Searching for neutrinoless double-beta decay of germanium-76 in the presence of backgrounds

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Outline

- Neutrinoless double-beta decay
- The MAJORANA DEMONSTRATOR
- Studies with an R&D detector
Neutrino questions

• What is the absolute mass scale of neutrinos?
• What is the neutrino mass hierarchy?
• Is the neutrino its own antiparticle (a Majorana particle)?
• Is lepton number a conserved quantity?
Double-beta decay

- Process that occurs for some nuclei with even number of protons and neutrons
- Occurs with the emission of two neutrinos (2νββ)
- Observed in many nuclei
- $T_{1/2} \sim 10^{19}$ to $10^{21}$ years
Observation would indicate:
- Neutrino is a Majorana particle
- Lepton number is violated
- Information about mass may be available

Neutrinoless double-beta decay ($0\nu\beta\beta$)
0νββ and neutrino mass

decay rate: \[ [T_{1/2}^{0\nu\beta\beta}]^{-1} = G^{0\nu\beta\beta}(E_0,Z) \ (M^{0\nu\beta\beta})^2 \ <m_{0\nu\beta\beta}>^2 \]

eff. mass: \[ m_{0\nu\beta\beta} = |U_{e1}|^2 m_1 + |U_{e2}|^2 m_2 e^{i\phi_2} + |U_{e3}|^2 m_3 e^{i\phi_3} \]
0νββ and neutrino mass

decay rate: \[ [T_{1/2}^{0\nu\beta\beta}]^{-1} = G^{\nu\beta\beta}(E_0, Z) (M^{0\nu\beta\beta})^2 <m_{0\nu\beta\beta}>^2 \]

eff. mass: \[ m_{0\nu\beta\beta} = \left| |U_{e1}|^2m_1 + |U_{e2}|^2m_2e^{i\phi_2} + |U_{e3}|^2m_3e^{i\phi_3} \right| \]
$0\nu\beta\beta$ and neutrino mass

decay rate: $[T_{1/2}^{0\nu\beta\beta}]^{-1} = G^{0\nu\beta\beta}(E_0, Z) \ (M^{0\nu\beta\beta})^2 \ <m_{0\nu\beta\beta}>^2$

eff. mass: $m_{0\nu\beta\beta} = |U_{e1}|^2 m_1 + |U_{e2}|^2 m_2 e^{i\phi_2} + |U_{e3}|^2 m_3 e^{i\phi_3}$
0νββ and neutrino mass

decay rate: \[ [T_{1/2}^{0νββ}]^{-1} = G^{0νββ}(E_0, Z) (M^{0νββ})^2 <m_{0νββ}>^2 \]

eff. mass: \[ m_{0νββ} = |U_{e1}|^2 m_1 + |U_{e2}|^2 m_2 e^{iφ_2} + |U_{e3}|^2 m_3 e^{iφ_3} \]
0νββ and neutrino mass

decay rate: \[ [T_{1/2}^{0νββ}]^{-1} = G^{0νββ}(E_0, Z) (M^{0νββ})^2 <m_{0νββ}>^2 \]
eff. mass: \[ m_{0νββ} = \left| |U_{e1}|^2 m_1 + |U_{e2}|^2 m_2 e^{iφ_2} + |U_{e3}|^2 m_3 e^{iφ_3} \right| \]
Criteria for $0\nu\beta\beta$ experiment

- Large mass of source
- Extremely low background rate
- Best possible background identification techniques

Criteria for $0\nu\beta\beta$ observation

- Peak at the correct energy
- Full energy spectrum, including backgrounds, understood
- Observe in several different isotopes in independent experiments
<table>
<thead>
<tr>
<th>Collaboration</th>
<th>Isotope</th>
<th>Technique</th>
<th>mass (0νββ isotope)</th>
<th>Status</th>
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</thead>
<tbody>
<tr>
<td>CANDLES</td>
<td>Ca-48</td>
<td>305 kg CaF(_2) crystals - liq. scint</td>
<td>0.3 kg</td>
<td>Construction</td>
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<tr>
<td>CARVEL</td>
<td>Ca-48</td>
<td>(^{48})CaWO(_4) crystal scint.</td>
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<tr>
<td>GERDA I</td>
<td>Ge-76</td>
<td>Ge diodes in LAr</td>
<td>15 kg</td>
<td>Operating</td>
</tr>
<tr>
<td>II</td>
<td></td>
<td>Point contact Ge in LAr or LN</td>
<td>30-35 kg</td>
<td>Construction</td>
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<tr>
<td>MAJORANA DEMONSTRATOR</td>
<td>Ge-76</td>
<td>Point contact Ge</td>
<td>30 kg</td>
<td>Construction</td>
</tr>
<tr>
<td>ITGe (GERDA &amp; MAJORANA)</td>
<td>Ge-76</td>
<td>Best technology from GERDA and MAJORANA</td>
<td>~ tonne</td>
<td>R&amp;D</td>
</tr>
<tr>
<td>NEMO3</td>
<td>Mo-100, Se-82</td>
<td>Foils with tracking</td>
<td>6.9 kg, 0.9 kg</td>
<td>Complete</td>
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<tr>
<td>SuperNEMO</td>
<td>Se-82</td>
<td>Foils with tracking</td>
<td>7 kg</td>
<td>R&amp;D</td>
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<td>MOON</td>
<td>Mo-100</td>
<td>Mo sheets</td>
<td>200 kg</td>
<td>R&amp;D</td>
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<td>CAMEO</td>
<td>Cd-116</td>
<td>CdWO(_4) crystals</td>
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<td>COBRA</td>
<td>Cd-116, Te-130</td>
<td>CdZnTe detectors</td>
<td>10 kg</td>
<td>R&amp;D</td>
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<tr>
<td>CUORICINO</td>
<td>Te-130</td>
<td>TeO(_2) Bolometer</td>
<td>10 kg</td>
<td>Complete</td>
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<tr>
<td>CUORE</td>
<td>Te-130</td>
<td>TeO(_2) Bolometer</td>
<td>206 kg</td>
<td>Construction</td>
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<tr>
<td>KamLAND-ZEN</td>
<td>Xe-136</td>
<td>2.7% in liquid scint.</td>
<td>380 kg</td>
<td>Operating</td>
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<tr>
<td>NEXT-100</td>
<td>Xe-136</td>
<td>High pressure Xe TPC</td>
<td>80 kg</td>
<td>R&amp;D</td>
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<td>EXO200</td>
<td>Xe-136</td>
<td>Xe liquid TPC</td>
<td>160 kg</td>
<td>Operating</td>
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<tr>
<td>EXO</td>
<td>Xe-136</td>
<td>Xe liquid TPC</td>
<td>~ tonne</td>
<td>R&amp;D</td>
</tr>
<tr>
<td>DCBA</td>
<td>Nd-150</td>
<td>Nd foils &amp; tracking chambers</td>
<td>&lt; kg</td>
<td>R&amp;D</td>
</tr>
<tr>
<td>SNO+</td>
<td>Nd-150</td>
<td>0.1% (\text{nat})Nd suspended in Scint</td>
<td>44 kg</td>
<td>Construction</td>
</tr>
</tbody>
</table>
Detector is source: demonstrated ability to enrich from 7.4% to 86% $^{76}$Ge

- Ge diodes are intrinsically high purity
- Excellent energy resolution: 0.13% FWHM at Q-value of 2039 keV
- Commercially available
- P-type point contact detectors
  - extremely low noise
  - low energy threshold
• **Design:** detectors submerged in liquid Argon at LNGS, Italy
• **Shield:** LAr, H₂O
• **Phase I:** 18 kg enr-Ge (2011)
• **Phase II:** 20 kg enr-Ge (2013)

• **Design:** detectors in high-purity electroformed copper cryostats at Sanford Lab, US
• **Shield:** copper, lead
• **Demonstrator:** 30 kg of enr-Ge

Open exchange of knowledge and technologies

**Future goal:** merge for tonne-scale experiment
Sensitivity of a tonne-scale $^{76}$Ge experiment

- Exposure [ton-years]
- Sensitivity (90% CL, QRPA NME) [meV]
- $10^2$ to $10^3$

- Inverted Hierarchy ($m_\nu \rightarrow 0$ eV)

- Background free
- 0.1 counts/ROI/t/y
- 1 count/ROI/t/y
- 4 counts/ROI/t/y


- $^{76}$Ge $T_{1/2}$ sensitivity (90% CL) [years]
- $10^{25}$ to $10^{28}$
The **Majorana Demonstrator**

Funded by DOE Office of Nuclear Physics and NSF Particle and Nuclear Astrophysics, with additional contributions from international collaborators.

**Goals:**
- Demonstrate backgrounds low enough to justify building a tonne scale experiment
- Establish feasibility to construct & field modular arrays of Ge detectors
- Test Klapdor-Kleingrothaus claim
- Low-energy dark matter (light WIMPs) search

- Located underground at 4850’ Sanford Lab
- Background Goal in the 0νββ peak region of interest (4 keV at 2039 keV)
  - 4 counts/ROI/t/y (after analysis cuts)
  - Scales to 1 count/ROI/t/y for a tonne experiment

- **40-kg of Ge detectors**
  - 30-kg of 86% enriched $^{76}$Ge crystals & 10-kg of $^{nat}$Ge
  - Detector Technology: P-type, point-contact.

- **2 independent cryostats**
  - Ultra-clean, electroformed Cu
  - 20 kg of detectors per cryostat
  - Naturally scalable

- **Compact Shield**
  - Low-background passive Cu and Pb shield with active muon veto
The MAJORANA DEMONSTRATOR

poly shield
plastic scintillator
muon veto
lead shield
outer commercial copper shield
inner electroformed copper shield
Three steps:

- **Prototype cryostat:** 2 strings natural Ge
- **Cryostat 1:** 3 strings enr. Ge, 4 strings nat. Ge
- **Cryostat 2:** 7 strings enr. Ge

- Early 2013
- Fall 2013
- Fall 2014
Home of the MAJORANA DEMONSTRATOR, Lead, SD
Recent DEMONSTRATOR progress
• Advised postdoc Matt Green on Cryostat Assembly.

Updater: Fast

• We anticipated receiving the dewar in June but it has not arrived. Once received, the dewar will then undergo inspection at PNNL prior to delivery to UNC for use on the prototype cryostat.

Updater: Elliott, Rielage, Rodriguez

• Delivered all vacuum hardware for cryostat 1 presently on-hand to SURF for storage.

• We performed a detailed inventory and compared to the recent parts list for the design. We identified the missing parts.

Updater: Pushkin

• Assisted Randy Hughes as a machinist assistant in the Davis Machine Shop.

Updater: Strain

• Etched copper parts for the prototype cryostat, including: thermosiphon, crossarm+hoop, top cryostat lid, bottom cryostat lid, cold plate, annulus and string parts.

Also began leaching plastic parts for the prototype cryostat and string test cryostats.
detector string evolution
detector string evolution

LANL thermal test string
Jan 2011

LBNL March 2011 thermal tests

Design as released for Prototype production Feb 2012: MJ80-02-195

LBNL Jan 2012 tests
10 baths at Sanford producing copper since July 2011
about 50% of EFCu complete, including major parts for cryostat 1
underground construction is underway
M. Kapust
Detector electronics

LMFE production

Spring clips

Negligible force applied so only single screws needed

Signal connectors (UW)

Epoxying jig

Loaded garage

images from J. Loach
detection of $0\nu\beta\beta$
The $0\nu\beta\beta$ signal in germanium

- Ionizing energy deposits in germanium produce a charge signal
- The $0\nu\beta\beta$ signal:
  - Single site
  - Single crystal
  - Uncorrelated in time with other events
- Near 2039-keV $^{76}\text{Ge}$ endpoint

Figure 5.2: Processing a sample waveform to calculate energy. The waveform is shown before any processing (top), after baseline subtraction and pole-zero correction (middle) and after trapezoidal filtering (bottom). The energy of this waveform is 500 keV.

digitized waveform from a 500-keV energy deposit

a germanium crystal in cross section
Sources of background

- Primordial contamination: $^{40}\text{K}$, $^{238}\text{U}$, $^{232}\text{Th}$
- Long-lived cosmogenics: $^{68}\text{Ge}$, $^{60}\text{Co}$, $^{65}\text{Zn}$
- Prompt cosmogenics: $\mu$, $\mu$-induced neutrons
- Other: anthropogenic contaminants, radon, solar neutrinos

Background reduction techniques

- Minimize mass of non-germanium components
- Use passive and active shielding
- Fabricate parts in shielding from clean copper and plastic
- Electroform and machine copper underground at Sanford and PNNL

![Background in above-ground laboratory, 15 cm Pb shielding](image-url)
Backgrounds in germanium detectors

One example: 2615-keV $\gamma$ from $^{208}$Tl in the $^{232}$Th decay chain

- $e^+e^-$ annihilation
- DEP
- SEP
- Region of interest
- Full-energy peak
Background mitigation techniques

- Time correlation: identify $^{68}\text{Ge}$ to $^{68}\text{Ga}$ decays
  
  $^{68}\text{Ge} \rightarrow 68\text{Ga}$
  
  $T_{1/2} = 271$ days
  
  Electron capture:
  
  K-shell: 10.4 keV, 86%
  
  L-shell: 1.2 keV, 11%

- Granularity: tag events that deposit energy in multiple detectors

- Pulse-shape discrimination: discriminate multi-site backgrounds

- Example of pulse-shape analysis

\[ Q = 2.9 \text{ MeV} \]
R&D detector: MALBEK

**MAJORANA** Low-background BEGe detector at Kimballton

- 0.4 kg natural germanium
- Customized CANBERRA Broad-Energy Germanium (BEGe) detector
  - Modified geometry of crystal ditch, surrounding components to minimize capacitance
  - Low-background copper cryostat
- Kimballton Underground Research Facility in Ripplemeade, VA (1700’, 1400 m.w.e.)
- R&D:
  - Dark matter search
  - **MAJORANA**-like data-acquisition system
  - Measurement & model of background energy spectrum
R&D detector: MALBEK
Kimballton Underground Research Facility
slow-rising, energy-degraded pulses

outer n+ contact

measured $^{60}$Co spectrum

slow pulses contribute throughout the energy spectrum
**MALBEK background model**

- **Material purity information**
  - **cosmogenic contaminants**: production rates from literature
  - **primordial contaminants**: material assay data from literature and direct measurements of bulk and surface contamination
  - **cosmic muon flux**: from literature

- **Monte Carlo simulation results**
  - **Geant4 simulations** to determine efficiencies for contamination to deposit energy in our detectors
    - 50k CPU hours
    - 8k+ runs, 40+ contaminants, 56 components, 21 materials

- **Exposure history**

- **Detector characteristics**
  - **energy resolution**: \( \sigma(E) = (0.12^2 + 0.09E + E^2)^{1/2} \) keV
  - **dead layer properties**: 0.93 ± 0.09 mm outer n+ contact [arXiv:1207.6716]
  - **preamplifier effects**: efficiency as a function of energy
Figure 6: Geant4 geometry model of the MALBEK detector in shielding at KURF shown in cross-section. Materials are indicated by color: polyethylene, scintillator, modern lead, ancient lead, aluminum, steel. The multicolored detector from Figure 6 is inside the ancient lead shield; the cold finger protrudes. The top section of the polyethylene shield rests on top of a steel trailer. The rest of the polyethylene shield is inside the trailer. The white empty space is air except inside the detector where it is vacuum.

Geant4 geometry model
Geant4 geometry model

6 cm (2.4 inches)

germanium
lead
copper
teflon (white)
brass
tin solder
resistors
beryllium copper
nickel silver
MALBEK background model

- MAGE/GEANT Prediction of MALBEK Backgrounds
  - 232-Th Lower Chain (224-Ra -- 208-Pb)
  - 232-Th Upper Chain (232-Th -- 224-Ra)
  - 238-U Lower Chain I (226-Ra -- 210-Pb)
  - 238-U Lower Chain II (210-Pb -- 206-Pb)
  - 238-U Upper Chain (238-U -- 226-Ra)
  - 3-H
  - 40-K
  - 46-Sc
  - 48-V
  - 54-Mn
  - 55-Fe
  - 56-Co
  - 57-Co
  - 58-Co
  - 59-Fe
  - 60-Co
  - 63-Ni
  - 65-Zn
  - 68-Ge
  - 76-Ge 2vBB
  - Cosmogenic muons

Counts / 5.0 keV / 55.2 days

Energy [keV]
validation tests

$^{60}$Co: integral count rate agrees within 2% between 5 and 3000 keV

$^{133}$Ba: integral count rate agrees within 3% between 5 and 400 keV

measured $^{60}$Co

Geant4 simulation + measured background

Measured $^{133}$Ba

Geant4 simulation + measured background
Shielded background energy spectrum measured at Kimballton

Counts / 2.0 keV / day

Pb x-rays

$\text{e}^+\text{e}^-\text{annihilation}$

$^{214}\text{Bi}$

$^{40}\text{K}$
Measurement exceeded our expectations

spectrum measured in shielding
model prediction
$^{210}\text{Pb}$ $^{210}\text{Bi}$ $^{210}\text{Po}$ $^{206}\text{Pb}$

- $T_{\text{1/2}} = 22$ years
- $\gamma$ 46.5 keV
- $T_{\text{1/2}} = 5$ days
- $\beta$ 1162 keV end point
- $T_{\text{1/2}} = 138$ days
- $\alpha$ 5.3 MeV

Counts / 0.5 keV / day

Energy [keV]

Counts / 0.5 keV / day

Energy [keV]
Possible sources of $^{210}$Pb contamination

- Ancient lead shims (< $1.3 \times 10^{-5}$ Bq/g)
- Ultra-low-background tin solder
- Brass pins and connectors (< 4% lead)
- Inner shielding: ancient lead bricks (< $1.3 \times 10^{-5}$ Bq/g)
Brass connectors

Inner lead shield

Lead shims

Solder
Background model fit of energy spectrum

\[ \chi^2 / \text{DOF} = 132.8 / 115 \]

P-value = 0.12
Lead shim removal

Removed 3g of lead from cryostat
Background model fit of spectrum after shim removal

ORCA/Struck data
Fit Result
232-Th Lower Chain (224-Ra -- 208-Pb) in GermaniumNat
232-Th Lower Chain (224-Ra -- 208-Pb) in StainlessSteel304
232-Th Lower Chain (224-Ra -- 208-Pb) in Teflon
232-Th Upper Chain (232-Th -- 224-Ra) in StainlessSteel304
232-Th Upper Chain (232-Th -- 224-Ra) in Zeolite
238-U Lower Chain I (226-Ra -- 210-Pb) in MoxtekFET
238-U Lower Chain I (226-Ra -- 210-Pb) in StainlessSteel304
238-U Lower Chain II (210-Pb -- 206-Pb) in Brass
238-U Lower Chain II (210-Pb -- 206-Pb) in LeadAin
238-U Lower Chain II (210-Pb -- 206-Pb) in LeadMod
238-U Lower Chain II (210-Pb -- 206-Pb) in Rn Exposure Outside Cryostat
238-U Upper Chain (238-U -- 226-Ra) in Brass
238-U Upper Chain (238-U -- 226-Ra) in CopperOFHC
238-U Upper Chain (238-U -- 226-Ra) in GermaniumNat
3-H in GermaniumNat
40-K in Brass
56-Co in CopperOFHC
60-Co in GermaniumNat
60-Co in NickelSilver
65-Zn in GermaniumNat
68-Ge in GermaniumNat
76-Ge 2νBB in GermaniumNat
Cosmogenic muons in KURF Experimental Hall

$\chi^2 / \text{DOF} = 97.2 / 114$

P-value = 0.87
Results from R&D detector

• Validated background model of the energy spectrum
• Identified and removed contaminated component from cryostat
• Studied slow pulses and developed a cut to remove them throughout the energy spectrum
• Tested MAJORANA data-acquisition system
• Developed and tested software for simulations and analysis of data
Simulated spectra, 40 kg yrs, detector resolution applied

- **raw spectrum**
- **after all cuts**

**Region of interest**

- $^{60}$Co
- $^{40}$K
- $^{214}$Bi
- $^{214}$Pb
- $^{208}$Tl
- U/Th $\alpha$'s

**Counts [keV$^{-1}$]**

**Energy [MeV]**
Conclusions

- Observation of neutrinoless double beta decay would determine Majorana nature of the neutrino, demonstrate lepton number violation, and provide information about neutrino mass.

- **Majorana Demonstrator** is a 40-kg detector array searching for 0νββ of $^{76}\text{Ge}$.
  - Under construction at Sanford Underground Laboratory.
  - On track to begin taking data in September 2013.
  - Tests of data taking, data analysis, and background modeling with an R&D detector have been successful.
Thank you!
supplemental slides
Airborne radioactivity in Seattle after the 2011 Fukushima earthquake

J. Diaz Leon et al., Journal of Environmental Radioactivity 102 (2011) 1032-1038
arXiv:1103.4853
Energy Linearity

FIG. 47: Energy linearity.

χ²/DOF: 194.21 / 14 (13.87), p-val: 8.33E-34
### Identified Peaks

<table>
<thead>
<tr>
<th>Peak</th>
<th>Energy [keV]</th>
<th>Centroid [keV]</th>
<th>Sigma [eV]</th>
<th>Count Rate [Hz]</th>
<th>(\chi^2 / \text{DOF} )</th>
<th>P-value</th>
</tr>
</thead>
<tbody>
<tr>
<td>(^{65}\text{Zn}^{+} )</td>
<td>8.98</td>
<td>8.98 ± 0.01</td>
<td>1434.4 ± 7.6</td>
<td>23.7 ± 1.3</td>
<td></td>
<td></td>
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<tr>
<td>(^{68}\text{Ga} )</td>
<td>9.66</td>
<td>9.66 ± 0.03</td>
<td>1417.1 ± 33.3</td>
<td>3.8 ± 0.8</td>
<td>39.3 / 53 (0.74)</td>
<td>0.920</td>
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<tr>
<td>(^{68}\text{Ge}^{1} )</td>
<td>10.37</td>
<td>10.38 ± 0.00</td>
<td>1318.2 ± 2.0</td>
<td>74.7 ± 2.0</td>
<td></td>
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</tr>
<tr>
<td>(^{210}\text{Pb}^{4} )</td>
<td>46.54</td>
<td>46.63 ± 0.03</td>
<td>1621.4 ± 25.0</td>
<td>4.1 ± 0.6</td>
<td>21.4 / 36 (0.59)</td>
<td>0.975</td>
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<tr>
<td>(^{234}\text{U}, ^{72}\text{Ge}(n, \gamma) )</td>
<td>53.20, 53.53</td>
<td>53.91 ± 0.03</td>
<td>71.8 ± 19.8</td>
<td>1.0 ± 0.3</td>
<td>19.5 / 36 (0.54)</td>
<td>0.989</td>
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<tr>
<td>(^{233}\text{Th}^{1} )</td>
<td>63.29</td>
<td>63.46 ± 0.06</td>
<td>224.5 ± 44.3</td>
<td>2.2 ± 0.0</td>
<td>19.3 / 36 (0.54)</td>
<td>0.989</td>
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<tr>
<td>Bi K(_{\alpha2} )</td>
<td>74.81</td>
<td>75.06 ± 0.06</td>
<td>223.4 ± 54.0</td>
<td>2.3 ± 0.6</td>
<td>34.3 / 59 (0.58)</td>
<td>0.996</td>
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<td>Bi K(_{\alpha1} )</td>
<td>77.11</td>
<td>77.23 ± 0.06</td>
<td>221.7 ± 50.5</td>
<td>2.7 ± 0.6</td>
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<tr>
<td>(^{234}\text{Th} )</td>
<td>92.38, 92.80</td>
<td>92.76 ± 0.05</td>
<td>440.9 ± 41.4</td>
<td>9.0 ± 0.0</td>
<td>28.3 / 36 (0.79)</td>
<td>0.816</td>
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<td>(^{57}\text{Co}^{1} )</td>
<td>122.06</td>
<td>121.81 ± 0.03</td>
<td>280.4 ± 27.8</td>
<td>8.3 ± 0.0</td>
<td>43.1 / 36 (1.20)</td>
<td>0.193</td>
</tr>
<tr>
<td>(^{57}\text{Co} + \text{atomic} )</td>
<td>143.58</td>
<td>143.52 ± 0.06</td>
<td>305.8 ± 65.7</td>
<td>4.0 ± 0.8</td>
<td>26.1 / 36 (0.73)</td>
<td>0.887</td>
</tr>
<tr>
<td>(^{228}\text{Ac} )</td>
<td>200.25</td>
<td>209.56 ± 0.16</td>
<td>226.5 ± 97.8</td>
<td>0.7 ± 0.0</td>
<td>20.5 / 36 (0.57)</td>
<td>0.982</td>
</tr>
<tr>
<td>(^{212}\text{Pb}^{4} )</td>
<td>238.63</td>
<td>238.52 ± 0.03</td>
<td>304.2 ± 33.2</td>
<td>8.0 ± 0.8</td>
<td>33.9 / 54 (0.63)</td>
<td>0.985</td>
</tr>
<tr>
<td>(^{214}\text{Pb}^{1} )</td>
<td>242.00</td>
<td>241.82 ± 0.04</td>
<td>338.1 ± 41.1</td>
<td>7.3 ± 0.8</td>
<td></td>
<td></td>
</tr>
<tr>
<td>(^{214}\text{Pb}^{1} )</td>
<td>295.22</td>
<td>295.12 ± 0.03</td>
<td>408.5 ± 29.7</td>
<td>13.8 ± 1.0</td>
<td>14.0 / 36 (0.39)</td>
<td>1.000</td>
</tr>
<tr>
<td>(^{228}\text{Ac} )</td>
<td>338.32</td>
<td>338.13 ± 0.10</td>
<td>265.5 ± 88.3</td>
<td>1.3 ± 0.4</td>
<td>28.1 / 36 (0.78)</td>
<td>0.822</td>
</tr>
<tr>
<td>(^{208}\text{Pb}(n, n'\gamma)^1 )</td>
<td>343.51</td>
<td>344.07 ± 0.08</td>
<td>387.7 ± 72.4</td>
<td>2.9 ± 0.6</td>
<td>26.3 / 36 (0.73)</td>
<td>0.881</td>
</tr>
<tr>
<td>(^{214}\text{Pb}^{4} )</td>
<td>351.93</td>
<td>351.89 ± 0.03</td>
<td>442.9 ± 21.5</td>
<td>20.8 ± 0.0</td>
<td>25.4 / 36 (0.71)</td>
<td>0.905</td>
</tr>
<tr>
<td>(^{228}\text{Ac}^{1} )</td>
<td>463.00</td>
<td>462.86 ± 0.30</td>
<td>1022.9 ± 217.2</td>
<td>2.1 ± 0.0</td>
<td>29.5 / 36 (0.82)</td>
<td>0.768</td>
</tr>
<tr>
<td>(^{208}\text{TI} + \text{annih.} )</td>
<td>510.77, 511.00</td>
<td>510.88 ± 0.20</td>
<td>1217.0 ± 190.1</td>
<td>5.2 ± 0.0</td>
<td>23.5 / 36 (0.65)</td>
<td>0.946</td>
</tr>
<tr>
<td>(^{208}\text{TI}^{1} )</td>
<td>583.19</td>
<td>583.18 ± 0.13</td>
<td>620.8 ± 100.0</td>
<td>2.7 ± 0.5</td>
<td>17.2 / 36 (0.48)</td>
<td>0.997</td>
</tr>
<tr>
<td>(^{214}\text{Bi}^{1} )</td>
<td>609.32</td>
<td>609.58 ± 0.05</td>
<td>703.4 ± 40.2</td>
<td>15.6 ± 1.0</td>
<td>21.2 / 36 (0.59)</td>
<td>0.976</td>
</tr>
<tr>
<td>(^{214}\text{Bi} )</td>
<td>768.36</td>
<td>768.36 ± 0.24</td>
<td>1106.2 ± 216.0</td>
<td>2.6 ± 0.5</td>
<td>15.1 / 36 (0.42)</td>
<td>0.999</td>
</tr>
<tr>
<td>(^{208}\text{Pb}(n, n'\gamma) )</td>
<td>803.10</td>
<td>803.61 ± 0.35</td>
<td>1042.7 ± 280.8</td>
<td>1.3 ± 0.4</td>
<td>14.4 / 36 (0.40)</td>
<td>0.999</td>
</tr>
<tr>
<td>(^{228}\text{Ac} )</td>
<td>911.20</td>
<td>911.80 ± 0.22</td>
<td>1025.3 ± 183.3</td>
<td>2.3 ± 0.5</td>
<td>13.9 / 36 (0.39)</td>
<td>1.000</td>
</tr>
<tr>
<td>(^{214}\text{Bi} )</td>
<td>1120.29</td>
<td>1122.00 ± 0.52</td>
<td>2129.8 ± 477.1</td>
<td>2.5 ± 0.6</td>
<td>23.6 / 36 (0.65)</td>
<td>0.945</td>
</tr>
<tr>
<td>(^{40}\text{K}^{1} )</td>
<td>1460.82</td>
<td>1461.08 ± 0.28</td>
<td>1887.3 ± 244.6</td>
<td>3.3 ± 0.5</td>
<td>12.7 / 36 (0.35)</td>
<td>1.000</td>
</tr>
<tr>
<td>(^{214}\text{Bi} )</td>
<td>1764.49</td>
<td>1765.05 ± 0.41</td>
<td>1042.3 ± 354.4</td>
<td>0.8 ± 0.2</td>
<td>11.1 / 36 (0.31)</td>
<td>1.000</td>
</tr>
<tr>
<td>(^{214}\text{Bi} )</td>
<td>2204.06</td>
<td>2257.12 ± 0.00</td>
<td>14567.5 ± 0.0</td>
<td>1.3 ± 0.0</td>
<td>2.4 / 36 (0.07)</td>
<td>1.000</td>
</tr>
</tbody>
</table>
Table J.4: Radiopurity information for Copper-OFHC. Table generated by *MJBMDbInfo*.

<table>
<thead>
<tr>
<th>Contaminant</th>
<th>Activity/Production Rate</th>
<th>Reference</th>
</tr>
</thead>
<tbody>
<tr>
<td>$^{232}\text{Th}$ to $^{228}\text{Ra}$ ($^{232}\text{Th}$ step 1)</td>
<td>9.00E-01 μBq/kg</td>
<td>DEMONSTRATOR Table [78]</td>
</tr>
<tr>
<td>$^{228}\text{Ra}$ to $^{226}\text{Th}$ ($^{232}\text{Th}$ step 2)</td>
<td>9.00E-01 μBq/kg</td>
<td>DEMONSTRATOR Table [78]</td>
</tr>
<tr>
<td>$^{228}\text{Th}$ to $^{224}\text{Ra}$ ($^{232}\text{Th}$ step 3)</td>
<td>9.00E-01 μBq/kg</td>
<td>DEMONSTRATOR Table [78]</td>
</tr>
<tr>
<td>$^{224}\text{Ra}$ to $^{208}\text{Pb}$ ($^{232}\text{Th}$ step 4)</td>
<td>9.00E-01 μBq/kg</td>
<td>DEMONSTRATOR Table [78]</td>
</tr>
<tr>
<td>$^{238}\text{U}$ to $^{234}\text{Th}$ ($^{238}\text{U}$ step 1)</td>
<td>3.00E+00 μBq/kg</td>
<td>DEMONSTRATOR Table [78]</td>
</tr>
<tr>
<td>$^{234}\text{Th}$ to $^{231}\text{U}$ ($^{238}\text{U}$ step 2)</td>
<td>3.00E+00 μBq/kg</td>
<td>DEMONSTRATOR Table [78]</td>
</tr>
<tr>
<td>$^{234}\text{U}$ to $^{230}\text{Th}$ ($^{238}\text{U}$ step 3)</td>
<td>3.00E+00 μBq/kg</td>
<td>DEMONSTRATOR Table [78]</td>
</tr>
<tr>
<td>$^{230}\text{Th}$ to $^{226}\text{Ra}$ ($^{238}\text{U}$ step 4)</td>
<td>3.00E+00 μBq/kg</td>
<td>DEMONSTRATOR Table [78]</td>
</tr>
<tr>
<td>$^{226}\text{Ra}$ to $^{222}\text{Rn}$ ($^{238}\text{U}$ step 5)</td>
<td>3.00E+00 μBq/kg</td>
<td>DEMONSTRATOR Table [78]</td>
</tr>
<tr>
<td>$^{222}\text{Rn}$ to $^{218}\text{Ti}$ or $^{219}\text{Pb}$ ($^{238}\text{U}$ step 6)</td>
<td>3.00E+00 μBq/kg</td>
<td>DEMONSTRATOR Table [78]</td>
</tr>
<tr>
<td>$^{210}\text{Pb}$ to $^{210}\text{Bi}$ or $^{206}\text{Pb}$ ($^{238}\text{U}$ step 7)</td>
<td>6.30E-04 μBq/kg</td>
<td>DEMONSTRATOR Table [78]</td>
</tr>
<tr>
<td>$^{210}\text{Bi}$ to $^{210}\text{Po}$ or $^{206}\text{Pb}$ ($^{238}\text{U}$ step 8)</td>
<td>3.00E+00 μBq/kg</td>
<td>DEMONSTRATOR Table [78]</td>
</tr>
<tr>
<td>$^{210}\text{Po}$ to $^{206}\text{Pb}$ ($^{238}\text{U}$ step 9)</td>
<td>3.00E+00 μBq/kg</td>
<td>DEMONSTRATOR Table [78]</td>
</tr>
<tr>
<td>$^{40}\text{K}$</td>
<td>1.24E+01 μBq/kg</td>
<td>EXO [75]</td>
</tr>
<tr>
<td>$^{46}\text{Sc}$</td>
<td>4.58E+00 atoms/kg/day</td>
<td>Heusser et al. [79]</td>
</tr>
<tr>
<td>$^{48}\text{V}$</td>
<td>9.56E+00 atoms/kg/day</td>
<td>Heusser et al. [79]</td>
</tr>
<tr>
<td>$^{56}\text{Co}$</td>
<td>1.99E+01 atoms/kg/day</td>
<td>Heusser et al. [79]</td>
</tr>
<tr>
<td>$^{57}\text{Co}$</td>
<td>1.56E+02 atoms/kg/day</td>
<td>Heusser et al. [79]</td>
</tr>
<tr>
<td>$^{58}\text{Co}$</td>
<td>1.43E+02 atoms/kg/day</td>
<td>Heusser et al. [79]</td>
</tr>
<tr>
<td>$^{59}\text{Fe}$</td>
<td>3.93E+01 atoms/kg/day</td>
<td>Heusser et al. [79]</td>
</tr>
<tr>
<td>$^{60}\text{Co}$</td>
<td>2.00E+02 atoms/kg/day</td>
<td>DEMONSTRATOR Table [78]</td>
</tr>
</tbody>
</table>

Table J.5: Radiopurity information for Germanium-Nat. Table generated by *MJBMDbInfo*.

<table>
<thead>
<tr>
<th>Contaminant</th>
<th>Activity/Production Rate</th>
<th>Reference</th>
</tr>
</thead>
<tbody>
<tr>
<td>$^{232}\text{Th}$ to $^{228}\text{Ra}$ ($^{232}\text{Th}$ step 1)</td>
<td>1.42E-02 μBq/kg</td>
<td>DEMONSTRATOR Table [78]</td>
</tr>
<tr>
<td>$^{228}\text{Ra}$ to $^{226}\text{Th}$ ($^{232}\text{Th}$ step 2)</td>
<td>1.42E-02 μBq/kg</td>
<td>DEMONSTRATOR Table [78]</td>
</tr>
<tr>
<td>$^{228}\text{Th}$ to $^{224}\text{Ra}$ ($^{232}\text{Th}$ step 3)</td>
<td>1.42E-02 μBq/kg</td>
<td>DEMONSTRATOR Table [78]</td>
</tr>
<tr>
<td>$^{224}\text{Ra}$ to $^{208}\text{Pb}$ ($^{232}\text{Th}$ step 4)</td>
<td>1.42E-02 μBq/kg</td>
<td>DEMONSTRATOR Table [78]</td>
</tr>
<tr>
<td>$^{238}\text{U}$ to $^{234}\text{Th}$ ($^{238}\text{U}$ step 1)</td>
<td>1.38E-02 μBq/kg</td>
<td>DEMONSTRATOR Table [78]</td>
</tr>
<tr>
<td>$^{234}\text{Th}$ to $^{230}\text{U}$ ($^{238}\text{U}$ step 2)</td>
<td>1.38E-02 μBq/kg</td>
<td>DEMONSTRATOR Table [78]</td>
</tr>
<tr>
<td>$^{234}\text{U}$ to $^{230}\text{Th}$ ($^{238}\text{U}$ step 3)</td>
<td>1.38E-02 μBq/kg</td>
<td>DEMONSTRATOR Table [78]</td>
</tr>
<tr>
<td>$^{230}\text{Th}$ to $^{226}\text{Ra}$ ($^{238}\text{U}$ step 4)</td>
<td>1.38E-02 μBq/kg</td>
<td>DEMONSTRATOR Table [78]</td>
</tr>
<tr>
<td>$^{226}\text{Ra}$ to $^{222}\text{Rn}$ ($^{238}\text{U}$ step 5)</td>
<td>1.38E-02 μBq/kg</td>
<td>DEMONSTRATOR Table [78]</td>
</tr>
<tr>
<td>$^{222}\text{Rn}$ to $^{218}\text{Ti}$ or $^{219}\text{Pb}$ ($^{238}\text{U}$ step 6)</td>
<td>1.38E-02 μBq/kg</td>
<td>DEMONSTRATOR Table [78]</td>
</tr>
<tr>
<td>$^{210}\text{Pb}$ to $^{210}\text{Bi}$ or $^{206}\text{Pb}$ ($^{238}\text{U}$ step 7)</td>
<td>2.89E-06 μBq/kg</td>
<td>DEMONSTRATOR Table [78]</td>
</tr>
<tr>
<td>$^{210}\text{Bi}$ to $^{210}\text{Po}$ or $^{206}\text{Pb}$ ($^{238}\text{U}$ step 8)</td>
<td>1.38E-02 μBq/kg</td>
<td>DEMONSTRATOR Table [78]</td>
</tr>
<tr>
<td>$^{210}\text{Po}$ to $^{206}\text{Pb}$ ($^{238}\text{U}$ step 9)</td>
<td>1.38E-02 μBq/kg</td>
<td>DEMONSTRATOR Table [78]</td>
</tr>
<tr>
<td>$^{3}\text{H}$</td>
<td>2.77E+01 atoms/kg/day</td>
<td>D.-M. Mei [80]</td>
</tr>
<tr>
<td>$^{54}\text{Mn}$</td>
<td>9.10E+00 atoms/kg/day</td>
<td>Avg. from Table I [81]</td>
</tr>
<tr>
<td>$^{55}\text{Fe}$</td>
<td>8.40E+00 atoms/kg/day</td>
<td>MAJORANA BSD – GENIUS [61]</td>
</tr>
<tr>
<td>$^{57}\text{Co}$</td>
<td>6.84E+00 atoms/kg/day</td>
<td>Avg. from Table I [81]</td>
</tr>
<tr>
<td>$^{58}\text{Co}$</td>
<td>1.61E+01 atoms/kg/day</td>
<td>MAJORANA BSD – GENIUS [61]</td>
</tr>
<tr>
<td>$^{60}\text{Co}$</td>
<td>5.00E+00 atoms/kg/day</td>
<td>DEMONSTRATOR Table [78]</td>
</tr>
<tr>
<td>$^{63}\text{Ni}$</td>
<td>4.60E+00 atoms/kg/day</td>
<td>MAJORANA BSD – GENIUS [61]</td>
</tr>
<tr>
<td>$^{62}\text{Zn}$</td>
<td>7.95E+00 atoms/kg/day</td>
<td>MAJORANA BSD – GENIUS [61]</td>
</tr>
<tr>
<td>$^{68}\text{Ge}$</td>
<td>3.00E+01 atoms/kg/day</td>
<td>DEMONSTRATOR Table [78]</td>
</tr>
<tr>
<td>$^{76}\text{Ge}$</td>
<td>9.03E+00 μBq/kg</td>
<td>A.S. Barabash [1]</td>
</tr>
</tbody>
</table>
Pulsed-reset preamplifier
Pulsed-reset preamplifier

charge

reset

reset

Q

Q

time
Pulsed-reset preamplifier

Charge vs. time graph showing two reset points with a maximum charge level $Q_{\text{max}}$.
Pulsed-reset preamplifier

Charge and time diagram with reset points at $Q_{\text{max}}$ and leakage current marked as $\Delta q$. The time interval $T \sim 40 \text{ ms}$ is indicated.
Pulsed-reset preamplifier

charge

reset

reset

reset

reset

Q_{\text{max}}

leakage current

\Delta t

\Delta q

Q_1

Q_2

T \sim 40 \text{ ms}

energy deposits
Energy-dependent efficiency

\[ \epsilon_{\text{preamp}}(E) = \begin{cases} 1 - \frac{E}{E_{\text{max}}} & \text{for } E \leq E_{\text{max}} \\ 0 & \text{for } E > E_{\text{max}} \end{cases} \]

\[ E_{\text{max}} = E_R \left( 1 - \frac{T_{\text{veto}}}{T_R} \right) \]
Figure 5.7: **Majorana Demonstrator** sensitivity to a WIMP signal (blue solid, 0.3 keV threshold; blue dashed, 0.5 keV threshold), comparing to SuperCDMS Phase A [96](red dashed) and LUX 300 [97] (black dotted). Plot generated with DMTools [86], lines are 90% CL exclusions.
Photon attenuation

- Energy [keV]
- \(1 / I_0\) vs. Energy [keV]

<table>
<thead>
<tr>
<th>Material</th>
<th>Color</th>
</tr>
</thead>
<tbody>
<tr>
<td>Lead</td>
<td>Blue</td>
</tr>
<tr>
<td>Copper</td>
<td>Red</td>
</tr>
<tr>
<td>Germanium</td>
<td>Green</td>
</tr>
<tr>
<td>Aluminum</td>
<td>Purple</td>
</tr>
<tr>
<td>Teflon</td>
<td>Gray</td>
</tr>
</tbody>
</table>

Photon attenuation curves for different materials, showing the relationship between photon intensity ratio and energy in keV.
EXO $0
\nu\beta\beta$ limit

IG. 6: Relation between the $T^{0\nu\beta\beta}_{1/2}$ in $^{76}$Ge and $^{136}$Xe for different matrix element calculations (GCM [20], NSM [21], 3M-2 [22], RQRPA-1 [23] and QRPA-2 [5]). For each matrix element $\langle m \rangle_{\beta\beta}$ is also shown (eV). The claim [4] is represented by the grey band, along with the best limit for $^{76}$Ge [19]. The result reported here is shown along with that from [7].
Slow energy-degraded pulses from the MALBEK transition dead layer

Total dead layer measurement

Fractional charge collection vs. depth

E. Agauayo et al, submitted to NIM A
arXiv:1207.6716
Pulsed-reset preamp
Pulsed-reset preamp
DEMONSTRATOR background model

Energy [MeV]

Counts / keV / tonne / year

before cuts

after cuts

before cuts

after cuts
questions

- GERDA: P1 = 18kg enr-Ge, P2 = 20kg enr-Ge?
- Cu purity: limits or measurements?
- PPC technology
- enr. Ge
- add DM/PPC slide
- add assay achievements/
- put status bullets on pics

Make sure slide # is visible on every slide!