neutrinoless double beta decay in $^{76}\text{Ge}$ with GERDA

on behalf of the GERDA collaboration
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Eberhard Karls Universität Tübingen
Bad Honnef 22. April 2014
summed electron energy spectrum of GERDA Phase I

$Q_{\beta\beta}$ of $^{76}$Ge: 2039 keV

resolution: $\pm 1\sigma$ (~4 keV)

no count!

with PSD

outline:

- introduction
- GERDA experiment
- GERDA results
- future Phase II
search for properties of $\nu$!

absolute mass scale, hierarchy

most interesting: is $\nu$ of Majorana type? 
$\nu \equiv \bar{\nu}$

lepton number violation 
extension to Standard Model 
baryon asymmetry

$2\nu2\beta$: $T_{1/2} \sim 10^{(18-21)}$ yr

$0\nu\beta\beta$ decay

$0\nu2\beta$: $T_{1/2} > 10^{25}$ yr
Notes from the Editors: Highlights of the Year 2013 (by APS)

Physics looks back at the standout stories of 2013.

- Dark Matter is Still Obscure
- Strangers from Beyond our Solar System
- Light Stopped for One Minute
- Four-Quark Matter
- What’s Inside a Black hole?

Majorana Fermions Annihilate in Nanowires

*nanowires are Quasi-Particles*

$v$ are elementary particles
sensitivity $S_{1/2}$ for $0
\beta\beta$

$$T_{1/2} = \ln 2 \cdot (N_A/A) \cdot M \cdot (N_{\beta\beta}/t)^{-1}$$

$N_{\text{obs}} \sim M \cdot t$

$N_{\text{BG}} \sim M \cdot t \cdot \delta E \cdot b$

sensitivity $\sim N_{\text{obs}} / \sqrt{N_{\text{BG}}}$

$$S_{1/2} \propto a \cdot \epsilon \cdot \sqrt{M \cdot t \cdot \delta E \cdot b}$$

relevant units for background index:

- $\text{cts/(mol yr } \delta E)$
- $\text{cts/(kg yr keV)}$

$a$ : isotop. enrichment
$\epsilon$ : efficiency
$M$ : mass
$t$ : time of measurement
$\delta E$ : energy resolution
$b$ : background rate
resolution

\( ^{48}\text{Ca} \)

\( ^{48}\text{Ca}, 2\nu2\beta \)

\( T_{1/2} = 4 \times 10^{19} \text{ yr} \)

\( 0\nu, T_{1/2} = 10^{26} \text{ yr} \)

FWHM = 2.5%

\( \Rightarrow \text{Ge: 0,2\%} \)

ratio 2\nu/0\nu !!!

FWHM = 2,5 %

\( T_{1/2} = 10^{26} \text{ yr} \)

FWHM = 2,0 %

\( T_{1/2} = 10^{27} \text{ yr} \)

\( \Rightarrow \text{Ge: 0,2\%} \)
$^{228}$Th spectrum

$^{228}$Th

$^{208}$Tl: 2615 keV

appears in natural decay chains

big source of background

$^{76}$Ge: $Q_{\beta\beta} = 2039$ keV
candidates

\[228^{\text{Th}}\]
**$^{76}\text{Ge experiments}$**

**previous experiments:** HDM (5 det) and IGEX (3 det)

Klapdor-Kleingrothaus et al.  

71.7 kg·yr  
$T_{1/2} > 1.9 \cdot 10^{25}$ yr (90%CL)

Aalseth et al.  

8.9 kg·yr  
$T_{1/2} > 1.6 \cdot 10^{25}$ yr (90%CL)

MPLA21 (2006)  

116.75 mole.years - 8.87 kg.y in $^{76}\text{Ge}$

$T_{1/2}(0\nu) > 1.57 \times 10^{25}$ yr (90% CL)  
$m_\nu < (0.3-1.1)$ eV

2038.5 keV
GERDA – the novel idea


“...low Z material around detector...”
“...mount the Ge diodes directly in cryo-liquid”

reduced radioactivity of environment
less muon-induced background

Ge diodes – enriched to 86%
selected material for holder and FE
liquid argon
stainless steel cryostat
water to moderate neutrons and
as muon veto (Cherenkov)
underground LNGS 3400 m w.e.

analysis: anti-coincidence, PSD

Phase I: aim at FWHM < 5 keV & BI ~ 10^{-2} cts/(keV·kg·yr)

→ HdM, Majorana: closed compact shielding
GERDA: design and construction
construction @ LNGS

February 2008

March 2008
construction @ LNGS

March 2008
construction @ LNGS

May 2008
rate of 66 Cherenkov PMT

Apr 22, 2014, WEH

P. Grabmayr
rate of 66 Cherenkov PMT

CNGS beam

$\mu$ [1/(s m^2)], #_con [1/d], $\mu$ [1/(s m^2)]
CNGS neutrino beam
comparison to effective temperature
Multiplicity of 66 Cherenkov PMT

muon rejection efficiency $\varepsilon > 97\%$
mounting the diodes

test in LARGE

note distance between diode and preamplifier
2 enriched detectors had problems from the very beginning, removed from physics analysis

6 enriched detectors with 14.6 kg total mass
3 natural detectors with 7.6 kg total mass

inserted of 1 & 3 string arm:
total of 8 enriched + 3 natural diodes in October 2011
add 5 BEGe detectors

3 data sets:
golden
silver
BEGe
summed electron energy spectra

- $^{39}\text{Ar} \beta^-$
- $2\nu\beta\beta$
- $^{210}\text{Po}$
- $^{226}\text{Ra}$
- $^{222}\text{Rn}$
- $^{218}\text{Po}$

Enriched coaxials, 19.20 kg × yr

Enriched BEGes, 2.40 kg × yr
analysis: blinding & publications

blinding of data within \( Q_{\beta\beta} \pm 20 \text{ keV} \)

[ raw data copied to backup; but not converted to analysis standard MGDO ]

EPJC 73 (2013) 2330 the GERDA experiment (setup)
EPJC 74 (2014) 2764 the background & models
EPJC 73 (2013) 2583 PSD: pulse shape for coax & BEGe

unblinding after fixing the parameters/procedures (@ Dubna meeting June 2013)
spectra with/without PSD uncovered @ Dubna

PRL 111 (2013) 122503 limit for \( T_{1/2}^{0\nu} > 2.1 \cdot 10^{25} \text{ yr} \) (90% C.L. frequentist)
(n,γ) in the $Q_{\beta\beta}$ region

G. Meierhofer et al. EPJA48 (2012) 20

$\sim 10^{-5}$ cts/(keV kg yr)
calibration & data processing

**processing:** diode → amplifier → FADC → filter → energy, rise time, PSD

**selection:** anti-coincidence muon / 2nd Ge (~20% rejected, @ $Q_{\beta\beta}$), quality cuts (~9% reject), pulse shape discrimination (~50% reject)

**calibration:** $^{228}$Th (bi)weekly & pulser every 20 seconds for short term drifts

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Shifts are small compared to FWHM $\sim 0.2\%$ $Q_{\beta\beta}$
**backgrounds $\alpha$ & $\gamma$**

<table>
<thead>
<tr>
<th>isotope</th>
<th>energy [keV]</th>
<th>$^{enr}$Ge (6.10 kg yr)</th>
<th>$H_0M$ (71.7 kg yr)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td>$\text{tot/bck [cts]}$</td>
<td>$\text{rate [cts/(kg yr)]}$</td>
</tr>
<tr>
<td>$^{40}$K</td>
<td>1460.8</td>
<td>125/42</td>
<td>$13.5^{+2.2}_{-2.1}$</td>
</tr>
<tr>
<td>$^{60}$Co</td>
<td>1173.2</td>
<td>182/152</td>
<td>$4.8^{+2.3}_{-2.8}$</td>
</tr>
<tr>
<td></td>
<td>1332.3</td>
<td>93/101</td>
<td>$&lt;3.1$</td>
</tr>
<tr>
<td>$^{137}$Cs</td>
<td>661.6</td>
<td>335/348</td>
<td>$&lt;5.9$</td>
</tr>
<tr>
<td>$^{228}$Ac</td>
<td>910.8</td>
<td>294/303</td>
<td>$&lt;5.8$</td>
</tr>
<tr>
<td></td>
<td>968.9</td>
<td>247/230</td>
<td>$2.7^{+2.3}_{-1.9}$</td>
</tr>
<tr>
<td>$^{208}$Tl</td>
<td>583.2</td>
<td>333/327</td>
<td>$&lt;7.6$</td>
</tr>
<tr>
<td></td>
<td>2614.5</td>
<td>10/0</td>
<td>$1.5^{+0.6}_{-0.5}$</td>
</tr>
<tr>
<td>$^{214}$Pb</td>
<td>352</td>
<td>1770/1688</td>
<td>$12.5^{+3.5}_{-7.7}$</td>
</tr>
<tr>
<td></td>
<td>351/311</td>
<td>6.8$^{+3.7}_{-4.1}$</td>
<td>105 ± 1</td>
</tr>
<tr>
<td>$^{214}$Rn</td>
<td>609</td>
<td>194/186</td>
<td>&lt;6.1</td>
</tr>
<tr>
<td></td>
<td>24/1</td>
<td>3.6$^{+0.9}_{-0.8}$</td>
<td>30.7 ± 0.7</td>
</tr>
<tr>
<td></td>
<td>6/3</td>
<td>0.4$^{+0.4}_{-0.4}$</td>
<td>8.1 ± 0.5</td>
</tr>
</tbody>
</table>

**GOLD-coax**

- Data
- Model
- $^{210}$Po on surface
- $^{224}$Ra & daughters on surface
- $^{224}$Ra & daughters in LAr

**Counts [50 keV]**

- Data/model
- 68%
- 95%
- 99.9%

**Counts per energy (keV)**

- $^{210}$Po

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Physikalisches Institut, Kepler Center for Astro and Particle Physics


<table>
<thead>
<tr>
<th>energy (keV)</th>
<th>events/(30 keV)</th>
</tr>
</thead>
<tbody>
<tr>
<td>500</td>
<td>500</td>
</tr>
<tr>
<td>400</td>
<td>400</td>
</tr>
<tr>
<td>300</td>
<td>300</td>
</tr>
<tr>
<td>200</td>
<td>200</td>
</tr>
<tr>
<td>100</td>
<td>100</td>
</tr>
<tr>
<td>50</td>
<td>50</td>
</tr>
</tbody>
</table>

**5.04 kg yr exposure**

\[
T_{1/2}^{2v} = 1.84 (^{+0.14/_.10} \cdot 10^{21} \text{ yr})
\]

**HdM**

![Graph showing experimental energy spectrum and model fit with data/model ratio](graph.png)

![Graph showing 5.04 kg yr exposure](graph.png)

**publication year**

- Barabash
- NNDC
- this work
background model @ \( Q_{\beta\beta} \)

“minimal fit” (all known contributions)

No line expected in blinding region

background flat between 1930-2190 keV
(without 2104±5 keV, without 2119±5 keV),

expect \(< 1\) event in other weak \(^{214}\)Bi lines (e.g. 2017, 2053 keV)

partial unblinding (grey window) after fixing of calibration & bkg model, no line in grey interval, expected 8.6-10.3 evts in grey part & see 13 events
**pulse shape discrimination (PSD)**

pulse shape discrimination to select $0\nu\beta\beta$ events

$0\nu\beta\beta$ events: range of 1 MeV electrons in Ge is $\sim$1 mm
  $\rightarrow$ single drift of electrons & holes, single site event (SSE)

background from $\gamma$'s: range of MeV $\gamma$ in Ge $>10x$ larger
  $\rightarrow$ often sum of several electron/hole drifts,
  multi site events (MSE)

surface events: only electrons or holes drift

charge and current signal for BEGe detectors (data events)

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

(Shockley-Ramo theorem)
**PSD for BEGe**

use double escape peak (DEP) of $^{228}$Th spectrum as proxy (two 511 $\gamma$ escape detector!) for $0\nu\beta\beta$

aim: develop the PSD method with $^{228}$Th calibration data and then apply it to physics data

Method: $A/E = \max$ of current pulse “$A$” / energy “$E$” is robust & simple & well understood
accept events $0.965 < A/E < 1.07$ (normalization $A/E$ for DEP events = 1)

$0\nu\beta\beta$ efficiency = 92±2 % determined from DEP efficiency & simulation
$2\nu\beta\beta$ efficiency = 91±5 % in good agreement to DEP efficiency
reject >80% of background events
PSD for semi-coaxial: neural network (ANN)

Input: time when charge signal reaches 1%, 3%, …, 99% of maximum

tested many methods implemented in TMVA, selected artificial neural network TMlpANN

select ANN cut position @ DEP survival = 90%

cross checks:
$2\nu\beta\beta$ eff. = 85±2 %,
Compton edge eff. = 85-94%,
$^{56}$Co DEP (1576 keV) eff. = 83%-95%
$^{56}$Co DEP (2231 keV) eff. = 83%-93%

$0\nu\beta\beta$ efficiency = $0.90^{+0.05}_{-0.09}$
PSD for semi-coaxial

cross check ANN classification with 2 other methods:
1) projective likelihood trained with Compton edge evt
2) “current pulse asymmetry * A/E”

90% of ANN rejected events also rejected by both,
3% only rejected by ANN
→ classification of background like events meaningful
findings

total exposure of 21.6 kg yr between Nov. 2011 and May 2013
3 data sets: golden, silver, BEGe

weekly calibration runs with $^{228}$Th source
mean resolution at 2 MeV: coax 4.8 keV, BEGe 3.2 keV FWHM (50 cm diode-CC2)
energy scale stable within ±1.3 keV

the strongest gamma line is 1525 keV from $^{42}$K
dominated by $^{214}$Bi and $^{228}$Th

nearby sources (det. holders etc.) and surface contaminations
far sources do not matter

background flat between 1930-2190 keV

PSD gains another factor 2 in BI

$(11 \pm 2) \times 10^{-3}$ cts/(kg yr keV)

$(6 \pm 1) \times 10^{-3}$ cts/(mol yr dE)
calibration & stability
data sets defined
background model
PSD parameters fixed
analysis methods defined

whole collaboration during 4 days
unblinding of final ±5 keV

<table>
<thead>
<tr>
<th></th>
<th>golden</th>
<th>silver</th>
<th>BEGe</th>
<th>total</th>
</tr>
</thead>
<tbody>
<tr>
<td>expt. w/o PSD</td>
<td>3.3</td>
<td>0.8</td>
<td>1.0</td>
<td>5.1</td>
</tr>
<tr>
<td>obs. w/o PSD</td>
<td>5</td>
<td>1</td>
<td>1</td>
<td>7</td>
</tr>
<tr>
<td>expt. w/ PSD</td>
<td>2.0</td>
<td>0.4</td>
<td>0.1</td>
<td>2.5</td>
</tr>
<tr>
<td>obs w/ PSD</td>
<td>2</td>
<td>1</td>
<td>0</td>
<td>3</td>
</tr>
</tbody>
</table>

no peak in spectrum at $Q_{\beta\beta}$,

event count consistent with bkg,

→ GERDA sets a limit
half life limit for $^{76}\text{Ge}$ $0\nu\beta\beta$

$$T_{1/2}^{0\nu} = \frac{\ln 2 \cdot N_A}{m_{\text{enr}} \cdot N_{0\nu}^{A}} M \cdot t \cdot f_{76} \cdot f_{\text{av}} \cdot \epsilon_{\text{fep}} \cdot \epsilon_{\text{psd}}$$

exposure averaged efficiencies

<table>
<thead>
<tr>
<th>data set</th>
<th>$M \cdot t$</th>
<th>$f_{76}$</th>
<th>$f_{\text{av}}$</th>
<th>$\epsilon_{\text{fep}}$</th>
<th>$\epsilon_{\text{psd}}$</th>
</tr>
</thead>
<tbody>
<tr>
<td>golden</td>
<td>17.9 kg yr</td>
<td>0.86</td>
<td>0.87</td>
<td>0.92</td>
<td>0.90</td>
</tr>
<tr>
<td>silver</td>
<td>1.3 kg yr</td>
<td>0.86</td>
<td>0.87</td>
<td>0.92</td>
<td>0.90</td>
</tr>
<tr>
<td>BEGe</td>
<td>2.4 kg yr</td>
<td>0.88</td>
<td>0.92</td>
<td>0.90</td>
<td>0.92</td>
</tr>
</tbody>
</table>

4 parameters: 3x bkg level & $1/T^{0\nu} 

$1/T^{0\nu} \geq 0$ constrain (best fit $1/T=0$)

fix gaussian $\mu=(2039.06\pm0.2)$ keV, $\sigma=(2.0\pm0.1)/(1.4\pm0.1)$ keV for coax/BEGe

systematic uncertainties on $f, \epsilon, \mu, \sigma$: Monte Carlo sampling & averaging

frequentist: profile likelihood fit → best fit $N_{0\nu}=0$, $T_{1/2}^{0\nu} > 2.1 \cdot 10^{25}$ yr (90% C.L.) (sensitivity = $2.4 \cdot 10^{25}$ yr)
GERDA Phase I

**Claim 2004**

\[ \mathcal{E} = 71.7 \text{ kg yr} \]

**Test of hypothesis**

\[ p = 0.01 \]

Claim 2004: excluded with 99%

\[ p(N^0 = 0 \mid H_1 = \text{signal} + \text{bkg}) = 0.01 \]

**GERDA Phase I**

\[ B_1 = 1.1 \times 10^{-2} \text{ cts/(kg yr keV)} \]

\[ \mathcal{E} = 21.6 \text{ kg yr} \]

\[ S \sim 0.006 \text{ cts/(mol yr } \delta\mathcal{E}) \]
comparison

include HdM & IGEX  
model free: no NME needed  
compare to Xe:  
NME needed, which ?  

\[
\frac{136}{76} \text{Xe/Ge} \sim 0.4
\]

⇒ weakest exclusion  

gives total Bayes factor  \( H_1/H_0 = 0.0022 \)  
→ claim of \( ^{76}\text{Ge} \) signal is strongly disfavored

\[0.2 < m_{\beta\beta} < 0.4 \text{ eV}\]
# Sensitivity for $0\nu\beta\beta$ Decay

The sensitivity for $0\nu\beta\beta$ decay can be described by the equation:

\[ S_{1/2} \propto a \epsilon \times \sqrt{\frac{M \cdot t}{\delta E \cdot b}} \]

<table>
<thead>
<tr>
<th>Experiment</th>
<th>$E$ (kg yr)</th>
<th>$\delta E$ (%)</th>
<th>$B$ (10$^{-3}$ cts/(kg yr keV))</th>
<th>$T_{1/2}$ &gt; $10^{25}$ yr (90% CL)</th>
</tr>
</thead>
<tbody>
<tr>
<td>KamLAND-Zen I</td>
<td>27.5</td>
<td>4.2%</td>
<td></td>
<td>&gt; 0.5</td>
</tr>
<tr>
<td>KamLAND-Zen II</td>
<td>89.5</td>
<td>4.2%</td>
<td>41</td>
<td>0.19 &gt; 1.9</td>
</tr>
<tr>
<td>EXO-200 1</td>
<td>32.5</td>
<td>1.67%</td>
<td>1.5 ± 0.1</td>
<td>0.044 &gt; 1.6</td>
</tr>
<tr>
<td>EXO-200 2</td>
<td>99.8</td>
<td>1.53%</td>
<td>1.7 ± 0.2</td>
<td>0.053 &gt; 1.1</td>
</tr>
<tr>
<td>GERDA Phase I</td>
<td>21.6</td>
<td>0.2%</td>
<td>11 ± 2</td>
<td>0.006 &gt; 2.1</td>
</tr>
</tbody>
</table>
Phase II

1) additional 30 BEGe Detectors:
   + 20 kg, better PSD

2) new FE- electronics

3) liquid-Argon-Instrumentation

   surface contaminations & Compton scattering
   produce scintillationslight (128nm) in LAr

   readout with
   a) WLS-fiber and SiPM
   b) 3” PMT

goal: BI\sim 10^{-3} \text{ cts/(keV-kg-yr)}

E \sim 100 \text{ kg yr} \Rightarrow T_{1/2} \sim 10^{26} \text{ yr}

poster Anne Wegmann/Tobias Bode
**Further Studies: $\gamma-\gamma$ Coincidences**

a) Background identification

b) $2\nu\beta\beta$ & $0\nu\beta\beta$ to excited states

Sum energy of two Ge-diodes

Energy of one diode (without 1525)

1525 keV
new experiments on $0\nu\beta\beta$
Kamland-Zen, EXO, GERDA, Majorana
$^{136}\text{Xe}$, $^{76}\text{Ge}$

GERDA for $^{76}\text{Ge}$
new $T_{1/2}^{2\nu} = 1.84 (^{+14/-10}) \cdot 10^{21} \text{ yr}$

new limit
$T_{1/2}^{0\nu} > 2.1 \cdot 10^{25} \text{ yr (90\% C.L. frequentist)}$

data taking Phase I stopped, data analyzed & published
GERDA Phase II with add. 20 kg BEGe and LAr instrumentation
in 2014 we still do not know

........ if he is right