Quest for the nature of the neutrino

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Overview

• Motivation for neutrino studies
• Neutrinoless double-beta decay
  – Theory and History
• Experimental Aspects
• Experimental Efforts
NEUTRINO STUDY MOTIVATION AND HISTORY
The weak force and neutrinos

• Three flavors that undergo only weak interactions
• Electrically neutral
• Neutrinos have mass, but very light
• Compelling evidence neutrinos undergo flavor oscillations.

+ Higgs!
Neutrino Sources

Most Abundant Particle in Universe!
Neutrino Flavor Mixing

Mass eigenstates different than flavor eigenstates.

⇒ Propagating neutrinos undergo flavor oscillations.

Mass to flavor relationship described by neutrino mixing matrix with 5 parameters.

\[
U = \begin{pmatrix}
1 & 0 & 0 \\
0 & c_{23} & s_{23} \\
0 & -s_{23} & c_{23}
\end{pmatrix}
\begin{pmatrix}
c_{13} & 0 & e^{i\delta} s_{13} \\
0 & 1 & 0 \\
-s_{13} & c_{13} & 0
\end{pmatrix}
\begin{pmatrix}
c_{12} & s_{12} & 0 \\
-s_{12} & c_{12} & 0 \\
0 & 0 & 1
\end{pmatrix}
\begin{pmatrix}
e^{ia_1} & 0 & 0 \\
0 & e^{ia_2} & 0 \\
0 & 0 & 1
\end{pmatrix}
\]

\[c_{ij} = \cos \theta_{ij} \quad s_{ij} = \sin \theta_{ij}\]

\[\theta_{12} \approx 34^\circ \quad \delta = ?\]
\[\theta_{23} \approx 42^\circ \quad \alpha_i = ?\]
\[\theta_{13} \approx 9^\circ\]
Neutrino Masses

Absolute masses weakly constrained, < 1eV.
Relative mass-squared differences known.
Three possible scenarios: Quasi-degenerate, also:

**“Normal”**

\[ \Delta m_{23}^2 = 2.4 \times 10^{-3} \text{ eV}^2 \]

\[ \Delta m_{12}^2 = 7.5 \times 10^{-5} \text{ eV}^2 \]

**“Inverted”**

\[ \Delta m_{12}^2 \]

\[ \Delta m_{23}^2 \]

\[ \nu_e \]

\[ \nu_{\mu} \]

\[ \nu_{\tau} \]

Needs to be resolved
Majorana vs. Dirac

Majorana fermions are their own anti-particles. Dirac fermions are not.

No fermions are known to be Majorana.

Electrically charged fermions have good QM # to distinguish particle/anti-particles, hence are Dirac.

Experimental evidence consistent with both Majorana or Dirac neutrinos.

Verification difficult due to small neutrino masses and handedness of weak interaction.

Neutrinoless double-beta decay is the only practical process that can resolve this mystery.
More about Majorana vs. Dirac*

Note: Only valid if neutrinos are massive.

* - original argument by Kayser, 1985
Origin of Matter

Majorana neutrinos

See-Saw mass-generating mechanism

Required by

Matter dominated universe?

Leptogenesis

Required (in general) by
NEUTRINOLESS DOUBLE-BETA DECAY: THEORY
What is neutrinoless double-beta decay ($0\nu\beta\beta$)?

$$Z A \Rightarrow Z+2 \ A + 2e^-$$

Energetically allowed in many nuclei.

Prefer nuclei stable against $\beta$-decay (about 30)

$2\nu\beta\beta$: Observed 2nd order weak process.

$$Z A \Rightarrow Z+2 \ A + 2e^- + 2\bar{\nu}_e$$
History

1935: Double beta decay postulated by Maria Goeppert-Mayer (assist by Wigner)
*Phys. Rev.* 48 (1935) 512

1937: Ettore Majorana formulates theory with no distinction between $\nu$ and anti-$\nu$.
*Nuovo Cimento* 14 (1937) 171

1937: Giulio Racah suggests zero-neutrino double-beta decay as test for Majorana’s theory.
*Nuovo Cimento* 14 (1937) 322
Motivation for $0\nu\beta\beta$ Search

• Implications of discovery:
  – Neutrino is Majorana* (own antiparticle)
  – Total lepton number is not conserved
  – Neutrino has mass* (known)
  – Absolute neutrino mass.

• $0\nu\beta\beta$ nuclear decay may occur via several processes (SUSY, RH currents, etc)

• Canonical example: Exchange of virtual Majorana neutrino + helicity flip

0νββ–decay and Majorana Neutrinos


Majorana nature verification *independent* of process that mediates $0\nu\beta\beta$ decay!
0νββ Rate and Neutrino Mass

\[
\left[ T_{1/2}^{0\nu} \right]^{-1} = G^{0\nu} (E_0, Z) \left\langle m_{\beta\beta} \right\rangle^2 | M^{0\nu} |^2
\]

\( T_{1/2}^{0\nu} \) : Half-life
\( G^{0\nu} \) : Phase Space (Known)
\( M^{0\nu} \) : Nuclear Matrix Element (large uncertainty)

\[
\left\langle m_{\beta\beta} \right\rangle = \left| \sum_i U_{ei}^2 m_{\nu_i} e^{i\alpha_i} \right| \quad \text{Effective Majorana electron neutrino mass}^*
\]

\( 0\nu\beta\beta \) decay can probe \textbf{absolute} neutrino mass scale and mixing.

Current neutrino experiments measure mass squared differences: \( \Delta m^2 \).

* Assumes \( \nu_m \) exchange
Combined Mass Limits

Estimated KATRIN Sensitivity

~ 100kg isotope
~ 1 ton
~ 100 ton

Effective $0\nu\beta\beta$ mass (eV)

Lightest mass (eV)

DBD

Inverted

Normal

Cosmology

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NEUTRINOLESS DOUBLE-BETA DECAY: EXPERIMENTAL PROGRAM
Artificial Radioactive Substances

T1. Double Beta Decay.* E. Fireman, Princeton University.—There exist a number of stable isobaric nuclei that differ by two in charge and may differ by several Mev in mass. The heavier should decay into the lighter with simultaneous emission of two electrons. The decay probability depends markedly upon whether or not the two electrons are accompanied by two neutrinos. No neutrinos are emitted if they obey the Majorana equation or if the interaction is composed of linear combinations of the usual interactions. Furry’s calculations using Majorana wave functions have been extended to linear combinations that arise from symmetry considerations and meson theories. Isobars belonging to a triple set are the most promising for double beta decay since the middle one is near the minimum of the isobaric mass defect curve. Therefore, $^{49}$Zr and $^{103}$Sn were investigated with a Geiger counter coincidence arrangement. Their activity was compared with elements that are stable against all types of decay. No difference was detected. On the basis of these measurements and the assumption of two-Mev mass difference, the lifetime of $^{103}$Sn is greater than $3 \cdot 10^{18}$ years. This result rules out the polar vector, axial vector, and tensor interactions with Majorana wave functions and the more important linear combinations.

* This work was supported in part by Navy contract.

Searched for coincident betas from target materials using Geiger tubes
In all situations specimen A gives 2 coincidence counts/hr. more than specimen B. By repeating this type of measurement with Al absorbers over one side of each specimen an absorption curve is obtained. This absorption curve is similar to that of electrons from a spectrum with an energy end point between 1.0 Mev and 1.5 Mev. The single counts from specimens A and B both give 6.5 ± 0.3 counts/min. If one interprets this effect as double beta-decay from Sn$^{124}$, one obtains a half-life between $0.4 \cdot 10^{16}$ yr. and $0.9 \cdot 10^{16}$ yr. Other alternative explanations for these observations have been considered but none have been found to be plausible. This result would indicate that double beta-decay is unaccompanied by neutrinos. A further consequence of these results pointed out to the author by Professor J. R. Oppenheimer is that the neutron-proton charge difference is exactly equal to the electron charge.

2.6 sigma effect
• Ruled out by subsequent measurements, though. Astropart. Phys. 31 (2009) 412) $T_{1/2}^{(124\text{Sn}, 0\nu)}>2.0\times10^{19}\text{yr}$

• Likely due to radioactive contamination, uncontrolled systematics (no discussion of calibrations), sample thickness

• Limited handles on data

• First use of lead/Fe shield, enriched sources (54% enriched Sn source)
• Still no conclusive evidence for the existence of DBD.
• About 10 “claims” in literature, all debunked
• Three explanations:
  – Unknown backgrounds
  – Statistical fluctuations
  – Systematics / unknown detector response
Experimental Considerations in Modern Experiments

- Measure **extremely** rare decay rates:
  \[ T_{1/2} \sim 10^{26} - 10^{27} \text{ years} \sim \text{few decays per tonne per year}. \]
- Large, highly efficient source mass.
- Extremely low (near-zero) backgrounds in the \( 0\nu\beta\beta \) peak region-of-interest (ROI)

1. High \( Q \) value

2. Best possible energy resolution
   - Minimize \( 0\nu\beta\beta \) peak ROI to maximize S/B
   - Separate \( 2\nu\beta\beta/0\nu\beta\beta \)

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Background Identification

- Natural isotope chains: $^{232}$Th, $^{235}$U, $^{238}$U, Rn
- $2\nu\beta\beta$-decays
- Cosmic Rays:
  - Activation at surface creates $^{68}$Ge, $^{60}$Co.
  - Hard neutrons from cosmic rays in rock and shield.
- Pushing limits in ICP-MS, materials science, radio-assay. I.e. Ultra-low radioactive background, fast, low-noise electronics
Background Reduction Challenges

Commercial HPGe detector in lead shield at surface

2 neutrino background

0 neutrino signal
KAMLAND-ZEN

EXO-200

CUORE

KamLAND LS
1000 ton in
R=6.5m balloon

Corrugated tube

Suspending film belts

Xe loaded LS in
R=1.54m inner balloon

Buffer oil

Outer detector
225 of 20 inch PMTs

1325 of 17 inch PMTs+ 554 of 20 inch PMTs
mounted on stainless-steel tank

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## Current Limits

<table>
<thead>
<tr>
<th>Isotope</th>
<th>$\beta\beta(0\nu)$ Half-life limit (years)</th>
<th>Natural Abundance [%]</th>
<th>$Q$-value (MeV)</th>
</tr>
</thead>
<tbody>
<tr>
<td>$^{48}$Ca</td>
<td>$&gt; 1.4 \times 10^{22}$ [31]</td>
<td>0.187</td>
<td>4.2737</td>
</tr>
<tr>
<td>$^{76}$Ge</td>
<td>$&gt; 3.0 \times 10^{25}$ [32]</td>
<td>7.8</td>
<td>2.0391</td>
</tr>
<tr>
<td>$^{82}$Se</td>
<td>$&gt; 1.0 \times 10^{23}$ [33]</td>
<td>9.2</td>
<td>2.9551</td>
</tr>
<tr>
<td>$^{100}$Mo</td>
<td>$&gt; 1.1 \times 10^{24}$ [34]</td>
<td>9.6</td>
<td>3.0350</td>
</tr>
<tr>
<td>$^{130}$Te</td>
<td>$&gt; 4.0 \times 10^{24}$ [35]</td>
<td>34.5</td>
<td>2.5303</td>
</tr>
<tr>
<td>$^{136}$Xe</td>
<td>$&gt; 1.07 \times 10^{26}$ [36]</td>
<td>8.9</td>
<td>2.4578</td>
</tr>
<tr>
<td>$^{150}$Nd</td>
<td>$&gt; 1.8 \times 10^{22}$ [37]</td>
<td>5.6</td>
<td>3.3673</td>
</tr>
</tbody>
</table>
**The MAJORANA DEMONSTRATOR**

Funded by DOE Office of Nuclear Physics, NSF Particle Astrophysics, & NSF Nuclear Physics 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.
- Searches for additional physics beyond the standard model.

- Located underground at 4850’ Sanford Underground Research Facility
- Background Goal in the $0
  \nu\beta\beta$ peak region of interest (4 keV at 2039 keV)
  3 counts/ROI/t/y (after analysis cuts) Assay U.L. currently $\leq$ 3.5
  scales to 1 count/ROI/t/y for a tonne experiment
- 44.1-kg of Ge detectors
  - 29.7 kg of 88% enriched $^{76}$Ge crystals
  - 14.4 kg of $\text{natGe}$
  - Detector Technology: P-type, point-contact.
- 2 independent cryostats
  - ultra-clean, electroformed Cu
  - 22 kg of detectors per cryostat
  - naturally scalable
- Compact Shield
  - low-background passive Cu and Pb shield with active muon veto
Early Activities

Underground Electroforming facility

Main underground Lab

Inside Electroforming Lab

Underground machine shop

Vacuum System Assembly

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MJD Construction
DEMONSTRATOR currently taking data since 2015
First Dark Matter paper undergoing internal collaboration review
First NDBD results this summer (possibly sooner)
“Tonne-scale”

We recommend the timely development and deployment of a U.S.-led ton-scale neutrinoless double beta decay experiment.

A ton-scale instrument designed to search for this as-yet unseen nuclear decay will provide the most powerful test of the particle-antiparticle nature of neutrinos ever performed. With recent experimental breakthroughs pioneered by U.S. physicists and the availability of deep underground laboratories, we are poised to make a major discovery.
Conclusions

• The search for NDBD has compelling physics motivation.
• There is a large, international effort to search for NDBD
Backups
The MAJORANA DEMONSTRATOR Module

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

(Excellent energy resolution, intrinsically clean detectors, commercial technologies)

- 40-kg of Ge detectors
  - 30-kg of 87% enriched $^{76}$Ge crystals
  - 10 kg $^{nat}$Ge
  - Point-contact detectors for MJD

- 2 independent cryostats
  - Ultra-clean
  - Naturally scalable
  - Compact low-background passive Cu and Pb shield with active muon veto

- Background Goal in the $0\nu\beta\beta$ peak ROI (4 keV at 2039 keV)
  ~ 3 count/ROI/t-\(\gamma\) (after analysis cuts)
Ge Detection Principle

- >50 years of experience
- Ge is semiconductor -- Diode.
- Ionizing radiation creates electron-hole pairs.
- Signal generated by collecting electrons and holes.
- Gamma-ray spectroscopy

Mature Technology

Gammasphere
GRETINA/AGATA

Canberra (Commercial)

RHESSI

Ionizing radiation interaction site

n
p
electrons
holes
An ultra-pure Germanium single crystal is being “pulled” from a melt contained in a silica crucible at 936°C. The atmosphere is pure Hydrogen. Heat is supplied by the water cooled radiofrequency (RF) coil surrounding the silica envelope. This bulk crystal growth technique carries the name of it’s inventor, Jan Czochralski.”
Electroformed copper
P-type Point-Contact (PPC) Detectors

Point contact:
- Small capacitance: $\sim 1\text{pF}$
- Pronounced weighting field
- Small electrical fields
- Sub-keV Thresholds
- Excellent Pulse-shape Analysis
Simulation of Backgrounds

60,000 combinations of parts and isotopes.
Detector Mount and String Design

LANL thermal test string
Jan 2011

LBNL test string (w/ thermal blanks)

Actual String built this year

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Cryostat Internals

- Top Lid
- Cold Plate
- Hoop
- Clamp Assembly
- Bottom Lid
- String Assembly

40 cm
Sanford Underground Research Facility
Lead, South Dakota
Underground Location of MAJORANA Laboratory

Majorana Lab
“Transition Space”

LUX

100’

Yates shaft

Davis Campus, 4850’ level, near Yates shaft

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OTHER PHYSICS WITH MAJORANA
• Low-E thresholds of PPC design opens new possibilities for experiments:
  – Direct Dark Matter Searches
  – Coherent neutrino nuclear scattering (an initial goal of PPCs)
  – Solar Axions
  – Low momentum transfer neutrino-electron scattering
  – Fractionally charged Particles in cosmic-rays
  – Pauli Exclusion Principle Violation
  – Lorentz Violation
  – ...

• Enrichment reduces low-E backgrounds
MALBEK (MAJORANA Low-background BEGe Experiment at KURF)

• MALBEK is a 450-g R&D mod.- BEGe detector, mounted in a low-background cryostat. R&D for MAJORANA

• MALBEK is operating since 2010 at KURF (1450 m.w.e.), located in Ripplemead, VA.

Goals:

– Systematically characterize spectrum.
– R&D low-energy triggering and DAQ (low-energy pulses difficult to distinguish from noise).
– R&D PSA in low-energy region
– Background model verification
– Dark Matter search
90% confidence limit

![Graph showing WIMP mass vs. WIMP-nucleon scattering cross section](image)

- CoGeNT 2013
- CoGeNT 2014 ML
- LUX 85 d
- superCDMS LT
- MALBEK constant cut (preliminary)
- MALBEK 99% cut (preliminary)
- TEXONO

Parameters:
- **WIMP mass (GeV):** 6, 8, 10, 12, 14, 16, 18, 20
- **σ_{SI} (cm^2):** 10^{-39}, 10^{-40}, 10^{-41}, 10^{-42}, 10^{-43}
Towards 1TGe

**MAJORANA**

- Modules of $^{enr}$Ge housed in high-purity electroformed copper cryostat
- Shield: electroformed copper / lead
- Initial phase: R&D demonstrator module: Total 40 kg (30 kg enr.)

**GERDA**

- ‘Bare’ $^{enr}$Ge array in liquid argon
- Shield: high-purity liquid Argon / H$_2$O
- Phase I (2011): ~18 kg (HdM/IGEX diodes)
- Phase II (2013): add ~20 kg new detectors - Total ~40 kg

**Joint Cooperative Agreement:**

- Open exchange of knowledge & technologies (e.g. MaGe, R&D)
- Intention is to merge for 1 ton exp. Select best techniques developed and tested in GERDA and MAJORANA
2 coincident plastic scintillators
Shielded by lead and John Hancock building + anti-coincidence tubes.

Used Blind Analysis!

During the portion of the experiment performed in the John Hancock building, the sample identifications were coded by Professor J. W. Rosengren and the key to the code was withheld from the author until the conclusion of the experiment to eliminate possible (but carefully guarded against) "bias effects."

Not sure what happened here
Statistical? (significance is < 3 sigma)
Debunked discovery claims not only cause of concern

Gotthard underground HPGe experiment found unidentified peak in spectrum at 2527 keV
Nightmare for Te DBD experiments, since $^{130}\text{Te}$ Q-value is 2527.01 keV


Fortunately, significant effort showed origin due to defective amplifier.

Strong case for program with more than one isotope
Nuclear structure approaches

In NSM (Madrid-Strasbourg group) a limited valence space is used but all configurations of valence nucleons are included. Describes well properties of low-lying nuclear states. Technically difficult, thus only few $0\nu\beta\beta$-decay calculations.

In QRPA (Tuebingen-Caltech-Bratislava and Jyvaskula-La Plata groups) a large valence space is used, but only a class of configurations is included. Describe collective states, but not details of dominantly few particle states. Relative simple, thus more $0\nu\beta\beta$-decay calculations.

In IBM (Iachello, Barea) the low-lying states of the nucleus are modeled in terms of bosons. The bosons have either $L=0$ (s boson) or $L=2$ (d boson). The bosons can interact through one and to body forces giving rise to bosonic wave functions.

In PHFB (India/Mexico groups) w.f. of good angular momentum are obtained by making projection on the axially symmetric intrinsic HFB states. Nuclear Hamiltonian contains only quadrupole interaction.

Differences: i) mean field; ii) residual interaction; iii) size of the model space; iv) many-body approximation.
Point Contact Detectors


Hole $v_{\text{drift}}$ (mm/ns) w/ paths, isochrones

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WIMP Signal in Ge

~20% of nuclear recoil energy deposited as ionization (the rest as heat).

Some experiments sensitive to both, e.g. CDMS.