Majorana Double Beta Decay Search Project
(Majorana Demonstrator)

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Outline

• Neutrino properties (short)
• Introduction to double-beta decay
• Majorana Demonstrator Project
• Summary
Current knowledge and open questions

**What we know (from $\nu$ oscillations):**

- Neutrino flavour eigenstates differ from their mass eigenstates
- Neutrinos oscillate, hence they must have mass
- Mixing angles and $\Delta m^2$ values known (with varying accuracies)

**What we don't know:**

- Normal or inverted hierarchy?
- Dirac or Majorana particle?
- CP violating phases in mixing matrix?
- **No information about absolute mass scale!** (only upper limits)
- Existence of sterile neutrinos?
Dirac or Majorana particle?

How test of Majorana nature of neutrinos ($\bar{\nu} \equiv \nu$)?

The key test originally proposed by G. Racah (1937):

\[ n \rightarrow p + e^- + \bar{\nu} \rightarrow (\bar{\nu} \equiv \nu) + n \rightarrow p + e^- + p + e^- \]

Such a combination of events would violate the conservation of lepton number ($\Delta L=2$)

One way to study the Racah process is use real $\bar{\nu}$:

Ray Davis (1955) performed the famous $^{37}\text{Cl} \rightarrow ^{37}\text{Ar}$ reaction using anti-neutrinos from reactor

( $\nu + ^{37}\text{Cl} \rightarrow ^{37}\text{Ar} + e^-$ - reaction for famous experiment with neutrinos from the Sun)

Can produce $\bar{\nu}$ indeed $^{37}\text{Ar}$ nuclei in reaction above?
“Rumors of a positive result reached Bruno Pontecorvo in Moscow in 1957 and caused him to invent neutrino oscillations in direct analogy with the Gell-Mann-Pais analysis of neutral Kaon decay. The rumors eventually died out but the idea of oscillations is still alive and kicking.” – S.P. Rosen (1992)

In 1957 with the discovery of parity nonconservation and the two-component neutrino, it was recognised that the two-step process of Racha is inhibited by helicity: the right-handed anti-neutrino emitted by the first neutron is in the wrong helicity state to be re-absorbed by another neutron. In order to complete the second step of the Racah process, the anti-neutrino must be able to flip its helicity and turn itself into a neutrino.

A much more sensitive method is to study double beta decay.
### Table 1. Emission and Absorption of Neutrinos in the Standard Model

<table>
<thead>
<tr>
<th>Process</th>
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<th>Neutrino</th>
</tr>
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<tbody>
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<td>Emission</td>
<td>$n \rightarrow p$</td>
<td>$e_L^-$</td>
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### Table 2. Emission and Absorption of Neutrinos in a Modified Standard Model. The parameter $\eta$ denotes small admixture of opposite helicities.

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<tbody>
<tr>
<td>Emission</td>
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<td>$e^-$</td>
<td>$\bar{\nu}<em>{eR} + \eta \bar{\nu}</em>{eL}$</td>
</tr>
<tr>
<td>Absorption</td>
<td>$n \rightarrow p$</td>
<td>$e^-$</td>
<td>$\nu_{eL} + \eta \nu_{eR}$</td>
</tr>
</tbody>
</table>
Important:

It can be treated the admixture of right-handed currents (RHC-mechanism) as a separate *phenomenological* mechanism for $0\nu\beta\beta$ decay. But it is not a separate *fundamental* mechanism. In gauge theories *the mass* is the fundamental mechanism for lepton number nonconserving processes: RHC-mechanism will not work unless there are mass term present in the neutrino mass matrix (*J. Schechter-J.Valle theorem*)
How to observe $\Delta L=2$

Expected for 35 isotopes, $2\nu\beta\beta$ found for 11 isotopes

$\beta^+\beta^+, \beta^+\mathrm{EC}$, ECEC rates smaller unless resonant enhancement
(e.g. for $^{152}\text{Gd} - ^{152}\text{Sm}$, ECEC Q=56 keV, Phys Rev Lett 106(2011) 052504)

Experimental signature for DBD

"Single" beta decay not allowed

only "double beta decay"

$$(A,Z) \rightarrow (A,Z+2) + 2 \, e^- + 2\bar{\nu} \quad \Delta L=0$$

$$(A,Z) \rightarrow (A,Z+2) + 2 \, e^- \quad \Delta L=2$$

Schechter Valle theorem: $0\nu\beta\beta \iff$ Majorana $\nu$

TAUP 2011, Munich

Schwingenheuer, Double Beta Decay
From $T_{1/2}$ to $\langle m_{ee} \rangle$

\[ \frac{1}{T_{1/2}^{0\nu}} = G^{0\nu} |M^{0\nu}|^2 \frac{\langle m_{ee} \rangle^2}{m_e^2} \]

- $T_{1/2}^{0\nu}$ = measured experimentally
- $G^{0\nu}$ = phase space factor $\sim Q^5$
- $M^{0\nu}$ = nuclear matrix element
- $m_e$ = electron mass

Experiment observes $N^{0\nu} = \ln2 \frac{N_A}{A} a \cdot \epsilon \cdot Mt / T_{1/2}$ and $N^{bkg} = Mt \cdot B \cdot \Delta E$

**Experimental sensitivity**

$T_{1/2}(90\% CL) > \begin{cases} \frac{\ln2}{2.3} \frac{N_A}{A} a \cdot \epsilon \cdot Mt & \text{for } N^{bkg} = 0 \\ \frac{\ln2}{1.64} \frac{N_A}{A} a \cdot \epsilon \sqrt{\frac{Mt}{B \cdot \Delta E}} & \text{for large } N^{bkg} \end{cases}$

$M$ = mass of detector
$t$ = measurement time
$A$ = isotope mass per mole
$N_A$ = Avogadro constant
$a$ = fraction of $0\nu\beta\beta$ isotope
$\epsilon$ = detection efficiency
$B$ = background index in units cmt/(keV kg y)
$\Delta E$ = energy resolution = energy window size
Focus on light neutrino exchange mode

Decay rate depends on an effective Majorana mass. Its calculation requires knowledge of nuclear physics quantities.

\[
\left( T_{1/2}^{0\nu} \right)^{-1} = G^{0\nu} \cdot \left| M^{0\nu} \right|^2 \cdot \left< m_{\beta\beta} \right>^2
\]

Because of the imaginary phases cancellations may occur.

\[
\left< m_{\beta\beta} \right> = m_1 \cdot U_{e1}^2 + m_2 \cdot U_{e2}^2 \cdot e^{2i\phi_{12}} + m_3 \cdot U_{e3}^2 \cdot e^{2i\phi_{13}}
\]

Assumes decay is driven by light neutrino exchange.
Nuclear $0\nu\beta\beta$-decay ($\bar{\nu} = \nu$)

strong in-medium modification of the basic process $dd \rightarrow uue^-e^-(\bar{\nu}_e\nu_e)$

Light neutrino exchange mechanism

virtual excitation of states of all multipolarities in $(A,Z+1)$ nucleus

GT amplitudes to $1^+$ states — from charge-exchange reactions

Nuclear Matrix Elements

\[ \left[ T_{1/2}^{0\nu} \right]^{-1} = G_{0\nu} |M_{0\nu}|^2 \langle m_{\beta\beta} \rangle^2 \]

Extracting an effective neutrino mass requires an understanding of the nuclear matrix elements (NME) at about the 20% theoretical uncertainty level.

Recent progress NSM-QRPA:
- 2005 within \( x \times 5 \)
- 2012 agree within \( x \sim 2 \)

Agreement between methods doesn’t necessarily provide an estimate of theoretical uncertainties or of actual values.

Dueck, Rodejohann & Zuber Phys. Rev. D 63 054031 (2011) with \( r_0 = 1.2 \) fm and \( g_A = 1.25 \)
Germanium for neutrinoless double-beta decay experiments

Germanium detectors

• Source is detector
• Good energy resolution
• Well established technology
• Intrinsically clean (high-purity germanium)

76Ge isotope for 0νββ

• Q-value of 2039keV above most backgrounds
• Can be enriched to >86% in 76Ge (nat. abundance ~ 8%)
• Slow 2νββ rate (10^{21} yr)
• Best limit to date on 0νββ
Sensitivity and backgrounds - $^{76}\text{Ge}$

Background free

\[
\left( T_{1/2}^{0v} \right)^{-1} \propto \epsilon_{\text{eff}} \cdot I_{\text{abundance}} \cdot \text{Source Mass} \cdot \text{Time}
\]

Background limited

\[
\left( T_{1/2}^{0v} \right)^{-1} \propto \epsilon_{\text{eff}} \cdot I_{\text{abundance}} \cdot \sqrt{\text{Source Mass} \cdot \text{Time} / \text{Bkg} \cdot \Delta E}
\]

Mod. Phys. Lett. A 21 (2006), p. 1547 (3σ): (1.30-3.55) x 10^{25} years

Inverted Hierarchy ($m_1 \rightarrow 0 \text{ eV}$)

0νββ-decay

Wednesday, February 6, 13

s, Feb. 6, 2013

Seminar 03/26/2014
Experiments & sensitivity to $0\nu\beta\beta$-decay

To reach IH region requires sensitivities of

$0\nu\beta\beta \ T_{1/2} \sim 10^{26} - 10^{27} \text{ years}$

$(2\nu\beta\beta \ T_{1/2} \sim 10^{19} - 10^{21} \text{ years})$

Most sensitive experiments to date using $^{76}\text{Ge}$, $^{130}\text{Te}$, and $^{136}\text{Xe}$ have attained $T_{1/2} > 10^{25} \text{ years}$

Typical Source Mass $\cdot$ exposure times of 30 - 90 kg-years

$$\left[ T_{1/2}^{0\nu} \right]^{-1} \propto \varepsilon_{\text{eff}} \cdot I_{\text{abundance}} \cdot \text{Source Mass} \cdot \text{Time}$$

Background free

$$\left[ T_{1/2}^{0\nu} \right]^{-1} \propto \varepsilon_{\text{eff}} \cdot I_{\text{abundance}} \cdot \frac{\sqrt{\text{Source Mass} \cdot \text{Time}}}{Bkg \cdot \Delta E}$$

Background limited
The MAJORANA Collaboration

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SURF Chronology: 2006-2013

- **2006**: Homestake donates mine. T. Denny Sanford donates $70M.
- **2007**: NSF selects Homestake to be the DUSEL.
- **2008**: Ross Shaft reentry and underground dewatering begin.
- **2009**: Yates Shaft reentry and construction on 4850 Level begin.
- **2010**: Davis Campus excavation completed. NSB terminates DUSEL funding.
- **2011**: Davis Campus outfitting begins. DOE funds operations at $15M / year.
- **2012**: Davis Campus completed. LUX and MAJORANA experiments deploy underground for assembly. Ross Shaft refurbishment begins.
- **2013**: LUX begins dark matter search. MAJORANA begins data collection. Designs advance for LBNE and LZ experiments. DIANA site selected.
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/yr* (after analysis cuts)
  - scales to 1 count/ROI/t/yr for a tonne experiment
- **40-kg of Ge detectors**
  - Baseline: 20-kg of 86% enriched $^{76}$Ge crystals & 20-kg of $^{nat}$Ge (up to 30-kg enriched $^{76}$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
Sensitivity and backgrounds

$^{76}$Ge Example

$T_{1/2}^{0\nu} = \ln(2)N\varepsilon t/UL(B)$

$\langle m_{\beta\beta} \rangle$ sensitivity (90\% CL, QRPA NME) [m eV]

Inverted Hierarchy ($m_1 \rightarrow 0$ eV)

Mod. Phys. Lett. A 21 (2006), p. 1547 (3\sigma): (1.30-3.55) x $10^{25}$ years

TAUP, Münich, 5 Sept. 2011
MJD Schedule

MJD will proceed in 3 steps

Prototype Cryostat (Spring 2013):
above ground, commercial copper, 2-3 strings $^{\text{nat}}$Ge
Test mechanical design
Test detector performance in cryostat and
Monte Carlo models (eg. granularity)

Cryostat 1 (Early 2014):
underground, electroformed copper, 3 strings $^{\text{enr}}$Ge, 4 strings $^{\text{nat}}$Ge

Cryostat 2 (Late 2014):
underground, electroformed copper, up to 7 strings $^{\text{enr}}$Ge

Prototype cryostat

Underground cryostat
and “monolith”
Electroforming Copper

• **Status**
- For the past 18 months have been operating 16 baths, 10 at 4850L SURF and 6 at shallow UG site at PNNL.
- Mandrels with Cu pulled from baths at PNNL and TCR. Cu machined, removed, and flattened.
- Properties look good.
- Small parts fabricated from EF Cu.
- All cryostat 1 parts complete.
- Part of inner shield

• **Major remaining activities** - 12 months of electroforming remain - cryo 2 parts, inner shield.
MJD Progress in FY13

0νββ-decay
Wednesday, February 6, 13

NuMass, Feb. 6, 2013
Enriched germanium processing

Enrichment to >86% at Electro-Chemical Plant (ECP) in Russia

Reduction to Ge metal at Electrochemical Systems Inc. (ESI)

Zone-refinement by commercial vendor

Pull crystal by commercial vendor

Detector fabrication by commercial detector vendor
P-type Point Contact Detectors

- P-type Point Contact HPGe detectors
- “Novel” technology
- Small point contact to readout charge, low capacitance
- Thick outer contact (n+, lithium diffused), strongly attenuates alphas

E. Aguayo et al. [The Majorana Collaboration],
(Left top) A typical charge pulse of an ordinary semi-coaxial high-purity germanium detector. 
(Left lower) The corresponding current pulse from differentiating the above pulse.  
(Right upper) A typical charge pulse from a point contact detector. 
(Right lower) the current pulse from differentiating the charging pulse above.
A gamma-ray spectrum taken with a point-contact detector using a 232Th calibration source (Black fitted line). The lines at 1581, 1588, 1621, 1625, 1631, and 1638 keV are full-energy peaks corresponding to gamma rays of those energies, and are dominantly multi-site. The peak at 1592-keV is the double-escape peak from the 2615-keV line in the daughter 208Tl and serves as a proxy for the 0-decay signal. The red spectrum shows the events remaining after the application of PSA cuts to remove multi-site events. A fit to the remnant peaks and background is also shown (red line).
P-type Point Contact Detectors

Low capacitance results in greatly reduced series noise
- opportunity for dark matter search
Discovery of $0\nu\beta\beta$-decay

- **Evidence**: a combination of
  - Correct peak energy
  - Single-site energy deposit
  - Proper detector distributions (spatial, temporal)
  - Rate scales with isotope fraction
  - Good signal to background
  - Full energy spectrum (backgrounds) understood.
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
  - Fabricate ultra-clean materials underground
  - Go deep — reduced μ’s & related induced activities

- Utilize background rejection techniques

  $0\nu\beta\beta$ is a single site phenomenon, many backgrounds have multiple site interactions

  - Energy resolution
  - Active veto detector
  - Tracking
  - Energy & Angular correlations
  - Ion Identification
  - Granularity [multiple detectors]
  - Pulse shape discrimination (PSD)
  - Segmentation
  - Single Site Time Correlated events (SSTC)
counts in the 0νββ region of interest
[counts / 4 keV / tonne-year]

- Electroformed Cu: 0.888
- OFHC Cu shielding: 0.288
- Lead shielding: 0.195
- Cables: 0.222
- Front ends: 0.187
- Ge (U/Th): 0.067
- Plastics + other: 0.030
- 68Ge, 60Co (enrGe): 0.176
- 60Co (Cu): 0.110
- External γ, (α,ν): 0.100
- Rn, surface α: 0.054
- Ge, Cu, Pb (n, ng): 0.210
- Ge(n,n): 0.170
- Ge(n,γ): 0.130
- Direct μ + other: 0.030
- ν backgrounds: 0.011

**Total:**
2.9 cts / 4 keV / t-y

**Notes:**
- Primordial contamination of the DEMONSTRATOR
- Long-lived cosmogenic activation
- Environmental backgrounds at Sanford
- In-situ μ-induced
- Neutrino backgrounds
Background mitigation techniques

Granularity

Pulse-shape analysis

Time correlation
Majorana Active Veto System (Contribution part from UT)

32 veto panels

- Dimensions of individual panels from $0.6 \, \text{m}^2$ to $2.0 \, \text{m}^2$.
- Veto should be 99% hermetic.
- Panels should be highly efficient for muons (>99%) and other penetrating particles but blind for gammas.
- False veto signals should not introduce large dead time.
• All 32 Veto Panels were assembled and tested at SERF (UT, Knoxville)
• All 32 Veto panels are shipped to SD
• 12 Veto panels are operated permanently at SURF in Davis campus since October 2013.
International Program in $0\nu\beta\beta$

- Previous Expts.
  - $\sim 1$ eV
  - $\sim$ kg scale

- Quasi-degenerate
  - $\sim$ 100’s meV
  - 30 - 200 kg
  - $\sim$ 8 - 10 expts

- Inverted hierarchy
  - $\sim$ 30 - 40 meV
  - 1 tonne (phased/scaled)
  - $\sim$ 3 expts (?)

- Normal hierarchy
  - $\sim$ 5 meV
  - $\geq$ 10’s ton scale

0νββ-decay Summary

- The observation of 0νββ-decay would demonstrate Lepton number violation and indicate that neutrinos are Majorana particles - constituting a major discovery.
  - Needs to be confirmed from independent experiments using different isotopes and measurement techniques.

- If 0νββ-decay is observed then it opens an exquisitely sensitive window to search for physics beyond the Standard model.
  - Measurements in different isotopes may provide insights into the underlying physics process(es) (η).
  - Extraction of $<m_{\beta\beta}>$ will be challenging.
Thanks for your attention!
Backup slides
Sensitivity from now onwards

Sensitivity of 0nbb Experiments

![Graph showing sensitivity of 0nbb experiments over time, with data points for CUORE, EXO-200, GERDA, KL-Zen, MJD, and SNO+ experiments.](image-url)
MPLA 16(2001)2409:
5 HP Ge, 1990.08-2000.05,
55.0 kg·xy, no PSA, 2.2-3.1σ effect

PLB 586(2004)198:
5 HP Ge, 1990.08-2003.05,
71.7 kg·xy, no PSA, 4.2σ effect

MPLA 21(2006)1547:
4 HP Ge, 1995-2003,
? kg·xy, PSA – 2 methods, 6.2σ effect
2$\beta$0$\nu$ decay of $^{76}$Ge in the H-M experiment

Heidelberg-Moscow experiment:
5 HP Ge detectors (11 kg), 86-88% enriched in $^{76}$Ge, Gran Sasso Underground Laboratory (3600 m w.e.), passive shielding, many years of measurements (start in 1990)

There are few articles on this subject:

0) H.V. Klapdor-Kleingrothaus et al. (HM collaboration, 14 persons), Eur. Phys. J. A 12 (2001) 147 (received 2001.08.22)
53.9 kg$\times$y full statistics (35.5 kg$\times$y with PSA for single site events): $T_{1/2}(0\nu) > 1.3(1.9)\times10^{25}$ yr at 90% C.L.

55.0 kg$\times$y full statistics (no PSA), $T_{1/2}(0\nu) = 1.6\times10^{25}$ yr [(0.8-35.1)$\times10^{25}$ yr at 95% C.L.]
46.5 kg$\times$y part of statistics (no PSA), $T_{1/2}(0\nu) = 1.5\times10^{25}$ yr [(0.8-18.3)$\times10^{25}$ yr]
2.2-3.1$\sigma$ effect

Criticized in number of works:
Yu.G. Zdesenko et al., Phys. Lett. B 546 (2002) 206  no effect or $\sim1.5\sigma$ effect
Also, Moscow part of the H-M collaboration derived only limit:

\[ T_{1/2}(0\nu) > 1.6 \times 10^{25} \text{ yr at 90\% C.L.} \]


2) H.V. Klapdor-Kleingrothaus, I.V. Krivosheina, A. Dietz, O. Chkvorets,


71.7 kg\times\text{y full statistics (no PSA)}, \( T_{1/2}(0\nu) = 1.2 \times 10^{25} \text{ yr} \) \([0.7-4.2] \times 10^{25} \text{ yr at 95\% C.L.} \]

\[ 4.2\sigma \text{ effect} \]

Not only statistics was bigger; \textbf{also summing procedure was improved:}

\text{Final spectrum = sum of 9570 individual spectra}
\text{360 calibration spectra for each of 5 detectors, FWHM(2615 keV)=3.27 keV for sum of 1800 calibration spectra}


? kg\times\text{y, PSA – 2 methods (pulse shapes were written since 1995)}

\[ T_{1/2}(0\nu) = 2.23^{+0.44}_{-0.31} \times 10^{25} \text{ yr – final result} \]

\[ 6.2\sigma \text{ effect} \]