (76%) | <8.3                     |
| Ge-76       | $>1.9\times10^{25}$   | <0.35                    |
|             | $>1.6\times10^{25}$   | <0.33 – 1.35             |
| Se-82       | $>2.7\times10^{22}$ (68%) | <5                       |
| Mo-100      | $>5.5\times10^{22}$   | <2.1                     |
| Cd-116      | $>7\times10^{22}$     | <2.6                     |
| Te-128,130  | From ratio of $T_{1/2}$ | <1.1 – 1.5               |
| Te-128      | $>7.7\times10^{24}$   | <1.1 – 1.5               |
| Te-130      | $>1.4\times10^{23}$   | <1.1 – 2.6               |
| Xe-136      | $>4.4\times10^{23}$   | <1.8 – 5.2               |
| Nd-150      | $>1.2\times10^{21}$   | <3                       |
Background Identification

• Majorana is background limited.
• Goal: 1 event / ton-year in 4 keV ROI
• Backgrounds:
  – Compton scattered gammas, surface alphas.
  – Natural isotope chains: $^{232}$Th, $^{235}$U, $^{238}$U, Rn
  – Cosmic Rays:
    • Activation at surface creates $^{68}$Ge, $^{60}$Co.
    • Hard neutrons from cosmic rays in rock and shield.
  – $2\nu\beta\beta$-decays.
• Need factor ~100 reduction over what has been demonstrated.
• Monte Carlo estimates of acceptable levels