Sensitivity and Discovery Prospects for $0\nu\beta\beta$-decay

- Introduction, $\nu$ properties, $0\nu\beta\beta$
- Sensitivity and Discovery Considerations
- Next-generation Experimental Challenges
- Nuclear Matrix Elements and $<m_{\nu ee}>$
- Summary
Motivation for $0\nu\beta\beta$-decay experiments

The recent discoveries of solar, reactor, and atmospheric neutrino oscillations provide a compelling argument for new $0\nu\beta\beta$-decay experiments with increased sensitivity.

$0\nu\beta\beta$-decay probes fundamental physics.

- It is the only technique able to determine if neutrinos might be their own anti-particles, or Majorana particles.
- If Majorana particles, $0\nu\beta\beta$ offers the most promising method for determining the overall absolute neutrino mass scale.
- Tests one of nature's most fundamental symmetries, lepton number conservation.
Constraints on $\nu$ masses

\[ \sum m_\nu \]

Upper Bound
Tritium $\beta$-decay
(Mainz)

Upper Bound
Cosmology
(WMAP, 2dF,
Lyman-$\alpha$)

Lower Bound
Atm. $\nu$ (SuperK)

Estimated $\beta\beta$-decay sensitivity

\[ \sim 10 \text{ kg (Present)} \]
\[ \sim 100 - 200 \text{ kg} \]
\[ \sim 1 \text{ t} \]
\[ \geq 10 \text{ t} ? \]

$0\nu\beta\beta$-decay $\nu$ mass sensitivity

S.R. Elliott

$U_{e1} = 0.866 \quad \delta m^2_{\text{sol}} = 70 \text{ meV}^2$
$U_{e2} = 0.5 \quad \delta m^2_{\text{atm}} = 2000 \text{ meV}^2$
$U_{e3} = 0$
### 0νββ-decay Searches - Current Results

\[
\left[ T_{1/2}^{0ν} \right]^{-1} = G_{0ν} \left| M_{0ν} \right|^2 \left\langle m_{ββ} \right\rangle^2
\]

| Isotope | Half-life (y) | \( |<m_ν>| \) (eV) | Exposure kg-yr | Background (cts/keV/kg-yr) | Reference |
|---------|--------------|----------------|----------------|--------------------------|------------|
| Ca-48   | > 1.4 \times 10^{22} | < 7.2 – 44.7 | 0.037 | 0.03 | You91 |
| Ge-76   | > 1.9 \times 10^{25} | < 0.32 - 1 | 35.5 | 0.19 | Kla01 |
| Ge-76   | > 1.6 \times 10^{25} | < 0.33 – 1.35 | 8.9 | 0.06 | Aal02 |
| Ge-76   | = 1.2 \times 10^{25} | = 0.24 – 0.58 | 71.7 | 0.11 | Kla04 |
| Se-82   | > 1.9 \times 10^{23} | < 1.3 – 3.2 | 0.68 | | Sar04 |
| Zr-96   | > 1 \times 10^{21} | < 16.3 – 40 | 0.0084 | | Arn98 |
| Mo-100  | > 3.5 \times 10^{23} | < 0.7 – 1.2 | 5.02 | 3.5 \times 10^{-3} | Sar04 |
| Cd-116  | > 1.7 \times 10^{23} | < 2.2 – 4.6 | 0.15 | 0.03 | Dan00 |
| Te-128  | > 7.7 \times 10^{24} | < 1.1 – 1.5 | Geoch. | Geoch. | Ber93 |
| Te-130  | > 1.8 \times 10^{24} | < 0.2 – 1.1 | 10.85 | 0.18 | Cap05 |
| Xe-136  | > 4.4 \times 10^{23} | < 2.2 – 5.2 | 4.84 | | Lue98 |
| Nd-150  | > 3.6 \times 10^{21} | < 4.9 – 17.1 | 0.015 | | Bar05 |

Typical “source” masses .5 - 10 kg
The KKDC Result


Best result - 5 $^{76}$Ge crystals, 10.96 kg of mass, 71 kg-years of data.

$$T_{1/2} = (1.19 +2.99/-0.5 ) \times 10^{25} \text{ y}$$

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

*Plotted a subset of the data for four of five crystals, 51.4 kg-years of data.*

$$T_{1/2} = (1.25 +6.05/-0.57 ) \times 10^{25} \text{ y}$$

*Pulse shape selected spectrum (single site events)*
0νββ-decay Sensitivity and Discovery

\[
\left[ T_{1/2}^{0\nu} \right]^{-1} = G_{0\nu} |M_{0\nu}|^2 \left\langle m_{\beta\beta} \right\rangle^2 \propto M \cdot t_{\text{exp}}
\]
 Assuming best case, 0 background!

Question 1 : What’s needed to reach sensitivities of \( T_{1/2} \) on the order of \( 10^{24} - 10^{27} \) y?
- Naïve response - 10-100 times more mass
- Approach near “0-background” conditions in the region of interest.

Question 2 : What will be the necessary level of proof for a convincing (accepted) discovery of 0νββ?
- “Good” Signal:Background & a clear understanding of signal(s) and backgrounds.
- Confirmation from independent experiments.
- Confirmation in different isotopes.

Question 3 : What’s required to extract a reliable effective neutrino mass?
- Improved understanding of Nuclear Matrix Elements (NME).
Basic Experimental Considerations

To measure extremely rare decay rates
\( T_{1/2} \sim 10^{24} - 10^{27} \) years

- Large, highly efficient source mass
- Extremely low (near-zero) backgrounds in the 0νββ peak region
  - Requires ultra-clean radiopure materials
  - the ability to discriminate signal from background
- Best possible energy resolution
  - Minimize 0νββ peak ROI to maximize S/B
  - Separate 2νββ/0νββ
Resolution and Sensitivity to $0\nu\beta\beta$

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\textit{Plotted a subset of the data for four of five crystals, 51.4 kg-years of data.}

\[ T_{1/2} = (1.25 +6.05/-0.57) \times 10^{25} \text{ y} \]

**Expected signal in Majorana**

**After cuts (for 0.46 t-y)**

135 counts

**With a background of**

Specification: < 1 total count in the ROI

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Sensitivity and Discovery Prospects for $0\nu\beta\beta$-decay

December 2, 2005

Neutrino Nuclear Responses Workshop, CAST/SPring-8, Japan
Additional Considerations

- Source serves as the detector
- Elemental (enriched) source to minimize active material.
- A large Q value - faster $0\nu\beta\beta$ rate and also places the region of interest above many potential backgrounds.
- A relatively slow $2\nu\beta\beta$ rate helps control this irreducible background.
- Identifying the decay progeny in coincidence with the $0\nu\beta\beta$ decay energy eliminates potential backgrounds except $2\nu\beta\beta$.
- Event reconstruction, providing kinematic data such as opening angle and individual electron energy aids in the elimination of backgrounds and demonstration of signal (can possibly use $2\nu\beta\beta$).
- Good spatial resolution and timing information helps reject background processes.
- Demonstrated technology at the appropriate scale.
- The nuclear theory is better understood in some isotopes than others. The interpretation of limits or signals might be easier to interpret for some isotopes.
“Relative” Sensitivities

Using Rodin et al. Nucl. Matrix elements

Isotope Comparison

R.G.H Robertson

9.2 / t y for 
<νν>, = 100 meV (Rodin et al.)

Ratio to 76-Ge

1/A
Phase Space
Matrix Element
Rate per ton

Isotope A

76
100
130
136

Sensitivity and Discovery Prospects for 0νββ-decay

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Challenges for next-generation experiments

Backgrounds and Scalability - Next generation experiments must strive for backgrounds in the $0\nu\beta\beta$ region of $\text{cnts/t-yr}$.
- Requires materials with $\mu$Bq/kg level radioimpurities.
  - Difficult to achieve sensitivity with direct radioassays
- Requires large scale cleanliness.
- "New background regimes" -- background sources that could previously be ignored

Signal and Background Characterizations
- Reliably simulate the entire observed spectrum.
- Demonstrate capability to measure the $2\nu\beta\beta$ spectrum
- Search for excited state decays for $2\nu\beta\beta$, $0\nu\beta\beta$
Reducing Backgrounds - Two Basic Strategies

- **Directly reduce intrinsic, extrinsic, & cosmogenic activities**
  - Select and use ultra-pure materials
  - Minimize all non “source” materials
  - Clean passive shield
  - Go deep — reduced $\mu$’s & related induced activities

- **Utilize background rejection techniques**
  - Energy resolution
    - $0\nu\beta\beta$ is a single site phenomenon
    - Many backgrounds have multiple site interactions
  - Granularity [multiple detectors]
  - Single Site Time Correlated events (SSTC)
  - Tracking
  - Energy & Angular correlations
  - Ion Identification
  - Active veto detector
  - Pulse shape discrimination (PSD)
  - Segmentation
Background reduction at the larger scale

- Many groups have built $0\nu\beta\beta$-decay experiments at the few to 10 kg level. - Need to scale this up to the 100s of kg level.
- Can utilize knowledge from groups that have demonstrated the construction of low-background, large-scale detectors underground:
  - e.g. KamLAND, SNO, SAGE, GNO, Borexino CTF
    - SNO Acrylic Sphere, 30 t, 120 segments, < 2 ppt $^{232}$Th

- SNO Neutral Current Detector
  Array of $^3$He proportional counters
  - 450 kg of material
  - 300 detector segments
  - Activity (Stonehill, 2005)
    - $23 \pm 4 \ \mu$Bq/kg $^{232}$Th
    - $35 \pm 8/-10 \ \mu$Bq/kg $^{238}$U
Characterization of Signal and Background

Heidelberg-Moscow $^{76}\text{Ge}$

Klapdor-Kleingrothaus et al.,
### 0νββ-decay Searches - Efforts Underway

<table>
<thead>
<tr>
<th>Collaboration</th>
<th>Isotope</th>
<th>Technique</th>
<th>Mass</th>
<th>Status</th>
<th>Talk at Workshop</th>
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<tr>
<td>CAMEO</td>
<td>Cd-116</td>
<td>CdWO₄ crystals</td>
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<td>60 CaF₂ crystals in liq. scint.</td>
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<td>COBRA</td>
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<td>R&amp;D</td>
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<td>CUROICINO</td>
<td>Te-130</td>
<td>TeO₂ Bolometer</td>
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<td>EXO200</td>
<td>Xe-136</td>
<td>Xe TPC</td>
<td>200 kg</td>
<td>Construction</td>
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<td>1 t</td>
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<td>35-40 kg</td>
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<td>1 t</td>
<td>Future</td>
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<td>Xe in liq. Scint.</td>
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Nuclear Matrix Elements and $0\nu\beta\beta$-decay

• If we discover neutrinos are Majorana particles, extracting the effective neutrino mass requires an understanding of the nuclear matrix elements at about the 25% theoretical uncertainty level.
  - NME theoretical uncertainties are a major limitation -- a factor of 2-3 between shell model and RQRPA techniques.
  - Using compilations or averages of previous sequential calculations should not be used to estimate theoretical uncertainties.

• Complementary experiments have been and are being pursued.
  - Ejiri et al. various charge exchange reactions
  - Zuber, Summary of May 05 Workshop
  - Garcia et al. EC in 100 and 116 systems.
  - Schiffer et al. recent interest in correlated pair transfer and the relationship to $0\nu\beta\beta$. 
Electron-Capture Branch of $^{100}$Tc

(A. Garcia et al.)

A bench-mark for testing 2$\beta\beta$-decay nuclear matrix element calculations

5 measurable observables in addition to energy of Giant Resonance:
1) $^{100}$Mo $\rightarrow ^{100}$Ru(g.s.) (known)
2) $^{100}$Mo $\rightarrow ^{100}$Ru(1130 keV) (known)
3) $^{100}$Tc $\rightarrow ^{100}$Ru(g.s.) (known)
4) $^{100}$Tc $\rightarrow ^{100}$Ru(1130 keV) (known)
5) $^{100}$Tc $\rightarrow ^{100}$Mo (difficult to measure)

Can calculations reproduce these?

QRPA (Griffiths-Vogel, PRC 46, 181 (1992)) predicts:
$B(GT, \, 0^+ \rightarrow 1^+) = 1.75$

Previous measurement: (Garcia et al, PRC 47, 2910 (1993))
$B(GT, \, 0^+ \rightarrow 1^+) = 0.66 \pm 0.33$

New measurement: (Sjue et al, To be published)
$B(GT, \, 0^+ \rightarrow 1^+) = 2.01 \pm 0.45 +.02/-10$

Will provide details in a later talk at the workshop
Probing via pair transfer (Schiffer, Freeman, Rehm, & Villari)

The importance of pairing to \( 0\nu\beta\beta \) needs to be better understood. The evidence is strong that pair correlations are very important in this region (>95% in the g.s.) but not quantitative.

**Simplest pairing picture:**

The four orbitals between 28 and 50 are completely mixed, and the ground states (neutrons and protons) consist of correlated BCS boson pairs, any neutron pair can decay into any proton pair vacancy: 8 n-pairs, 9 p-pair vacancies in this limited model space, yield.

\[
8 \times 9 = 72
\]
The overlap is between a pair of correlated neutrons in the $0^+$ ground state and a similar pair of protons in the final state.

For a nucleus such as $^{76}$Ge the pairing correlations produce something like a BCS state.

Such correlations are probed by $(t,p)$ or $(p,t)$ transfer of correlated neutrons pairs or ($^3$He,n) for protons.
But, there are two complicating issues:

1.) To what extent is the required range of the correlations in the $0^+$ ground state similar in pair transfer to what is relevant in $(0\nu\beta\beta)$ decay? For $(p,t)$ the range is the distance between the pair of neutrons in the triton. How does this compare with what is relevant in $(0\nu\beta\beta)$? Question for theorists!

2.) The other is a matter of reaction mechanism -- there can be sensitivity to the microscopic orbits in $(p,t)$ that could be different in $(0\nu\beta\beta)$. (some limited data.)
• **NME questions I hope to see addressed:**
  - What are the prospects (and time scale) for improvements in shell model calculations?
  - How predictive are QRPA calculations?
  - What are the most useful measurements or benchmarks that should be pursued?
  - How useful an aid would neutrino beam measurements be and what are the realistic prospects and timescales for such experiments?
  - Are measurements of $2\nu\beta\beta$ ($0\nu\beta\beta$) excited state decays useful?
    - As predictive tests?
  - What should we be doing to further facilitate interest and progress?
    - Session at CIPANP 06, Puerto Rico, May 30 – June 3?
Summary and Outlook

- A number of 100-200 kg scale next-generation experiments are under construction or preparing to submit proposals.
  - The U.S. NuSAG committee (a Joint NSAC-HEPAP sub-committee) has recently completed and issued recommendations for the U.S double beta decay program and DOE Office of Science has approved a “Mission Need” Statement.

- These next-generation $0
  \nu\beta\beta$ experiments should be able to:
  - Definitively test the Klapdor-Kleingrothaus claim in the 400 meV region.
  - Probe the quasi-degenerate neutrino mass region of 100 meV.
  - Demonstrate backgrounds that would justify scaling up to a 1-ton or larger detector.

- To get the maximum benefit from next generation measurements, additional theoretical and complementary experimental work on nuclear matrix elements needs to be vigorously pursued.