Double-beta decay: a very difficult experiment

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International Workshop on Double-beta decay and Neutrinos
Osaka, Nov 14–17, 2011
Double-beta decay:

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

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<th>$Q$ (MeV)</th>
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<td>9.2</td>
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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:
- $M_\nu \neq 0$
- $\nu = \bar{\nu}$
- $|\Delta L| = 2$
- $|\Delta(B-L)| = 2$
"Dirac" neutrinos
(some "redundant" information but the "good feeling" of things we know...)

"Majorana" neutrinos
(more efficient description, no lepton number conservation, new paradigm...)

\[ \nu^D = \begin{pmatrix} \nu_L \\ \bar{\nu}_L \\ \nu_R \\ \bar{\nu}_R \end{pmatrix} \]

\[ \nu^M = \begin{pmatrix} \nu_L \\ \nu_R \end{pmatrix} \]

Which way Nature chose to proceed is an experimental question

Strangely enough Majorana-type excitations are today thought to possibly exist in p-wave superconductors: we better make sure CM colleagues don't discover Majorana particles (even if not "elementary") first!

(see e.g. F.Wilczek Nature Physics vol 5, Sept 2009)
The idea of double-beta decay is almost as old as neutrinos themselves

The possibility of neutrinos-less decay was first discussed in 1937:

E. Majorana, Nuovo Cimento 14 (1937) 171

G. Racah, Nuovo Cimento 14 (1937) 322

Even earlier the study of nuclear structure led to the conclusion that the 2 neutrino mode would have half lives in excess of $10^{20}$ years

M. Goeppert-Mayer, Phys. Rev. 48 (1935) 512
Our knowledge of the $\nu$ mass pattern

The connection of $\nu$ masses with cosmological measurements is particularly interesting because it ties together very different fields. We need both, the connection between the two is the interesting part!
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
c   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 Majorana masses
→ Discovery of lepton number violation
Note that along with the double $\beta^-$ decay

\[ ^A_Z N \rightarrow ^A_{Z+2} N' + e^- + e^- \]

there is also a $\beta^+$ mode that in practice would appear as a single or double electron capture

\[ ^A_Z N \rightarrow ^A_{Z-2} N' + e^+ + e^+ \]

\[ ^A_Z N + e^- \rightarrow ^A_{Z-2} N' + e^+ \]

\[ ^A_Z N + e^- + e^- \rightarrow ^A_{Z-2} N' \]

All these processes are phase-space suppressed respect to the $\beta^-$ case and isotope fractions low in natural mix: usually not considered
If $0\nu\beta\beta$ is due to light $\nu$ Majorana masses

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

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

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

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

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

effective Majorana $\nu$ mass ($\varepsilon_i = \pm 1$ if CP is conserved)
Nuclear structure approaches

In **NSM** (Madrid-Strasbourg group) a limited valence space is used but all configurations of valence nucleons are included. Describes well properties of low-lying nuclear states. Technically difficult, thus only few 0νββ-decay calculations.

In **QRPA** (Tuebingen-Caltech-Bratislava and Jyvaskula-La Plata groups) a large valence space is used, but only a class of configurations is included. Describe collective states, but not details of dominantly few particle states. Relative simple, thus more 0νββ-decay calculations.

In **IBM** (Iachello, Barea) the low-lying states of the nucleus are modeled in terms of bosons. The bosons have either \( L=0 \) (s boson) or \( L=2 \) (d boson). The bosons can interact through one and to body forces giving rise to bosonic wave functions.

In **PHFB** (India/Mexico groups) w.f. of good angular momentum are obtained by making projection on the axially symmetric intrinsic HFB states. Nuclear Hamiltonian contains only quadrupole interaction.

**Differences:** i) mean field; ii) residual interaction; iii) size of the model space iv) many-body approximation

**Good news:** Lots of activity!

A number of new groups and ideas are entering the game!
Calculations differ by about a factor of two
(but care is necessary in treating some of them
generally regarded as obsolete)
Note, however, that to discover Majorana neutrinos and lepton number violation the value of the nuclear matrix element is inessential!

→ $0
\nu\beta\beta$ decay always implies new physics

This is comforting for the one of us spending their time building experiments!
### Simplified List of Limits for $\beta\beta 0\nu$ decay

<table>
<thead>
<tr>
<th>Candidate nucleus</th>
<th>Detector type</th>
<th>Present $T_{1/2}^{0\nu\beta\beta}$ (yr)</th>
<th>$&lt;m&gt;$ (eV)</th>
</tr>
</thead>
<tbody>
<tr>
<td>$^{48}\text{Ca}$</td>
<td>Ge diode</td>
<td>$&gt;5.8 \times 10^{22}$ (90%CL)</td>
<td>&lt;0.35</td>
</tr>
<tr>
<td>$^{76}\text{Ge}$</td>
<td>Ge diode</td>
<td>$&gt;1.9 \times 10^{25}$ (90%CL)</td>
<td></td>
</tr>
<tr>
<td>$^{82}\text{Se}$</td>
<td>Ge diode</td>
<td>$&gt;2.1 \times 10^{23}$ (90%CL)</td>
<td></td>
</tr>
<tr>
<td>$^{96}\text{Zr}$</td>
<td>Ge diode</td>
<td>$&gt;9.2 \times 10^{21}$ (90%CL)</td>
<td></td>
</tr>
<tr>
<td>$^{100}\text{Mo}$</td>
<td>Ge diode</td>
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<td>$&gt;1.1 \times 10^{23}$ (90%CL)</td>
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</tr>
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<td>$^{128}\text{Te}$</td>
<td>Ge diode</td>
<td>$&gt;3 \times 10^{24}$ (90%CL)</td>
<td>&lt;0.19 - 0.68</td>
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<tr>
<td>$^{160}\text{Gd}$</td>
<td>Foil Geiger</td>
<td>$&gt;5.8 \times 10^{22}$ (90%CL)</td>
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ββ0ν discovery claim

Fit model:
6 gaussians + linear bknd.

Fitted excess @ $Q_{ββ}$
$28.75 \pm 6.86$.

Claimed significance: 4.2 $σ$

$T_{1/2} = 2.23^{+0.44}_{-0.31} \cdot 10^{24}$ yr

$\langle m_ν \rangle = 0.32 \pm 0.03$ eV


However, this is a very controversial matter

See e.g. Strumia+Vissani
Nucl Phys B726 (2005) 294
**Measured 2νββ decay half lives, now observed for all interesting isotopes**

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<th>Isotope</th>
<th>Experimental $T_{1/2}^{2ν}$ (yr)</th>
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<td>$(4.3\pm2.2)\cdot10^{19}$</td>
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<td>$(1.77\pm0.12)\cdot10^{21}$</td>
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<tr>
<td>$^{82}\text{Se}$</td>
<td>$(9.6\pm1)\cdot10^{19}$</td>
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<td>$(9.4\pm3.2)\cdot10^{18}$</td>
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<td>$(2.1\pm0.6)\cdot10^{19}$</td>
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<td>$(2.11\pm0.21)\cdot10^{21}$</td>
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<tr>
<td>$^{150}\text{Nd}$</td>
<td>$(1.4\pm0.7)\cdot10^{20}$</td>
</tr>
<tr>
<td>$^{238}\text{U}$</td>
<td>$(2.0\pm0.6)\cdot10^{21}$ *</td>
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Slowest processes ever measured in nature!

...a good explanation for my title!

Arbitrarily simplified from PDG

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§Geochemical experiment

*Radiochemical experiment
Need very large fiducial mass (tons) of isotopically separated material (except for $^{130}$Te)

[using natural material typically means that 90% of the source produced background but not signal]

This is expensive and provides encouragement to use the material in the best possible way:

For no bkngd $\langle m_\nu \rangle \propto 1/\sqrt{T_{1/2}^{0v\beta\beta}} \propto 1/\sqrt{Nt}$

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The statistical significance of a signal is determined by how strongly you reject the null hypothesis.
The importance of clean, multi-parameter measurements grows as the size of detectors grows, making cross-checks painfully slow and expensive.

“Background” runs with un-enriched or depleted material do not seem to be a panacea as isotopic separation alters, sometimes drastically, the background in the source.
How to "organize" an experiment: the source

- High Q value reduces backgrounds and increases the phase space & decay rate,
- Large abundance makes the experiment cheaper
How to “organize” an experiment: the source

- High Q value reduces backgrounds and increases the phase space & decay rate,
- Large abundance makes the experiment cheaper
- A number of isotopes have similar matrix element performance
How to “organize” an experiment: the technique

• Final state ID: 1) “Geochemical”: search for an abnormal abundance of \((A,Z+2)\) in a material containing \((A,Z)\)
  2) “Radiochemical”: store in a mine some material \((A,Z)\) and after some time try to find \((A,Z+2)\) in it
    + Very specific signature
    + Large live times (particularly for 1)
    + Large masses
    - Possible only for a few isotopes (in the case of 1)
    - No distinction between \(0\nu\), \(2\nu\) or other modes

• “Real time”: ionization or scintillation is detected in the decay
  a) “Homogeneous”: source=detector
  b) “Heterogeneous”: source\(\neq\)detector
    + Energy/some tracking available (can distinguish modes)
    + In principle universal (b)
    - Many \(\gamma\) backgrounds can fake signature
    - Exposure is limited by human patience
Shielding a detector from gammas is difficult because the absorption cross section is small.

Example: γ interaction length in Ge is 4.6 cm, comparable to the size of a germanium detector.

Shielding double-beta decay detectors is much harder than shielding Dark Matter ones.
Background due to the Standard Model $2\nu\beta\beta$ decay

The two can be separated in a detector with sufficiently good energy resolution.

Topology and particle ID are also important to recognize backgrounds.

$\sigma/E = 1.6\%$
(EXO conservative $E$ resolution)
About energy resolution

Superior energy resolution:
- $^{76}$Ge (diode): 0.2% FWHM
- $^{130}$Te (bolometer): 0.4% FWHM

Intermediate energy resolution:
- $^{136}$Xe (liquid TPC): 3.3% FWHM

Modest energy resolution:
- $^{100}$Mo, $^{136}$Xe, $^{150}$Nd (scintillators): 10%-15% FWHM
Pattern recognition can be a very powerful tool against background (example from $2\nu\beta\beta$ in EXO-200)
“Extreme” pattern recognition (at the expense of fiducial mass)

700k $2
\nu\beta\beta$ events "without" bkg

$T^{0\nu}_{1/2} = (7.16 \pm 0.54) \times 10^{18}$ y (prelim.)

$2\nu\beta\beta$ results also for other six isotopes, see Victor Tretyak's talk at MEDEX 2011

for 4.5 years

$T^{0\nu}_{1/2} > 1.0 \times 10^{24}$ y

at 90% CL

$<m_{ee}> < 0.5-1$ eV

[2.8, 3.2] MeV:

$\epsilon(0\nu) = 0.055$

Tot MC = $11.0 \pm 0.8$, Data: 12 events

MC $2\nu\beta\beta = 5.8 \pm 0.4$

MC radon = $2.5 \pm 0.4$

MC int bkg = $2.7 \pm 0.4$ ($^{214}Bi = 0.4, \^{208}Tl = 2.3$)

TAUP 2011, Munich

Schwingenheuer, Double Beta Decay
Xe possibly offers an extra tool against background: 

\[ ^{136}\text{Xe} \rightarrow ^{136}\text{Ba}^{++} \text{ e}^- \text{ e}^- \] final state can be identified using optical spectroscopy (M. Moe PRC 44 (1991) 931)

\[ \text{Resonant ionization scheme} \]

\[ \begin{align*}
\text{Ba}^+ 5d & \quad \text{5d8d } ^1P_1 \\
\text{Ba}^+ 6s & \quad 6s6p \ ^1P_1 \\
\text{Ba}^+ 6s & \quad 6s^2 \ ^1S_0
\end{align*} \]

\[ \text{Barium window} \]

\[ \text{Desorption+RIS lasers (Black)} \]

\[ \text{Desorption only (Red)} \]

\[ \text{~2\% Ba tagging efficiency obtained in the lab.} \]

\[ \text{Plenty of R&D still left to do to demonstrated if the technique is viable} \]
It is very important to understand that a healthy neutrinoless double-beta decay program requires more than one isotope. This is because:

- There could be unknown gamma transitions and a line observed at the “end point” in one isotope does not necessarily imply that $0\nu\beta\beta$ decay was discovered
- Nuclear matrix elements are not very well known and any given isotope could come with unknown liabilities
- Different isotopes correspond to vastly different experimental techniques
- 2 neutrino background is different for various isotopes
- The elucidation of the mechanism producing the decay requires the analysis of more than one isotope
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### Experiments taking data or under construction

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<th>Isotope</th>
<th>Experiment</th>
<th>Main principle</th>
<th>Fid mass</th>
<th>Lab</th>
</tr>
</thead>
<tbody>
<tr>
<td>$^{76}$Ge</td>
<td>Majorana†</td>
<td>Eres, 2site tag, Cu shield</td>
<td>30 kg</td>
<td>SUSEL</td>
</tr>
<tr>
<td></td>
<td>Gerda†</td>
<td>Eres, 2site tag, LAr shield</td>
<td>15-35 kg</td>
<td>G Sasso</td>
</tr>
<tr>
<td>$^{150}$Nd</td>
<td>SNO+</td>
<td>Size/shielding</td>
<td>44 kg</td>
<td>SNOlab</td>
</tr>
<tr>
<td>$^{130}$Te*</td>
<td>CUORE</td>
<td>E Res.</td>
<td>204 kg</td>
<td>G Sasso</td>
</tr>
<tr>
<td>$^{136}$Xe</td>
<td>KamLAND-Zen</td>
<td>Size/shielding</td>
<td>400 kg</td>
<td>Kamioka</td>
</tr>
<tr>
<td></td>
<td>EXO-200</td>
<td>Tracking/Eres</td>
<td>150 kg</td>
<td>WIPP</td>
</tr>
</tbody>
</table>

* No isotopic enrichment

Not built to measure limits...
More ideas for the future *(not a complete list!)*

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</thead>
<tbody>
<tr>
<td>$^{76}\text{Ge}$</td>
<td>MaGe/GeMa</td>
<td>Best from GERDA and Majorana</td>
<td>~1ton</td>
<td></td>
</tr>
<tr>
<td>$^{116}\text{Cd}$</td>
<td>Cobra</td>
<td>Eres/tracking</td>
<td></td>
<td>Gran Sasso</td>
</tr>
<tr>
<td>$^{48}\text{Ca}$</td>
<td>CandlesIII</td>
<td>Size/shielding</td>
<td>0.35 kg</td>
<td>Oto-Cosmo</td>
</tr>
<tr>
<td>$^{150}\text{Nd}$</td>
<td>DCBA</td>
<td>Tracking</td>
<td>32 kg</td>
<td></td>
</tr>
<tr>
<td>$^{150}\text{Nd}$ \ $^{82}\text{Se}$</td>
<td>MOON</td>
<td>Tracking</td>
<td></td>
<td></td>
</tr>
<tr>
<td>$^{82}\text{Se}$</td>
<td>SuperNEMO</td>
<td>Tracking</td>
<td>~100 kg</td>
<td>Modane</td>
</tr>
<tr>
<td></td>
<td>Lucifer</td>
<td>Eres + particle ID</td>
<td></td>
<td></td>
</tr>
<tr>
<td>$^{136}\text{Xe}$</td>
<td>NEXT</td>
<td>Tracking/Eres</td>
<td>100 kg</td>
<td>Canfranc</td>
</tr>
<tr>
<td></td>
<td>EXO</td>
<td>Ba tag, Tracking/Eres</td>
<td>1-10ton</td>
<td></td>
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</tbody>
</table>
For the first time there is a clear opportunity to make an important discovery pushing the $\langle m \rangle$ sensitivity to the 5 - 200 meV region.

$\langle m_{\text{eff}} \rangle / \text{eV}$

- Klapdor–Kleingrothaus et al.
- MPLA 21, 2006

$10^{-2}$

- Inverted

$10^{-3}$

- Normal

100kg-class

$\sim 100$ meV sensit.

maybe as good as

$\sim 5$ meV
Not quite a linear path: we have to be flexible

Does one of the 100kg-scale experiments see $0
\nu\beta\beta$ decay?

No

Yes!

Do others see it too?

No

Yes!

Build ton-scale experiments

Build low density tracking detectors to investigate mechanism
Conclusions

Two nus is good news, even better will be no nus!

R. Blandford (inspired by the recent 2ν measurement by EXO-200)
Conclusions

Two nus is good news, even better will be no nus!
R. Blandford (inspired by the recent 2ν measurement by EXO-200)

Exciting time for neutrino physics:

- Neutrino-less double-beta decay
- $\theta_{13}$ from reactors
- Hierarchy/CP violation parameters
- Mass measurements from cosmology
- Sterile neutrinos
- Supernova neutrinos

...could all be accessible in the next ~10 years
Conclusions

Two nus is good news, even better will be no nus!

R. Blandford (inspired by the recent $2\nu$ measurement by EXO-200)

Over the years neutrino physics has provided plenty of surprises and required forays in many different areas of science and technology.

The search for neutrinoless double beta decay really belongs to this tradition!

- Isotope enrichment on a large scale is a reality
- 100kg-class experiments have started data taking
- ton-class experiments are being planned for the near future using exquisite techniques
Conclusions

Two nus is good news, even better will be no nus!

R. Blandford (inspired by the recent 2ν measurement by EXO-200)

As in the past, neutrinos may surprise us again

(...and, maybe, they already have, ...well, this is rushing a bit...)
...and Raju will be smiling from somewhere...