The future of double-beta decay experiments

ICFA Seminar
SLAC, 28 Oct 2008
The measurement of the absolute mass scale, $\theta_{13}$ and the choice of hierarchy are the next big challenges in neutrino physics.
**Double-beta decay:**

*a second-order process
only detectable if first
order beta decay is energetically forbidden*

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**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>
There are two varieties of $\beta\beta$ decay

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

$0\nu$ mode: a hypothetical process can happen only if:
- $M_\nu \neq 0$
- $\nu = \overline{\nu}$
- $|\Delta L| = 2$
- $|\Delta (B-L)| = 2$

Since helicity has to "flip"
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

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

$M_F^{0\nu\beta\beta}$ and $M_{GT}^{0\nu\beta\beta}$ can be calculated within particular nuclear models

$G^{0\nu\beta\beta}$

$T_{1/2}^{0\nu\beta\beta}$ a known phasespace factor

is the quantity to be measured

$$
\langle m_{\beta\beta} \rangle = \sum_{k=1}^{3} \left| U_{e,k} \right|^2 m_k \, e^{i\alpha_k}
$$

effective Majorana $\nu$ mass

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

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

Lower bound on $T_{1/2}$ used for $^{136}$Xe

### Present Limits for $0^\nu$ double beta decay

<table>
<thead>
<tr>
<th>Candidate nucleus</th>
<th>Detector type</th>
<th>Present $\langle m \rangle$ (eV)</th>
</tr>
</thead>
<tbody>
<tr>
<td>$^{48}$Ca</td>
<td>$^{76}$Ge</td>
<td>$&lt;0.35^*$</td>
</tr>
<tr>
<td>$^{76}$Ge</td>
<td>$^{82}$Se</td>
<td>$&lt;0.6-2.7$</td>
</tr>
<tr>
<td>$^{100}$Mo</td>
<td>$^{116}$Cd</td>
<td>$&lt;0.41 - 0.98$</td>
</tr>
<tr>
<td>$^{128}$Te</td>
<td>$^{130}$Te</td>
<td>$&lt;0.8 - 5.6$</td>
</tr>
<tr>
<td>$^{136}$Xe</td>
<td>$^{150}$Nd</td>
<td></td>
</tr>
<tr>
<td>$^{160}$Gd</td>
<td>$^{100}$Mo</td>
<td></td>
</tr>
</tbody>
</table>

*But also claim of signal by part of same group*

Adapted from Avignone, Elliott, Engel; Rev Mod Phys 80 (2008) 481
There is also a discovery claim (using $^{76}\text{Ge}$)

EVIDENCE FOR NEUTRINOLESS DOUBLE BETA DECAY

H.V. Klapdor-Kleingrothaus$^{1,3}$, A. Dietz$^1$, H.L. Harney$^1$, I.V. Krivosheina$^{1,2}$

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$^2$Radiophysical-Research Institute, Nishnii-Novgorod, Russia
$^3$Spokesman of the GENIUS and HEIDELBERG-MOSCOW Collaborations,

\begin{align*}
\text{With the values } & T_{1/2}^{\nu\nu\beta\beta} = 2.23^{+0.44}_{-0.31} \\
\text{and } & m_{\nu}^{\text{eff}} = 0.32^{±0.03}
\end{align*}

...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
For the first time there is a clear opportunity to make an important discovery if one pushes the $<m>$ sensitivity to the 0.01 - 1 eV region.

**Assumptions:**
- Majorana neutrinos
- No cancellations

### Plot Details

- **Degenerate**
  - Klapdor et al. 0.24 - 0.58 eV
- **Inverted**
  - 100 kg-scale exps
- **Normal**
  - >1ton scale experiments

*Plot from Avignone, Elliott, Engel; Rev Mod Phys 80 (2008) 481*
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 to large experiments

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

Discovering $0\nu\beta\beta$ decay:

→ Discovery of the neutrino mass scale
→ Discovery of Majorana particles
→ Discovery of lepton number violation
## Future projects# (a 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†</td>
<td>Eres, 2site tag, Cu shield</td>
<td>30±30kg</td>
<td>SUSEL</td>
</tr>
<tr>
<td></td>
<td>Gerda†</td>
<td>Eres, 2site tag, LAr shield</td>
<td>18→40 kg</td>
<td>G Sasso</td>
</tr>
<tr>
<td></td>
<td>MaGe/GeMa</td>
<td>See above</td>
<td>~1ton</td>
<td>DUSEL? G Sasso?</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†</td>
<td>Tracking</td>
<td>100–200 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</td>
<td>150 kg</td>
<td>WIPP</td>
</tr>
<tr>
<td></td>
<td>Ba tag, Tracking</td>
<td></td>
<td>1–10ton</td>
<td>DUSEL?</td>
</tr>
</tbody>
</table>

# Many other ideas for the future are omitted in the interest of time

* No isotopic enrichment in baseline design

† Plan to merge efforts for ton-scale experiment

‡ Non-homogeneous detector
Bare Ge crystals in LAr

More than 1 year of operation at low leakage current in LAr with prototype detector; parameters are not deteriorated

(\textit{this contradicts an earlier claim of stability problems} [\textit{Klapdor-Kleingrothaus \\& Krivosheina} \textit{NIM A 566 (2006) 472}])
Shielding requirements make these detectors large...

Installing the GERDA cryostat

08 March 06
In addition new development (Majorana group) with point contact detectors: crude “tracking” in a Ge detector

P.S. Barbeau et al. nucl-ex/0701012 Jan 2007
**Calorimetric detectors**

- Heat bath
- (weak) thermal link
- Source/absorber
- Sensor

- \( \Delta T = E/\text{heat capacity} \)
- Need mK temperatures to have small heat capacity.
- Very generic technique: in principle can use for many materials

Cuoricino TeO\(_2\) crystals ran at Gran Sasso in a dilution refrigerator at \(~10\) mK (can use Te that is at \(~30\)% the right isotope \([^{130}\text{Te}]\))

NTD thermistor readout:
- 1 MeV = \( \Delta T = 300 \) \( \mu \)V
CUORE will be a closely packed array of
988 detectors
741 kg of TeO$_2$
204 kg of $^{130}$Te

19 towers with
13 planes of
4 crystals each
Scintillators

Poor energy resolution/tracking compensated by

- Well known technology
- (relatively) simple detectors
- Little material near fiducial volume (if the source is part of the scintillator)
- Cheaper self-shielding

Candles
(CaF in liquid scintillator)
• 1000 tons liquid scintillator in the SNO cavern
• 0.1% $^{nat}$Nd dissolved in the scintillator containing 56 kg of $^{150}$Nd isotope
• $^{150}$Nd has a high (3.37MeV) endpoint
• Much of the infrastructure recycled from SNO (need to reverse the acrylic sphere tethering system and acquire LAB-based scintillator compatible with the Nd compound)
• Possibility to enrich Nd at AVLIS facility (France)

Background shape needs to be very well understood in order to extract meaningful results
Tracking with very large fiducial masses is hard...
SuperNEMO

- Planar geometry with 20 modules for 100kg source
- Source is 40mg/cm², 3x4m², ¹⁵⁰Nd or ⁸²Se
- Each module has 2000 Geiger cells and 600 PMT calorimetry channels for a total of ~40k Geiger channels and 12k PMTs
- Coils to provide 25 Gauss magnetic field in each module (PMTs have mumetal shields)
Full layout for a 100kg $^{82}\text{Se}$ SuperNEMO (22 modules)
**Xe is ideal for a large experiment**

- No need to grow crystals
- Can be re-purified during the experiment
- No long lived Xe isotopes to activate
- Can be easily transferred from one detector to another if new technologies become available

**Noble gas: easy(er) to purify**

- $^{136}\text{Xe}$ enrichment easier and safer:
  - noble gas (no chemistry involved)
  - centrifuge feed rate in gram/s, all mass useful
  - centrifuge efficiency $\sim \Delta m$. For Xe 4.7 amu

- $^{129}\text{Xe}$ is a hyperpolarizable nucleus, under study for NMR tomography... a joint enrichment program?
Xe offers a qualitatively new tool against background:

\[ ^{136}\text{Xe} \rightarrow ^{136}\text{Ba}^{++} e^- e^- \] final state can be identified using optical spectroscopy (M. Moe PRC44 (1991) 931)

Ba\(^+\) system best studied (Neuhauser, Hohenstatt, Toshek, Dehmelt 1980)

Very specific signature “shelving”

Single ions can be detected from a photon rate of 10\(^7\)/s

- Important additional constraint
- Drastic background reduction
Improved energy resolution in LXe:

Use (anti)correlations between ionization and scintillation signals (now also used in DM detectors)

~570 keV
EXO-200 LXe TPC field cage & readout planes

Central HV plane (photo-etched phosphor bronze)

flex cables on back of APD plane

acrylic supports

~35cm
EXO-200 at WIPP
$V \cos(\Omega t) + U$

Ba oven

Scope

Spectroscopy lasers

CCD

Ba oven

DC potential [V]

-5 Volts

0 Volts

$e^-$ gun

Ba

Buffer gas
Electrode structure being prepared
First single ion detection in high pressure gas (He, Ar)

Remaining challenge is the efficient transfer of single Ba ions from LXe to the ion trap.

Cryogenic dipstick
- Capture ion on SXe coating
- LHe cooling (~20K) to maintain stable SXe coating in 10^-8 torr vacuum
- Microcapacitor used to measure and stabilize SXe with accuracy of a few monolayers in LXe and vacuum.
With EXO-200 closer to data taking
GXe R&D activities are picking up speed

EXO GXe concept
M. Danilov et al,

This is also pursued by the NEXT collaboration

Variable length drift cell for resolution and gas composition studies
Conclusions

Exciting time for neutrino-less double beta decay!

Several 100kg-class experiments will start data taking in the next 2-3 years. R&D for ton-class experiments is on-going.

General reflections about these experiments:

*The bad news...* they are really difficult experiments. We all tend to underestimate difficulty (less optimistic people would not start!)

*The good news...* they are happening!

We may soon know whether Ettore Majorana was right and what the mass scale of the neutrino is.
**EXO-200kg Majorana mass sensitivity**

**Assumptions:**
1) 200kg of Xe enriched to 80% in 136
2) $\sigma(E)/E = 1.4\%$ obtained in EXO R&D, Conti et al Phys Rev B 68 (2003) 054201
3) Low but finite radioactive background:
   - 20 events/year in the $\pm2\sigma$ interval centered around the 2.481MeV endpoint
4) Negligible background from $2\nu\beta\beta$ ($T_{1/2} > 1 \cdot 10^{22}$yr R.Bernabei et al. measurement)

<table>
<thead>
<tr>
<th>Case</th>
<th>Mass (ton)</th>
<th>Eff. (%)</th>
<th>Run Time (yr)</th>
<th>$\sigma_E/E @ 2.5$MeV (%)</th>
<th>Radioactive Background (events)</th>
<th>$T_{1/2}^{0\nu}$ (yr, 90%CL)</th>
<th>Majorana mass (eV)</th>
</tr>
</thead>
<tbody>
<tr>
<td>EXO-200</td>
<td>0.2</td>
<td>70</td>
<td>2</td>
<td>1.6*</td>
<td>40</td>
<td>$6.4 \times 10^{25}$</td>
<td>0.133†</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>0.186*</td>
</tr>
</tbody>
</table>

What if Klapdor's observation is correct?

Central value $T_{1/2}^{0\nu} (Ge) = 1.2^{+3}_{-0.5} \cdot 10^{25}$, ($\pm3\sigma$) (Phys. Lett. B 586 (2004) 198-212) 
consistently use Rodin's matrix elements for both Ge and Xe)

In 200kg EXO, 2yr:
- Worst case (QRPA, upper limit) 15 events on top of 40 events bkgd $\rightarrow 2\sigma$
- Best case (NSM, lower limit) 162 events on top of 40 bkgd $\rightarrow 11\sigma$
EXO neutrino effective mass sensitivity

Assumptions:
1) 80% enrichment in 136
2) Intrinsic low background + Ba tagging eliminate all radioactive background
3) Energy res only used to separate the 0ν from 2ν modes:
   Select 0ν events in a ±2σ interval centered around the 2.481MeV endpoint
4) Use for 2νββ $T_{1/2} > 1 \cdot 10^{22}$yr (Bernabei et al. measurement)

<table>
<thead>
<tr>
<th>Case</th>
<th>Mass (ton)</th>
<th>Eff. (%)</th>
<th>Run Time (yr)</th>
<th>$\sigma_E/E @ 2.5$MeV (%)</th>
<th>2νββ Background (events)</th>
<th>$T_{1/2}^{0\nu}$ (yr, 90%CL)</th>
<th>Majorana mass (meV)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Conservative</td>
<td>1</td>
<td>70</td>
<td>5</td>
<td>1.6*</td>
<td>0.5 (use 1)</td>
<td>2*10^{27}</td>
<td>24</td>
</tr>
<tr>
<td>Aggressive</td>
<td>10</td>
<td>70</td>
<td>10</td>
<td>1†</td>
<td>0.7 (use 1)</td>
<td>4.1*10^{28}</td>
<td>5.3</td>
</tr>
</tbody>
</table>

* $\sigma(E)/E = 1.4\%$ obtained in EXO R&D, Conti et al. Phys Rev B 68 (2003) 054201
† $\sigma(E)/E = 1.0\%$ considered as an aggressive but realistic guess with large light collection area
# Caurier, et. al., arXiv:0709.2137v1