GERDA:
The GERmanium Detector Array for the search for neutrinoless $\beta\beta$ decays of $^{76}\text{Ge}$
What we know

Mass Scale

NORMAL

INVERTED

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

| \[ | \Delta m_{13}^2 | \text{ known} \]

Mixing Matrix

\[ U_{ij} \] can be characterized by three mixing angles, \( \Theta_{12}, \Theta_{23}, \Theta_{13} \), one Dirac CP phase, \( \delta \), and two Majorana phases \( \Phi_2, \Phi_3 \)

\( \Theta_{12}, \Theta_{23} \) measured, upper limit on \( \Theta_{13} \)
What we do not know about neutrinos:

1. absolute mass scale (offset)
2. mass hierarchy (1,2,3 or 3,1,2)
3. nature of neutrino (Majorana, Dirac particle)
4. value of third mixing angle ($\Theta_{13}$)
5. CP phases ($\delta, \Phi_2, \Phi_3$)

Double beta decay experiment can address 3, and, if neutrinos are Majorana particles, then also a combination of 1,2,5
How can we test if neutrinos are Dirac or Majorana particles?

Experimental Problem:

\[ P(\nu_L \rightarrow \nu_R) \propto \left( \frac{m_\nu}{E_\nu} \right)^2 \]

Only known technique is neutrinoless double beta decay:
Double Beta Decay

Very rare decay lifetimes >$10^{20}$ years!

$(A,Z) \rightarrow (A,Z+1) + e^+ + \nu$ energetically forbidden
$(A,Z) \rightarrow (A,Z+2) + 2e + 2\nu$ is allowed.

Then, for Majorana particle $(A,Z) \rightarrow (A,Z+2) + 2e$ possible

Note: process would violate lepton number conservation!
Decay Rate & Spectrum

Normalized energy spectrum

If resolution poor

If resolution good

$\frac{1}{\tau} = G(Q,Z) |M_{nucl}|^2 <m_{ee}>^2$

$0^\nu$ - DBD rate

Phase space $Q^5$ 

Nuclear matrix element

Effective Majorana mass
Effective Neutrino Mass

\[
m_{ee} = |m_{ee}^{(1)}| + e^{i\Phi_2} |m_{ee}^{(2)}| + e^{i\Phi_3} |m_{ee}^{(3)}| \\
|m_{ee}^{(1)}| \equiv |U_{e1}|^2 m_1 \\
|m_{ee}^{(2)}| \equiv |U_{e2}|^2 \sqrt{m_1^2 + \Delta m_{21}^2} \\
|m_{ee}^{(3)}| \equiv |U_{e3}|^2 \sqrt{m_1^2 + \Delta m_{31}^2}
\]

Complicated relationship between effective mass in neutrinoless double beta decay and neutrino masses, mixing angles and phases

Cancellation possible: \(m_{ee}\) could be vanishingly small 😞
Effective Neutrino Mass

F. Feruglio, A. Strumia, F. Vissani, NPB 637

- Inverted hierarchy
- Normal hierarchy
- Degenerate

- Lightest neutrino $(m_1, m_3)$ in eV
- $m_{ee}$ in eV

- 90% CL
- Disfavoured by $0\nu2\beta$
- Negligible errors from oscillations; width due to CP phases

90% CL (1 dof)
A Measurement of the Half-Life of Double Beta-Decay from $^{60}$Sn$^{124}$ *

E. L. Fireman  
Department of Physics, Princeton University, Princeton, New Jersey  
November 29, 1948

If two isobars differ by two units in atomic number, the heavier may decay into the lighter by double beta-decay.\cite{1,2} This is the simultaneous emission of two neutrinos if the heavier has lower atomic number or the simultaneous emission of two positons, 1 positon+1K capture, or 2K captures if the heavier has higher atomic number. The half-life depends markedly upon whether or not two neutrinos are emitted in the process. If no neutrinos are

Coincidences and single counts from both specimens are recorded simultaneously. The specimen holder is rotated through 180° every other hour and the positions of the specimens in the holder are interchanged every 20 hours. These data are summarized in Table II.

In all situations specimen A gives 2 coincidence counts/hr. more than specimen B. By repeating this type of measurement with Al absorbers over one side of each specimen an absorption curve is obtained. This absorption curve is similar to that of electrons from a spectrum with an energy end point between 1.0 Mev and 1.5 Mev. The single counts from specimens A and B both give 6.5±0.3 counts/min. If one interprets this effect as double beta-decay from Sn$^{124}$, one obtains a half-life between $4.4 \times 10^{16}$ yr. and $9.9 \times 10^{16}$ yr. Other alternative explanations for these observations have been considered but none have been found to be plausible. This result would indicate that double beta-decay is unaccompanied by neutrinos. A further consequence of these results pointed out to the author by Professor J. R. Oppenheimer is that the neutron-proton charge difference is exactly equal to the electron charge.

Note: 0ν predicted to have shorter lifetime from phase space arguments

Positive result corresponds to $\langle m_{ee} \rangle \approx 30$ keV \text{(my estimate)}
Heidelberg-Moscow Experiment

H.V. Klapdor-Kleingrothaus, I.V. Krivosheina, A. Dietz, O. Chkvorets

- Experiment with Ge detectors enriched in $^{76}\text{Ge}$
- Exposure 71.7 kg-yr
- Experiment carried out in Gran Sasso lab
- Background: 0.11/(keV kg yr)

Claim: 4.2σ signal

$T_{1/2} = 0.69-4.18 \times 10^{25}$ yr

$m_{ee} = 440$ meV (best fit) KK Matrix Element

$m_{ee} \approx 700$ meV Rodin et al. Matrix Element
GERDA (GERmanium Detector Array) is a collaboration of 12 institutes, ca. 80 physicists, from Germany, Italy, Russia, Poland, Belgium. The experiment has been approved by the LNGS (Gran Sasso)
GERDA Locations

Gerda at LNGS

Underground detector laboratory (LArGe-facility)
Some of the possible isotopes

<table>
<thead>
<tr>
<th>Decay</th>
<th>Q(keV)</th>
<th>Nat. Abundance</th>
<th>Experiments</th>
</tr>
</thead>
<tbody>
<tr>
<td>(^{48}\text{Ca} \to ^{48}\text{Ti})</td>
<td>4271</td>
<td>0.2%</td>
<td>CANDLES</td>
</tr>
<tr>
<td>(^{76}\text{Ge} \to ^{76}\text{Se})</td>
<td>2039</td>
<td>7.4%</td>
<td>GERDA,Majorana</td>
</tr>
<tr>
<td>(^{82}\text{Se} \to ^{82}\text{Kr})</td>
<td>2995</td>
<td>8.4%</td>
<td>NEMO</td>
</tr>
<tr>
<td>(^{96}\text{Zr} \to ^{96}\text{Mo})</td>
<td>3350</td>
<td>2.8%</td>
<td>NEMO,Moon</td>
</tr>
<tr>
<td>(^{100}\text{Mo} \to ^{100}\text{Ru})</td>
<td>3034</td>
<td>9.6%</td>
<td>NEMO,Moon</td>
</tr>
<tr>
<td>(^{116}\text{Cd} \to ^{116}\text{Sn})</td>
<td>2802</td>
<td>7.5%</td>
<td>COBRA,CUORE</td>
</tr>
<tr>
<td>(^{128}\text{Te} \to ^{128}\text{Xe})</td>
<td>867</td>
<td>32%</td>
<td>EXO,XMASS</td>
</tr>
<tr>
<td>(^{130}\text{Te} \to ^{130}\text{Xe})</td>
<td>2529</td>
<td>34%</td>
<td>EXO,XMASS</td>
</tr>
<tr>
<td>(^{136}\text{Xe} \to ^{136}\text{Ba})</td>
<td>2479</td>
<td>8.9%</td>
<td>EXO,XMASS</td>
</tr>
<tr>
<td>(^{150}\text{Nd} \to ^{150}\text{Sm})</td>
<td>3367</td>
<td>5.6%</td>
<td>EXO,XMASS</td>
</tr>
</tbody>
</table>
We like Germanium because:

- excellent energy resolution (3 keV @ 2 MeV)
- considerable experience built up over the years - best background levels, best limits to date!
- still improvements possible

There are also some downsides:

- Q=2039 keV in region of $\gamma$ backgrounds
- Q=2039 keV not among the higher Q values (recall $\tau \propto 1/Q^5$)
- enrichment possible, but expensive!
- limited number of crystal growers, detector makers
Detector Setup

Maximum charge

Organized in strings

Start with existing detectors

Phase I
HdM & IGEX
p-type Ge diodes

Cu 80.8 g
Si 4.5 g
PTFE 6.4 g
Bayesian analysis: discovery defined as $P(\text{background only}|\text{spectrum}) < 0.0001$

Phase I: 15 kg-yr, existing $^{\text{enr}}$Ge crystals

Phase II: 100 kg-yr, new segmented $^{\text{enr}}$Ge crystals
Sensitivity

Central value from KK et al.

### Background Suppression

<table>
<thead>
<tr>
<th>Source</th>
<th>Action</th>
</tr>
</thead>
<tbody>
<tr>
<td>γ’s external to crystals from $^{208}$Tl($^{232}$Th), $^{214}$Bi($^{226}$Ra), $^{60}$Co,…</td>
<td>Shield: high-purity liquid argon shield. Minimize material close to detector.</td>
</tr>
<tr>
<td>Front-end electronics</td>
<td>Cold ASIC</td>
</tr>
<tr>
<td>μ Induced prompt signals</td>
<td>Underground location (LNGS - 3400 mwe); Water Cerenkov veto</td>
</tr>
<tr>
<td>μ Induced delayed signals (e.g. n+ $^{76}$Ge→$^{77}$Ge→$^{77}$As)</td>
<td>Low-Z material shield (Ar)</td>
</tr>
<tr>
<td>Internal to crystal (cosmogenic)</td>
<td>Minimize time above ground after enrichment ($^{68}$Ge), crystal pulling ($^{60}$Co)</td>
</tr>
</tbody>
</table>

In addition: segmented detectors and pulse shape analysis (Phase II)
Backgrounds

The types of things we worry about:
e.g., cosmogenic activation of $^{68}\text{Ge}$ (about $6/(\text{day kg})$ in enriched Ge)

$^{68}\text{Ge} \rightarrow ^{68}\text{Ga}$ via EC (10.6 KeV X-ray)
$\tau=271 \text{ days}$

$^{68}\text{Ga} \rightarrow ^{68}\text{Zn}$ via $\beta^+$ (90%, 1.9 MeV)
$+ \gamma (0.511 \text{ MeV})$
$+ \gamma (0.511 \text{ MeV})$
$\tau=68 \text{ minutes}$
Existing Detectors

**Heidelberg-Moscow detectors for Phase I of GERDA.** In addition, three detectors from IGEX experiment. Total mass approx 18 kg. Detectors need to be refurbished to fit into GERDA scheme. This process is well underway.

<table>
<thead>
<tr>
<th>FWHM [keV]</th>
<th>ANG1</th>
<th>ANG2</th>
<th>ANG3</th>
<th>ANG4</th>
<th>ANG5</th>
<th>RG1</th>
<th>RG2</th>
<th>RG3</th>
</tr>
</thead>
<tbody>
<tr>
<td>Mass [kg]</td>
<td>2.54</td>
<td>2.29</td>
<td>2.93</td>
<td>2.47</td>
<td>2.59</td>
<td>2.21</td>
<td>2.31</td>
<td>2.26</td>
</tr>
<tr>
<td></td>
<td>0.980</td>
<td>2.906</td>
<td>2.446</td>
<td>2.400</td>
<td>2.781</td>
<td>2.150</td>
<td>2.194</td>
<td>2.121</td>
</tr>
</tbody>
</table>
Phase II detectors 18-fold segmented detectors (true-coaxial, 3x6, n-type)
New Detectors
Sample screening coordinated between: MPIK, GEEL, Baksan, LNGS

All materials which can produce background are measured

GeMPI at LNGS:
Active Background Suppression

Background sources:

- Cosmogenically produced $^{68}$Ge and $^{60}$Co
- U/Th contamination, $^{210}$Pb on surface
- External gammas

Signatures:

- Signal has two electrons in final state $\rightarrow$ range $\sim$mm
- Background sources mostly $\gamma$ with $E_\gamma > 2$ MeV
- Compton scattering dominant interaction, range $\sim$few cm

Signal:

Background ($^{60}$Co):
Background Suppression

With prototype 18-fold segmented detector
1. We will confirm or rule out the Klapdor-Kleingrothaus et al. claim.
2. If not verified and background reduction to the level $10^{-3}/(\text{kg yr keV})$ demonstrated, go for Phase III (ca. 1 ton, 20 meV level).