Search for Neutrinoless Double Beta Decay in the GERDA Experiment

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— on behalf of the Gerda Collaboration —

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Flavour Physics Conference

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Outline

1. Neutrinos and Double Beta Decay ($2\nu\beta\beta$ vs. $0\nu\beta\beta$)
2. GERDA experimental design
3. Phase I data: energy calibration, resolution and spectrum
4. Background modeling
5. Pulse shape discrimination
6. Unblinding and results of $0\nu\beta\beta$ analysis
7. Outlook on Phase II

Open questions from neutrino oscillations...

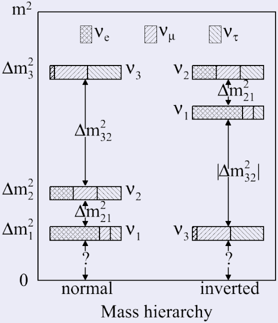
Flavour eigenstates ν_α (with $\alpha = \mathrm{e}, \mu, \tau$) as linear superposition of mass eigenstates ν_i

$|\nu_\alpha\rangle = \sum_{i=1}^{3} U_{\alpha i} |\nu_i\rangle$

Pontecorvo-Maki-Nakagawa-Sakata (PMNS) matrix

$$U = \begin{pmatrix} c_{12}c_{13} & s_{12}c_{13} & s_{13}e^{-i\delta} \\ -s_{12}c_{23} - c_{12}s_{23}s_{13}e^{i\delta} & c_{12}c_{23} - s_{12}s_{23}s_{13}e^{i\delta} & s_{23}c_{13} \\ s_{12}s_{23} - c_{12}s_{23}s_{13}e^{i\delta} & -c_{12}c_{23} - s_{12}s_{23}s_{13}e^{i\delta} & c_{23}c_{13} \end{pmatrix}$$

where $s_{ij} = \sin\theta_{ij}$ and $c_{ij} = \cos\theta_{ij}$



What we know

- squared mass differences Δm^2_{12} and $|\Delta m^2_{23}|$
- mixing angles θ_{12}, θ_{23} and θ_{12}

from e.g. solar neutrino + long baseline reactor, amospheric neutrino + long baseline accelerator or short baseline reactor / accelerator experiments

What we do not know

- new physics behind SM
- absolute mass scale
- mass hierarchy
- nature of the neutrino (Dirac or Majorana?)

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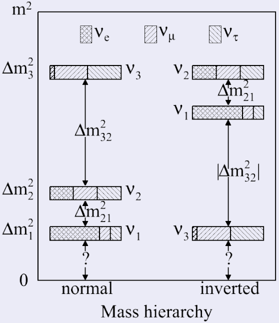

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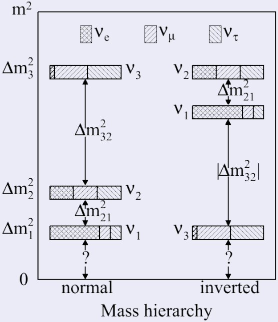

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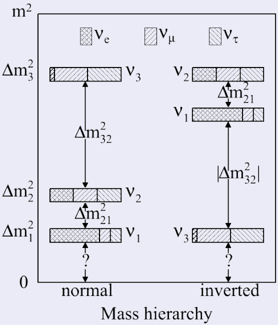

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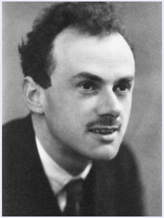
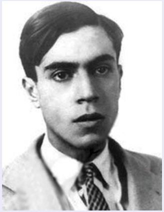
Unveiling the nature of the neutrino

Dirac: $\nu \neq \overline{\nu}$



vs.

Majorana: $\nu = \overline{\nu}$



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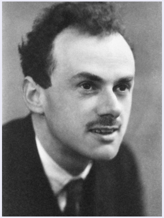

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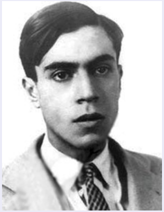
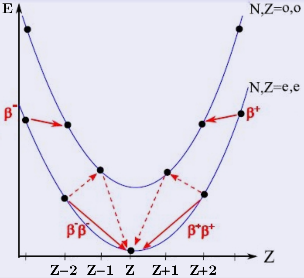


Double Beta ($\beta\beta$) Decay: allows for an unambigous test

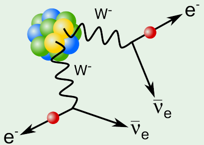
- rare second order nuclear transision
- occurs between 2 even-even isobars
- only if single β decay energetically forbidden or ΔJ large



- 35 canditates in nature
- predominantly used isotopes for experimental $\beta\beta$ search: ^{48}Ca, ^{76}Ge, ^{82}Se, ^{96}Zr, ^{100}Mo, ^{116}Cd, ^{128}Te, ^{130}Te, ^{136}Xe, ^{150}Nd, ...

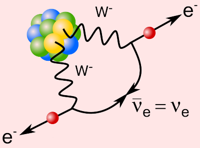
Double Beta Decay

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



- so far observed in 12 nuclei
- half lifes in the range of $10^{19} - 10^{24}\mathrm{yr}$ with $T^{2\nu}_{1/2}(^{76}\mathrm{Ge}) = 1.84^{+0.14}_{-0.10} \cdot 10^{21}\mathrm{yr}$
  J. Phys. G: Nucl. Part. Phys. 40 (2013) 035110
- $\Delta L = 0$: Lepton-number conserved
- allowed by Standard Model

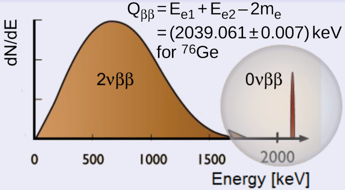
$0\nu\beta\beta$: $(A,Z) \rightarrow (A,Z+2) + 2e^-$



- only if ν's have Majorana mass component
- still hunted process
- note: one claim by subgroup of HdM with $T^{0\nu}_{1/2}(^{76}\mathrm{Ge}) = 1.19^{+0.37}_{-0.23} \cdot 10^{25}\mathrm{yr}$
  Phys. Rev. Lett. B 586, 198-212 (2004)
- $\Delta L = 2$: Lepton-number violation
- not allowed by Standard Model

Experimental signatures

- measure the electrons sum energy spectrum
- distribution sensitive to the underlying process



Phys. Rev. 401 C81 (2010) 032501

- continuum → $2\nu\beta\beta$ or $0\nu\beta\beta$ + Majoron(s)
- monoenergetic peak @ $Q_{\beta\beta}$-value → $0\nu\beta\beta$

Double Beta Decay

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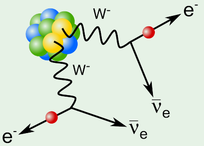

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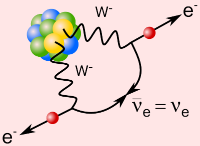

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can be mediated by e.g. light Majorana ν, R-handed weak currents, SUSY particles, ...

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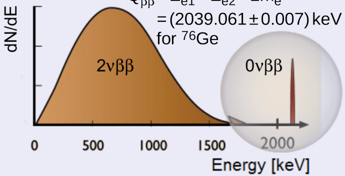


$Q_{\beta\beta} = E_{e1} + E_{e2} - 2m_e$
$= (2039.061 \pm 0.007)\,\mathrm{keV}$
for $^{76}\mathrm{Ge}$

Phys. Rev. 401 C81 (2010) 032501

- continuum $\rightarrow 2\nu\beta\beta$ or $0\nu\beta\beta$ + Majoron(s)
- monoenergetic peak @ $Q_{\beta\beta}$-value $\rightarrow 0\nu\beta\beta$

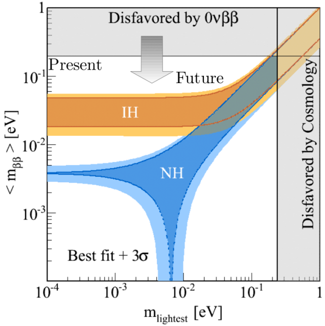
Neutrinoless Double Beta Decay

Expected decay rate:

assuming light Majorana ν exchange to be dominating process

$$(T^{0\nu}_{1/2})^{-1} = G^{0\nu}(Q_{\beta\beta}, Z)|M^{0\nu}|^2\langle m_{\beta\beta}\rangle^2$$ where:

- $G^{0\nu}(Q_{\beta\beta}, Z) \propto Q^5_{\beta\beta}$ = phase space integral
- $|M^{0\nu}|$ = nuclear matrix element
- $\langle m_{\beta\beta}\rangle = |\sum_{i=1}^{3} U_{ei} m_i|$ = effective ν mass



Values taken from:
Phys. Rev. D86 (2012) 013012;
JCAP 07 (2012) 053

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Experimental Sensitivity

1. Background $\ll 1$:
   $T^{0\nu}_{1/2} \propto \epsilon \cdot a \cdot M \cdot t$
2. Background $\gg 1$:
   $T^{0\nu}_{1/2} \propto \epsilon \cdot a \cdot \sqrt{\frac{M \cdot t}{BI \cdot \Delta E}}$

where:

- ϵ = total detection efficiency
- a = abundance of $0\nu\beta\beta$ isotope
- $M \cdot t$ = exposure (detector mass × livetime)
- BI = background index
- ΔE = energy resolution @ $Q_{\beta\beta}$

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Search in ^{76}Ge (with well established semiconductor technology)

Advantages

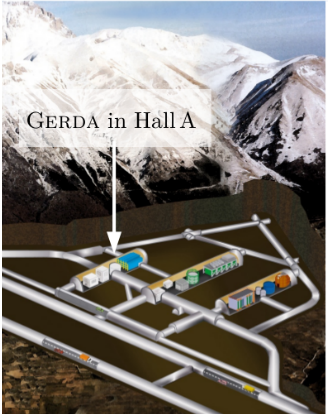
- source = detector → high ϵ
- High Purity Ge → low intrinsic BI
- FWHM @ $Q_{\beta\beta} \sim 0.2\%$ → excellent ΔE
- test of claim for $0\nu\beta\beta$ observation by HdM without depending on NME

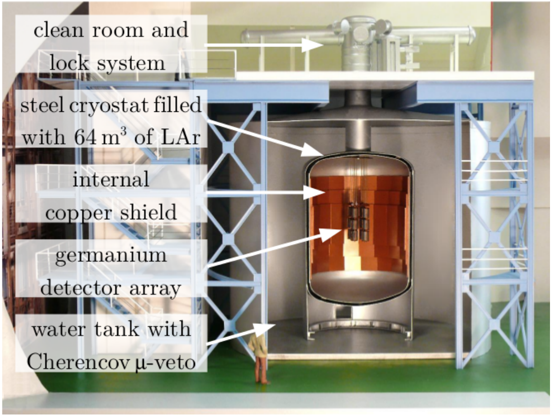
Disadvantages

- low $Q_{\beta\beta}$-value → possible external BI from e.g. ^{208}Tl + small $G^{0\nu}(Q_{\beta\beta}, Z)$
- $a = 7.8\%$ for ^{76}Ge → enrichment needed
- rather long and costly process to get large active detector mass

GERmanium Detector Array

Eur. J. Phys. C73 (2013) 2330





Background reduction techniques from construction of setup:

- located in Hall A of LNGS underground laboratory, Italy → cosmic μ flux reduced by 10^6
- novel idea: Ge detectors are operated bare in LAr as coolant
- only minimal amount of (screened) material close to detectors
- rock shielded by ultra-pure water → copper lined steel cryostat → LAr
- active μ-veto by using water tank instrumented with PMTs and plastic scintillator above the cryostat neck

GERDA Phase I data

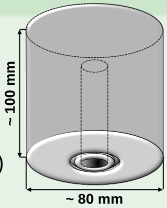
Experiment proceeds in two phases:

Phase	Mass [kg]	Aspired BI [cts/(keV·kg·yr)]	Livetime [yr]	$T^{0\nu}_{1/2}$ Sensitivity [yr]
I	15	10^{-2}	1	$2.4 \cdot 10^{25}$
II	35	10^{-3}	3	$1.4 \cdot 10^{26}$

Phase II → liquid argon scintillation veto upgrade

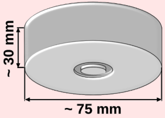
8× semi-coaxial detectors

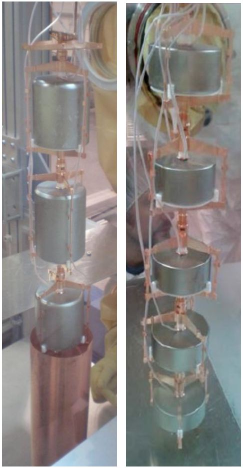
- inherited from HdM (ANG1-5) & IGEX (RG1-3) experiments; all reprocessed at Canberra
- enrichement fraction of ^{76}Ge: $\sim 86\%$
- data taking: November 2011 – May 2014
- 2 detectors not considered (high leakage current)
- total mass used for analysis: 14.6 kg



5× Broad Energy Germanium (BEGe) detectors

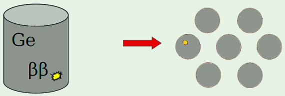
- from ~ 30 newly processed Phase II detectors
- enrichement fraction of ^{76}Ge: $\sim 88\%$
- data taking (first test): July 2012 – May 2014
- 1 detector not considered (unstable behaviour)
- total mass used for analysis: 3.0 kg





Additional background reduction (by off-line analysis)

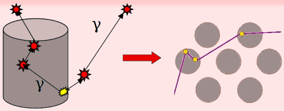
Signal



- $\beta\beta$ events: range for 1MeV electrons in Ge about $\sim$1 mm
- interaction via ionization or exitation of absorber atoms
- one drift of electrons and holes originated close-by in located charge cloud

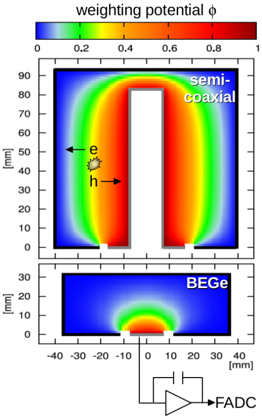
→ single-site event (SSE)

Background



- γ events: range of 1MeV γ's in Ge $\lesssim 10\times$ larger (compared to electrons)
- interaction via compton scattering, e^+e^- pair creation or photelectric absorption
- sum of several separated electron-hole drifts

→ multi-site event (MSE)



Ramo-Shockley theorem:

$Q(t) = -q \times [\phi(\boldsymbol{r}_{\mathrm{h}}(t)) - \phi(\boldsymbol{r}_{\mathrm{e}}(t))]$

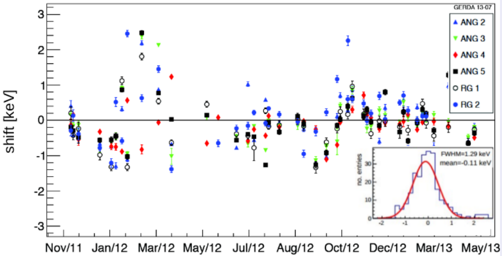
- distinguish between SSE's and MSE's
- different PSD for semi-coaxial and BEGe detectors

Signal processing: diode → amplifier → FADC → digital filter → E, pulse shape, ...

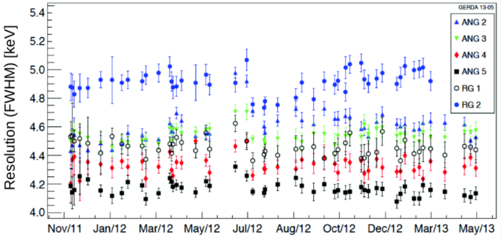
- anti-coincidence between detectors: $\sim$20% rejected @ $Q_{\beta\beta}$
- quality cuts (e.g. T, E instabilities): $\sim$9% rejected @ $Q_{\beta\beta}$
- pulse shape discrimination (PSD): $\sim$50% rejected @ $Q_{\beta\beta}$

Calibration, time stability and energy resolution

Shift of 2614.5 keV position



Energy resolution @ 2039 keV



- (bi-) weekly calibration with movable ^{228}Th sources
- offline energy reconstruction (semi-Gaussian filter)
- stability monitored with test pulser $(0.05$ Hz)

drift of 2614.5 keV γ-line small $(\pm 0.05\%)$ compared to FWHM @ $Q_{\beta\beta}$ of $\sim 0.2\%$

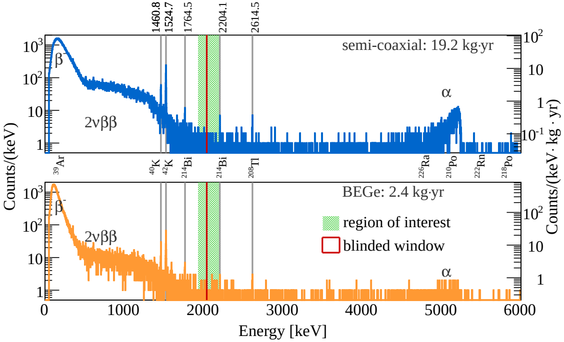
Mean FWHM of detectors @ $Q_{\beta\beta}$

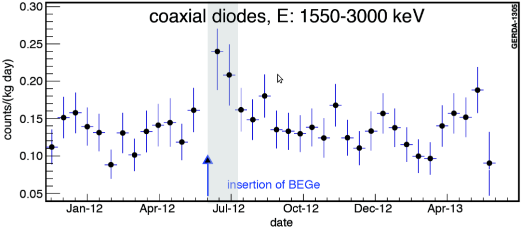
① semi-coaxial: (4.8 ± 0.2) keV

② BEGe: (3.2 ± 0.2) keV

automatic blinding of the $Q_{\beta\beta} \pm 20$ keV (later ± 5 keV) region applied to allow for an unbiased data analysis; validated background model and PSD before perform unblinding

Blinded physics spectrum





Region Of Interest (ROI) = interval $[1930 - 2190]$ keV

Main background components:

- β-spectrum of ^{39}Ar (with $Q = 565$ keV)
- $2\nu\beta\beta$-spectrum of ^{76}Ge
- γ-lines from ^{40}K, ^{42}K, ^{60}Co, ^{214}Bi, ^{212}Bi, ^{208}Tl & ^{228}Ac
- α-spectrum of ^{238}U chain (in semi-coaxial detectors)

Division in 3 data sets:

- semi-coaxial data splitted in two sets ("golden", "silver") according to BI
- "BEGe" set kept seperated due to different resolution and background

data set	Exposure [kg·yr]	FWHM @ $Q_{\beta\beta}$ [keV]
golden	17.9	4.8 ± 0.2
silver	1.3	4.8 ± 0.2
BEGe	2.4	3.2 ± 0.2

Background model

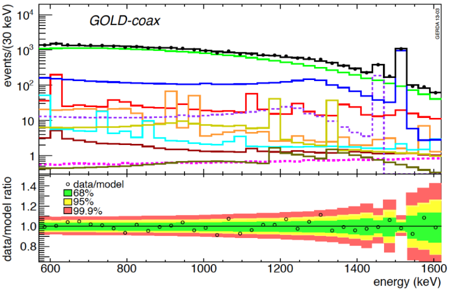
Eur. Phys. J. C74 (2014) 2764

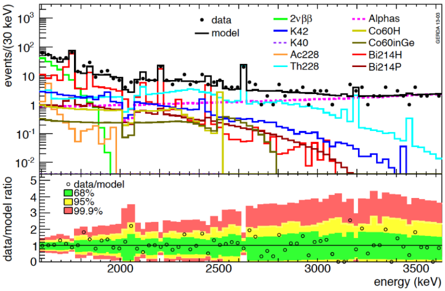
General procedure:

- simulation of known (from material screening) and observed (from detector operation) background sources
- spectral fit with combination of all components in the energy region between 570 keV and 7500 keV on the 3 data sets
- 2 extremes: "minimum" (all known + visible contributions) & "maximum" (additional contributions from other possible locations)

Results:

- no γ-line expected in the blinded window around $Q_{\beta\beta}$
- flat background between 1930 keV and 2190 keV (= ROI) excluding known peaks @ 2103 keV (^{208}Tl SEP) as well as 2119 keV (^{214}Bi)
- $BI = (1.76 - 2.38) \cdot 10^{-2}\ \frac{\text{cts}}{\text{kg}\cdot\text{keV}\cdot\text{yr}}$ (depending on assumption of source location)





Background model

Eur. Phys. J. C74 (2014) 2764

General procedure:

- simulation of known (from material screening) and observed (from detector operation) background sources
- spectral fit with combination of all components in the energy region between 570 keV and 7500 keV on the 3 data sets
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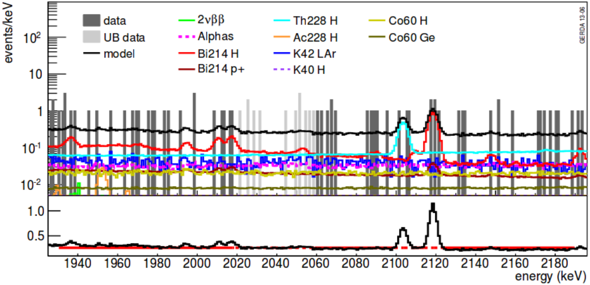
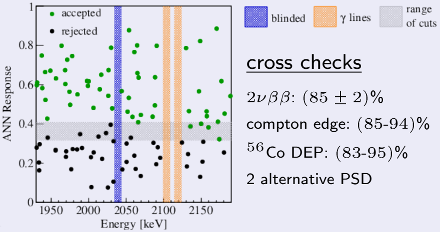
Partial unblinding @ $Q_{\beta\beta}$ ±20 keV → ±5 keV with $8.6 - 10.3$ expected and 13 observed events



Pulse shape discrimination (PSD) Eur. Phys. J. C73 (2013) 2583

semi-coaxial: artificial neural network (ANN)

- TMVA / TMlpANN with 2 hidden layers of n_{var} and $n_{\mathrm{var}}+1$ nodes
- Input: time when charge pulse reaches 1%, 3%,...,90% of maximum ($n_{\mathrm{var}}=50$)
- training using ^{228}Th calibration data
  → SSE: ^{208}Tl DEP @ 1620.7 keV
  → MSE: ^{212}Bi FEP @ 1592.5 keV
- cut defined such that acceptance of ^{208}Tl DEP @ 2614.5 keV is fixed to 90%
- $0\nu\beta\beta$ acceptance $= 90^{+5}_{-9}\%$;
  background acceptance @ $Q_{\beta\beta}$ $\sim 55\%$



cross checks

$2\nu\beta\beta$: $(85 \pm 2)\%$

compton edge: $(85\text{-}94)\%$

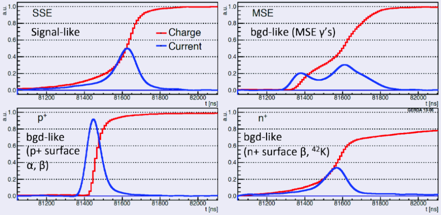
^{56}Co DEP: $(83\text{-}95)\%$

2 alternative PSD

BEGe: mono-parametric A/E

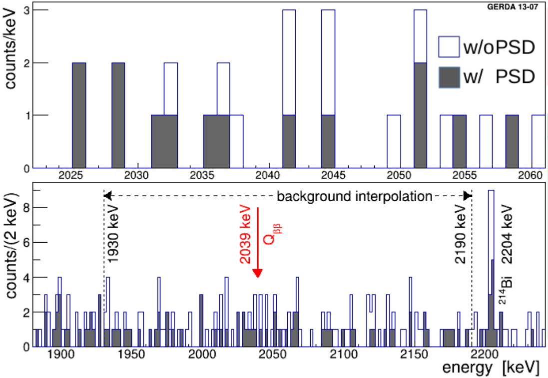
- A = amplitude of current pulse
- E = energy

- high capability of distinguising SSE from MSE and surface p$^+$/n$^+$ events
- tuned using ^{208}Tl DEP (per definition $A/E=1$) → keep $0.965 < A < 1.07$
- well tested and understood method
- $0\nu\beta\beta$ acceptance $= (92 \pm 2)\%$
  (determined from ^{208}Tl DEP and MC);
  background acceptance @ $Q_{\beta\beta}$ $\leqslant 20\%$



Unblinding @ $Q_{\beta\beta} \pm 5$ keV

Phys. Rev. Let. 111 (2013) 122503



after energy calibration, data selection, analysis method and PSD cut is fixed
→ unblinding @ meeting in June 2013

full data set:

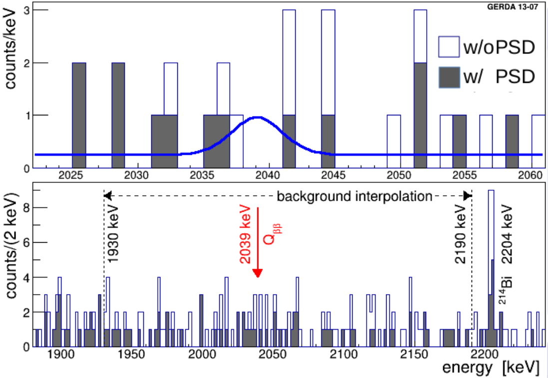
- total exposure: $M{\cdot}t = 21.6$ kg·yr
- no peak in spectrum @ $Q_{\beta\beta}$
- $N_{\text{obs}} =\ \ 7$ (w/o) ↔ 3 (w/)
  $N_{\text{exp}} = 5.1$(w/o) ↔ 2.5(w/)
- event count N_{obs} consistent with expected background N_{exp}

→ GERDA sets limit on $0\nu\beta\beta$ half-live

data set	PSD	Exposure [kg·yr]	FWHM @ $Q_{\beta\beta}$ [keV]	Efficiency $f_{76}{\cdot}f_{\text{av}}{\cdot}\epsilon_{\text{fep}}{\cdot}\epsilon_{\text{psd}}$	Events @ ROI	N_{exp}	N_{obs}
golden	w/o	17.9	4.8±0.2	0.688	76	3.3	5
	w/			0.619	45	2.0	2
silver	w/o	1.3	4.8±0.2	0.688	19	0.8	1
	w/			0.619	9	0.4	1
BEGe	w/o	2.4	3.2±0.2	0.720	23	1.0	1
	w/			0.663	3	0.1	0

Unblinding @ $Q_{\beta\beta} \pm 5$ keV

Phys. Rev. Let. 111 (2013) 122503



data set	PSD	Exposure [kg·yr]	FWHM @ $Q_{\beta\beta}$ [keV]	Efficiency $f_{76} \cdot f_{\rm av} \cdot \epsilon_{\rm fep} \cdot \epsilon_{\rm psd}$
golden	w/o	17.9	4.8±0.2	0.688
	w/			0.619
silver	w/o	1.3	4.8±0.2	0.688
	w/			0.619
BEGe	w/o	2.4	3.2±0.2	0.720
	w/			0.663

$$T^{0\nu}_{1/2} = \frac{\ln(2) \cdot N_A}{m_A \cdot N^{0\nu}} \cdot M \cdot t \cdot f_{76} \cdot f_{\rm av} \cdot \epsilon_{\rm fep} \cdot \epsilon_{\rm psd}$$

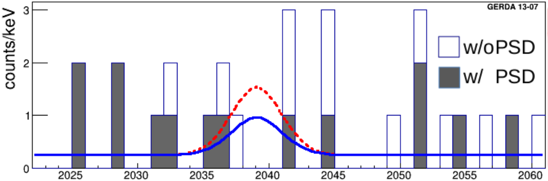
- fit in $[1930 - 2190]$ keV with 4 free parameters: $3\times$ constant background plus $1\times$ gauss with $T^{0\nu}_{1/2} > 0$
- gaussian parameters fixed:
  $\mu = (2039.06 \pm 0.2)$ keV
  $\sigma = (2.0 \pm 0.1)$ kev for semi-coaxial
  $\sigma = (1.4 \pm 0.1)$ kev for BEGe
- systematic uncertainties on f, ϵ, μ, σ: MC sampling & averaging

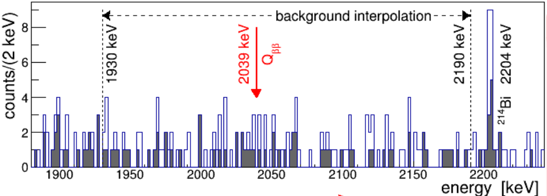
Results on $T^{0\nu}_{1/2}$ limit

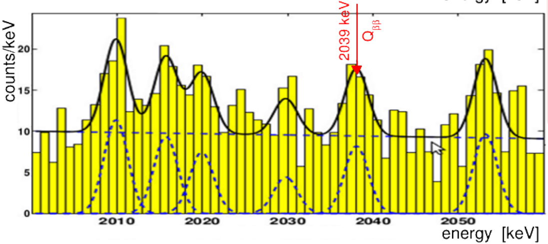
- Frequentist: profile likelihood fit
  → best fit $N^{0\nu} = 0$
  → $T^{0\nu}_{1/2}(90\%\mathrm{C.L.}) > 2.1 \cdot 10^{25}$ yr
  → median sensitivity: $2.4 \cdot 10^{25}$ yr
- Bayes: flat $1/T$ prior $0 - 10^{-24}$ yr
  → best fit $N^{0\nu} = 0$
  → $T^{0\nu}_{1/2}(90\%\mathrm{C.L.}) > 1.9 \cdot 10^{25}$ yr
  → median sensitivity: $2.0 \cdot 10^{25}$ yr

Unblinding @ $Q_{\beta\beta} \pm 5$ keV

Phys. Rev. Let. 111 (2013) 122503







Claim by subgroup of HdM (2004)

- total exposure: $M \cdot t = 71.7$ kg·yr
- 28.75 ± 6.86 signal events observed
- $T^{0\nu}_{1/2} = 1.19^{+0.37}_{-0.23} \cdot 10^{25}$ yr

Phys. Rev. Lett. B 586, 198-212 (2004)

Comparison with Phase I result

- assuming the claimed signal GERDA should see 5.9 ± 1.4 $0\nu\beta\beta$ events in $\pm 2\sigma$ interval above background of 2.0 ± 0.3
- probability from profile likelihood: p$(N^{0\nu}{=}0|\mathrm{H1{=}signal{+}bkg}){=}0.01$ → claim ruled out @ 99% level
- Bayes factor: p$(\mathrm{H1{=}signal{+}bkg})/p(\mathrm{H0{=}bkg})$ gives 0.024

→ search for $0\nu\beta\beta$ "open" again, many proposals to push sensitivity

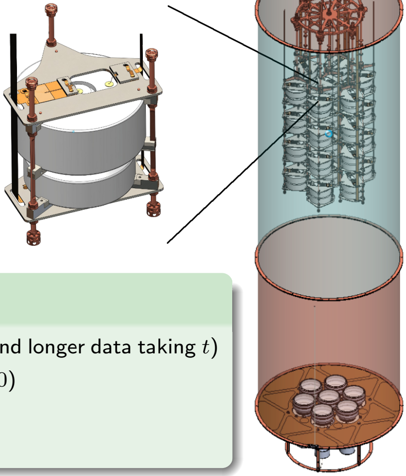
Phase I finished → currently preparing Phase II

Goal:

- Phase I: 20 kg·yr with a BI of $\sim 10^{-2}$ cts/(kg·keV·yr)
- Phase II: 100 kg·yr with a BI of $\sim 10^{-3}$ cts/(kg·keV·yr)

Upgrade:

- $2\times$ detector mass
  (~ 20 kg BEGe + ~ 15 kg semi-coax)
- liquid argon veto instrumented with PMTs
- optimized readout electronics
- low mass detector suspension + wedge bond contact (made of clean material)



$T^{0\nu}_{1/2} \propto f_{76} \cdot \epsilon \cdot \sqrt{\frac{M \cdot t}{BI \cdot \Delta E}}$ (if background is present)

- increased statistic (higher $\beta\beta$ emitter mass M and longer data taking t)
- lower background index BI (by about factor 10)
- better energy resolution ΔE

→ expected sensitivity $\simeq 1.4 \cdot 10^{26}$ yr (90% C.L.)

Conclusion: Phase I $(2011 - 2013)$

- data taking completed with an exposure of 21.6 kg·yr
- blind analysis performed (first time in this field)
- unprecedented BI of $\sim 10^{-2}$ cts/(kg·keV·yr) after PSD (order of magnitude lower than previous experiments)
- observed 3 events @ $Q_{\beta\beta} \pm 5$ keV compared to expected background of 2.5 ± 0.3 → no $0\nu\beta\beta$ signal
- upper half-life limit from profile likelihod fit:

  $T^{0\nu}_{1/2}(90\%\mathrm{C.L.}) > 2.1 \cdot 10^{25}$ yr with GERDA alone

  → HdM claim (2004) rejected @ 99% level

  $T^{0\nu}_{1/2}(90\%\mathrm{C.L.}) > 3.0 \cdot 10^{25}$ yr with GERDA + HdM[1] + IGEX[2]

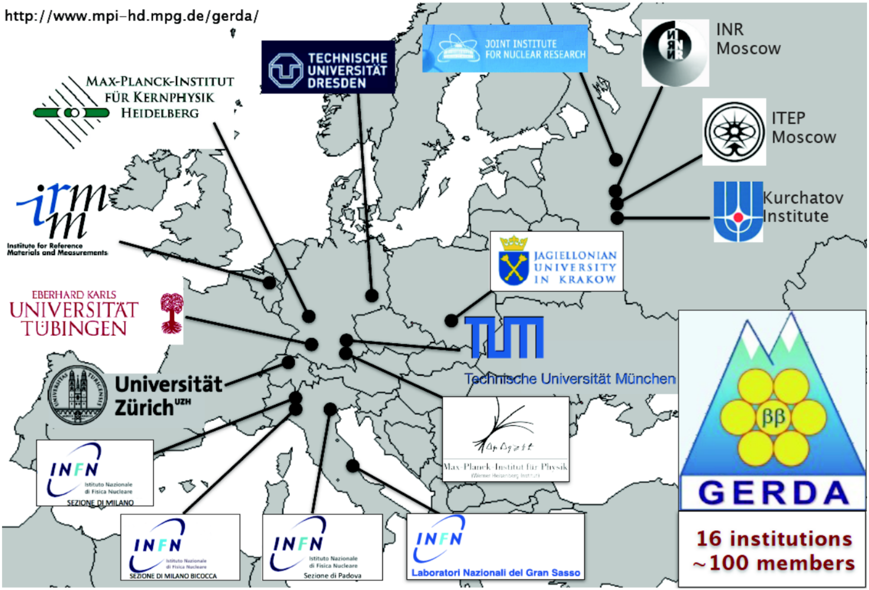
  [1] Euro Phys J A12 (2001) 147
  [2] Phys Rev D65 (2002) 092007

Outlook: Phase II (start scheduled end 2014)

- new BEGe detectors of additional ~ 20 kg → available
- upgrade of infrastructure (lock system, glove box, ...) → finished
- liquid argon scintillation veto → currently installed
- last integration tests (new contacting, electronics, ..,) → ongoing

The Collaboration

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



16 institutions
~100 members

The Collaboration

… and the people behind the GERDA experiment.

Picture taken during last GERDA Meeting in June 2014 hosted by the Max-Planck-Institut für Kernphysik @ Heidelberg, Germany