How can we search for double beta decay?

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Neutrinoless Double Beta Decay ($\beta\beta0\nu$)

Forbidden if neutrino mass is Dirac only

$N(Z,A) \rightarrow N(Z+2,A)e^-e^-$

Inside a nucleus

Virtues:
- Gets rid of the un-interesting $10^{18}$ events – trigger rate now extremely small.
- Chiral suppression is still severe, but we can fight it with Avagadro’s number
Two-Neutrino Double Beta Decay:

Two neutrons convert to two protons and four leptons.

First direct observation by Moe, Elliott, and Hahn in $^{100}\text{Mo}$ (1988)

No direct implications for neutrino physics, but useful for constraining the nuclear matrix element calculations.
$\beta\beta 0\nu$ strategy: search for a peak in the summed electron energy spectrum at the known $Q$ value

$\beta\beta 2\nu$ spectrum (normalized to 1)

$0\nu\beta$ peak (5% FWHM) (normalized to $10^{-6}$)

$\beta\beta 0\nu$ signal (5% FWHM) (normalized to $10^{-2}$)

Summed electron energy in units of the kinematic endpoint ($Q$)
Choosing a double beta decay source isotope:

\[ ^{N}(Z,A) \rightarrow ^{N}(Z+2,A)e^-e^- \]: daughter nucleus must have a smaller mass than the parent for the decay to occur.

“Q value”: how much KE is available
Choosing a double beta decay source isotope

<table>
<thead>
<tr>
<th>Decay candidate</th>
<th>Q value (MeV)</th>
<th>natural abundance (%)</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>

$^{\text{N}} \rightarrow ^{\text{N'}}\text{e}^-\text{e}^-$

Q value = $M(\text{N}) - M(\text{N'})$

The electron energies must sum to the Q value by energy conservation.

A large Q value is desirable because the decay rate is faster (larger phase space) and the radioactive backgrounds are smaller.

Large natural abundance make the experiment cheaper.
$\beta\beta_0\nu$ candidate isotopes:

Q value and natural abundance

High Q value reduces backgrounds and increases the phase space & decay rate, large abundance makes the experiment cheaper.
ββ0ν candidate isotopes:

Q value and natural abundance

High Q value reduces backgrounds and increases the phase space & decay rate, large abundance makes the experiment cheaper.
Virtually all materials contain small amounts of radioactive isotopes:

\[ ^{238}\text{U} \rightarrow ^{208}\text{T} \xrightarrow{\alpha} ^{234}\text{Th} \xrightarrow{\beta} ^{230}\text{Pa} \xrightarrow{\beta} ^{226}\text{Ra} \xrightarrow{\beta} ^{222}\text{Th} \xrightarrow{\beta} ^{218}\text{Rn} \xrightarrow{\beta} ^{214}\text{Po} \]  

half lives ~ $10^9$ years

\[ ^{208}\text{Tl} \rightarrow ^{204}\text{Pb} \xrightarrow{\beta} ^{204}\text{Bi} \xrightarrow{\beta} ^{200}\text{Po} \xrightarrow{\beta} ^{196}\text{At} \xrightarrow{\beta} ^{192}\text{Rn} \xrightarrow{\beta} ^{188}\text{Po} \xrightarrow{\beta} ^{184}\text{At} \xrightarrow{\beta} ^{180}\text{Po} \]  

γ emitters

Natural radioactive decay chains

Compton scattering: $\gamma e^- \rightarrow \gamma e^-$  

broad energy spectrum

Photoelectric effect: $\gamma e^- \rightarrow e^-$  

monochromatic

Pair production: $\gamma \rightarrow e^+ e^-$  

monochromatic
Shielding a detector from gammas is difficult because the absorption cross section is small.

Example: $\gamma$ interaction length in Germanium is 4.6 cm, comparable to the size of a germanium detector.
Why go underground?

- Studies for rare events, either decays (e.g., proton or $0\nu\beta\beta$) or weak interactions (dark matter, natural or generated neutrino), require very radio-quiet environments to undertake searches.

- Deep underground facilities provide significant rock overburden and commensurate reduction in c.r. flux, and c.r.-spallation induced neutrons.

- Additional science programmes possible with such infrastructure - nuclear astrophysics, extreme biosystems, geology, geophysics, ...
The most sensitive double beta decay experiments to date are based on 76-Germanium.

Heidelberg-Moscow (76Ge) energy spectrum

Half-life limit: $1.9 \times 10^{25}$ years (H-M and IGEX)
Majorana neutrinos ruled out for masses greater than $\sim 0.35$-1.0 eV
Energy resolution of $\beta\beta0\nu$ candidate isotopes

Gotthard TPC (136Xe) energy spectrum (1998)

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

Modest energy resolution:
- 136Xe (liquid TPC): 3.3% FWHM
- 100Mo, 82Se (plastic scintillator): ~14% FWHM
$\beta\beta^0\nu$ discovery claim – 2001-2006

Fit model:
6 gaussians + linear background.

Mean, width and intensity of each gaussian floats in the fit.

Total of 20 free parameters.

Fit intensity \( @ Q_{\beta\beta} = 28.75 \pm 6.86 \).

Authors claim significance of 4.2 \( \sigma \).

Mean value of \( \beta\beta0\nu \) candidate line displaced from \( Q_{\beta\beta} \) by 2.1 \( \sigma \).

\( 214^{\text{Bi}} \) intensity from fit is \( 2 - 2.5 \sigma \) larger than MC prediction.
Discovery of the $\Omega^-$

The statistical significance of a signal is determined by how strongly you reject the null hypothesis.
Germanium-76
Heidelberg-Moscow, IGEX, GERDA, MAJORANA experiments

Fantastic energy resolution (4 keV FWHM).
Cooled with Liquid Nitrogen to suppress thermal noise.
Pulse shape analysis rejects multiple site events within a single crystal.
Suffers from low Q value (2039 keV), and cosmogenic activation of germanium and copper cryostats.

2-3 kg Ge diodes, 80% $^{76}$Ge

Lead shielding  Cu cryostats
MAJORANA project status

- **Demonstrator** approved for FY 2010-2013
  - 30 kg $^{nat}$Ge & 30 kg $^{enr}$Ge
  - Running 3 years (90 kg·y) $\rightarrow T_{1/2} \geq 10^{26}$ y (90% CL)
  - $B = 10^{-3}$ cts/(kg·keV·y)

- **Objective**: Demonstrate background low enough to justify building a ton scale Ge experiment

- **Schedule**:
  - Start of Cu electroforming deep underground at DUSEL this year
  - First cryostat with 20 kg of $^{nat}$Ge modified BEGe p-type detectors ready in fall 2011

See posters 4, 95 & 120
Design of GERDA

Clean room: Detector handling

Lock system: Detector insertion

1400 m thick rock shield

Liquid Ar cryostat: Shielding, cooling of detectors

Cu shield

Phase I detector array

Water tank instrumented with PMTs: Shielding, Cherenkov muon-veto
GERDA status

- Summer/autumn ‘09: Integration test of Phase I detector string, FE, lock, DAQ
- Nov/Dec.’09: Liquid argon filling
- Apr/May’10: Installation of 1-string lock in the GERDA cleanroom
- May ’10: Deployment of FE & detector mock-up, followed by first deployment of a of non-enriched detector
- June ‘10: Water tank filling
- June ‘10: Commissioning run with $^{nat}$Ge detector string
Tellurium basics: low temperature bolometers

Take advantage of tiny heat capacity of crystals at low temperature to measure energy deposition with a thermometer(!).

Technique applicable to many isotopes – currently $^{130}$Te is used to take advantage of its high isotopic abundance (30%).

Drawbacks: no information beyond energy is available, like particle ID ($\alpha, \beta, \gamma$), event location, or topology.
CUORICINO is a 40.7 kg tower of TeO2 crystals (34% 130Te) in operation at Gran Sasso.
CUORICINO: 0ν DBD result

TOTAL EXPOSURE
19.75 [kg$^{130}$Te] yr

@ 90% C.L.
\[ \tau_{1/2} > 2.8 \times 10^{24} \text{ [yr]} \]
\[ m_{ee} < 0.3 \div 0.7^{1-4} \text{ eV} \]

NME bibliography:
1 Šimkovic et al.,
PRC 77 (2008) 045503
2 Civitarese et al.,
JoP:Conference series
173 (2009) 012012
3 Menéndez et al.,
NPA 818 (2009) 139
4 Barea and Iachello,
PRC 79 (2009) 044301

see POSTER – M. Carrettoni
From CUORICINO to CUORE
New Hardware

CUORICINO
44 5x5x5 cm³ + 18 3x3x6 cm³
TeO₂ crystals

1 TOWER: 40.7 kg TeO₂
11 kg ¹³⁰Te

CUORE:
988 5x5x5 cm³ TeO₂ crystals

19 TOWER: 740 kg TeO₂
~200 kg ¹³⁰Te
CUORE goal

5 years sensitivity

<table>
<thead>
<tr>
<th>Background [c/keV/kg/y]</th>
<th>( \Delta E_{\text{FWHM}} ) [keV]</th>
<th>( \tau_{1/2}^{0\nu} ) \text{ [y] @ 68%C.L.}</th>
<th>( m_{ee} ) [meV]</th>
</tr>
</thead>
<tbody>
<tr>
<td>0.01</td>
<td>5</td>
<td>2.1\times10^{26}</td>
<td>R(QRPA)^1: 35 \div 66, pn(QRPA)^2: 41 \div 67, ISM^3: 65 \div 82, IBM-2^4: 41</td>
</tr>
<tr>
<td>0.001</td>
<td>5</td>
<td>6.5\times10^{26}</td>
<td>20 \div 38, 23 \div 38, 37 \div 47, 23</td>
</tr>
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</table>

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**100Mo: NEMO-3**

France, Russia, Japan, US, Czech Republic, currently taking data in Frejus, France.

Passive isotope on thin foils surrounded by Geiger mode drift cells for electron tracking and plastic scintillator for energy measurement

NEMO is designed to investigate the $\beta\beta$0$\nu$ mechanism: multiple isotopes and electron angular distribution.
100Mo: NEMO-3

Tracking provides powerful background rejection

Scintillator

Source foil

Drift cells
100Mo: NEMO-3

25 Gauss magnetic field measures $\beta$ charge.

6.9 kg of 100Mo and 0.93 kg of 82Se for $\beta\beta0\nu$ search.

Other isotopes for $\beta\beta2\nu$ measurements and background studies.
100Mo and 82Se: NEMO-3

Data for 100Mo $\beta\beta2\nu$ agree beautifully with simulations.

Super-NEMO: 100 kg with neutrino mass sensitivity of 50 meV.
1000 t D$_2$O will be replaced by Nd loaded LS

0.1 wt% = 780 kg Nd(natural)
  = 44 kg Nd-150

9500 PMTs

Energy res = 5 %@ 1 MeV

7000 t pure water shield

Hold down ropes will be installed
Double beta decay signal at the “KKDC level”
From K. Nakamua, Neutrino 2010

Sensitivity

![Graph showing sensitivity of effective neutrino mass upper limit over data taking time with various confidence levels.](image)
From K. Nakamua, Neutrino 2010

KamLAND-Zen

$^{136}\text{Xe}$ 400 kg:
2.7 wt% dissolved into LS
easy handling/ enrichment (90%)
longer 2v beta decay life time
$T^{2v} > 10^{22}$ years (cf: $\sim 10^{19-20}$)

KamLAND exists:
ultra pure environment ($U/Th \sim 10^{-17}$ g/g)
LS techniques
Balloon experience
LS Density control techniques
Reactor/Geo neutrino

$^{136}\text{Xe}$ 400 kg loaded LS in mini-balloon, $R=1.7$ m
<m_\nu> = 0.15 \text{ eV} \text{ (minimum KKDC)}
T_{1/2} (0\nu) = 9.8 \times 10^{25} \text{ y}
T_{1/2} (2\nu) = 1.0 \times 10^{22} \text{ y}
From K. Nakamua, Neutrino 2010

Sensitivity

Upper Limit [meV]

KKDC

400 kg $^{136}$Xe

Degenerate

2 years

90 % C.L.

Exposure [kg-year]
Enriched Xenon Observatory
for double beta decay
Xenon can be continuously purified of chemical and radioactive contaminants.

Fluids often have extraordinarily low radioactivity, and noble gases are particularly simple to purify.
Liquid xenon calorimetry

Measure the event energy by collecting the ionization on the anode and/or observing the scintillation.
Liquid xenon data show an anti-correlation between ionization and scintillation

Energy resolution: 3.0% @ 570 keV or 1.4 % @ Q(ββ)

Factor of two better than most recent Xe experiment
The crown jewels of EXO

200 kg of xenon enriched to 80\% in $^{136}$Xe:

11 times larger than previous double beta decay experiments.
EXO-200: the first 200 kg $\beta\beta 0\nu$ experiment

- Copper liquid xenon vessel
- Copper cryostat
- HFE-7000 cryofluid
- 25 cm lead shielding
EXO-200 Cryostat & Lead (March 2008)
EXO-200 TPC Construction
EXO-200 – Final TPC installation in January 2010
EXO-200: First data expected in September
Sensitivity of EXO-200

<table>
<thead>
<tr>
<th>Case</th>
<th>Mass (ton)</th>
<th>Eff. (%)</th>
<th>Run Time (yr)</th>
<th>$\sigma_E/E@2.5\text{MeV}$ (%)</th>
<th>Radioactive Background (events)</th>
<th>$T_{1/2}^{0v}$ (yr, 90%CL)</th>
<th>Majorana mass (meV)</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>109</td>
</tr>
</tbody>
</table>

2) Menendez et al., Nucl. Phys. A818, 139(2009), (use UCOM results)
Xe offers a new tool to reduce background:

$^{136}\text{Xe} \rightarrow ^{136}\text{Ba}^{++}$ 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

Barium tagging would eliminate all radioactive backgrounds, leaving only $2\nu\beta\beta$.
EXO Ba+ trapping Experiment

RF quadrupole trap loaded in UHV from a Ba dispenser and e-beam ionizer. Xe can be injected while observing the ions at pressures from 10^{-10} torr to 0.1 torr.
EXO spectroscopy lab

650 nm: External Cavity Diode Laser (ECDL)

493 nm: Frequency doubled 986 nm

Ba Oven
RF trap

e-gun
Ba$^+$ Tagging: Ion Trap + fluorescence

$\cos(\Omega t) + U$

$e^-$ gun

Ba oven

Scope

Spectroscopy lasers

CCD

DC potential [V]

0 Volts

-5 Volts

\(~9\sigma\) discrimination in 5s integration


B. Flatt et al., NIM A 578 (2007) 409
Resonant Ionization Spectroscopy uses lasers tuned to atomic resonances to first *excite* and then *ionize* specific atoms.

- We use pulsed dye lasers at 553.5 nm and 389.7 nm.
- Autoionization: The 5d8d \(^1\text{P}_1\) state decays to a lower energy ionized state, allowing use of the high cross section of the resonance to achieve ionization.
Ba\(^+\) Tagging: RIS

Efficiency of \(\sim10^{-3}\) in “bulk mode” setup. New “single ion mode” setup about to start taking data.
Sensitivity of ton-scale EXO with barium tagging

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<tr>
<th>Case</th>
<th>Mass (ton)</th>
<th>Eff. (%)</th>
<th>Run Time (yr)</th>
<th>$\sigma_E/E @ 2.5\text{MeV}$ (%)</th>
<th>$2\nu\beta\beta$ 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>$2 \times 10^{27}$</td>
<td>19</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>$4.1 \times 10^{28}$</td>
<td>4.3</td>
</tr>
</tbody>
</table>

What to expect in the next decade

Next ~2-3 years

~3-5 years

~5-10 years

Figure from Strumia & Vissani, Nucl. Phys. B 726 294 (2005)