The GERDA Experiment - A Search for Neutrinoless Double Beta Decay

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05. August 2011

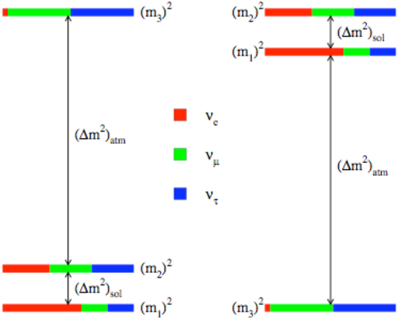
Neutrino Physics

We know

- Neutrinos have mass
- Mass difference between eigenstates

Three big questions

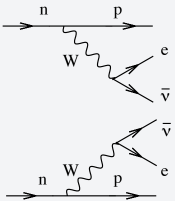
- Absolute mass scale
- Mass hierarchy
- Majorana vs. Dirac



Double Beta Decay

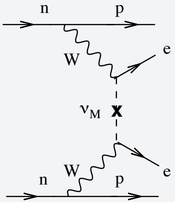
$2\nu\beta\beta$

- $(Z, A) \rightarrow (Z+2, A) + 2e^- + 2\bar{\nu}_e$
- $\Delta L = 0$
- $\left|T^{2\nu}_{1/2}\right|^{-1} = G^{2\nu}(Q_{\beta\beta}, Z)\,|M_{2\nu}|^2 \sim \left|10^{20}\ \mathrm{y}\right|^{-1}$
- Measured for a dozen of isotopes



$0\nu\beta\beta$

- $(Z, A) \rightarrow (Z+2, A) + 2e^-$
- $\Delta L = 2$
- $\left|T^{0\nu}_{1/2}\right|^{-1} = G^{0\nu}(Q_{\beta\beta}, Z)\,|M_{0\nu}|^2\,\langle m_{\beta\beta}\rangle^2 \sim \left|10^{25}\ \mathrm{y}\right|^{-1}$
- $\langle m_{\beta\beta}\rangle = \left|\sum_i U^2_{ei}\, m_i\right|$



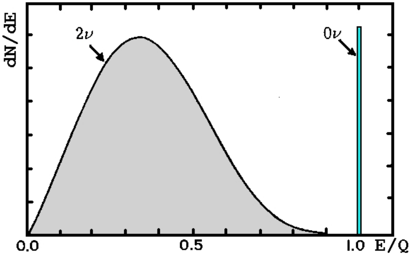
Signature

Measuring the energy of both electrons

- $2\nu\beta\beta$: Continuous energy spectrum
- $0\nu\beta\beta$: Sharp peak at Q value of decay

$$Q = E_{\text{mother}} - E_{\text{daugther}} - 2m_e$$

- Schechter & Valle (1982): Measuring $0\nu\beta\beta \Rightarrow \nu$ Majorana particle



Heidelberg-Moscow Experiment

The Claim

- 5 HPGe crystals with 71.7 kg y
- Background rate: 0.11 ± 0.01 cts/(keV kg y)
- Peak at Q value (2039 keV):

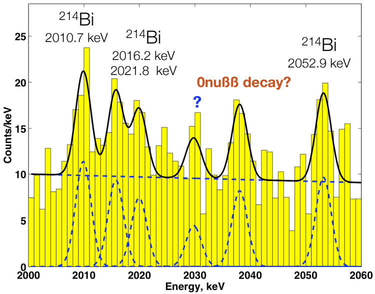
$$T_{1/2}^{0\nu} = 1.2^{+3.0}_{-0.5} \times 10^{25} \text{ y} \qquad (4\sigma)$$

$$\langle m_{\beta\beta} \rangle = 0.44^{+0.14}_{-0.20} \text{ eV}$$

- Problem: Confidence depends on background model and energy region selected for analysis

$\Rightarrow$ New experiments with higher sensitivity needed

H.V.Klapdor-Kleingrothaus et al., Phys. Lett. B 586 (2004) 198



The Experimental Challenge

Sensitivity

$$T^{0\nu}_{1/2} \propto \langle m_{\beta\beta} \rangle^{-2} \propto const \sqrt{\frac{M \times t}{\Delta E \times B}}$$

- M Mass
- t Time
- B Background rate
- ΔE Energy resolution

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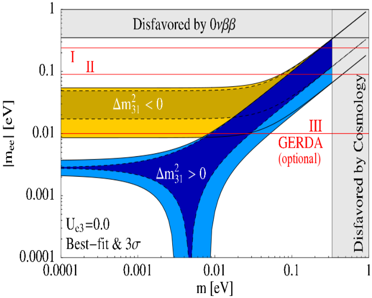
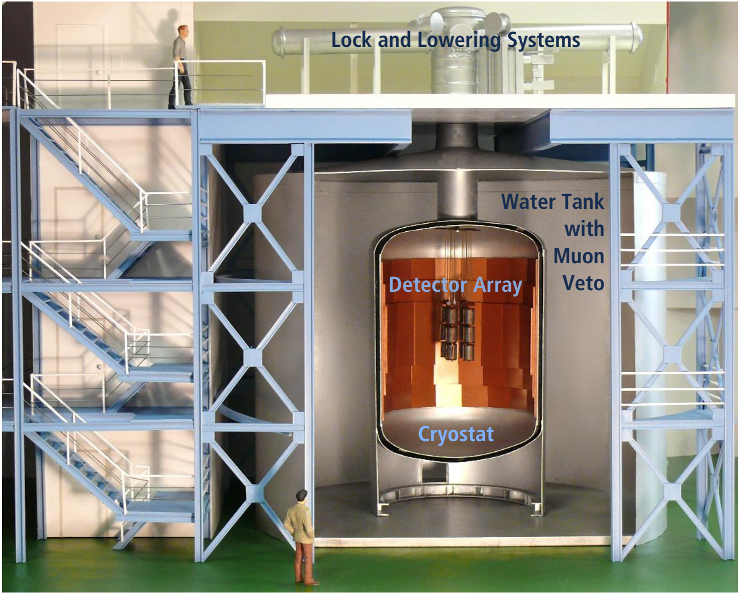


Maneschg, Merle, Rodejohan, arXiv:0812.0479v1

Possibilities to Reduce Background

Underground Location	LNGS 1400 m (3400 mwe) underground
Material Reduction	Immerse Ge detectors nakedly into liquid argon
Material Selection	Low radioactive materials used
Shielding	Large cryostat inside a water Cherenkov tank
Identification	Muon veto Discrimination between single scatter (signal) and multi-scatter (background) events

Design



Lock and Lowering Systems
Water Tank with Muon Veto
Detector Array
Cryostat

Phase I

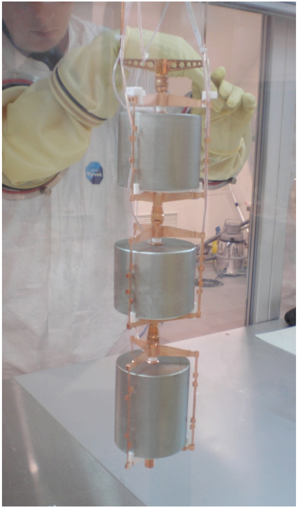
The Detectors

- Closed-ended coaxial detectors
- 8 diodes from HdM and IGEX enriched in ^{76}Ge
- 6 diodes from Genius test facility, natural Ge
- $\sim$ 15 kg of ^{76}Ge

The Goals

Test Klapdor's Claim

Exposure	15 kg y
Background	10^{-2} cts/(keV kg y)
Half-life	$T_{1/2} > 2.2 \times 10^{25}$ y
Majorana mass	$m_{ee} < 0.27$ eV



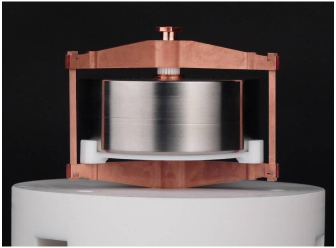
Phase II

The Detectors

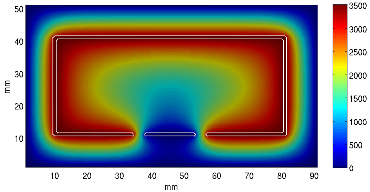
- All Phase I detectors
- Broad-Energy Germanium (BEGe) detectors enriched in ^{76}Ge
- A total of ~ 40 kg of ^{76}Ge

The Goals

Exposure	100 kg y
Background	10^{-3} cts/(keV kg y)
Half-life	$T_{1/2} > 15 \times 10^{25}$ y
Majorana mass	$m_{ee} < 0.11$ eV

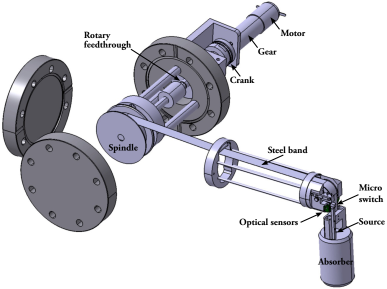


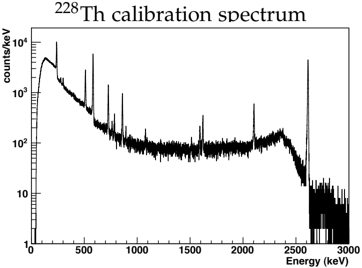
Electric potential [V]



Agostini 2009, Master thesis

Detector Performance
Calibration Runs





- Deployment of first string with three detectors in June 2010
- Natural Ge detectors used to study performance and background
- Calibration with up to 3 ^{228}Th sources
- Energy resolution (FWHM@2.6 MeV):
  Coaxial: 3.6 keV to $\sim$ 5 keV
  BEGe: 2.8 keV
- Optimization of offline pulse processing to improve energy resolution ongoing

Background

^{42}Ar / ^{42}K

The Surprise

Background a factor of ~ 18 higher than Phase I goal

Explanation: ^{42}Ar / ^{42}K

- GERDA proposal: $^{42}\text{Ar}/^{\text{nat}}\text{Ar} < 3 \cdot 10^{-21}$ Barabash et al. 2002
- True value up to $\times 10$ higher

^{42}Ar

$T_{1/2} = 32.9$ y

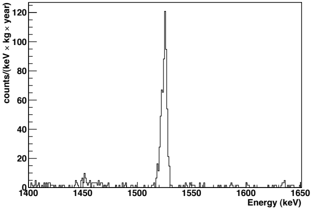
$Q_\beta = 599$ keV

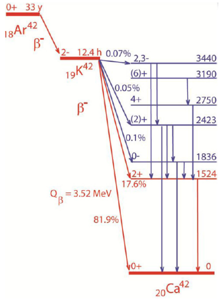
^{42}K

$T_{1/2} = 12.36$ h

$Q_\beta = 3525$ keV

^{42}K line at 1525 keV





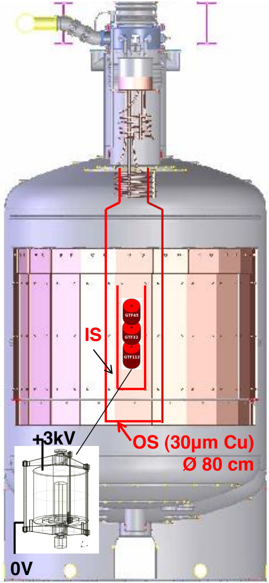
Background Improvements

The Theory

High-energy background from β-decays of ^{42}K ions collected on the outer surface of the detector

The Solution: Cu Cylinder

- Cu foil cylinder with an inner diameter of 113 mm
- Reduces volume which the ions can be collected
- Can be biased with $\pm$ HV
- Reduces background in ROI by a factor of ~ 3



Background in Low Energy Region

^{39}Ar

Consistent with Monte Carlos and activity of 1Bq/kg

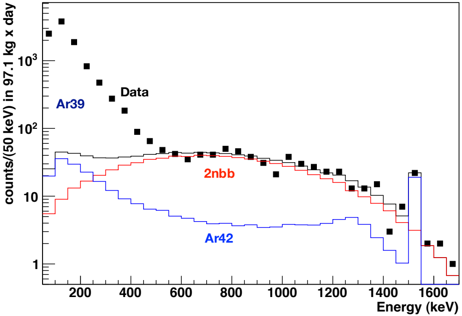
^{42}Ar

Contribution normalized to 1525 keV line

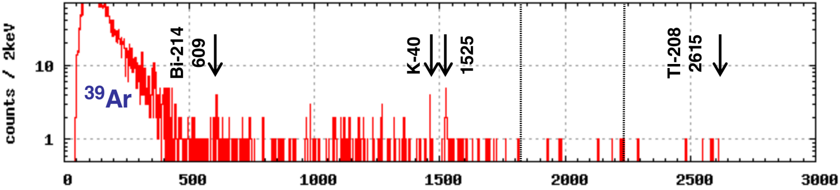
$2\nu\beta\beta$

Predictions for specrum with $T_{1/2} = 1.74 \cdot 10^{21}$ y

First energy spectrum of enriched detector



Background in Region of Interest



Combination of

- Residual ^{42}K background
- Compton continuum events from Th/U decays
- Degraded α particles
- Background from cosmogenically produced isotopes in the detectors

More statistics needed for spectral analysis

Best Result

$$0.055 \pm 0.023 \text{ cts/(keV kg y)}$$

Phase I

Current Run

- First string with enriched detectors deployed in June 2011
- Now 6 detectors running: 3 enriched, 3 natural Ge
- Cu cylinder installed and grounded
- Background comparable with past runs
- Data taking ongoing to improve statistics

Plan

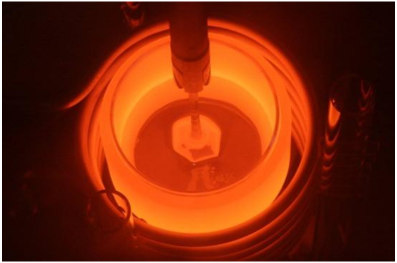
- 5 more detectors ready
- Physics run will start soon
- Pulse shape analysis to improve background in progress
- Different possibilities to instrument LAr under investigation

Phase II

Detector Production

Enriched $^{76}GeO_2$	ECP Zelenogorsk, RU
Metal Reduction & Zone Refinement	Langelsheim, DE
Crystal Pulling	Canberra, Oakridge, TN, USA
BEGe Detector Production	Canberra, Olen, BE

Production chain tested with depleted Ge



Conclusion

- Neutrinoless double beta decay can answer questions about mass and nature of neutrino
- Detectors running stable with improvable energy resolution
- Background with 0.055 cts/(keV kg y) already factor of 2-3 lower than Heidelberg-Moscow
- Installation of more detectors to understand background contributions, more studies ongoing
- Initially high count rate of ^{42}Ar could be reduced with Cu cylinder
- First GERDA physics run will start soon

The GERDA Collaboration

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ADDITIONAL MATERIAL

Nuclear Matrix Elements

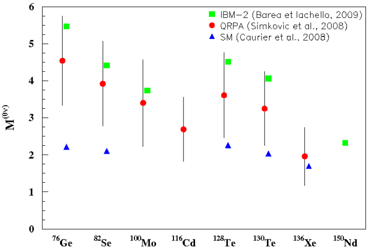
Three different methods for calculation:

Nuclear Shell Model (SM) Uses Pauli exclusion principle to describe the structure of the nucleus in terms of energy levels

Quasi-Particle Random Phase Approximation (QRPA) Uses 3 parameters accounting for pairing, particle-particle and particle-hole interactions.

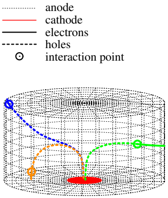
Interacting Boson Model (IBM) Bosons can interact through 1- and 2-body interactions giving rise to bosonic wave functions.

- QRPA and IBM (coincidentally?) in agreement
- SM a factor of 2 lower

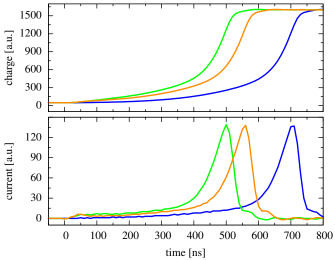


Pulse Shape Discrimination with BEGe's

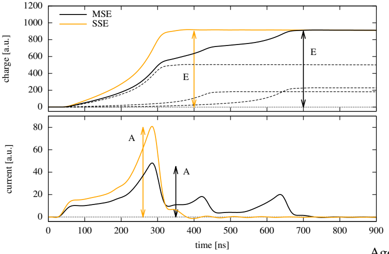
Trajectories



Signal for different trajectories



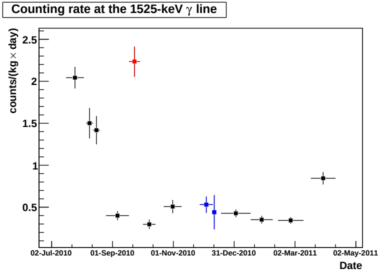
Discrimination between single-scatter and multi-scatter events



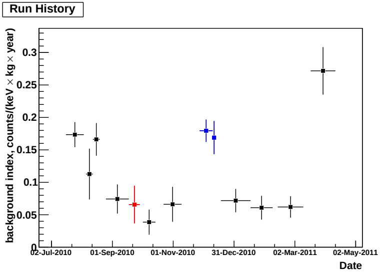
Agostini et al. JINST, 6 (2011) P03005

Background History

Counts in 1525 γ line

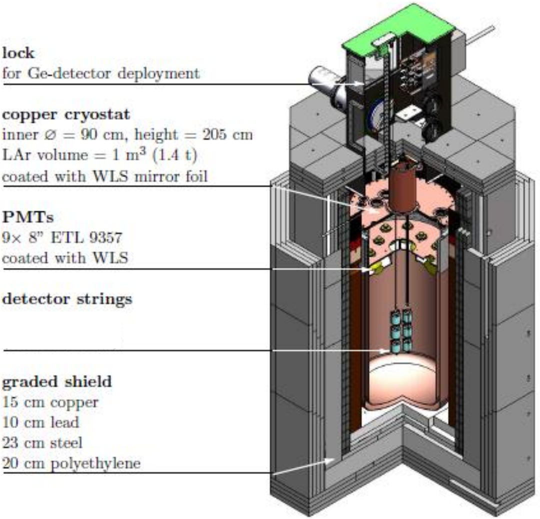


Background in the region of interest



Red: Run with electrical field attracting electrical field
Blue: Run with BEGe

R&D Liquid Argon Instrumentation



GERDA-LArGe

- Low background test facility at LNGS
- Detection of coincident liquid argon scintillation light to discriminate background