GERMANIUM DETECTOR ARRAY

A search for neutrinoless double beta decay

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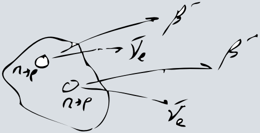
GERDA

Neutrinoless Double Beta Decay

Effective Majorana Neutrino Mass

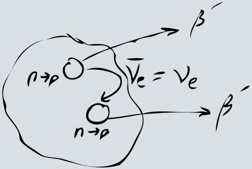
$2\nu\beta\beta$ $(A, Z) \rightarrow (A, Z+2) + 2e^- + 2\bar{\nu}_e$

SM allowed and observed in many isotopes.



$0\nu\beta\beta$ $(A, Z) \rightarrow (A, Z+2) + 2e^-$

$\Delta L = 2$



Half-life

$$(\mathrm{T}^{0\nu}_{1/2})^{-1} = \mathrm{G}^{0\nu} \cdot |\mathrm{M}^{0\nu}|^2 \cdot \langle m_{\beta\beta} \rangle^2$$

$\mathrm{G}^{0\nu}$: Phase space integral

$\mathrm{M}^{0\nu}$: Nuclear matrix elements

$\langle m_{\beta\beta} \rangle^2 = |\sum_i U_{ei}^2 m_{\nu_i}|^2$

Searching in ^{76}Ge

Experimental Design Considerations

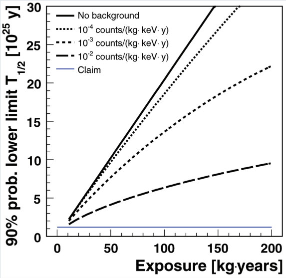
- Large target mass & long exposures
- Extreme low background levels
- High signal efficiency

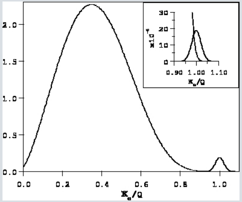
Advantages of Germanium

- Source $\leftrightarrow$ Detector
  High signal efficiency $\sim$ 85–95%
- Ultrapure material, High Purity Ge
- High resolution (FWHM $\sim$0.1-0.2%)
  Helps to reduce background from $2\nu\beta\beta$
  and avoid γ's from the Compton continuum.
- Vast experience base

Disadvantages

- $Q_{\beta\beta}$=2039 keV, still plenty of γ's
- Enrichment is possible, but expensive!
- Limited sources of crystal & detector manufacturers





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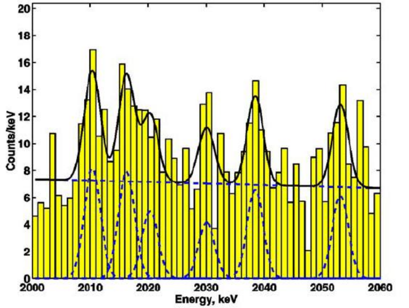
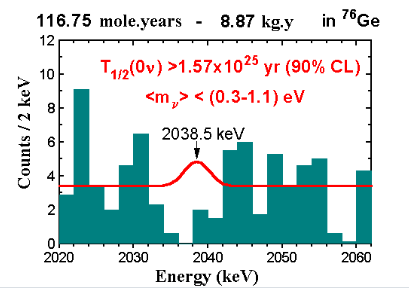
Previous ^{76}Ge Experiments

	HdMo	IGEX		
Location	LNGS	Homesteak	Baksan	Canfranc
Overburden [m.w.e.]	3800	4000	660	2450
Exposure [kg · yr]		2.4	2.5	4.0
	71.1		8.9	
Bg [counts/kg·keV·yr]	0.11		0.17	
$T_{1/2}$ limit (90% CL)[yr]	1.9×10^{25}		1.57×10^{25}	

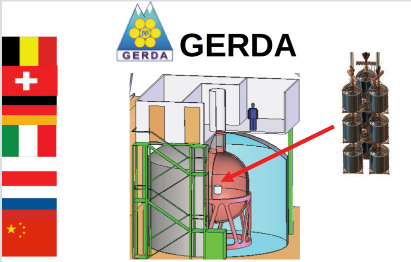
"Evidence for $0\nu\beta\beta$" $0.69 - 4.18 \times 10^{25}$ [yr] 3σ

H.V. Klapdor-Kleingrothaus, *et. al*, Phys. Lett. B 586 (2004) 198-212

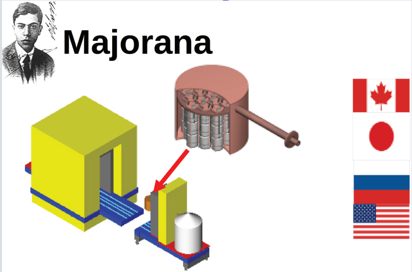




Two New ^{76}Ge Projects



- 'Bare' ^{enr}Ge array in liquid argon
- Shield: high-purity liquid argon/H_2O
- Phase I: 18 kg (HdMo/IGEX)/15 kg nat.
- Phase II: add $\sim$ 20 kg new enr. detectors total $\sim$ 40 kg



- Array(s) 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.)

Physics goals: degenerate mass range
Technology: study of bgds. and exp. techniques

LoI
- open exchange of knowledge & technologies (e.g. MaGe MC)
- intention to merge for O(1 ton) exp. (inv. Hierarchy) selecting the best technologies tested in GERDA and Majorana

GERDA Collaboration

INFN Laboratori Nazionali del Gran Sasso, Assergi, Italy
Institute of Physics, Jagellonian University, Cracow, Poland
Institut für Kern- und Teilchenphysik, Technische Universität Dresden, Germany
Joint Institute for Nuclear Research, Dubna, Russia
Institute for Reference Materials and Measurements, Geel, Belgium
Max-Planck-Institut für Kernphysik, Heidelberg, Germany
Dipartimento di Fisica, Universitá Milano Bicocca, Milano, Italy
INFN Milano Bicocca, Milano, Italy
Dipartimento di Fisica, Universitá degli Studi di Milano e INFN Milano, Milano, Italy
Institute for Nuclear Research of the Russian Academy of Sciences, Moscow, Russia
Institute for Theoretical and Experimental Physics, Moscow, Russia
Russian Research Center Kurchatov Institute, Moscow, Russia
Max-Planck-Institut für Physik (Werner-Heisenberg-Institut), München, Germany
Physik Department E15, Technische Universität München, Germany
Dipartimento di Fisica dell'Universitá di Padova, Italy
INFN Padova, Padova, Italy
Shanghai Jiaotong University, Shanghai, China
Physikalisches Institut, Eberhard Karls Universität Tübingen, Germany
Physik Institut der Universität Zurich, Switzerland

100 Members
19 Institutes
7 Countries

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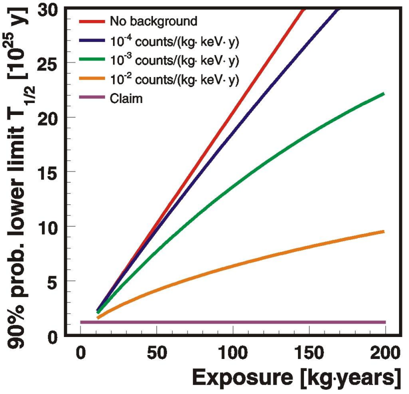
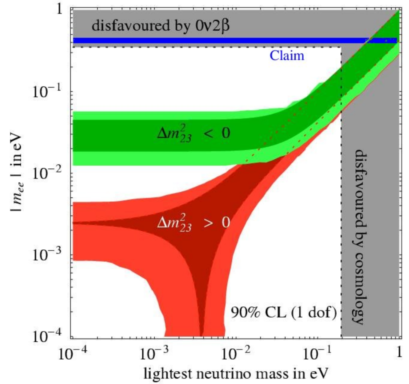
GERDA Physics Goal

Phase	I	II
Exposure [kg·yr]	15	100
Bg [counts/kg·keV·yr]	10^{-2}	10^{-3}
Upper limit $m_{\beta\beta}$[eV]	0.23-0.39	0.09-0.15

A. Smolnikov, P. Grabmayr

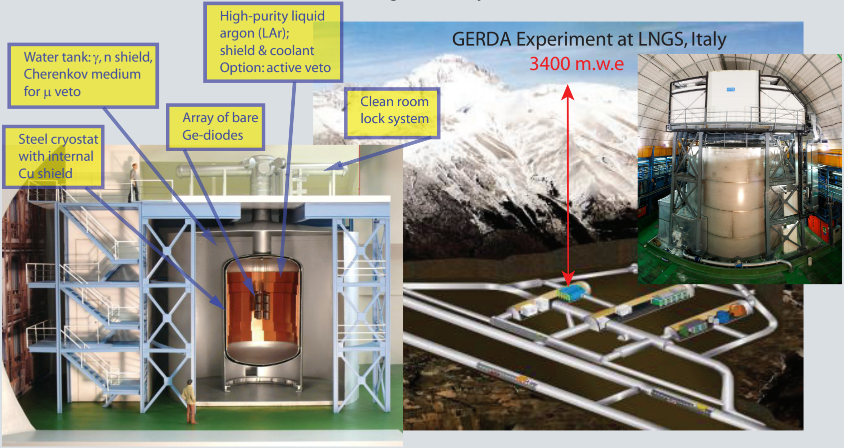
PRC 81 028502(2010)





Background Reduction

Deep underground site for suppression of cosmic ray muons
Graded shielding against ambient radiation
Rigorous material selection
Signal Analysis



Suppression of μ-flux $> 10^6$

Unloading of vacuum cryostat
(6 March 08)

Produced from selected
low-background austenitic steel

Construction of water tank

∅ 10 m

H = 9.5 m

V = 650 m^3

Designed for external γ,n,μ background ~10^{-4} cts/(keV kg y)


construction of clean room
27 feb 09

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Water tank and cryostat prior muon veto installations


WT and cryostat with muon veto installed


"Pill box"

Glove-box for Ge-detector handling and mounting into commissioning lock under N_2 atmosphere installed in clean room

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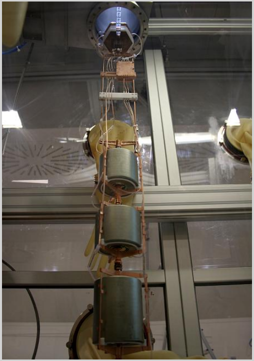
- **Nov/Dec.'09**: Liquid argon fill
- **Jan '10:** Commissioning of cryogenic system
- **Apr/Mai '10:** emergency drainage tests of water tank
- **Apr/Mai '10:** Installation c-lock
- **May '10:** 1st deployment of FE&detector mock-up (27 pF) - pulser resolution 1.4 keV (FWHM); first deployment of non-enriched detector
- **June '10:** Start of commissioning run with ^{nat}Ge detector string
- **Soon**: start of Phase I physics data taking

Background Measurements

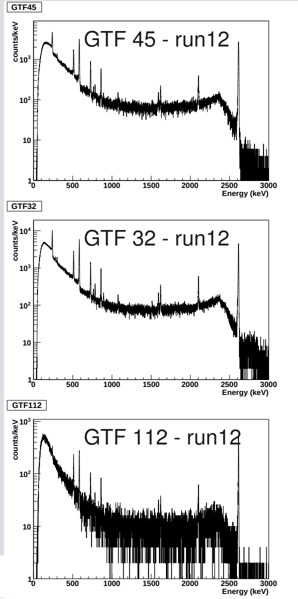
Commissioning Lock PLC

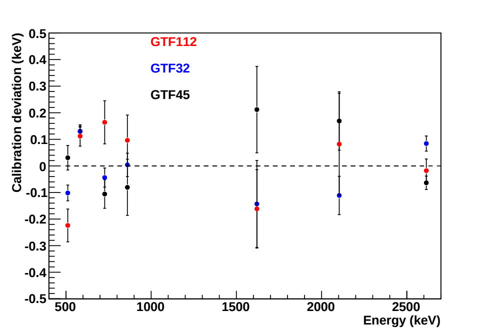
Natural Genius-TF Detectors



Commissioning runs with non-enriched low-background detectors to study performance and backgrounds

Energy Calibration with ^{228}Th γ-Source



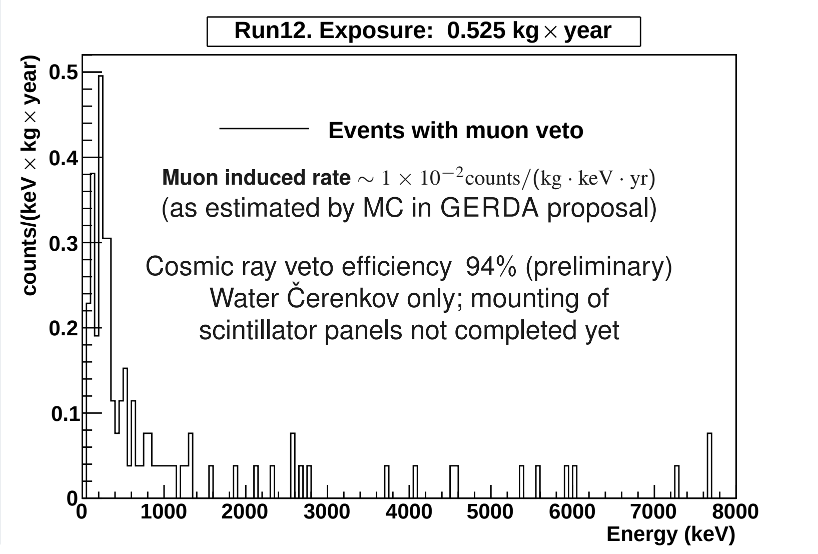


Energy Resolution in GERDA during commissioning

Dependant on chosen detector configuration

In range 3.6 keV-6keV FWHM @ 2.6 MeV

Muon induced events

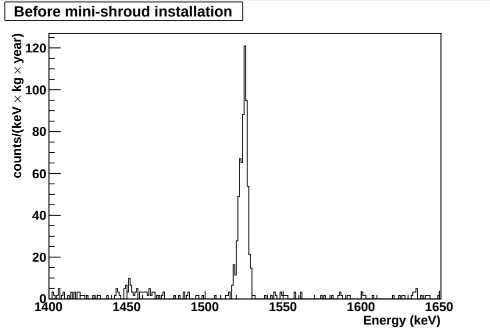


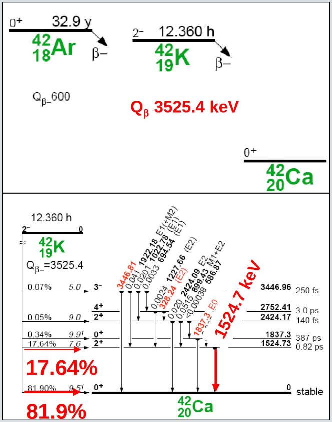
The Unexpected $^{42}\mathrm{Ar}(^{42}\mathrm{K})$ Signal

GERDA **Proposal:** $^{42}\mathrm{Ar}/^{\mathrm{nat}}\mathrm{Ar} < 3 \times 10^{-21}$

[Barabash et al. 2002]

GERDA **Measurement:**

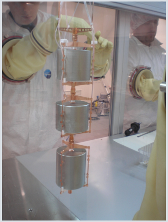


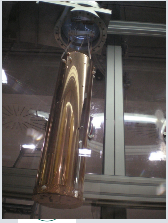


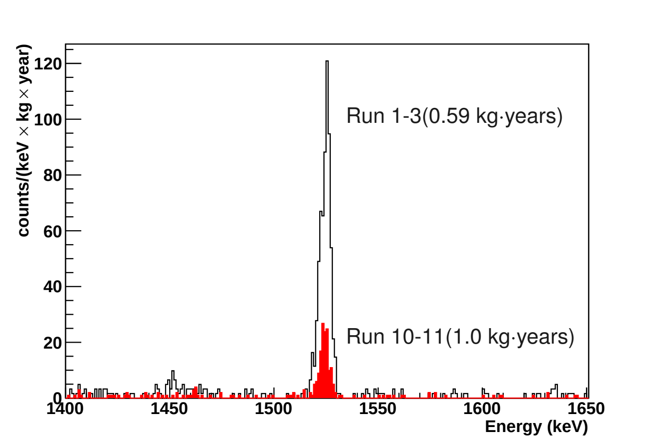
- True Value could be x10 higher than limit
- Additional enhancement of count rate due to collection of ^{42}K ions by E-field of diodes

if ^{42}K decay on detector surface $\Rightarrow$ bgd to $0\nu\beta\beta$

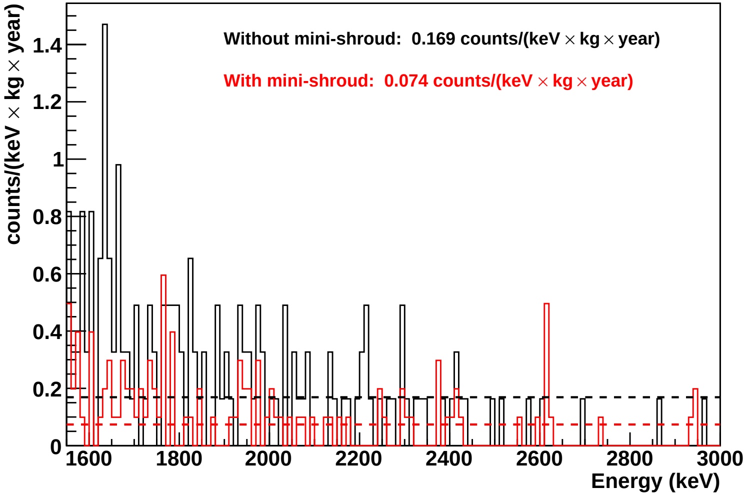
E-Field Enhancement of ^{42}K Peak Rate



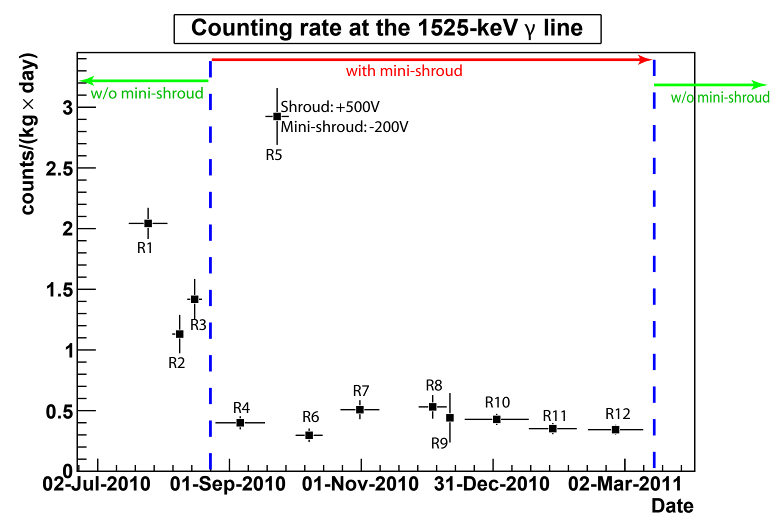




E-Field Enhancement of ^{42}K
High Energy Rate



Summary of Commissioning Runs (Non-Enriched Detectors)



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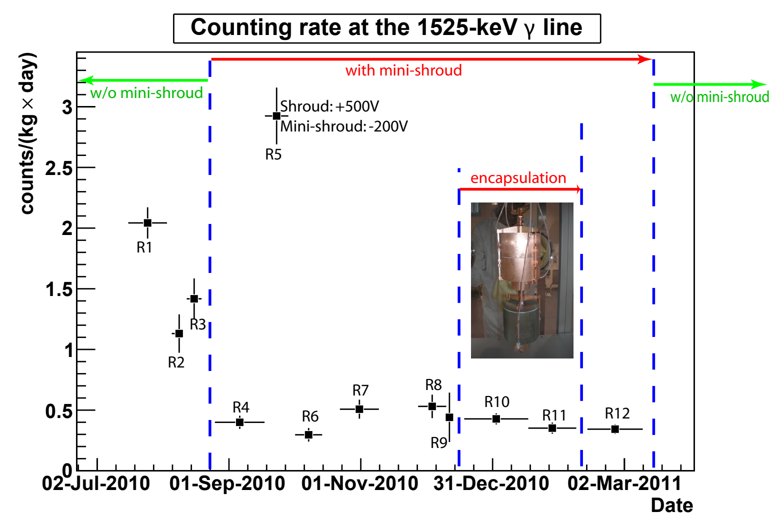

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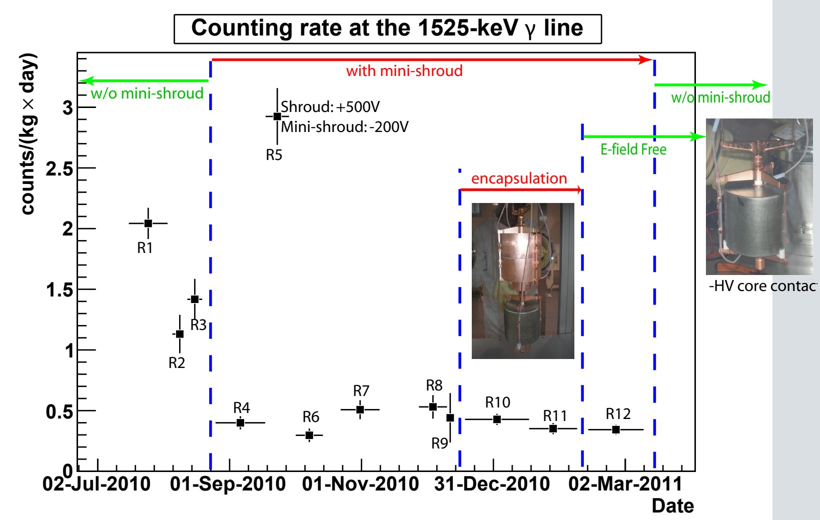

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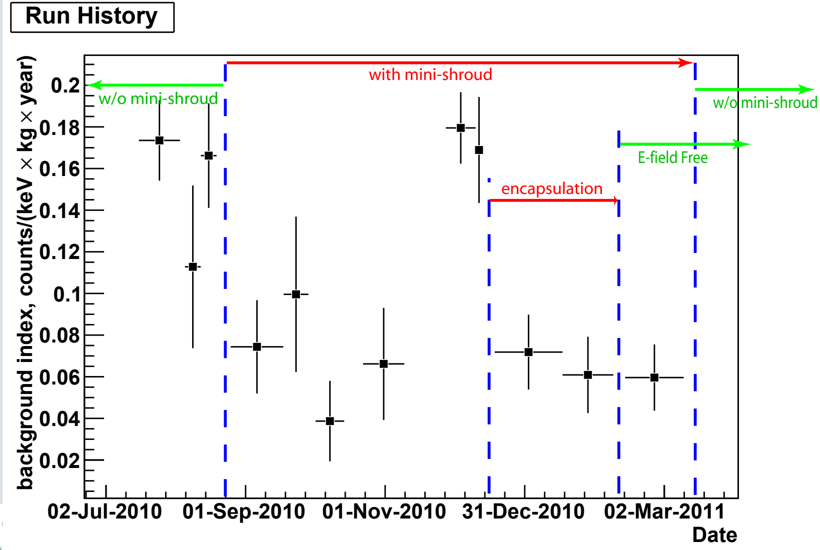
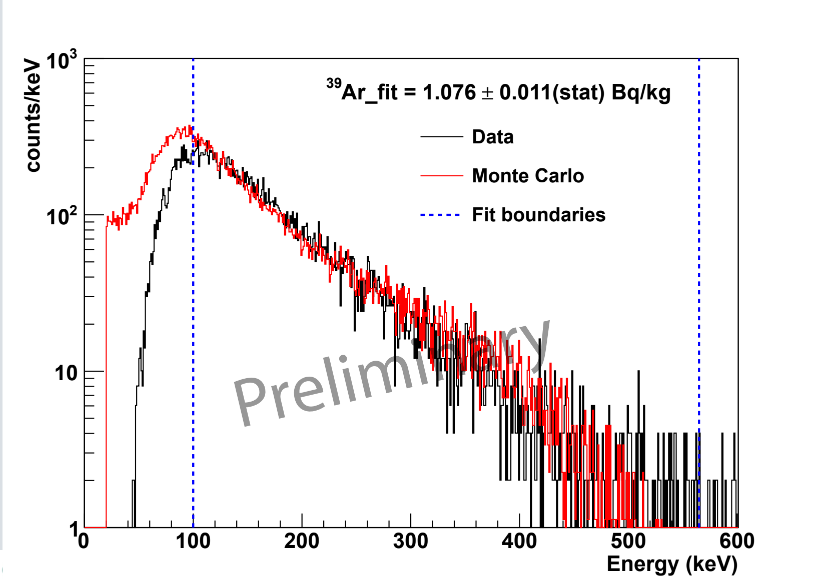
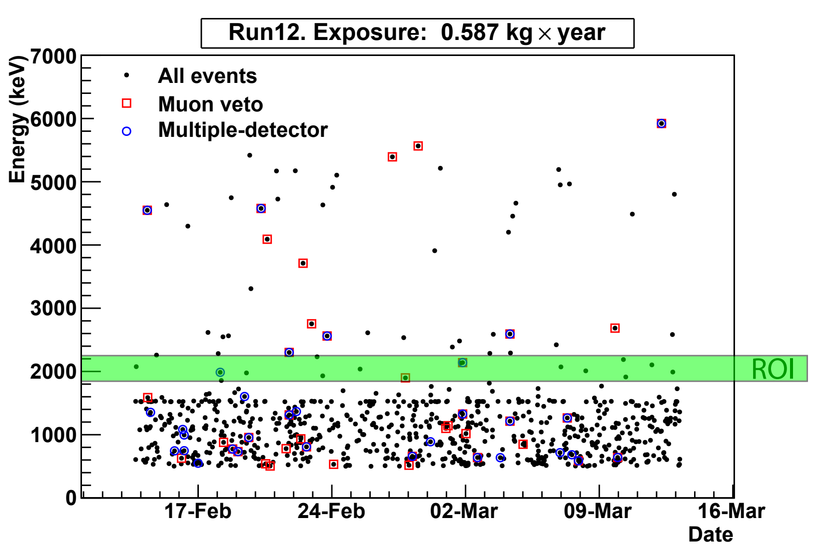


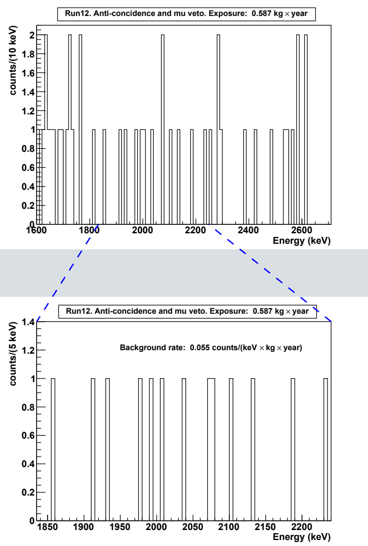
The Low Energy Spectrum: ^{39}Ar

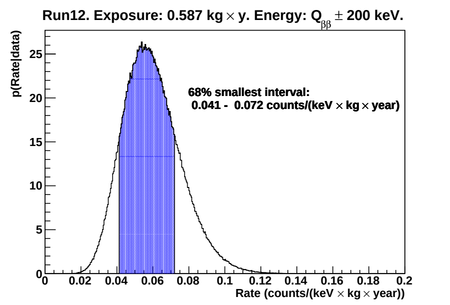


Event Time Distribution



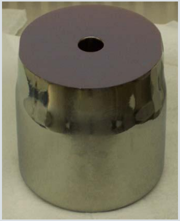
Count Rate in Region of Interest

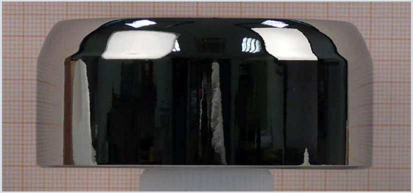




- Bgd rate significantly lower than previous experiments (HdMo, IGEX), but still higher than Phase I bgd goal (0.01 cnts/$(\mathrm{kg} \cdot \mathrm{keV} \cdot \mathrm{yr})$)
- Possible cosmogenic bgd contribution due to exposure history of diodes
- Run 13: ”Field-free” (n+ outer contact @0V) & removal of mini-shroud
- Deployment of 3 enriched detectors with known low activation history

GERDA Detectors





Phase I

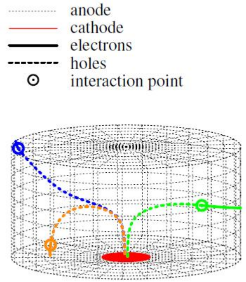
- 3 IGEX & 5 HdMo Detectors 17.9 kg
- (6 non-enriched Genius-TF for reference)

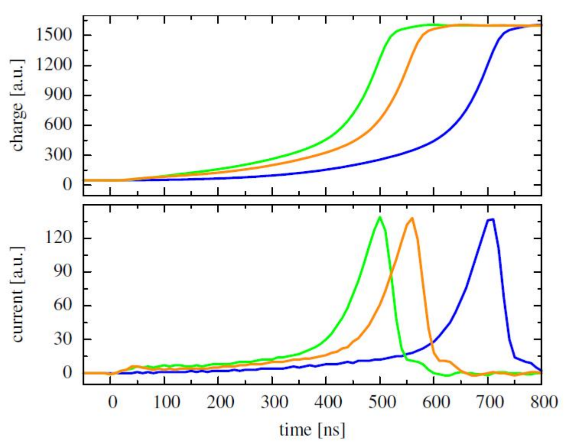
Phase II

- 35 kg 6N enriched Ge Metal
- 18 kg Detector slices expected for BEGe diode production
- IKZ Crystal pulling R&D for segmented detectors

Background Identification

- Time structure of the charge signal: Pulse Shape Analysis





- Granulation/Segmentation: 18 fold-segmented n-type detectors
- Liquid Argon Veto Instrumentation

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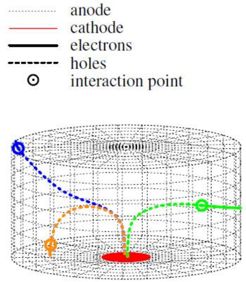

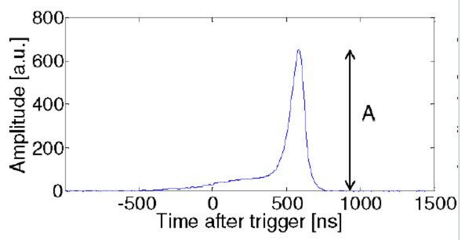

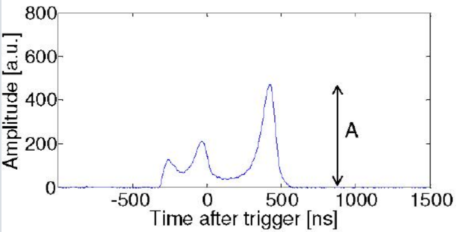

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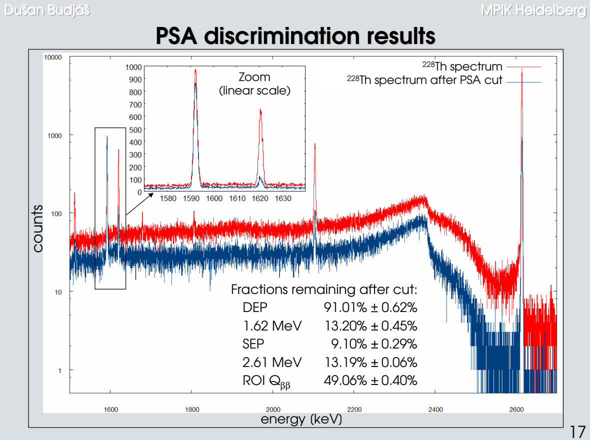

D. Budjáš *et al.*, J INST 4 P10007(2009)

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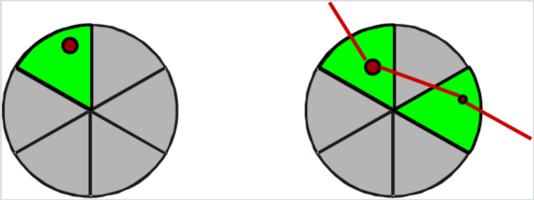

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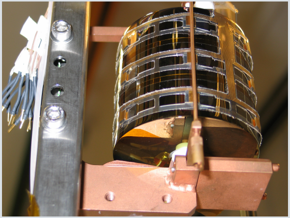

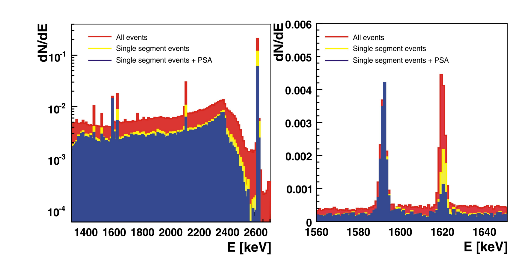

I. Abt *et al.* EPJ C 52(2007)
I. Abt *et al.* NIM A 583(2007)

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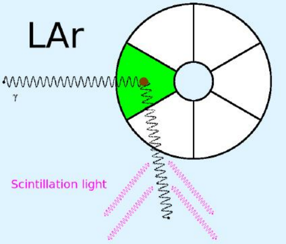

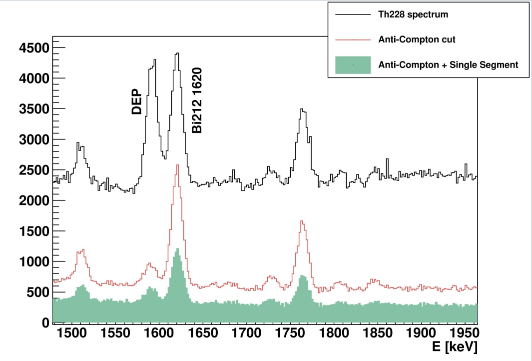

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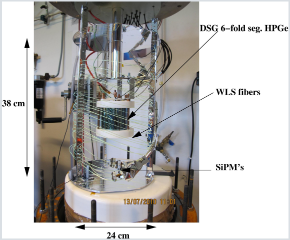
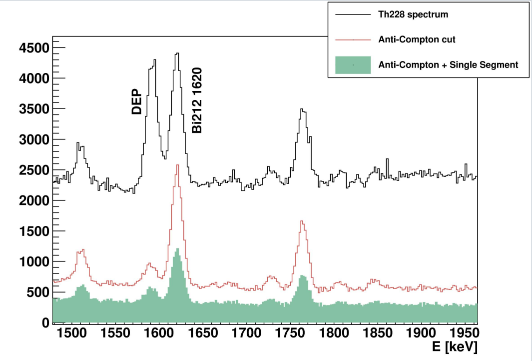


J. Janisckó-Csáthy *et al.*, arXiv:1011.2748v1 [physics.ins-det]



Phase II Detector Production

- Purchase Enriched $^{76}GeO_2$: ECP Zelenogorsk, RU

- Metal Reduction and Zone Refinement: Langelsheim, DE 08.03.2010 to 30.4.2010
- Crystal Pulling at Canberra: Oakridge, TN, USA
- BEGe Detector Diode Production: Olen, BE
- Crystal Pulling Institut für Kristallzüchtung: Berlin, DE
- Segmented Detector Diode Production: Lingolsheim, Fr

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35.5 kg Enriched HPGe 6N material

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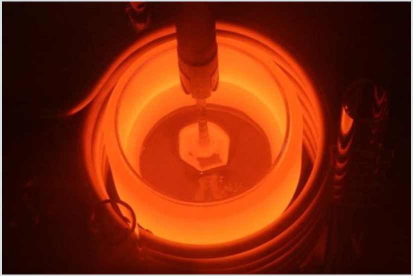

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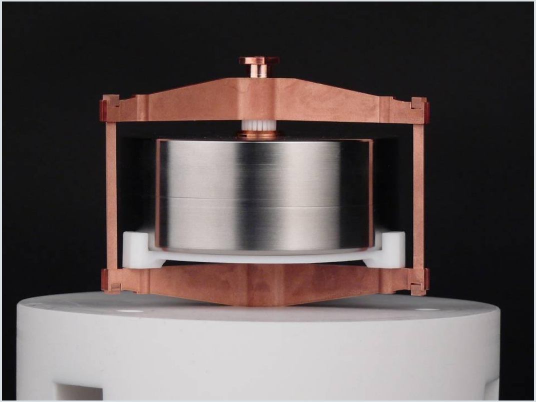

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- Segmented Detector Diode Production: Lingolsheim, Fr

Phase II Detector Production

- Purchase Enriched $^{76}GeO_2$: ECP Zelenogorsk, RU
- Metal Reduction and Zone Refinement: Langelsheim, DE 08.03.2010 to 30.4.2010
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- BEGe Detector Diode Production: Olen, BE
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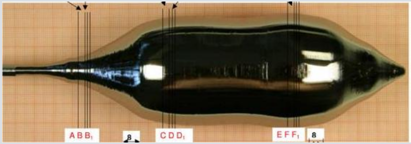

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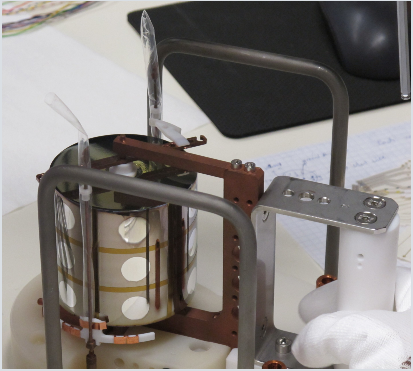
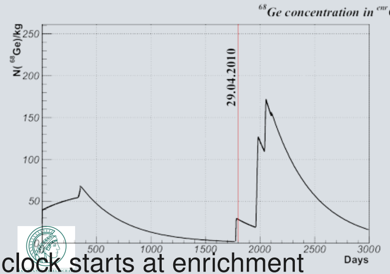
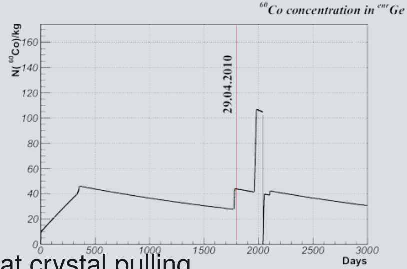


Production Chain Worldwide





clock starts at enrichment

at crystal pulling

Production Chain Worldwide

GERDA

Conclusions

- GERDA experimental installations completed
  cryogenic and auxiliary systems operations stable
- Detector commissioning with non-enriched detectors started summer 2010 and is ongoing
- Initial count rate dominated by increased $^{42}\mathrm{K}$ ($^{42}\mathrm{Ar}$ progenitor) concentration due to diode E-field $\Rightarrow$ "Field-free" configuration identified
- Background with non-enriched detectors currently at 0.05 cts/$(\mathrm{kg} \cdot \mathrm{keV} \cdot \mathrm{yr})$. Goal for Phase I: 0.01 cts/$(\mathrm{kg} \cdot \mathrm{keV} \cdot \mathrm{yr})$.
- Deployment of first string(s) with enriched detectors, Phase I, to start soon
- Thick window p-type BEGe detectors for Phase II, production chain has been tested on depleted Ge
- 37.5 kg of 86% $^{\mathrm{enr}}\mathrm{Ge}$ $(\mathrm{GeO_2})$ reduced and purified to 35.4 kg 6N HPGe
- Crystal pulling and detector production under preperation

Neutrino Properties

Simplest explanation for observations by 3-neutrino flavor mixing

Quark Mixings

Weakly interacting and mass eigenstates are independant basis

$$\begin{bmatrix} |d'\rangle \\ |s'\rangle \\ |b'\rangle \end{bmatrix} = \begin{bmatrix} V_{ud} & V_{us} & V_{ub} \\ V_{cd} & V_{cs} & V_{cb} \\ V_{td} & V_{ts} & V_{tb} \end{bmatrix} \begin{bmatrix} |d\rangle \\ |s\rangle \\ |b\rangle \end{bmatrix}$$

$$V_{ij} = \begin{bmatrix} c_{12}c_{13} & s_{12}c_{13} & s_{13}e^{-i\delta_{13}} \\ -s_{12}c_{23} - c_{12}s_{23}s_{13}e^{i\delta_{13}} & c_{12}c_{23} - s_{12}s_{23}s_{13}e^{i\delta_{13}} & s_{23}c_{13} \\ s_{12}c_{23} - c_{12}c_{23}s_{13}e^{i\delta_{13}} & -c_{12}s_{23} - s_{12}c_{23}s_{13}e^{i\delta_{13}} & c_{23}c_{13} \end{bmatrix}$$

Neutrino Properties

Simplest explanation for observations by 3-neutrino flavor mixing

Neutrino Mixings

Weakly interacting and mass eigenstates are independant basis

$$\begin{bmatrix} |\nu_e\rangle \\ |\nu_\mu\rangle \\ |\nu_\tau\rangle \end{bmatrix} = \begin{bmatrix} U_{e1} & U_{e2} & U_{e3} \\ U_{\mu 1} & U_{\mu 2} & U_{\mu 3} \\ U_{\tau 1} & U_{\tau 2} & U_{\tau 3} \end{bmatrix} \begin{bmatrix} |m_1\rangle \\ |m_2\rangle \\ |m_3\rangle \end{bmatrix}$$

$$U_{\nu i} = \begin{bmatrix} c_{12}c_{13} & s_{12}c_{13} & s_{13}e^{-i\delta_{13}} \\ -s_{12}c_{23} - c_{12}s_{23}s_{13}e^{i\delta_{13}} & c_{12}c_{23} - s_{12}s_{23}s_{13}e^{i\delta_{13}} & s_{23}c_{13} \\ s_{12}c_{23} - c_{12}c_{23}s_{13}e^{i\delta_{13}} & -c_{12}s_{23} - s_{12}c_{23}s_{13}e^{i\delta_{13}} & c_{23}c_{13} \end{bmatrix} \begin{bmatrix} 1 & 0 & 0 \\ 0 & e^{i\frac{\alpha_{21}}{2}} & 0 \\ 0 & 0 & e^{i\frac{\alpha_{31}}{2}} \end{bmatrix}$$

Neutrino Properties

Observed Properties

Two mass differences

- $m_2^2 - m_1^2 = \Delta m_\odot^2$
- $|m_1^2 - m_3^2| = \Delta m_{atm}^2$

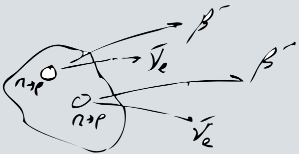
Two mixing angles

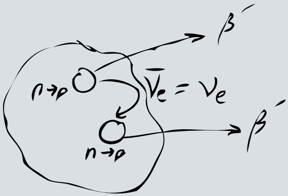
- $\theta_{12} = \theta_\odot$ and $\theta_{23} = \theta_{atm}$

and an upper limit on θ_{13}

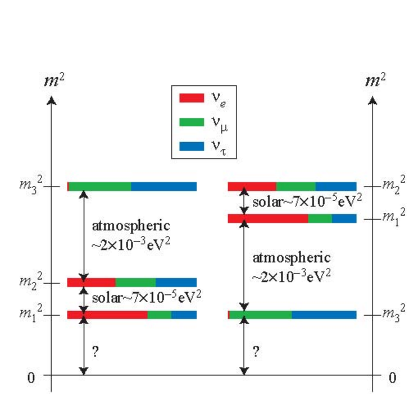
Still Missing

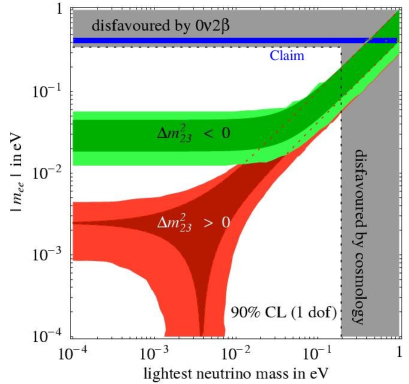
- Value of the third mixing angle
- Absolute mass scale
- Mass hierarchy
- CP violating phases
- Nature of the neutrino mass (Majorana or Dirac)





The Hierarchy Problem





F. Feruglio *et al.*, Nucl. Phys. B 637(2002)