Search for $0\nu\beta\beta$ Decay: New Results from GERDA Phase II

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Laboratoire APC, Paris, October, 23 2017
The GERDA Collaboration: searching for $0\nu\beta\beta$ decay of $^{76}\text{Ge}$

http://www.mpi-hd.mpg.de/gerda/

16 institutions ~100 members

Victoria Wagner

GERDA Phase II results

APC Paris, 23.10.2017
Double Beta Decay

Double beta decay ($2\nu\beta\beta$)
- single $\beta$ decay energetically forbidden
- $(A,Z) \to (A,Z+2) + 2e^- + 2\bar{\nu}$
- e.g. $^{76}\text{Ge}$, $^{136}\text{Xe}$, $^{130}\text{Te}$, $^{116}\text{Cd}$
- half-life of $2\nu\beta\beta$ decay of $^{76}\text{Ge}$ measured by GERDA (most recent and precise measurement):

$$T^{2\nu}_{1/2} = (1.926 \pm 0.095) \cdot 10^{21} \text{ yr}$$

arXiv:1501.02345v1
Double Beta Decay

Double beta decay (2νββ)
- single β decay energetically forbidden
- (A,Z) → (A,Z+2) + 2e⁻ + 2ν
- e.g. $^{76}$Ge, $^{136}$Xe, $^{130}$Te, $^{116}$Cd
- half-life of 2νββ decay of $^{76}$Ge measured by GERDA (most recent and precise measurement):

$$T_{1/2}^{2\nu} = (1.926 \pm 0.095) \times 10^{21} \text{ yr}$$

[arXiv:1501.02345v1]

Neutrinoless double beta decay (0νββ)
- (A,Z) → (A,Z+2) + 2e⁻
- lepton number violated by $\Delta L = 2$
  - physics beyond SM
- proof of Majorana mass component of neutrinos
0νββ Observable

- Measure sum energy of electrons

Observable: \( (T_{1/2}^{0\nu})^{-1} \propto N_{0\nu} \)
0νββ Observable

Measure sum energy of electrons

Observable:
\[
\left( T_{1/2}^{0\nu} \right)^{-1} \propto N_{0\nu}
\]

- zero background regime

\[
T_{1/2}^{0\nu} \propto M \cdot t
\]

- background, i.e. statistical fluctuation limited scenario

\[
T_{1/2}^{0\nu} \propto \sqrt{\frac{M \cdot t}{\Delta E \cdot BI}}
\]

M·t: exposure [kg yr], ΔE: energy resolution, BI: background index [counts/(keV kg yr)]

Need to achieve
- < 1 bck event in ROI
- excellent energy resolution
Effective Majorana Neutrino Mass

Measure sum energy of electrons

\[ \text{Number of events} \]

\[ 2\nu\beta\beta \quad \text{and} \quad 0\nu\beta\beta \]

\[ \text{Q} \quad \text{Energy} \]

Access to
- absolute neutrino mass scale
- mass hierarchy

- Assuming light Majorana neutrino exchange

\[ (T_{1/2}^{0\nu})^{-1} \propto |m_{\beta\beta}|^2 \equiv \left| \sum_i U_{ei} m_i \right|^2 \]

Disfavored by 0νββ (2001)

Disfavored by 0νββ (2016)
$0\nu\beta\beta$ Candidates

- no favored $0\nu\beta\beta$ isotope
- experimental considerations more important
- many different approaches to $0\nu\beta\beta$ search
  - multi-layer
  - scintillators
  - time projection chambers
  - (scintillating) bolometers
  - semi-conductors

\[
\frac{1}{T_{1/2}} = G^{0\nu}(Q, Z) \cdot |M^{0\nu}|^2 \cdot \left(\frac{m_{\beta\beta}}{m_e}\right)^2
\]
High Purity Germanium (HPGe) Detectors

- 3-4 keV FWHM at $Q_{\beta\beta} = 2039$ keV (0.2%)
- HPGe detectors isotopically enriched in $^{76}\text{Ge}$ (~87%)
- high detection efficiency of $\beta\beta$: source = detector
- discrimination of signal- from background like events using pulse shape analysis
The GERDA HPGe

**BEGe Detectors**
- enhanced energy resolution and pulse shape discrimination
- low mass (~700 g)

**Semi-coaxial Detectors**
- former HdM and IGEX experiment
- high mass (2-3 kg)
GERDA @ LNGS

cosmic muon flux reduced by a factor
\( \sim 10^6 \rightarrow 1 \, \mu/m^2/h \)
The Germanium Detector Array

**Concept:**
operate bare HPGe detectors in LAr which serves as coolant & (active) shielding

**GERDA Phase I (Nov 2011- May 2013)**
- **17.8 kg** enriched semi-coaxial + **3.6 kg** enriched BEGe
- exposure 21.6 kg·yr
- BI ~ 10^{-2} counts/(keV·kg·yr)
- $T^{0\nu}_{1/2} > 2.1 \cdot 10^{25}$ yr (90% C.L.)

PRL 111, 122503 (2013)

**GERDA Phase II (Dec 2015 - ongoing)**
- **30** enriched BEGe (= **20.0 kg**) + 7 enriched semi-coaxial (= **15.6 kg**)
- LAr instrumentation
- goal: BI ~ 10^{-3} counts/(keV·kg·yr)

GERDA Phase II Array

- wire bonding for contacting
- low radioactivity electronics
- new low mass holders with reduced mass and Cu → Si

~8cm
Discriminating Signal from Background Events

**ββ event**
- local energy deposition (SSE) in single detector

**background event**
- energy deposition in multiple locations (MSE) in single detector or on detector surface (α/β)
  - pulse shape discrimination
- coincident energy deposition in more than one detector
  - detector anti-coincidence
- additional energy deposition in LAr
  - LAr veto
LAr Instrumentation – Hybrid Design

- 16 photomultiplier tubes (PMTs)
- Cu cylinder with wavelength shifting reflector foil
- 810 wavelength shifting fibers coupled to SiPMs
- 49cm
- 60cm
- 100cm
$^{42}\text{K}$ Background

- **solution:** transparent nylon cylinder coated with wavelength shifter
- **tested in test cryostat LArGe**
- **nylon from BOREXINO**
Start of GERDA Phase II

Full Integration of Phase II Array finished in December 2015
- all Ge and LAr detector channels working
Start of GERDA Phase II

Full Integration of Phase II Array finished in December 2015
- all Ge and LAr detector channels working

- 35 out of 37 detectors used for analysis
- blinded region: $Q_{\beta\beta} \pm 25$ keV
- quality cuts (phys. acc. > 99.9%)
- events in coincidence with muon veto (phys. Acc.~ 99.9 %)
- first data release in June 2016
- 2nd data release in June 2017
Background:
- coax: $3.5 \cdot 10^{-3}$ counts/(keV·kg·yr)
- BEGe: $7 \cdot 10^{-4}$ counts/(keV·kg·yr)

→ expect < 1 bck count in ROI during full exposure of 100 kg·yr

New limit on $^{76}$Ge $T_{1/2}^{0\nu} > 5.3 \cdot 10^{25}$ yr
with median sensitivity of $4.0 \cdot 10^{25}$ yr (90 % C.L.)
Second Phase II Data Release

- Phase II exposure until April 2017: 34.4 kg·yr
  → additional 12.4 kg·yr (11.2 kg·yr) in BEGe (coax) data set with respect to Nature publication

FWHM @ $Q_{\beta\beta}$:
- BEGe's: 2.93(6) keV
- Coax: 3.90(7) keV
Performance of the LAr Veto

- $2\nu\beta\beta: bck = 96:4$ (1.0-1.3 MeV)

2$\nu\beta\beta$ MC with $T_{1/2} = 1.9 \cdot 10^{21}$ yr from Phase I

EPJC 75 (2015) 416
Performance of the LAr Veto

- random coincidences: 2.3%
- $^{42}\text{K}$ line suppressed by factor 5-6

$^{40}\text{K} \rightarrow ^{40}\text{Ar}$ (EC) no energy in LAr

$^{42}\text{K} \rightarrow ^{42}\text{Ca}$
- $\gamma$ (1.5 MeV) in Ge
- $\beta^-$ ($\leq$ 2 MeV) in LAr
Signals of BEGe's

- final drift paths of holes nearly independent of interaction point
- high gradient of weighting potential

→ single site events (SSE) have similar pulse shape

\[
current \text{ signal} = q \cdot v \cdot \nabla \phi
\]

q: charge, v: velocity

figures taken from JINST 6 P03005, 2011
Signals of BEGe's

- final drift paths of holes nearly independent of interaction point
- high gradient of weighting potential

→ single site events (SSE) have similar pulse shape

\[ \text{current signal} = q \cdot v \cdot \nabla \phi \]

\( q \): charge, \( v \): velocity

figure taken from JINST 6 P03005, 2011
**SSE vs MSE**

- $A/E = \text{maximum amplitude of current signal over deposited energy}$

- $A/E$ to suppress external $\gamma$-rays of $^{214}\text{Bi}$, $^{208}\text{Tl}$ and $^{60}\text{Co}$ (detector assembly)

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**Graph**

- **SSE** $A/E = 1$
- **MSE** $A/E < 1$
Surface Events: $\beta$-Decays

- $^{42}\text{Ar}^\beta (0^+, 32.9\text{ y}) ightarrow ^{42}\text{Ca}^0$
- $^{42}\text{K}^\beta (2^-, 12.360\text{ h}) ightarrow ^{42}\text{Ar}^0$

(charged) $^{42}\text{K}$ drift in field of Ge detectors $^{42}\text{Ca}^0$

- decays on the detector surface ($n^+$) typically produce slow pulses with low A/E

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![Graph showing SSE and $n^+$ events with A/E values](image-url)

- SSE: $A/E = 1$
- $n^+$ event: $A/E < 1$
Surface Events: $\alpha$-Decays

- $\alpha$’s cannot penetrate n$^+$, only p$^+$ contact
- decays on the detector p$^+$-contact and groove typically produce fast pulses with high A/E
Regular $^{228}$Th calibrations:
- single Compton events = SSE band
- prominent DEP = signal proxy
Regular $^{228}$Th calibrations:
- adjust 2-sided cut
  - MSE/n$^+$ cut at 90% DEP acceptance
  - p$^+$ cut twice the distance to SSE band
0ν\(\beta\beta\) Signal Efficiency

- signal efficiency given by DEP acceptance:

\[
\varepsilon_{\text{PSD}} = (87.4 \pm 0.2\text{ (stat)} \pm 2.6\text{ (sys)})\%
\]
A/E in Physics Data

- $2\nu\beta\beta$ survival fraction$^1$: 
  $(85.4 \pm 0.4 \text{ (stat)} + 1.4 \text{ (sys)})\%$

- good agreement with signal efficiency

- FEP highly suppressed

- all events at high energies rejected by high A/E cut

- $\sim$80% of bck-events rejected by PSD
Phase II Spectra

- PSD for coaxial detectors to be further optimized to reject α-decays on detector groove
- PSD for BEGe cuts all α-events
Opening the Box

Spectra after LAr veto and PSD around $Q_{\beta\beta}$

- **Coax data set:**
  - 5 kg·yr unblinded + 11.2 kg·yr still blinded

- **BEGe data set:**
  - 5.8 kg·yr unblinded + 12.4 kg·yr unblinded

- **PSD for coaxial detectors** to be further optimized to reject α-decays on detector groove
- **PSD for BEGe cuts all α-events**

\[
BI_{\text{Coax}} = 2.7^{+1.0}_{-0.8} \cdot 10^{-3} \frac{\text{counts}}{\text{keV} \cdot \text{kg} \cdot \text{yr}}
\]

\[
BI_{\text{BEGe}} = 1.0^{+0.6}_{-0.4} \cdot 10^{-3} \frac{\text{counts}}{\text{keV} \cdot \text{kg} \cdot \text{yr}}
\]
Statistical Analysis

6 data sets in total according to BI and FWHM:

→ Phase I (4 sets)
  23.5 kg · yr

→ Phase II - coax
  5.0 kg · yr

→ Phase II – BEGe
  (5.8 + 12.4) kg · yr

+Frequentist approach after Cowan et al., EPJC 71 (2011) 1554
Statistical Analysis

Extended unbinned profile likelihood:

- flat background in 1930-2190 keV
- signal = Gaussian with mean at $Q_{\beta\beta}$ and standard deviation $\sigma_E$
- 7 parameters: 6 BI + common $T_{1/2}$
- systematics folded in by pull terms

- best fit for $N_{0\nu} = 0$
- lower limit $T_{1/2} > 8.0 \cdot 10^{25}$ yr
  $m_{\beta\beta} < (120 – 270)$ meV
  with $T_{1/2}$ sensitivity $5.8 \cdot 10^{25}$ yr
  (90 % C.L.)
The Frequentist Method

- recipe according to Cowan et al., EPJC 71 (2011) 1554
- see also Nature 544 (2017) 47, Extended "Methods" Section
- threshold for 90% CL coverage calculated by toy MC
- actual limit stronger than median sensitivity (30% chance)
GERDA within $0\nu\beta\beta$ Field

- KamLAND-Zen sets current best limit on $0\nu\beta\beta$ decay of $^{136}\text{Xe}$:

  \[ T_{1/2}^{0\nu} > 10.7 \cdot 10^{25} \text{ yr @ 90 C.L.} \]
  \[ m_{\beta\beta} < 165 \text{ meV} \]

  - median sensitivity $5.6 \cdot 10^{25}$ yr
  - exposure: 504 kg \cdot yr

- GERDA sets current best limit on $0\nu\beta\beta$ decay of $^{76}\text{Ge}$:

  \[ T_{1/2}^{0\nu} > 8.0 \cdot 10^{25} \text{ yr @ 90 C.L.} \]
  \[ m_{\beta\beta} < 270 \text{ meV} \]

  - median sensitivity $5.8 \cdot 10^{25}$ yr
  - exposure: 47 kg \cdot yr
Next Steps

- mid 2018 a sensitivity on $T_{1/2}$ of $10^{26}$ yr will be reached
- all ingredients for discovery:
  - excellent energy resolution (FWHM) of 2.9 keV (3.9 keV) BEGe (Coax) at $Q_{\beta\beta}$
  - flat background in ROI
  - lowest background at $Q_{\beta\beta}$ (within FWHM): $10^{-3}$ counts/ (keV·kg·yr)
- final sensitivity at design exposure 100 kg yr:
  - will stay background-free
  - $1.3 \cdot 10^{26}$ yr (for limit)
  - $0.8 \cdot 10^{26}$ yr ($50\%$ for $3\sigma$ discovery)
Beyond GERDA

- LEGEND (Large Enriched Germanium Experiment for Neutrinoless Double Beta Decay)

- new collaboration formed in Oct 2016 (=GERDA+Majorana+new groups)

- goals:
  - 1 t enriched Ge
  - first phase: 200 kg in existing infrastructure @ LNGS
  - reduce background with respect to GERDA → remain background-free

→ best discovery potential
Conclusions

- GERDA proved to be a true high resolution and background free experiment
- sets a new limit on the half-life of $0\nu\beta\beta$ decay of $^{76}$Ge

$$T_{1/2}^{0\nu} > 8.0 \cdot 10^{25} \text{ yr @ 90 C. L.}$$

$$m_{\beta\beta} < 270 \text{ meV}$$

- next generation Ge experiment LEGEND has best discovery potential
Bonus Slides
GERDA Spectra

- background in ROI assumed to be flat
- + Gaussian signal centered at $Q_{\beta\beta}$
- pdf for single data set:

\[
 f(E|b, \frac{1}{T^{0v}_{1/2}}) = \frac{1}{240 \text{ keV} \cdot b + N_{0v}} \left( b+ \frac{N_{0v}}{\sqrt{2\pi\cdot\sigma}} \exp \left( -\frac{(E-Q_{\beta\beta})^2}{2\sigma^2} \right) \right)
\]

- extended unbinned likelihood function

\[
 L(b, \frac{1}{T^{0v}_{1/2}}) = \prod_k \mu_k^{N_k} \cdot e^{-\mu_k} \cdot \frac{N!}{N_k!} \prod_{i=0}^{N} f(E_i|b_k, \frac{1}{T^{0v}_{1/2}})
\]

$b_k$: BI for given data set, $\sigma$: energy resolution in given data set, $\mu_k = b \cdot 240 \text{ keV} + N_{0v}$: number of expected events
Phase I + II Data Sets (June 2016)

\[
(T_{1/2}^{0\nu})^{-1} \propto N_{0\nu} = \frac{\ln 2 \cdot N_A}{m_{76}} \frac{M \cdot t}{T_{1/2}^{0\nu}} \cdot \epsilon \cdot \epsilon_{PSD} \cdot \epsilon_{LAr}
\]

<table>
<thead>
<tr>
<th>data set</th>
<th>exposure [kg yr]</th>
<th>signal eff</th>
<th>Energy resolution (keV, FWHM)</th>
<th>Background index 0.001 cnts/(keV kg yr)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Phase I gold</td>
<td>17.9</td>
<td>0.57 (3)</td>
<td>4.3 (1)</td>
<td>11 ± 2</td>
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<tr>
<td>Phase I silver</td>
<td>1.3</td>
<td>0.57 (3)</td>
<td>4.3 (1)</td>
<td>30 ± 10</td>
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<tr>
<td>Phase I BEGe</td>
<td>2.4</td>
<td>0.66 (2)</td>
<td>2.7 (2)</td>
<td>5^{+4}_{-3}</td>
</tr>
<tr>
<td>Phase I extra</td>
<td>1.9</td>
<td>0.58 (4)</td>
<td>4.2 (2)</td>
<td>5^{+4}_{-2}</td>
</tr>
<tr>
<td>Phase II coax</td>
<td>5.0</td>
<td>0.53 (4)</td>
<td>4.0 (2)</td>
<td>3^{+3}_{-1}</td>
</tr>
<tr>
<td>Phase II BEGe</td>
<td>5.8</td>
<td>0.60 (1)</td>
<td>3.0 (2)</td>
<td>0.7^{+1.3}_{-0.5}</td>
</tr>
</tbody>
</table>

\(N_A\): Avogadro's constant, \(m_{76}\): molar mass of \(^{76}\text{Ge}\)

\(M \cdot t\): exposure [kg yr], \(T_{1/2}^{0\nu}\): half-life of 0\(\nu\)\(\beta\beta\) decay,

\(\epsilon_{LAr}\): LAr efficiency, \(\epsilon_{PSD}\): PSD efficiency,

\(\epsilon\): exposure averaged efficiency incl. active volume, enrichment, FEP
Comparison of Searches

\[ \frac{1}{T^{1/2}} = G^{0\nu}(Q, Z) \cdot |M^{0\nu}|^2 \cdot \left( \frac{m_{\beta\beta}}{m_e} \right)^2 \]

![Graph showing comparison of searches with lines and markers representing different experiments and sensitivities.](figure taken from L. Yang, talk at Neutrino 2016, London)
Duty Cycle
A/E Cut

Detector based A/E cut

- energy dependent cut following A/E broadening
- MSE/ $n^+$ cut set to 90% acceptance in DEP
- $p^+$ cut twice the distance to A/E = 1
Survival Efficiencies vs Cut Position
0νββ Signal Efficiency

• signal efficiency given by DEP acceptance

• final signal efficiency:

\[(87.4 \pm 0.2\text{(stat)} \pm 2.6\text{ (sys))\%}\]

<table>
<thead>
<tr>
<th>uncertainty</th>
<th>[%]</th>
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<tr>
<td>statistics</td>
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<td>diff. phy and cal</td>
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<td>energy dep. cut</td>
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<td>energy scale of A/E</td>
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<td>geometrical distribution</td>
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<td>Instability A/E scale</td>
<td>1.0</td>
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<tr>
<td>topology of 0νββ events</td>
<td>2.03</td>
</tr>
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</table>
PSD with Coaxial HPGe


- To identify signal like events artificial neural network algorithm TMlpANN from TMVA is used
- Input variables: times when charge pulse reach 1%, 3%, …, 99% of maximum amplitude
- DEP events of at 1503 keV serve as signal sample
- FEP events at 1621 keV as multi site event sample
- second training on $2\nu\beta\beta$ and $\alpha$ events
- combined $0\nu\beta\beta$ signal efficiency is $(79\pm5)$ %

current signal = $q \cdot v \cdot \Delta \phi$
$q$: charge, $v$: velocity
Coax PSD

- $2\nu\beta\beta$ [1000 keV, 1300 keV]
- $\alpha$ [3500 keV, 4500 keV]

$^{208}\text{Tl DEP}$
$^{212}\text{Bi FEP}$
$^{42}\text{K FEP}$

$^{208}\text{Tl DEP}$
$^{208}\text{Tl SEP}$
Background Model

Background Model BEGe

Counts/(30 keV)

Preliminary results before PSD & LAr veto
Background Composition at $Q_{\beta\beta}$

Monte Carlo Simulation of BEGe Background

<table>
<thead>
<tr>
<th></th>
<th>$^{\text{enr}}$BEGe</th>
<th>$^{\text{enr}}$Coax</th>
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<tbody>
<tr>
<td>$\alpha$</td>
<td>$\sim 1/3$</td>
<td>$\sim 1/3$</td>
</tr>
<tr>
<td>$^{214}\text{Bi}$ and $^{208}\text{Ti}$</td>
<td>$\sim 1/3$</td>
<td>$\sim 1/3$</td>
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<tr>
<td>$^{42}\text{K}$ LAr</td>
<td>$\sim 1/3$</td>
<td>$\sim 1/3$</td>
</tr>
<tr>
<td>BI counts/(keV kg yr)</td>
<td>0.014</td>
<td>0.015</td>
</tr>
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</table>

Preliminary results before PSD & LAr veto

Expect flat background in ROI
Results from GERDA Phase I

- 21.6 kg · y exposure
- blind analysis: events in ROI not available for analysis
- background index (BI) after pulse shape discrimination

\[
\text{BI} = 1.0 \cdot (1) \cdot 10^{-2} \frac{\text{counts}}{\text{keV kg yr}}
\]

- 10 times better BI than previous experiments

\[Q_{\beta\beta} = 2039 \text{ keV}\]

number of events in \(Q_{\beta\beta} \pm 2\sigma_{E}\) after cuts (gray):

- \(2.0 \pm 0.3\) expected from background
- 3 observed

no signal observed at \(Q_{\beta\beta}\)
profile likelihood: best fit for \(N_{\nu\beta\beta} = 0\)
→ limit on the half-life
\[T_{1/2}^{0\nu} > 2.1 \cdot 10^{25} \text{ yr} \quad (90\% \text{ C.L.})\]
→ claim rejected with 99\% probability

GERDA: 90\% lower limit \((T_{1/2}^{0\nu})\) [Phys. Rev. Lett. 111 (2013) 122503]
Claim: \(T_{1/2}^{0\nu} = 1.19 \times 10^{25} \text{ yr}\) [Phys. Lett. B 586 198(2004)]