P-Type HPGe Ring Diode Detectors for use in $0\nu\beta\beta$ Decay Experiments

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2νββ and 0νββ

2νββ – Standard Model
τ_{1/2} = 10^{18} - 10^{21} yrs

0νββ is proposed

Decay rate is inversely proportional to half-life

Simulated 2νββ and 0νββ spectra in Ge76
Source: MAJORANA
Implications of $0\nu\beta\beta$ if Discovered

- Physics beyond the Standard Model
  - Lepton number violation
  - Information about absolute neutrino mass scale
  - Neutrino is a Majorana fermion
  - Would provide mechanism for observed matter/antimatter asymmetry
Mission: “The collaboration aims to develop a phased, Ge-76 based double-beta decay experimental program with discovery potential at a half-life beyond $10^{28}$ years, using existing resources as appropriate to expedite physics results.”

Source: LEGEND
Germanium

- Semiconductor
  - High Purity Germanium Detectors (HPGe)
    - Good energy resolution for gamma ray spectroscopy
    - Operates at ~80 K
  - $^{76}$Ge decays into $^{76}$Se via $2\nu\beta\beta$
    - Possibly also via $0\nu\beta\beta$
      - Half-life > $10^{25} - 10^{26}$ years

Ionizing radiation produces electron-hole pairs

Source: Mirion Technologies, Inc.
Single-Site v. Multi-Site Event Discrimination

Fig. courtesy of C. Wiseman

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Single-Site
(0νββ-like)
accepted

Multi-Site
(γ-like)
rejected

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<table>
<thead>
<tr>
<th>Layer Description</th>
<th>Color</th>
<th>Region</th>
</tr>
</thead>
<tbody>
<tr>
<td>p+ Point Contact (Ge)</td>
<td>Yellow</td>
<td>Transition Region (~1 mm)</td>
</tr>
<tr>
<td>n+ Outer Contact (Li)</td>
<td>Green</td>
<td>Transition Region (~1 mm)</td>
</tr>
<tr>
<td>Active (Intrinsic) Volume</td>
<td>Blue</td>
<td>Transition Region (~1 mm)</td>
</tr>
<tr>
<td>Transition Region (~1 mm)</td>
<td>Red</td>
<td>Active (Intrinsic) Volume</td>
</tr>
<tr>
<td>Passivated Surface (~1 μm)</td>
<td>Purple</td>
<td>Transition Region (~1 mm)</td>
</tr>
<tr>
<td>Passivation Boundary</td>
<td>Black</td>
<td>Transition Region (~1 mm)</td>
</tr>
</tbody>
</table>

We would like to characterize the HPGe passivated surface and n+ dead layer. A variety of different radiation sources are interesting (α, β, γ). MAJORANA PPC’s have larger passivated surfaces than other designs (more IR sensitive). Let’s design a versatile test stand that can accommodate large LEGEND detectors.
Detector Geometries

Semi-coaxial detectors from Heidelberg-Moscow experiment.


Cross section of semi-coaxial design (left) and the new proposed ring-diode detector (right).

Source: Reine, et al.
Simulating the Fields

Poisson’s Equation

- Solved in The Julia Programming Language
- Used Solid State Detectors Package

$$\nabla^2 \phi = \frac{\rho}{\varepsilon}$$

$\phi =$ electric potential
$\rho =$ charge density
$\varepsilon =$ dielectric constant
Simulations

Bias Voltage: 3500V
Simulated Depletion Voltage: 2700V
Simulations

Bias Voltage: 1900V
Simulated Depletion Voltage: 1450V

Electric Potential

Electric Field Lines
Simulations

Bias Voltage: 2000V
Simulated Depletion Voltage: 1100V
Simulations

Bias Voltage: 2000V
Simulated Depletion Voltage: 700V

Linear Impurity Profile
- Impurity at Z=0: \(-8\times10^9 \text{ cm}^{-3}\)
- Gradient: \(1.55\times10^9 \text{ cm}^{-4}\)
Simulations

Bias Voltage: 2000V
Simulated Depletion Voltage: 500V
Linear Impurity Profile
• Impurity at Z=0: \(-8\times10^9\) cm\(^{-3}\)
• Gradient: \(1.55\times10^9\) cm\(^{-4}\)

Electric Potential

Electric Field Lines
Discussion and Conclusion

- Feasible to manufacture
  - Reine et al.
  - Suggested Pulse Shape Discrimination Abilities
- Texas A&M Manufacturing
  - Future experimental analysis and comparison with simulations
- Future work to simulate pulses of single-site and multi-site events
Acknowledgements

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Alvis et al. Search for neutrinoless double-β decay in 76Ge with 26 kg yr of exposure from the MAJORANA DEMONSTRATOR. https://doi.org/10.1103/PhysRevC.100.025501

Alvis et al. Multi-site event discrimination for the MAJORANA DEMONSTRATOR. 10.1103/PhysRevC.99.065501

Clark M. Tracing a particle from Event to Result. https://indico.cern.ch/event/846070/timetable/#20200212.detailed


$\beta$-Decay

$(A, Z) \rightarrow (A, Z + 1) + e^- + \bar{\nu}_e$

- Ex: $\beta$-Decay of Tritium

Source: Krane
Germanium Detectors

- Apply potential difference across detector
- Create “depletion region”
- “Extra” electron-hole pairs travel across potential difference

Sources: Knoll, MAJORANA