The Majorana $0\nu\beta\beta$-decay Experiment

- Advantages of $^{76}$Ge
- 180 kg Majorana Overview
- Sensitivity Goals
- Reduction of Backgrounds
- Summary

J.F. Wilkerson on behalf of the Majorana Collaboration

June 23, 2005

INT Underground Science Workshop
The Majorana Collaboration

Brown University, Providence, Rhode Island
Michael Attisha, Rick Gaitskell, John-Paul Thompson

Institute for Theoretical and Experimental Physics, Moscow, Russia
Alexander Barabash, Sergey Konovalov, Igor Vanushin, Vladimir Yumatov

Joint Institute for Nuclear Research, Dubna, Russia

Lawrence Berkeley National Laboratory, Berkeley, California
Yuen-Dat Chan, Mario Cromaz, Martina Descovich, Paul Fallon, Brian Fujikawa, Bill Goward, Reyco Henning, Donna Hurley, Kevin Lesko, Paul Luke, Augusto O. Macchiavelli, Akbar Mokhtarani, Alan Poon, Gersende Prior, Al Smith, Craig Tull

Lawrence Livermore National Laboratory, Livermore, California
Dave Campbell, Kai Vetter

Los Alamos National Laboratory, Los Alamos, New Mexico

Oak Ridge National Laboratory, Oak Ridge, Tennessee
Cyrus Baktash, Jim Beene, Fred Bertrand, Thomas V. Cianciolo, David Radford, Krzysztof Rykaczewski

Osaka University, Osaka, Japan
Hiroyasu Ejiri, Ryuta Hazama, Masaharu Nomachi

Pacific Northwest National Laboratory, Richland, Washington

Queen's University, Kingston, Ontario
Marie Di Marco, Aksel Hallin, Art McDonald

Triangle Universities Nuclear Laboratory, Durham, North Carolina and Physics Departments at Duke University and North Carolina State University
Henning Back, James Esterline, Mary Kidd, Werner Tornow, Albert Young

University of Chicago, Chicago, Illinois
Juan Collar

University of South Carolina, Columbia, South Carolina
Frank Avignone, Richard Creswick, Horatio A. Farach, Todd Hossbach, George King

University of Tennessee, Knoxville, Tennessee
William Bugg, Yuri Efremenko

University of Washington, Seattle, Washington
John Amsbaugh, Tom Burritt, Jason Detwiler, Peter J. Doe, Joe Formaggio, Mark Howe, Rob Johnson, Kareem Kazkaz, Michael Marino, Sean McGee, Dejan Nilic, R. G. Hamish Robertson, Alexis Schubert, John F. Wilkerson

Note: Red text indicates students
To measure extremely rare decay rates ($T_{1/2} \sim 10^{26} - 10^{27}$ years) Majorana utilizes:

- Large, highly efficient source mass of enriched $^{76}$Ge
- Extremely low (near-zero) backgrounds in the $0\nu\beta\beta$ peak region-of-interest (ROI) (1 count/t-y)
  - Requires ultra-clean materials & sophisticated discrimination techniques
- Best possible energy resolution ($0.16\%, 4$ keV ROI)
  - Minimize $0\nu\beta\beta$ peak ROI to maximize S/B
  - Separate $2\nu\beta\beta/0\nu\beta\beta$
Advantages for Majorana

\(^{76}\text{Ge}\) offers the best combination of capabilities and sensitivities. Majorana is ready to proceed, with demonstrated technologies.

- Favorable nuclear matrix element \(<M^{0\nu}> = 2.4\) [Rod05].
- Reasonably slow \(^{2}\nu\beta\beta\) rate (\(T_{1/2} = 1.4 \times 10^{21}\) y).
- Demonstrated ability to enrich from 7.44% to 86%.
- Ge as source & detector.
- Elemental Ge maximizes the source-to-total mass ratio.
- Intrinsic high-purity Ge diodes.
- Excellent energy resolution — 0.16% at 2.039 MeV, for a ROI of 4 keV.
- Powerful background rejection. Segmentation, granularity, timing, pulse shape discrimination
- Best limits on \(^{0}\nu\beta\beta\) - decay used Ge (IGEX & Heidelberg-Moscow) \(T_{1/2} > 1.9 \times 10^{25}\) y (90%CL)
- Well-understood technologies
  - Commercial Ge diodes
  - Existing, well-characterized large Ge arrays (Gammasphere)
The Majorana Scientific Goals

Search for neutrinoless double-beta decay in $^{76}\text{Ge}$

- Definitively test the Klapdor claim in the 400 meV region.
- Probe the quasi-degenerate neutrino mass region of 100 meV.
- Demonstrate backgrounds that would justify scaling up to a 1-ton or larger detector.
The Majorana 180 kg Experiment Overview

The 180 kg Experiment (M180)
- Reference Design
  - 171 segmented, n-type, 86% enriched $^{76}$Ge crystals.
  - 3 independent, ultra-clean, electroformed Cu cryostat modules.
  - Enclosed in a low-background passive shield and active veto.
  - Located deep underground (6000 mwe).
- Background Specification in the $0\nu\beta\beta$ peak ROI
  1 count/t-y
- Expected Sensitivity to $0\nu\beta\beta$
  (for 3 years, or 0.46 t-y of $^{76}$Ge exposure)
  $T_{1/2} \geq 5.5 \times 10^{26}$ y (90% CL)
  $<m_\nu> < 100$ meV (90% CL) ([Rod05] RQRPA matrix elements)
  or a 10% measurement assuming a 400 meV value.

Majorana is scalable, allowing expansion to 1000 kg.
The Majorana Modular Approach

- **57 crystal module**
  - Conventional vacuum cryostat made with electroformed Cu.
  - Three-crystal stack are individually removable.

![Diagram of Majorana modular approach](image)

- Vacuum jacket
- Cold Plate
- Cold Finger
- 1.1 kg Crystal
- Thermal Shroud
- Bottom Closure
- Cap
- Tube (0.007” wall)
- Ge (62mm x 70 mm)
- Tray (Plastic, Si, etc)

1 of 19 crystal stacks
The Majorana Shield - Conceptual Design

- Allows modular deployment, early operation
- Contains up to eight 57-crystal modules
  (M180 populates 3 of the 8 modules)
- Four independent, sliding units
- 40 cm bulk Pb, 10 cm ultra-low background shield
- Active $4\pi$ veto detector
Sensitivity and Background Specifications

- Sensitivity to $0\nu\beta\beta$ decay is ultimately limited by Signal-to-Background.
- Our specification for backgrounds is $1 \text{ cnt/} t\cdot y$ in the $0\nu\beta\beta$ ROI. The specification is based on existing assay limits plus demonstrated techniques for impurity reduction.

<table>
<thead>
<tr>
<th>Bkg Location</th>
<th>Purity Issue</th>
<th>Target Exposure</th>
<th>Activation Rate Spec.</th>
<th>Demonstrated Rate</th>
<th>Ref.</th>
</tr>
</thead>
<tbody>
<tr>
<td>Ge Crystals</td>
<td>$^{68}\text{Ge}$ &amp; $^{60}\text{Co}$</td>
<td>100 d</td>
<td>1 atom/kg/d</td>
<td>1 atom/kg/d</td>
<td>[Avi92]</td>
</tr>
<tr>
<td>Inner Mount</td>
<td>Target Mass</td>
<td>Target Purity Spec.</td>
<td>Achieved Assay</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Cryostat</td>
<td>$^{232}\text{Th}$ in Cu</td>
<td>2 kg</td>
<td>1 $\mu$Bq/kg</td>
<td>&lt;8 $\mu$Bq/kg</td>
<td>2-4 $\mu$Bq/kg</td>
</tr>
<tr>
<td>Cu Shield</td>
<td>38 kg</td>
<td>310 kg</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Small Parts</td>
<td>1 g/crystal</td>
<td>1 mBq/kg</td>
<td>1 mBq/kg</td>
<td>1 mBq/kg</td>
<td>[Mil92]</td>
</tr>
</tbody>
</table>

Simulation connects activity to expected count rate

1 $\mu$Bq/kg of $^{232}\text{Th}$ in Cu is 0.25 pg/g Th
Majorana M180 Sensitivity vs. Background

\[ T_{1/2} = \frac{\ln(2)}{\sqrt{B}} \times eNt = \frac{\ln(2)}{\sqrt{B}} \times e \alpha \frac{A_0}{W} M \times t \]

\[ \langle m_\nu \rangle \propto (T_{1/2})^{-1/2} \propto B^{1/4} \]

\[ \langle m_\nu \rangle = \text{of} \]

100 meV

[Rod05]
KKDC used five $^{76}$Ge crystals, with a total of 10.96 kg of mass, and 71 kg-years of data.

$$T_{1/2} = 1.2 \times 10^{25} \text{ y}$$

$$0.24 < m_{\nu} < 0.58 \text{ eV} \ (3 \text{ sigma})$$

Background level depends on intensity fit to other peaks.

**Expected signal in Majorana**

(for 0.46 t-\(\text{y}\))

135 counts

With a background of

Specification: < 1 total count in the ROI

(Demonstrated < 8 counts in the ROI)
Reducing Backgrounds - Two Basic Strategies

• Directly reduce intrinsic, extrinsic, & cosmogenic activities
  - Select and use ultra-pure materials
  - Minimize all non “source” materials
  - Clean passive shield
  - Go deep — reduced μ’s & related induced activities

• Utilize background rejection techniques
  - Energy resolution
  - Active veto detector
    • $0\nu\beta\beta$ is a single site phenomenon
    • Many backgrounds have multiple site interactions
  - Granularity [multiple detectors]
  - Pulse shape discrimination (PSD)
  - Single Site Time Correlated events (SSTC)
  - Segmentation
Cuts vs. Background Estimates

2039 keV peak plus cuts discriminates $0\nu\beta\beta$-decay from backgrounds

Only known activities that occur at 2039 keV are from very weak branches, with corresponding strong peaks that will appear elsewhere in the spectrum.

<table>
<thead>
<tr>
<th>0$\nu\beta\beta$ signal</th>
<th>Backgrounds</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Counts / ROI / ty</strong></td>
<td><strong>Counts / ROI / ty</strong></td>
</tr>
<tr>
<td>Raw 0$\nu\beta\beta$</td>
<td>Raw</td>
</tr>
<tr>
<td>Final 0$\nu\beta\beta$</td>
<td>Granularity</td>
</tr>
<tr>
<td></td>
<td>PSD</td>
</tr>
<tr>
<td></td>
<td>SSTC</td>
</tr>
<tr>
<td></td>
<td>Segmentation</td>
</tr>
</tbody>
</table>

**For $T_{1/2} = 3 \times 10^{26}$ y**
## Estimated backgrounds in the $0\nu\beta\beta$-decay ROI

<table>
<thead>
<tr>
<th>Background Source</th>
<th>Gross and Net Rates for Important Isotopes</th>
<th>Total Est. Background (per t·y)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Counts in ROI per t·y</td>
<td>Counts in ROI</td>
</tr>
<tr>
<td></td>
<td>$^{68}\text{Ge}$</td>
<td>$^{60}\text{Co}$</td>
</tr>
<tr>
<td>Germanium (100 day exp)</td>
<td>Gross 2.54</td>
<td>1.22</td>
</tr>
<tr>
<td></td>
<td>Net 0.01</td>
<td>0.02</td>
</tr>
<tr>
<td></td>
<td>$^{208}\text{TI}$</td>
<td>$^{214}\text{Bi}$</td>
</tr>
<tr>
<td>Inner Mount</td>
<td>Gross 0.12</td>
<td>0.03</td>
</tr>
<tr>
<td></td>
<td>Net 0.01</td>
<td>0.00</td>
</tr>
<tr>
<td></td>
<td>Gross 0.77</td>
<td>0.16</td>
</tr>
<tr>
<td></td>
<td>Net 0.22</td>
<td>0.04</td>
</tr>
<tr>
<td></td>
<td>Gross 2.28</td>
<td>0.30</td>
</tr>
<tr>
<td></td>
<td>Net 0.64</td>
<td>0.06</td>
</tr>
<tr>
<td></td>
<td>Gross 0.18</td>
<td>0.04</td>
</tr>
<tr>
<td></td>
<td>Net 0.02</td>
<td>0.01</td>
</tr>
<tr>
<td>External Sources (6000 mwe)</td>
<td>Gross 0.03</td>
<td>1.33</td>
</tr>
<tr>
<td></td>
<td>Net 0.003</td>
<td>0.18</td>
</tr>
<tr>
<td>$2\nu\beta\beta$-decay</td>
<td>&lt; 0.01</td>
<td></td>
</tr>
<tr>
<td>TOTAL SUM</td>
<td>1.21</td>
<td></td>
</tr>
</tbody>
</table>

- "Gross" indicates level of activity before any analysis cuts are applied.
- "Net" indicates level of activity after cuts have been applied.

*Crystals are clean*

*Dominated by $^{232}\text{Th}$ in Cu*

*Must go deep*
At Sudbury depth, 6000 mwe, calculate that about 15-20% of the expected background in the ROI will be from $\mu$ induced activities in Ge and the nearby cryostat materials (dominated by fast neutrons).

Hime and Mei 2005
Demonstrating Backgrounds

- **Simulations**
  - MaGe — GEANT4 based development package
    - being developed in cooperation with GERDA
  - Verified against a variety of Majorana low-background counting systems as well as others, e.g. MSU Segmented Ge, GERDA.
  - Fluka for μ-induced calculations, tested against UG lab data.

- **Assay**
  - Radiometric (Current sensitivity ~8 μBq/kg (2 pg/g) for $^{232}$Th)
    - Counting facilities at PNNL, Oroville (LBNL), WIPP, Soudan, Sudbury.
  - Mass Spect. (Current sensitivity 2-4 μBq/kg (0.5-1 pg/g) for $^{232}$Th)
    - Using Inductively Coupled Plasma Mass Spectrometry, have made recent progress on using $^{229}$Th tracer.
    - ICPMS has the requisite sensitivity (fg/g).
    - Present limitations on reagents being addressed by sub-boiling distillation.
    - ICPMS expected to reach needed 1 μBq/kg sensitivity.

- **Key specifications**
  - Cu at 1 μBq/kg (current ≤ 8 μBq/kg)
  - cleanliness on a large scale (100 kg)
Producing Ultra-Pure Cu

- **Constructed electroformed Cu cryostat**
  - 30 cm dia x 30 cm high
  - Vacuum tested
- **Th chain purity in Cu is key**
  - Ra and Th must be eliminated
  - Remove Ra, Th by ion exchange during electroforming
  - Starting stock <9 $\mu$Bq/kg $^{232}$Th
- **Using $^{229}$Th tracer, demonstrated a factor of > 8000 Th rejection via electroforming**

We expect to achieve the 1 $\mu$Bq/kg $^{232}$Th specification
Background reduction at the larger scale

- The collaboration has groups experienced with building 2-10 kg level $0\nu\beta\beta$ decay experiments: IGEX, ELEGANT, NEMO, $^{82}$Se
- The collaboration has groups experienced with building low-background, large-scale detectors underground: SNO, KamLAND, SAGE
- SNO Acrylic Sphere, 30 t, 120 segments, < 2 $\mu$Bq/kg $^{232}$Th

- SNO Neutral Current Detector
  Array of $^3$He proportional counters
  - 450 kg of material
  - 300 detector segments
  - Activity 100 - 1000 x cleaner than best previous counters
  - Activity $\leq$ 5 $\mu$Bq/kg $^{232}$Th
Array Granularity  

- **detector-to-detector rejection**

- Simultaneous signals in two detectors cannot be $0\nu\beta\beta$
- Requires tightly packed Ge
- Successful against:
  - $^{208}$Tl and $^{214}$Bi
    - Supports/small parts (~5x)
    - Cryostat/shield (~2x)
  - Some neutrons
  - Muons (~10x)
- Simulation and validation with Clover

Granularity is basically free and a powerful background suppressor.

The Majorana Experiment  

June 23, 2005  
INT Underground Science Workshop
Background reduction - Crystal Segmentation

- **Segmentation**
  - Multiple conductive contacts
  - Additional electronics and small parts
  - Rejection greater for more segments

- **Background discrimination**
  - Multi-site energy deposition
    - Simple two-segment rejection
    - Sophisticated multi-segment signal processing can provide 2 mm reconstruction of events

- **Demonstrated**
  (Note: reference plan has 2 segments)
  - MSU experiment (4x8 segments)
  - LANL Clover detector (2 segments)
  - LLNL+LBNL detector (8x5 segments)
Experiment with MSU/NSCL Segmented Ge Array

- N-type, 8 cm long, 7 cm diameter
- 4x8 segmentation scheme: 4 angular 90 degrees each, 8 longitudinal, 1 cm each
- $^{60}$Co source
- Segmentation successfully rejects backgrounds.
- Data are in good agreement with the simulations
Pulse Shape Discrimination (PSD)

Central contact (radial) PSD

- Excellent rejection for internal $^{68}$Ge and $^{60}$Co (x4)
- Moderate rejection of external 2615 keV (x0.8)
- Shown to work well with segmentation
- Demonstrated capability
  - central contact
  - outer contacts

PSD uses off-the-shelf waveform digitizers
We have data that demonstrates the hypothesis that the PSD and segmentation cuts are independent.

Clover detector

Th source

\[ ^{228}\text{Ac} \ \gamma \]

\[ ^{208}\text{Tl} \text{ double escape} \]
Background reduction - Time Correlations

- $^{68}$Ge is worst initial raw background
  - $^{68}$Ge $\rightarrow$ 10.367 keV x-ray, 95% eff
  - $^{68}$Ga $\rightarrow$ 2.9 MeV beta
- Cut for 3–5 half-lives after signals in the 11 keV X-ray window reduces $^{68}$Ga $\beta$ spectrum substantially
- Independent of other cuts

SSTC is powerful against our largest raw background, $^{68}$Ge.
Proposed Schedule

<table>
<thead>
<tr>
<th>Year</th>
<th>Event Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>2005</td>
<td>Proposal/CD-0 Package</td>
</tr>
<tr>
<td>2006</td>
<td>R&amp;D Module</td>
</tr>
<tr>
<td>2007</td>
<td>Conceptual Design</td>
</tr>
<tr>
<td>2008</td>
<td>Site Selection</td>
</tr>
<tr>
<td>2009</td>
<td>R&amp;D Module</td>
</tr>
<tr>
<td>2010</td>
<td>Pre-Operational Testing</td>
</tr>
<tr>
<td>2011</td>
<td>Full Detector Operations</td>
</tr>
<tr>
<td>2012</td>
<td>Decommissioning</td>
</tr>
<tr>
<td>2013</td>
<td>M180 Operating Phase</td>
</tr>
<tr>
<td>2014</td>
<td></td>
</tr>
<tr>
<td>2015</td>
<td></td>
</tr>
<tr>
<td>2016</td>
<td></td>
</tr>
</tbody>
</table>

Notes:
- CD-1: Review Mission Need
- CD-2,3,5: Approve Baseline, Long Lead Procurement
- CD-3: Start Construction
- CD-4: Start of Operations
- CD-5: Pre-Operational Testing
- CD-6: Operations
- CD-7: M180 Operating Phase
- CD-8: Enriched Ge
- CD-9: 1st 60 kg running
- CD-10: 2nd 60 kg running
- CD-11: 3rd 60 kg running
Majorana Sensitivity: Realistic runtime

$$<m_v>\text{ of } 100 \text{ meV}$$

[Rod05]
Majorana Summary

- The Majorana 180 kg experiment satisfies the APS Multi-Divisional Goals for probing the quasi-degenerate neutrino mass region.
- The Majorana design is scalable to the 500-1000 kg level.
- Compared to best previous $0\nu\beta\beta$ experiments, M180
  - has 18 times more Ge
  - 8 times lower radioactivity
  - Improved design and detector technology should yield 30 times better background rejection.
- We are confident we can reach a lifetime limit of $5.5 \times 10^{26}$ y (90% CL) corresponding to a neutrino mass of 100 meV or perform a 10% measurement assuming a 400 meV value.
- Awaiting the νSAG Committee Report.