Neutrinoless Double-Beta Decay and the MAJORANA Experiment

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Outline

- Double-Beta Decay
- The MAJORANA Experiment
- The Initial MAJORANA Module
- Backgrounds and Background Rejections
- Detectors
- Recent Progress and Plans
Two Neutrino Double-Beta Decay

- **An allowed nuclear physics process**
  - Can occur when single $\beta$ decay not allowed
  - Lepton number is conserved
  - Observed in a number of isotopes

\[ 2^{-} \quad _{76}^{2-}\text{As} \]

\[ 0^{+} \quad _{76}^{0^{+}}\text{Ge} \]

\[ \beta \beta \quad Q = 2.039 \text{ MeV} \]

\[ 2^{+} \quad _{76}^{2^{+}}\text{Se} \]

\[ 0^{+} \quad _{76}^{0^{+}}\text{Se} \]
Two Neutrino Double-Beta Decay

- An allowed nuclear physics process
  - Can occur when single $\beta$ decay not allowed
  - Lepton number is conserved
  - Observed in a number of isotopes

\[
\begin{align*}
\text{76 Ge} & \rightarrow 76\, \text{Se} + 2e^- + 2\bar{\nu}_e \\
\text{76 Ge} & \rightarrow 76\, \text{Se} + 2\bar{\nu}_e + 2e^- \\
\end{align*}
\]
Neutrinoless Double-Beta Decay

- No neutrinos emitted
- Discovery provides:
  - Neutrino is own antiparticle (Majorana)
  - Lepton number violation
  - Neutrino mass

\[ 76 \text{Ge} \Rightarrow 76 \text{Se} + 2e^- \]

\[ n \Rightarrow p + e^- + \bar{\nu}_e \quad (RH \bar{\nu}_e) \]

\[ (LH \nu_e) \quad \nu_e + n \Rightarrow p + e^- \]
How to Measure $\beta\beta$

Observe double-beta decay by collecting the energy of the 2 $e^-$ in a detector
How to Measure $\beta\beta$

Observe double-beta decay by collecting the energy of the 2 $e^-$ in a detector

- With 2 neutrino double-beta decay, the electrons share the decay energy with the neutrinos

\[
\frac{dN}{dE} \quad \text{Endpoint} \quad \text{Energy} \\
Q = 2.039 \text{ MeV}
\]
How to Measure $\beta\beta$

Observe double-beta decay by collecting the energy of the 2 $e^-$ in a detector

- With 2 neutrino double-beta decay, the electrons share the decay energy with the neutrinos
- With neutrinoless double-beta decay, the electrons carry the full decay energy

Energy distribution with $2\nu$ and $0\nu$ modes. The endpoint energy $Q=2.039$ MeV.
How $\beta \beta$ Relates to the Neutrino

Measure decay rate of to get neutrino absolute mass scale

$$\Gamma_{0\nu} = G_{0\nu} |M_{0\nu}|^2 \langle m_\nu^2 \rangle$$

- $G$ are calculable phase space factors
- $M$ are nuclear physics matrix elements
  - Hard to calculate
- $m_\nu$ is the effective Majorana mass

Endpoint Energy $Q=2.039$ MeV
A Ge Detector Can Detect $\beta\beta$

Ge detectors are commercially available radiation spectroscopy detectors.
The MAJORANA Approach to $\beta\beta$

Ge crystal
The MAJORANA Approach to $\beta\beta$

Ge crystal

Low mass mount
The **MAJORANA Approach to $\beta\beta$**

- **Ge crystal**
- **Array inside cryostat**
- **Low mass mount**
The MAJORANA Approach to $\beta\beta$

- Ge crystal
- Array inside cryostat
- Shield
- Low mass mount
MAJORANA Favors $^{76}\text{Ge}$

$^{76}\text{Ge}$ offers an excellent combination of capabilities & sensitivities.

- **Ge is the source & detector**
  - maximizes source to total mass ratio
  - Well-understood technologies
  - Excellent energy resolution: 0.16% at 2.039 MeV, 4-keV ROI
    - Advantage for improving signal to background
  - Existing, well-characterized large Ge arrays

- **Demonstrated ability to enrich 7.44% to 86%**

- **Favorable nuclear matrix element**
  - e.g. $<M_{0\nu}> = 3.9$ [Rodin et al. 2005, erratum], 2.6 [Caurier et al. 2007]

- **Slow $2\nu\beta\beta$ rate ($T_{1/2} = 1.4 \times 10^{21} \text{ y}$)**

- **Powerful background rejection technologies**
  - Segmentation, granularity, timing, pulse shape discrimination

- **Best current limit on $0\nu\beta\beta$ used Ge**
  - IGEX & Heidelberg-Moscow $T_{1/2} > 1.9 \times 10^{25} \text{ y}$
Actively pursuing R&D aimed at a \(~1\) tonne scale \(^{76}\text{Ge}\) \(0\nu\beta\beta\)-decay experiment

- Technical Goal: Demonstrate background low enough to justify building a ton-scale experiment
- Science Goal: Build a prototype module to test the recent claim of an observation of \(0\nu\beta\beta\)
- Work cooperatively with the GERDA Collaboration to prepare for a single international ton-scale Ge experiment that combines the best technical features of MAJORANA and GERDA
- Pursue longer term R&D to minimize costs and optimize the schedule for a ton-scale experiment
Goal is to achieve ultra-low backgrounds of less than 1 count per ton of material per year in the Region of Interest (ROI) about the $\beta\beta(0\nu)$ Q-value energy.
Evaluate MAJORANA Design with Initial Module

R&D Reference Design

- **60 kg of Ge crystals**
  - 30 kg of 86% enriched $^{76}\text{Ge}$ crystals
    - to test claim of $0\nu\beta\beta$
  - Additional 30 kg of natural Ge or depleted in $^{76}\text{Ge}$
    - for background sensitivity
- Examine detector technology options
  - Emphasis on p-type point-contact (PPC) detectors,
  - Additional physics with low-energy (~100 eV) threshold

- **Low-background cryostat and shielding**
  - Ultra-clean, electro-formed Cu cryostats
  - Early implementation with first (of 3) cryostat with nat-Ge PPC detectors
  - Compact low-background passive Cu and Pb shield with active muon veto

- **Agreement to locate at 4850’ level (4200 m.w.e) at Sanford Lab/ (future home of DUSEL)**
Prototype Module Probes to 200 meV

- **Expected Sensitivity to $0\nu\beta\beta$**
  - for 30 kg enriched material, running 3 years, or 78 kg-yr of $^{76}\text{Ge}$ exposure
  - $T_{1/2} \geq 1.0 \times 10^{26}$ yr (90\% CL) Sensitivity to $\langle m_\nu \rangle < 140$ meV (90\% CL) [Rod06 erratum] RQRPA NME

![Graph showing sensitivity versus live time](image)
MAJORANA Must Achieve Low Background

The key of the MAJORANA design is the ability to reduce backgrounds to unprecedented levels

- **Advanced Detector Design**
  - allow greater signal processing
  - reduce sensitivity to backgrounds
  - allow multi-dimensional event reconstruction

- **Controlling intrinsic and external backgrounds**
  - Ultra-clean, electro-forming of cryostat and shield
  - Detector purity
Majorana Backgrounds

- **Goal:** ≤1 event / ton-year in 4 keV ROI
- **Backgrounds:**
  - Natural isotope chains: $^{232}$Th, $^{235}$U, $^{238}$U, Rn
  - Cosmic Rays:
    - Activation at surface creates $^{68}$Ge, $^{60}$Co.
    - Hard neutrons from cosmic rays in rock and shield.
      - $(n,n'\gamma)$ in Pb, Ge, Cu
    - $2\nu\beta\beta$-decays.
- **Need factor ~100 reduction over what has been demonstrated.**
- **Monte Carlo estimates of acceptable levels**

Most backgrounds are multi-site. Signal is single-site
MAJORANA Materials

• 2009 campaign to further reduce limits on backgrounds in electroformed Cu (previous best: $\sim0.7 \, \mu \text{Bq/kg}$, addressing bath purity)

• Procuring enough plastic for detector supports, with NAA to follow

• Staged Pb procurement with ICPMS program for shield

• Cables and electronics materials screening

• Enriched Ge
  - UMICORE not interested in processing enriched Ge
  - Fully costed plan to establish a small processing facility in Oak Ridge
  - Collaborator has funding to start an underground crystal pulling lab
Electroforming Cu
Background Rejection Techniques Exist

Pulse Shape Analysis

Single-site event

Multi-site event
Background Rejection Techniques Exist

Pulse Shape Analysis

Single-site event

Multi-site event

Timing Analysis

- $^{68}\text{Ga} \beta^+$ can deposit single-site at Q-value
- Look back in time for X-ray from $^{68}\text{Ge}$

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Detector Design Aids in Background Rejection

Segmentation Analysis

- Multi-site depositions occur over many segments
- Single-site deposition in one segment
Detector Design Aids in Background Rejection

Segmentation Analysis

- Multi-site depositions occur over many segments
- Single-site deposition in one segment
- Proximity of additional detectors pick up escaping events
• An exciting novel P-type Ge detectors design.
• A solid p-type detector: simpler to fabricate, easier handle, instrument, very low capacitance.
• The longer drift distance in the PPC stretches the pulse leading to a clear indication of a multiple site event.
• Advantage of segmented detectors, without extra complexity and backgrounds.
• Low energy threshold permits additional physics applications: e.g. Dark Matter, Axions
P-type Point Contact Detectors

Rising edge “stretched” in time \Rightarrow \text{improved PSD}

Barbeau et al., JCAP 09 (2007) 009
arXiv:0807.0879v4 CoGeNT Collaboration
Segmented N-type Detectors

- Segmented Enriched Germanium Assembly detector
  - Crystal description
    - N-type $^{76}\text{Ge}$ detector (86%)
    - 12 segments - 6 outer X 2 inner
    - Currently in temporary cryostat
      - Segmentation studies
      - Pulse shape analysis techniques
  - Currently electro-forming detector mount components
  - Deploy at WIPP late 2009
Lower Sensitivity - New Backgrounds

Pb excitations

- Specific Pb gamma rays are problematic backgrounds
  - $^{206}\text{Pb}$ has a 2041-keV $\gamma$ ray
  - $^{207}\text{Pb}$ has a 3062-keV $\gamma$ ray
  - $^{208}\text{Pb}$ has a 3060-keV $\gamma$ ray

- The DEP of the ~3062 keV $\gamma$ ray is a single site energy deposit at $\beta\beta$ Q-value

- Neutron interactions in Pb can excite these levels

- Cross sections unknown
Measured gamma-ray production cross sections from a Pb target in a neutron beam at LANSCE

\[ \text{nat} \text{Pb}(n,xn\gamma)^{206}\text{Pb} \ 2041 \text{ keV} \]

\[ \text{nat} \text{Pb}(n,xn\gamma)^{207,208}\text{Pb} \ 3062 \text{ keV} \]

Other cross sections in Cu and Ge being measured

V.E. Guiseppi et al. (2009) PRC 79, 054604

V. E. Guiseppi
Cosmic Activation of Ge

- Some uncertainty in the cosmogenic activation rate of some radionuclides in $^{\text{nat}}$Ge and $^{76}$Ge
- $^{68}$Ge and $^{60}$Co are troublesome internal backgrounds

Activation rate measured by placing a working $^{\text{nat}}$Ge detector in a high-intensity neutron beam (LANSCE)

Fluence [$n \text{ cm}^{-2} \text{ pulse}^{-1} \text{ MeV}^{-1}$]

Flux [$n \text{ cm}^{-2} \text{ s}^{-1} \text{ MeV}^{-1}$]

Energy [MeV]

Cosmic Ray Flux:

Cosmic Activation of $^{\text{nat}}\text{Ge}$

- $\beta^+$ spectrum constructed by tagging on external back-to-back annihilation $\gamma$-rays
Cosmic Activation of $^{76}$Ge

Activation rate measured by placing a $^{76}$Ge sample in a high-intensity neutron beam (LANSCE)

Cosmic Ray Flux:
Recent R&D

- **Design background simulations**
  - Internal front-ends
  - Internal Cu
  - $^{40}$K in plastics
  - New structural components
  - Detector contacts
- **Neutron interaction simulations**
- **Low energy modeling and verification**
- **Detector characterization**
- **Rn deposition on crystal surfaces**
- **Surface alpha background characterization**
- **Spectral shape as a function of source position** *(see arxiv:0902.4370)*

![Graph showing spectral shape as a function of energy](image)
Background modeling
- Simulated major background sources for detector components using MaGe
- Calculated total backgrounds individually for each detector technology under consideration
- Cu purity of ~0.3 Bq/kg is required; sizeable contribution from $^{208}$Tl in the cryostat and shield.
- Higher rejection of segmented designs is roughly balanced by extra readout components.
- P-PC appears to achieve the best backgrounds with minimal readout complexity.
First Sub-Module

• 18 natural-Ge Canberra BEGe’s now being delivered
  - $\phi = 70\pm2.5$ mm, $h = 30\pm2.5$ mm
  - 579 g active mass
  - contact $r < 6.5$ mm (5 mm nom.)
  - Front surface metalized for HV
• 4 to 6 crystals per string
• Front-ends mounted next to the crystal
• Closed cold plate and beefier Cu in detector mounts for added strength
Detector Mounts

- Single detector units that attach to form strings
- HV on outer contact
- Mostly electro-formed Cu with minimal amount of plastics
- Front ends integrated into contact pin; encapsulate in electro-formed Cu for α, β shielding
- Currently iterating design and prototyping
Front End Electronics

Pulse Reset

Resistive Feedback

COGENT front ends (U Chicago)

UW “Hybrid” Design

LBNL Design
String Designs
MAJORANA Lab Space

- Design of underground space at Sanford Lab 4850’ level near Davis Cavity
MAJORANA Lab Space

- Design of underground space level near Davis Cavity

4850 Level, June 22, 2009:
T. Denny Sanford, left,
and South Dakota Gov. Mike Rounds.
(Photo by Bill Harlan, SDSTA)
MAJORANA Demonstrator Schedule

- 2009: Create Lab
- 2010: Purchase $^{nat}\text{Ge}$ PPCs
- 2011: Purchase PPCs
- 2012: Assemble 1st cryostat of PPCs
- 2013: Purchase $^{enr}\text{Ge}$
  - Fabricate $^{enr}\text{Ge}$ dets
  - Assembly of $^{enr}\text{Ge}$ sub-modules
MAJORANA Status

• Support: As a R&D Project by DOE Nuclear Physics & NSF Particle and Nuclear Astrophysics

• Progress towards Demonstrator Module
  - Much design work and prototyping in progress

  - UG clean room laboratory space preparations are proceeding, initial installations in 2009/2010 at Sanford Laboratory (Homestake gold mine, Lead, SD).

  - UG Electroforming facility will be initial focus due to required time to prepare Cu parts of shield.

  - Primary focus on deployment of first demonstrator sub-module cryostat with point-contact detectors.

  - Working with industrial partner to develop Ge refinement process that could be located either near detector fabrication facility or UG.
**Majorana & Gerda**

**Majorana**
- Modules of $^{enr}\text{Ge}$ housed in high-purity electroformed copper cryostat
- Shield: electroformed copper and lead
- Initial phase: R&D Demonstrator module - 60kg (30 kg enriched)

**Gerda**
- Bare $^{enr}\text{Ge}$ in liquid Argon
- Shield: high-purity Argon/H$_2$O
- Phase I: $\sim$18 kg (HdM/IGEX crystals)
- Phase II: add $\sim$20kg new detectors
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Note: Red text indicates students