The search for neutrino-less double beta decay with GERDA @ LNGS: Results from the commissioning and start-up of Phase I

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On behalf of the GERDA collaboration

Workshop in Celebration of SNOLAB’s Grand Opening
May 14-16, 2012, SNOLAB
~ 100 members
19 institutions
6 countries

Characteristics of $^{76}\text{Ge}$ for $0\nu\beta\beta$ search

- **Favorable nuclear matrix** element $|M^{0\nu}| = 3 - 9$
- **Reasonable slow $2\nu\beta\beta$ rate** ($T_{1/2} = 1.4 \times 10^{21}$ y) and **high $Q_{\beta\beta}$ value** ($2039$ keV)
- Ge as **source and detector**
- **Elemental Ge** maximizes the source-to-total mass ratio
- **Industrial techniques** and facilities available to enrich from 7% to ~87%
- **Intrinsic high-purity** Ge diodes & HP-Ge detector technologies well established
- **Excellent energy resolution**: FWHM ~3 keV at 2039 keV (0.16%)
- **Powerful signal identification & background rejection possible with novel detector concepts**:
  - time structure of charge signal (PSA) using BEGe detectors
  - liquid argon scintillation as **active veto system**
- **Best limits** on $0\nu\beta\beta$ - decay used Ge (IGEX & Heidelberg-Moscow) $T_{1/2} > 1.9 \times 10^{25}$ y (90%CL) [*& claim for evidence*]
Two $^{76}$Ge projects:

**GERDA**
- ‘Bare’ $^{enr}$Ge array in liquid argon
- Shield: high-purity liquid Argon / $H_2O$
- Phase I: 18 kg (HdM/IGEX) / 15 kg nat.
- Phase II: add ~20 kg new enr. detectors; total ~40 kg

**Majorana**
- Array(s) of $^{enr}$Ge housed in high-purity electroformed copper cryostat
- Shield: electroformed copper / lead
- Initial phase: R&D demonstrator module: Total ~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
Phases and physics reach

required for ‘background free’ exp. with $\Delta E \sim 3.3$ keV (FWHM):

$$O(10^{-3}) \quad O(10^{-4}) \quad \text{counts}/(\text{kg} \cdot \text{y} \cdot \text{keV})$$

Background requirement for GERDA/Majorana:

$\Rightarrow$ Background reduction by factor $10^2 - 10^3$ required w.r. to precursor exps.

$\Rightarrow$ Degenerate mass scale $O(10^2 \text{ kg} \cdot \text{y})$ $\Rightarrow$ Inverted mass scale $O(10^3 \text{ kg} \cdot \text{y})$

assuming $|M^{0\nu}| = 2.99 - 8.99$
[Smol&Grab PRC’ 10] and 86% enrichment

$2 \cdot 10^{27}$ (90 % CL) *

$2 \cdot 10^{26}$ (90 % CL) *

$2 \cdot 10^{25}$ (90 % CL)*

KK

*: no event in ROI

$< 24 - 41 \text{ meV}$

$< 75 - 129 \text{ meV}$

$O(10^{-3}) \quad O(10^{-4}) \quad \text{counts}/(\text{kg} \cdot \text{y} \cdot \text{keV})$
GERDA @ LNGS

- clean room with lock
- plastic $\mu$-veto
- muon & cryogenic infrastructure
- control rooms
- water plant & radon monitor
- Ge-detector array (enriched in $^{76}$Ge)
- cryostat, Ø4m, with internal Cu shield
- water tank, Ø10m, part of muon-veto detector
- 14.8m

GERDA @ LNGS
GERDA construction: 2008-2010

March 2008

6 April 2009
Earthquake
negligible impact on lab - but on people...

GERDA construction: 2008-2010
Phase I detectors

8 diodes (from HdM, IGEX):
- Enriched 86% in $^{76}$Ge
- Total mass 17.66 kg

- All diodes reprocessed and optimized for LAr
- Well tested procedure for detector handling
- Long term stability in LAr established
- Energy resolution in LAr: $\sim2.5$ keV (FWHM) @1.3 MeV

6 diodes from Genius-TF:
- $\text{nat}^{74}$Ge
- Total mass: 15.60 kg
Commissioning runs (with non-enriched detectors)

Calibration with $^{228}$Th:

- **GTF 45**:
  - Energy resolutions during commissioning:
  - Coaxial (Phase I): 4-5 keV (FWHM) @ 2.6 MeV
  - BEGe (Phase II): 2.8 keV (FWHM) @ 2.6 MeV

- **GTF 32**:
- **GTF 112**:

Commissioning runs with non-enriched low-background detectors to study performance and backgrounds (June 2010 – Mai 2011)
Commissioning runs:
The unexpected $^{42}\text{Ar}$ ($^{42}\text{K}$) signal

**GERDA proposal:** $^{42}\text{Ar}/^{\text{nat}}\text{Ar} < 3 \cdot 10^{-21}$

[Barabash et al. 2002, Final publication: 2.3 $10^{-21}$ ]

**GERDA measurement:**

- measurement in apparent contradiction with limit from literature
- however enhancement of count rate by collection of $^{42}\text{K}$ ions by E-field of diodes
Commissioning runs:
Rate of $^{42}\text{K}(^{42}\text{Ar})$: 1525 keV peak

Two spectra normalized to the same exposure
Commissioning runs:
Rate of $^{42}\text{K}$: high-energy region

Without mini-shroud (Run 1-3): 0.169 counts/(keV kg year)

With mini-shroud (Run 4): 0.074 counts/(keV kg year)
Last commissioning runs (June – September 2011): 3 *enriched* + 5 non-enriched detectors

- All detectors installed inside new mini-shrouds
- First GERDA $2\nu\beta\beta$ spectrum measured!
- Ready to deploy all enriched detectors
Commissioning phase completed: all enriched detectors in GERDA since October 2011!
Commissioning phase completed: all enriched detectors in GERDA in October 2011!
Phase I started on 1.11.11!
First $^{228}$Th calibration spectra
Energy spectrum

(data from 9 Nov. 2011 until 16 Feb. 2012)

Enriched detectors, 3.80 kg × year

40 keV blinded window (energy resolution at $Q_{\beta\beta}$: 4.5 keV (FWHM))

Natural detectors, 1.97 kg × year
GERDA Phase I: $2\nu\beta\beta$ spectrum

**GERDA February 2012**

$^{39}\text{Ar} (1.01 \text{ Bq/kg})$ from NIM A 574 (2007) 83

$^{40}\text{K} (\text{MC})$

$^{42}\text{Ar} (\text{MC})$

$2\nu\beta\beta$ of $^{76}\text{Ge}$ $T_{1/2} = 1.74 \times 10^{21}$ y, from NIM A 513 (2003) 596

S/B~10/1

Successful reduction of background w.r. to precursor experiments
Zoom into background spectrum of enriched detectors

Candidate background contributions at $Q_{\beta\beta}$:
- γ’s from $^{214}$Bi and $^{208}$Tl,
- degraded α’s from $^{210}$Po (and possibly $^{222}$Rn and progenitors)
- β’s from $^{42}$K
- possibly from internal contaminations like $^{60}$Co.

Quantitative estimate of their relative contributions is ongoing

Nov – Feb. (3.8 kg × y):
Background index at $Q_{\beta\beta}$ ± 200 keV:

\[ \text{enrGe: } 0.017 \pm 0.007 \pm 0.003 \text{ cts/(keV kg y)} \]

(c.f. natural detectors:
\[ \text{natGe: } 0.051 \pm 0.011 \pm 0.009 \text{ cts/(keV kg y)} \])
Background comparison

- GERDA without PSA
- Phase I - NAT
- Phase I - ENR

IGEX without PSA, NIM A515 (2003) 634
HdM without PSA, NIM A522 (2004) 371

 GERDA 12-04

Phase I goal
GERDA Phase I sensitivity

GERDA Phase I Sensitivity

Today

- Current BI, 10 keV Window, 3.5kg BEGe 1/5/2012

Assuming current BI

11. Nov.

0 5 10 15 20

Months of Running

$T_{1/2}$ 90% lower limit

$10^2$ $10^3$ $10^4$ $10^5$
Two independent measurements of $^{42}\text{Ar}$ concentration in LAr

**GERDA:**
Measurement in best ‘E-field free’ configuration & comparison MC

**LArGe:**
LAr spiked with known amount of $^{42}\text{Ar}$ & measurements at different HV

Previous best limit: <4.3 $10^{-21}$ g/g (or < 41 $\mu$Bq/kg) (90% CL), V.D. Ashitkov et al. 2003
R&D: liquid argon instrumentation for Phase II

Low background GERDA-LArGe test facility @ LNGS: Detection of coincident liquid argon scintillation light to discriminate background
R&D liquid argon instrumentation

Operation of Phase II detector prototype in LArGe:

**Measured** suppression factor at $Q_{\beta\beta}: \sim 0.5 \times 10^4$ for a $^{228}$Th calibration source

Also: successful read out scintillation light with fibers coupled to SiPMs
LAr instrumentation for Phase II

- **PMT option (Ø500)**

- **SiPM & scintillating fiber option (Ø250)**

- 3rd option: R&D on large area avalanche photodiodes or UV sensitive SiPMs on custom low activity substrates has started
- MC campaign to compare competing options ongoing
- Hardware for PMT and fiber options available & prototype/test setup construction started
**Phase II detectors**: novel thick window BEGe detectors with advanced pulse shape performance

Signal shape provides clear topology for event-by-event signal ID / bgd discrimination:
- **SSE/MSE** discrimination
- **Surface** events:
  - n+ slow pulses
  - p+: ‘amplified’ current pulses

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**Single-site (0νββ-like)**

**Multi-site (bgd: γ FE peak)**

Budjas et al., JINST 4 P10007 (2009)
M. Agostini et al., JINST 6P03005 (2011)
Suppression of $p^+$ contact pulses via PSD measured using Am-241 alpha source

<table>
<thead>
<tr>
<th>surface</th>
<th>$p^+$ contact</th>
<th>groove inner</th>
<th>groove bottom</th>
<th>groove outer</th>
</tr>
</thead>
<tbody>
<tr>
<td>event survival fraction *</td>
<td>$&lt; 0.011$</td>
<td>$&lt; 0.12$</td>
<td>$&lt; 0.009$</td>
<td>$&lt; 0.011$</td>
</tr>
</tbody>
</table>

* 90% confidence upper limits

results limited by background in test setup; improved measurement analysis under way
Suppression of n+ surface events via PSD measured using Sr-90 and Ru-106 beta sources

MC cut set to 20% survival of gamma-like events and 0.1% survival of beta-like events

good quantitative agreement of simulated suppression with measurement

Sr-90

PSD cut tuned to 90% survival of $0\nu\beta\beta$

Ru-106 beta survival fraction as a function of energy

beta n+ surface event PSD rejection power demonstrated stable in region 1 - 2 MeV

average = 0.0082(6)
Suppression of K-42 n+ and p+ events via PSD measured with BEGe detector in LArGe with spiked $^{42}$Ar

MC cut set to 20% survival of gamma-like events and 0.1% survival of beta-like events

expected surviving fraction at $Q_{\beta\beta}$: 0.13%

exp. suppression factor: 800

“Standard cut”:
$0\nu\beta\beta$ survival: 89%
K-42 survival at $Q_{\beta\beta}$: 0.4% - 2%
suppression factor: 50 - 250

“Strong cut”:
$0\nu\beta\beta$ survival: 65%
K-42 survival at $Q_{\beta\beta}$: < 0.23%
suppression factor: > 430
(90% C.L.)
Path of new 37.5 kg of $^{\text{enr}}\text{Ge}$ (87% enrichment in $^{76}\text{Ge}$): from isotope separation to final Phase II detectors

1) Isotope enrichment at ECP, Svetlana (Ru)
2) Reduction and zone refinment at Goettingen (Germany)
3) Crystal pulling at Oak Ridge (USA)
4) Detector production at Olen (Be)

To minimize activation by cosmic ray:
- Transportation by truck or ship in shielded containers
- deep underground storage
Production test of BEGe detectors from depleted Ge for GERDA Phase II

After successful test of production production chain with $^{\text{depl}}_{\text{Ge}}$:

- 37.5 kg of 86% $^{\text{enr}}_{\text{Ge}}$ (in form of GeO2) purified to 35.4 kg (94%) of 6N (+ 1.1 kg tail = 97%);
Production of enriched Ge crystals at Oak Ridge (USA) started October 17, 2011

- Crystal production started on 17\textsuperscript{th} of October
- Completion planned for June
- Production of first detectors: Jan/Feb 2012
- Autumn 2012: all Phase II detectors available

Transportation in shielded container to minimize cosmic ray activation

Ge stored underground storage when not processed
Acceptance test of enriched BEGe detectors underground at HADES facility (vicinity of Canberra, Olen, Be)

Complete detector characterization including energy resolution, dead layer, active volume, PSA, precision surface scan

<table>
<thead>
<tr>
<th>Diode</th>
<th>Crystal</th>
<th>Mass (kg)</th>
<th>Resolution (keV)</th>
<th>Average 133Ba</th>
</tr>
</thead>
<tbody>
<tr>
<td>ARCHIMEDES</td>
<td>#2432AA</td>
<td>0.5</td>
<td>1.62 ± 0.02</td>
<td>0.8</td>
</tr>
<tr>
<td>AGAMENNONE</td>
<td>#2432BB</td>
<td>0.7</td>
<td>1.64 ± 0.01</td>
<td>0.8</td>
</tr>
<tr>
<td>ANDROMEDA</td>
<td>#2432CC</td>
<td>0.7</td>
<td>1.59 ± 0.01</td>
<td>0.8</td>
</tr>
<tr>
<td>ANUBIS</td>
<td>#2432DD</td>
<td>0.7</td>
<td>1.59 ± 0.01</td>
<td>0.8</td>
</tr>
<tr>
<td>ARGO</td>
<td>#2435AA</td>
<td>0.8</td>
<td>1.60 ± 0.01</td>
<td>0.7</td>
</tr>
<tr>
<td>ACHILLES</td>
<td>#2435BB</td>
<td>0.8</td>
<td>1.65 ± 0.01</td>
<td>0.8</td>
</tr>
<tr>
<td>ARISTOTELES</td>
<td>#2435CC</td>
<td>0.6</td>
<td>1.62 ± 0.02</td>
<td>-</td>
</tr>
</tbody>
</table>

Table 2: First results of the first BEGe prototypes. The diodes have been produced from different slices (AA-DD and AA-CC) from two grown crystals (#2432 and #2435).

Production of 7 crystal slices and detector tests completed:
- All detectors have excellent energy res.: 1.7 keV (FWHM) @1.3 MeV
Conclusions & Outlook

• GERDA experimental installations completed successfully; cryogenic and auxiliary systems operate very stable
• Detector commissioning with non-enriched detectors started summer 2010 and completed September 2011
• 20 commissioning runs with different detectors, read-out schemes, E-field configurations completed successfully
• Initial count rate (run 1-3,5) dominated by $^{42}\text{K}$ ($^{42}\text{Ar}$ progenitor) due to concentration of $^{42}\text{K}$ close to the detectors by E-field of diodes ⇒ field-free configuration
• Deployment of enriched detectors Phase I in October 2011 and start of Phase I physics run 1. November 2011
• Background with enriched detectors $\sim 0.02$ cts/(keV kg year).
Conclusions & Outlook (cont.)

- Thick-window p-type BEGe detectors for Phase II
- Powerful particle ID and background discrimination by pulse shape analysis: MSE/SSE, p+ contact ($\alpha$) and n+ ($\beta$) surface events
- Full production chain tested for BEGe Phase II detectors
- 37.5 kg of 86% enrGe (in form of GeO2) successfully transformed to 35.4 kg (94%) of 6N
- Crystal pulling and detector production started October 2011, four crystals pulled successfully, first 7 detectors tested, completion: autumn 2012
- Liquid argon instrumentation shown in GERDA-LArGe test stand to be a powerful method to discriminate backgrounds: implementation in GERDA Phase II
- BEGe & LAr readout complementary background reduction methods; expect to gain more than factor 10
- Get ready for Phase II