NSAC Subcommittee

Double Beta Decay Overview

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$2\nu\beta\beta$ Decay

Bethe-Von Weizsacker semi-empirical mass relation

$$M(A, Z) = Zm_p + (A - Z)m_n - a_v A + a_s A^{2/3} + a_c Z^2 A^{-2/3} + a_a (A - 2Z)^2 A^{-1} + \delta$$

$$\delta = -a_p A^{-3/4} \text{ (even, even)} \text{ or } +a_p A^{-3/4} \text{ (odd, odd)} \text{ or } 0 \text{ (even, odd)}$$

$$a_p \rightarrow 33.5 \text{ MeV}$$
If $0\nu\beta\beta$ occurs then the neutrino is a Majorana particle and the neutrino and antiparticle are not distinct. Lepton number is not conserved!
Experimental Signal of Double Beta Decay

\[ \frac{dN}{dE} \approx E(Q - E)^5 \left(1 + 2E + \frac{4E^2}{3} + \frac{E^3}{3} + \frac{E^4}{30}\right) \]

\[ \Gamma_{0v} = G_{0v}(Q,Z) |M_{\text{nucl}}|^2 <m_{\beta\beta}>^2 \]
Higgs Boson, Majorana Mass and Lepton Number Conservation
A Theorem

(Schechter and Valle)
First direct detection of $2\nu\beta\beta$

$^{82}\text{Se}$, 35 events

$NEMO$ 3 (Phase I)
$^{82}\text{Se}$
$0.993$ kg·y
$2,750$ $\beta\beta$ events
$S/B = 4$
A search for lepton non-conservation in double beta decay with a germanium detector

Fig. 1. Experimental setup.

$^{76}$Ge

$\geq 3 \times 10^{20}$ years

Limits for lepton-conserving and lepton-nonconserving double beta decay in $^{48}$Ca

$^{48}$Ca

$\geq 2 \times 10^{20}$ years
Claimed Observation of $0\nu\beta\beta$ in $^{76}\text{Ge}$

5 detectors of overall 10.96 kg enriched to 86%. Most sensitive to date.

$T_{1/2} = (0.67 - 4.45) \times 10^{25}$ years (99.73% C.L.)

Majorana $\nu$ Mass

$\langle m_{\beta\beta} \rangle = (0.1 - 0.9)$ eV (99.73% C.L.)

$\langle m_{\beta\beta} \rangle_{\text{best}} = 0.45$ eV
\[ \Gamma_{0\nu} = G_{0\nu}(Q,Z) |M_{\text{nucl}}|^2 \langle m_{\beta\beta} \rangle^2 \]

\[ \langle m_{\beta\beta} \rangle = \sum_{i=1}^{3} |U_{ei}|^2 m_i \varepsilon_i \]

\[ U = \begin{pmatrix} U_{e1} & U_{e2} & U_{e3} \\ U_{\mu1} & U_{\mu2} & U_{\mu3} \\ U_{\tau1} & U_{\tau2} & U_{\tau3} \end{pmatrix} \]

\[ = \begin{pmatrix} 1 & 0 & 0 \\ 0 & \cos\theta_{23} & \sin\theta_{23} \\ 0 & -\sin\theta_{23} & \cos\theta_{23} \end{pmatrix} \times \begin{pmatrix} \cos\theta_{13} & 0 & e^{-i\delta_{CP}} \sin\theta_{13} \\ 0 & 1 & 0 \\ -e^{i\delta_{CP}} \sin\theta_{13} & 0 & \cos\theta_{13} \end{pmatrix} \times \begin{pmatrix} \cos\theta_{12} & \sin\theta_{12} & 0 \\ -\sin\theta_{12} & \cos\theta_{12} & 0 \\ 0 & 0 & 1 \end{pmatrix} \times \begin{pmatrix} 1 & 0 & 0 \\ 0 & e^{i\alpha/2} & 0 \\ 0 & 0 & e^{i\alpha/2 + i\beta} \end{pmatrix} \]
Neutrino Mass Hierarchy

\[ \Delta m_{\text{atm}}^2 \]

\[ m_\nu > 40 \text{ meV} \]

\[ \Delta m_{\odot}^2 \]

\[ m_\nu > 8 \text{ meV} \]
Experimental Sensitivity

\[ F_N \propto \varepsilon \frac{a}{A} \left[ \frac{MT}{B\Gamma} \right]^{1/2} \]

- Isotopic fraction
- Detector efficiency
- Detector Mass
- Running time
- Atomic mass
- Background
- Detector resolution

\[ \left\langle m_{\beta\beta} \right\rangle \propto 1 / \sqrt{T_{1/2}^{0\nu}} \propto 1 / (MT)^{1/2} \]

- Background Free

\[ \left\langle m_{\beta\beta} \right\rangle \propto 1 / \sqrt{T_{1/2}^{0\nu}} \propto 1 / (MT)^{1/4} \]

- With Background
Guide to selecting an experiment

\[ \Gamma_{0\nu} \sim G_{0\nu}(Q,Z) |M_{\text{nucl}}|^2 \]

**Natural Isotopic Abundance**

**Q-value**

**Nuclear Matrix Element**
• We recommend, as a high priority, that a phased program of sensitive searches for neutrinoless nuclear double beta decay be initiated as soon as possible.
Cuoricino

Total detector mass: $40.7 \text{ Kg} \Rightarrow 11.64 \text{ Kg}^{130}\text{Te}$

11 modules, 4 detector each
- Crystal dimension: $5x5x5 \text{ cm}^3$
- Crystal mass: $790 \text{ g}$
- $44 \times 0.79 = 34.76 \text{ Kg of TeO}_2$

2 modules x 9 crystals each
- Crystal dimension: $3x3x6 \text{ cm}^3$
- Crystal mass: $330 \text{ g}$
- $9 \times 2 \times 0.33 = 5.94 \text{ Kg of TeO}_2$
  - (2 enriched in $^{128}\text{Te} @ 82.3\%$)
  - (2 enriched in $^{130}\text{Te} @ 75\%$)
Cuoricino

TOTAL EXPOSURE
19.75 [kg(^{130}\text{Te}) yr]

$Q$-value =
2527.518 ± 0.013 keV

90% C.L.
$t_{1/2} > 2.8 \times 10^{24}$ [yr]

$<m_{\beta\beta}> < 0.3 - 0.7$ eV
For the region of degenerate neutrino masses, NuSAG recommends the following implementation strategy for the specific experiments. The following three experiments, listed in alphabetical order, have the highest priority for funding:

- **CUORE**: The CUORE $^{130}$Te experiment has potential for good energy resolution and low background, provided the technology develops as planned. The high natural abundance of $^{130}$Te results in a relatively low cost for a detector sensitive to the degenerate neutrino mass region. The cost of enriched $^{130}$Te needed to extend the sensitivity is lower than for some other isotopes. The schedule presented by CUORE is timely. The panel is concerned that the requested budget share is not commensurate with the U.S. involvement in the project.

- **EXO**: The EXO-200 $^{136}$Xe experiment is presently under construction and should continue to be supported. R&D for barium tagging is a priority as a step to a one ton scale $0\nu\beta\beta$ experiment. If barium tagging is successful, EXO may offer a unique and cost effective approach to a one ton or larger experiment.

- **Majorana**: The excellent background rejection achieved from superior energy resolution in past $^{76}$Ge experiments must be extended using new techniques. The panel notes with interest the communication between the Majorana and GERDA $^{76}$Ge experiments which are pursuing different background suppression strategies. The panel supports an experiment of smaller scope than Majorana-180 that will allow verification of the projected performance and achieve scientifically interesting physics sensitivity, including confirmation or refutation of the claimed $^{76}$Ge signal. A larger $^{76}$Ge experiment is a good candidate for a larger international collaboration due to the high cost of the enriched isotope.
**$^{0}\beta\beta_{\nu}$ Experiments**

<table>
<thead>
<tr>
<th>Experiment</th>
<th>Isotope</th>
<th>Mass</th>
<th>Technique</th>
<th>Present Status</th>
<th>Location</th>
</tr>
</thead>
<tbody>
<tr>
<td>CANDLES</td>
<td>$^{48}$Ca</td>
<td>1 ton</td>
<td>$^{48}$Ca scint. crystals</td>
<td>Prototype - 2009</td>
<td>Kamioka</td>
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<tr>
<td>CARVEL</td>
<td>$^{48}$Ca</td>
<td>183 kg</td>
<td>$^{48}$Ca scint. crystals</td>
<td>Development</td>
<td>Solotvina</td>
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<td>COBRA</td>
<td>$^{116}$Cd</td>
<td>11 kg</td>
<td>$^{150}$Te, Cd CZT semicond. det.</td>
<td>Prototype</td>
<td>Gran Sasso</td>
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<tr>
<td>CUORICINO</td>
<td>$^{136}$Te</td>
<td>200 kg</td>
<td>$^{136}$Te, TeO$_2$ bolometers</td>
<td>Complete - 2008</td>
<td>Gran Sasso</td>
</tr>
<tr>
<td>CUORE</td>
<td>$^{136}$Te</td>
<td>20 kg</td>
<td>$^{136}$Nd foils and tracking</td>
<td>Construction - 2012</td>
<td>Gran Sasso</td>
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<tr>
<td>DCBA</td>
<td>$^{150}$Ne</td>
<td>20 kg</td>
<td></td>
<td>Development</td>
<td>Kamioka</td>
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<tr>
<td>EXO-200</td>
<td>$^{136}$Xe</td>
<td>160 kg</td>
<td>Liquid $^{136}$Xe TPC/scint.</td>
<td>Construction - 2009</td>
<td>WIPP</td>
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<tr>
<td>EXO</td>
<td>$^{136}$Xe</td>
<td>1-10 t</td>
<td>Liquid $^{136}$Xe TPC/scint.</td>
<td>Proposal</td>
<td>DUSEL</td>
</tr>
<tr>
<td>GEM</td>
<td>$^{76}$Ge</td>
<td>1 ton</td>
<td>$^{76}$Ge det. in liq. nitrogen</td>
<td>Inactive</td>
<td></td>
</tr>
<tr>
<td>GENIUS</td>
<td>$^{76}$Ge</td>
<td>1 ton</td>
<td>$^{76}$Ge det. in liq. nitrogen</td>
<td>Inactive</td>
<td></td>
</tr>
<tr>
<td>GERDA</td>
<td>$^{76}$Ge</td>
<td>$\approx$35 kg</td>
<td>$^{76}$Ge semicond. det.</td>
<td>Construction - 2009</td>
<td>Gran Sasso</td>
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<tr>
<td>GSO</td>
<td>$^{160}$Gd</td>
<td>2 ton</td>
<td>Gd$_2$SiO$_5$:Ce crys. scint. in liq. scint.</td>
<td>Development</td>
<td></td>
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<tr>
<td>KamLAND</td>
<td>$^{136}$Xe</td>
<td>400 kg</td>
<td>$^{136}$Xe dissolved in liq. scint.</td>
<td>Construction - 2012?</td>
<td>Kamioka</td>
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<tr>
<td>MAJORANA</td>
<td>$^{76}$Ge</td>
<td>26 kg</td>
<td>$^{76}$Ge semicond. det.</td>
<td>Construction - 2011</td>
<td>SUL</td>
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<tr>
<td>MOON</td>
<td>$^{100}$Mo</td>
<td>1 t</td>
<td>$^{76}$Ge semicond. det.</td>
<td>Development</td>
<td>Canfranc</td>
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<tr>
<td>NEXT</td>
<td>$^{136}$Xe</td>
<td>80 kg</td>
<td>$^{100}$Mo foil/scint. gas TPC</td>
<td>Development</td>
<td>SNO Lab</td>
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<tr>
<td>SNO+</td>
<td>$^{150}$Nd</td>
<td>55 kg</td>
<td>$^{136}$Xe, Nd loaded liq. scint.</td>
<td>Construction - 2011</td>
<td>Frejus</td>
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<tr>
<td>SuperNEMO</td>
<td>$^{82}$Se</td>
<td>100 kg</td>
<td>$^{82}$Se foils/tracking</td>
<td>Proposal</td>
<td></td>
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<td>Xe</td>
<td>$^{136}$Xe</td>
<td>1.56 t</td>
<td>$^{136}$Xe in liq. scint.</td>
<td>Development</td>
<td></td>
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<tr>
<td>XMASS</td>
<td>$^{136}$Xe</td>
<td>10 ton</td>
<td>Liquid Xe</td>
<td>Inactive for $^{0}\beta\beta_{\nu}$</td>
<td>Kamioka</td>
</tr>
<tr>
<td>HPXe</td>
<td>$^{136}$Xe</td>
<td>tons</td>
<td>High Pressure Xe gas</td>
<td>Development</td>
<td></td>
</tr>
</tbody>
</table>
Experiments that can confront the existing claims about $0\nu\beta\beta$

<table>
<thead>
<tr>
<th>Experiment</th>
<th>Mass</th>
<th>Plan</th>
</tr>
</thead>
<tbody>
<tr>
<td>CUORE0</td>
<td>~10 Kg</td>
<td>2012</td>
</tr>
<tr>
<td>CUORE</td>
<td>~200 Kg</td>
<td>2014</td>
</tr>
<tr>
<td>EXO-200</td>
<td>~200 Kg</td>
<td>2011</td>
</tr>
<tr>
<td>GERDA I/II</td>
<td>~34 Kg</td>
<td>2011/2013</td>
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<tr>
<td>KamLAND-Zen</td>
<td>~300 Kg</td>
<td>2012</td>
</tr>
<tr>
<td>MAJORANA</td>
<td>~30 Kg</td>
<td>2013</td>
</tr>
<tr>
<td>NEXT</td>
<td>~100 Kg</td>
<td>2014</td>
</tr>
<tr>
<td>SNO+</td>
<td>~60 Kg</td>
<td>2013</td>
</tr>
<tr>
<td>SuperNEMO</td>
<td>~7 Kg</td>
<td>2013</td>
</tr>
</tbody>
</table>
Recent results from $^{136}\text{Xe}$
CUORE
Cryogenic Underground Observatory for Rare Events
CUORE Bolometer

TeO$_2$ Bolometer: Source = Detector

Heat sink: $\sim$8 mK
Thermal coupling: Teflon
Absorber: TeO$_2$ crystal
Thermometer: NTD Ge thermistor

![CUORE Bolometer diagram]

![Graph showing time (msec) vs. amplitude]
CUORE and CUORE0

**Single tower:**
52 5x5x5 cm$^3$ crystals

**CUORE0:**
A single tower of CUORE in the Cuoricino cryostat

**CUORE:**
19 towers of 52 crystals each in a specially designed cryostat and $^3$He-$^4$He dilution refrigerator
Sensitivity of CUORE0 and CUORE

Live time [y] vs. Sensitivity $\sigma_{[y]}^{1/2}$

- Cuoricino
- CUORE-0 - bkg: 0.05 cts/(keV kg y)
- CUORE - bkg: 0.01 cts/(keV kg y)

$T_{1/2}^{0\nu}$ [y] $\sigma$ Sensitivity

- $10^{25}$
- $10^{26}$
EXO - Enriched Xenon Observatory

$^{136}\text{Xe} \rightarrow ^{136}\text{Ba}^{++} + 2 \text{e}^- \quad (Q = 2.4 \text{ MeV})$

- LXe time projection chamber (TPC) with liquid $^{136}\text{Xe}$
- Eventual Ba tagging
The TPC

- Cylindrical Cu vessel (1.37 mm wall thickness), 110 kg of liquid Xenon (enriched to 80.6% $^{136}$Xe) in active volume. 175 kg Xe are in liquid phase.
- HV cathode in the middle. 2D event reconstruction by crossed wires. Third coordinate from time.
- Light read-out via 234 avalanche photodiodes per side.
  → This design allows full 3-dim event reconstruction.

Active background rejection in EXO-200:
- 3D tracking discriminates single from multi site events ($\beta/\gamma$).
- Ratio of charge and scint. signals discriminates $\alpha$ from $\beta/\gamma$.
- Position sensitivity finds decays on electrodes and walls.

EXO-200

Scintillation: 6.8%
Ionization: 3.4%
Combined: 1.6%
(at 2615 keV gamma line)
No peak observed at \( Q_{\beta\beta} \).

Use the same background model to construct a limit for peak at \( Q_{\beta\beta} \) via a likelihood ratio hypothesis test.
MAJORANA - GERDA

MAJORANA
- Modules of $^{enr}$Ge housed in high-purity electroformed copper cryostat
- Shield: electroformed copper / lead
- Initial phase: R&D demonstrator module: Total $\sim$60 kg (30 kg enr.)

GERDA
- ‘Bare’ $^{enr}$Ge array in liquid argon
- Shield: high-purity liquid Argon / $H_2O$
- Phase I: $\sim$18 kg (HdM/IGEX diodes)
- Phase II: add $\sim$20 kg new detectors - Total $\sim$40 kg

SURF

Gran Sasso
GERDA

- clean room with lock
- muon & cryogenic infrastructure
- control rooms
- water plant & radon monitor
- cryostat, $\varnothing 4m$, with internal Cu shield
- water tank, $\varnothing 10m$, part of muon-veto detector
**MAJORANA DEMONSTRATOR (MJD)**

- Located underground at 4850’ Sanford Lab in SD

- 40 kg of HPGe detectors:
  - 30 kg of 86% enriched $^{76}$Ge crystals
  - 10 kg of natural Ge crystals

- 2 independent cryostats
  - Ultra-clean, electroformed Cu
  - 20 kg of detectors per cryostat
  - Scalable design

- Compact shield
  - Low background passive Cu and Pb shield
  - Active muon veto

**Background Goal in the $0\nu\beta\beta$ peak ROI (4 keV at 2039 keV):**

$\sim 3 \text{ count/ROI/t-y after analysis cuts (scales to 1 count/ROI/t-y for tonne expt.)}$
Status: Detectors

- 20 kg of $^{\text{nat}}\text{Ge}$ detectors ("modified BEGe detectors" by Canberra) in hand, and are stored underground at SURF.
- ORTEC selected to produce $^{\text{enr}}\text{Ge}$ detectors.
- ORTEC has produced a detector from natural Ge purified by ESI. $^{\text{enr}}\text{Ge}$ detector production begins in Fall 2012.
- Detector mounts and signal processing electronics for prototype cryostat in good shape.
Reaching 100 kg-ν Exposure

- With 30 kg $^{76}$Ge and 10 kg $^{76}$Ge, MJD is competitive with GERDA Phase II in total exposure.
- Both projects aim to demonstrate the feasibility of a tonne-scale $^{76}$Ge experiment, which will require a background level of 1 count/ROI/t/y.

MAJORANA

GERDA
SNO+ ‘repurposed SNO’

The organic liquid is lighter than water so the Acrylic Vessel must be held down.

New scintillator purification systems are required.

Existing AV Support Ropes

1000 tonnes of liquid scintillator (LAB)

(plus 1 tonne of natural Nd = 56 kg of $^{150}$Nd for Double Beta Decay)

New AV Hold Down Ropes

The Simulated Spectrum of Double Beta Decay Events

Events per 15 keV

Energy (MeV)

$^{214}$Bi 2$\nu$ 0$\nu$ $^{208}$Tl
KamLAND Zen – ‘repurposed KamLAND’

- 3.0 wt% Xe (390 kg)
- 90% enriched 136Xe
- $<m> = 150 \text{ meV}$
- Balloon: 25 µm
- Rballoon: 1.7 m
- 232Th, 238U: 10-12g/g
- 10C: 95% tag
NEMO Experiment at Modane

Neutrino Ettore Majorana Observatory

- 6180 octogonal Geiger cells
- 1940 plastic scintillators (d=10 cm)
- source-foils (d=50 µm A=20 m²)

³²Se
SuperNEMO preliminary design

Plane and modular geometry: ~5 kg of enriched isotope per module

1 module: Source (40 mg/cm²) 4 x 3 m²
  - Tracking volume: drift wire chamber in Geiger mode, ~ 3000 cells
  - Calorimeter: scintillators + PMTs

20 modules: 100 kg of enriched isotope
  - ~ 60 000 channels for drift chamber
  - ~ 20 000 PMT if scint. block
  - ~ 2 000 PMT if scint. bars