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Note: Red text indicates students
Neutrinoless Double Beta Decay

• Immediate Implications of Discovery:
  - Neutrino is Majorana (own antiparticle)
  - Total Lepton Number is not conserved
  - Neutrino has mass (known)

• Well-studied example: Exchange of virtual neutrino.

• Could probe absolute Mass-scale of Neutrino:

\[
\left( T_{1/2}^{0\nu} \right)^{-1} = \text{(Matrix Element)} \times \text{(Phase Space)} \times |\langle m_\nu \rangle| 
\]

\[
^{Z}A \rightarrow ^{Z+2}A + 2e^{-}
\]
$0\nu\beta\beta$ Decay Sensitivity to $<m_{\beta\beta}>$

$Amp[0\nu\beta\beta] \propto \sum_i m_i U_{ei}^2 \xi_i \equiv <m_{\beta\beta}>$

$0\nu\beta\beta$ limits for: $^{48}$Ca, $^{76}$Ge, $^{82}$Se, $^{100}$Mo, $^{116}$Cd, $^{128}$Te, $^{130}$Te, $^{136}$Xe, $^{150}$Nd

Disfavoured by $0\nu2\beta$

KKDC $^{76}$Ge claimed signal

Quasi-Degenerate

Inverted

Normal

90% CL (1 dof)

Experimental Considerations

• Measure **extremely** rare decay rates:
  \[ T_{1/2} \sim 10^{26} - 10^{27} \text{ years} \ (\sim 10^{13} \times \text{age of universe!}) \]
• Large, highly efficient source mass.
• Extremely low (near-zero) backgrounds in the \(0\nu\beta\beta\) peak region-of-interest (ROI) (1 count/t-y)

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

![Graph showing 2\nu\beta\beta and 0\nu\beta\beta peaks with 1% resolution]
Experimental Program in $0\nu\beta\beta$ Search

Previous Expts.
~ 1 eV
~ kg scale

Quasi-degenerate
~ 100's meV
100-200 kg
3-5 Expts

If $0\nu\beta\beta$ Observed

Program to study 8-12 $0\nu\beta\beta$
isotopes, using various techniques
100-200 kg scale

Inverted hierarchy
~ 30-40 meV
1 ton scale
at least 2 Expts

Normal hierarchy
~ 5 meV
≥ 10's ton scale
~ 2 Expts?

1980 - Present
2007 - 2014
2013 - 2020
Ge Detection Principle

- Majorana uses $^{76}$Ge
- Enriched HPGe Diodes -- Detector is Source.
- Excess at $Q = 2039$ keV
- Demonstrated in IGEX, Heidelberg Moscow.
- Intrinsically clean

HPGe Detectors have excellent energy resolution
- $0.16\%$ at ROI for Majorana
We don’t want to repeat that …

- The Klapdor-Kleingrothaus Result


Best result - 5 $^{76}$Ge crystals, 10.96 kg of mass, 71 kg-years of data.

$$T_{1/2} = (1.19 +2.99/-0.5 ) \times 10^{25} \text{ y}$$

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

Plotted a subset of the data for four of five crystals, 51.4 kg-years of data.

$$T_{1/2} = (1.25 +6.05/-0.57) \times 10^{25} \text{ y}$$

- Much smaller background
- More (efficient) tools to identify and suppress background
- Better systematic handles on data
\[ T_{1/2} = \frac{\ln(2) \cdot \varepsilon_{\text{eff}} \cdot \text{atoms} \cdot \text{time}}{\text{decays}} \propto \frac{1}{< m_\nu >^2} \] Limiting case of no obs. decays

\[ T_{1/2} > \frac{\ln(2) \cdot \varepsilon_{\text{eff}} \cdot \text{atoms} \cdot \text{time}}{\sqrt{\int B_i(t) \cdot dt}} \]

\[ <m_\nu>_\text{of 100 meV} \]

[Rod06]
Background Identification

- Majorana is background limited.
- 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.
  - $2\nu\beta\beta$-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
The Majorana Modular Approach

1 Concept: 57 crystal modules
- Conventional vacuum cryostat made with electroformed Cu.
- Scalable to 1-tonne

Vacuum jacket
Cold Plate
Cold Finger
Crystal
Thermal Shroud
Bottom Closure

Cap
Tube (0.007” wall)
Ge (62mm x 70 mm)
Tray (Plastic, Si, etc)

1 of 19 crystal stacks
Materials and Shielding

- Ultra-radiopure materials
- Deep underground: >5000’
- Modular deployment.
- 40 cm bulk Pb, 10 cm ultra-low background shield
- Active $4\pi$ veto detector

Top view

- Veto Shield
- Sliding Monolith
- LN Dewar
- Inner Shield
- 57 Detector Module
Concepts for background suppression

Pulse-shape discrimination

Segmentation

- Pulse-shape discrimination
- Segmentation

0νββ

γ ("High" Energy)

γ ("Low" Energy)

60Co

γ ("High" Energy)

γ ("Low" Energy)
Advanced Concepts in Detector and Data Processing Technologies

• Ge-drift/ modified electrode/ point contact detector
• Highly segmented coaxial HPGe detectors
  – N-type (e.g. GRETA, LLNL Coaxial Imager)
  – P-type (?)

• Low mass/ high resolution FE electronics (FET, preamplifiers)

• Digital acquisition and processing system
  – 1D-3D signal and data processing
Highly Segmented N-Type Detectors

- **Approach**: Highly 2-D segmented n-type HPGe detector with 3D PSA of segments
- **Advantage**:
  - Best background rejection
  - Best event characterization in 3D with interaction separation and gamma-ray reconstruction (w/ accuracy of the size of $0\nu\beta\beta$ event - 1 to 2 mm)
  - Significant R&D effort completed (GRETA, AGATA, LLNL Compton imager)
  - Direct connection to NP projects
- **Drawback**:
  - Slower detector production rate
  - Most additional components (contacts, readout)
  - Most complicated acceptance, characterization, and assembly
  - Requires design modifications (electronics, mechanically)

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**Suppression by segmentation and 3D PSA**

- $^{60}$Co suppression w/ 32-fold segmented MSU detector
  - Red: single segment
  - Blue: with PSA

- Measured with 40-fold segmented LLNL detector
- Full 3D event reconstruction and Compton imaging with LLNL detector
- Compton image of $^{137}$Cs source
**Ge-drift/ modified electrode/ point contact detector**

- **Approach**: Non-segmented p-type HPGe detectors employing pulse-shape analysis in modified electrode or Ge-drift configuration

- **Advantage**:
  - High background rejection due to PSA sensitivity
  - Low energy threshold (~300 eV)
  - P-type material for potentially high fabrication rate and low cost
  - Minimum number of readout components
  - Simple configuration in terms of design, production, and operation of cryostat, mounts, readout, and cooling.
  - Easy acceptance, characterization, and assembly.
  - “Thick” outside contact attenuating potential surface $\alpha$
  - Contamination

- **Drawback**:
  - Only one detector fabricated
  - Production rate, sensitivity to Ge material requirements (e.g. impurity concentration) uncertain.
  - No 3D reconstruction possible
Anticipated background rates

Counts per Region of Interest per Ton-Year

Background rates are comparable!
- Background suppression compensates the increased background level for segmented and more complex implementations.
Majorana R&D
Towards a 1-ton experiment

- Phase I: Construct 30-60 kg R&D Module
- Mixed detectors, enrichment levels
- Goals:
  - Selection of optimal detector design:
    - Highly/modestly segmented
    - Modified electrode
    - Unsegmented p-type
  - Verification of background simulation.
  - Materials, in particular cable and copper shielding.
- Continued cooperation with GERDA collaboration (MaGe, materials, Liquid Ar Shield)
Majorana R&D Module

- Reference Design
  - Based on 60 kg module, containing 57 crystals. A mix of p-type and n-type crystals.
    30-60 kg of 86% enriched $^{76}\text{Ge}$ crystals.
    Some crystals segmented.
  - Scalable, with independent, ultra-clean, electroformed Cu cryostat modules
  - Enclosed in a low-background passive shield and active veto
  - Located deep underground (4500 mwe)

- Background Specification Goal
  in the $0\nu\beta\beta$ peak region of interest (4 keV at 2039 keV)
  • ~ 1 count/ROI/t-y (after analysis cuts)

- Expected Sensitivity to $0\nu\beta\beta$
  (for 60 kg enriched material, running 2 years, or 0.12 t-y of $^{76}\text{Ge}$ exposure)
  - $T_{1/2} = 1.6 \times 10^{26}$ y (90% CL)
  - Sensitivity to $<m> < 190$ meV (90% CL) ([Rod06] RQRPA NME)
  - Able to confirm/refute KKDC 400 meV value (20% measurement).
Schedule

- Submit R&D proposal this summer for demonstration prototype for 1-ton.
- Construction in FY09.
- Collect data FY11. 30-60 kg. of enriched material.
Opportunities for UC

• What does it take to build a 1-ton $0\nu\beta\beta$ $^{76}$Ge experiment?
  – Fabrication challenges: Cost & schedule …
  – Do we have the best technology?

• Can we enlarge our vision: $^{76}$Ge $\leftrightarrow$ $0\nu\beta\beta$-in general $\leftrightarrow$ fundamental physics
  – Instrumentation as common link?
  – Institute for NPAC Instrumentation? Center of Excellence?
  – Instrumentation technologies
    • Detector
    • Data processing
  – Material processing with emphasis on (radio) purity

• Ties to
  – DUSEL
  – Homeland Security/ Nuclear Nonproliferation
Majorana & GERDA

- 60kg $^{enr}$Ge modules based in electroformed Cu cryostat
- E-formed Cu / Pb passive shielding
- $4\pi$ plastic scintillator $\mu$ veto

- $^{enr}$Ge array submersed in LAr
- Water cherenkov $\mu$ veto
- Phase I: $\sim$18 kg (H-M/IGEX xtals)
- Phase II: +20 kg segmented xtals

Joint Cooperative Agreement:
Open exchange of knowledge & technologies (e.g. MaGe, R&D)
Intention to merge for larger scale exp.
Select best techniques developed and tested in GERDA and Majorana