GERDA and the search for neutrinoless double beta decay: first results and perspectives

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DPG Frühjahrstagung - Fachverband Teilchenphysik
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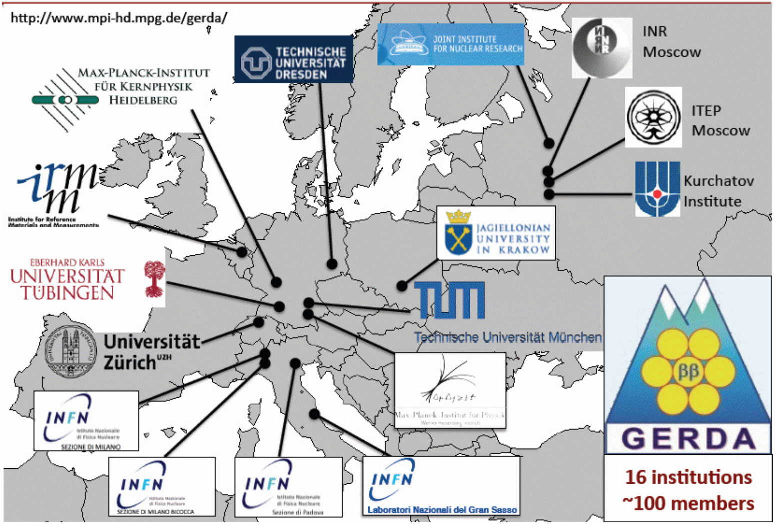
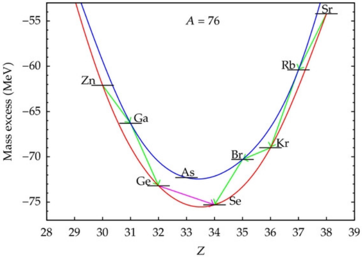
The GERDA collaboration



Search for the rare neutrinoless double beta decay



Towards the valley of stability:

- Second-order nuclear transition occuring between 2 even-even isobars: → single β decay energetically forbidden
- 35 candidates in Nature; Examples: ^{76}Ge, ^{82}Se, ^{96}Zr, ^{100}Mo, ^{116}Cd, ^{130}Te, ^{136}Xe

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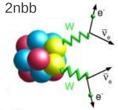
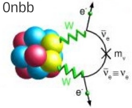


0nbb

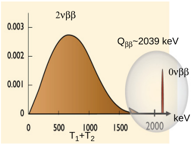


Role of neutrinos in $\beta\beta$ decay:

1. $2\nu\beta\beta$ decay
   → Allowed by Standard Model
   → Observed in 12 candidates:

   $O(T^{2\nu}_{1/2})=10^{18}$-$10^{24}$ yr
2. $0\nu\beta\beta$ (or $0\nu\chi^0(\chi^0)\beta\beta$) decay
   → Lepton-number violation (ΔL=2), thus not allowed by Standard Model
   - Note: One claim (in ^{76}Ge) by subgroup of Heidelberg-Moscow collaboration

Expected signature from $2\nu\beta\beta$ and $0\nu\beta\beta$ decays



From the observable $T^{0\nu}_{1/2}$ to the effective neutrino mass

Experimentally:

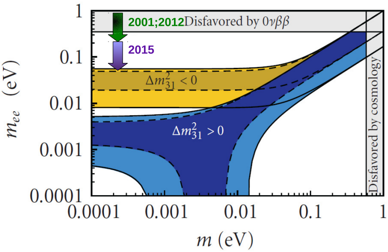
$$T_{1/2} \propto \begin{cases} a \cdot \epsilon \cdot M \cdot T, & \text{background-free} \\ a \cdot \epsilon \cdot \sqrt{\frac{M \cdot T}{\Delta E \cdot B}}, & \text{if background is present} \end{cases}$$

with a: Abun./Enrich.; M: Mass; ϵ: act.volume; ΔE: e-res.; T: life-time; B: bkgd

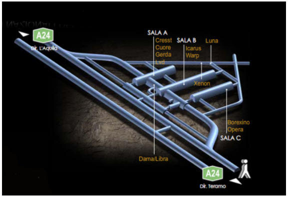
Nuclear physics meets elementary particle physics

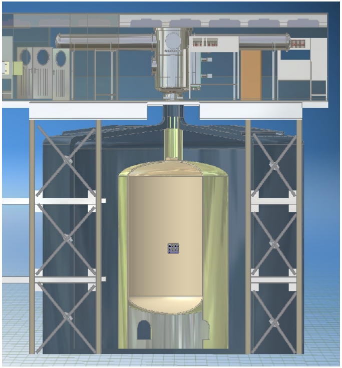
$$(T_{1/2})^{-1} = G^{0\nu} \left| M^{0\nu} \right|^2 \langle m_{\beta\beta} \rangle^2$$

with $G^{0\nu}$: phase space factor, $M^{0\nu}$: nuclear matrix element, $\langle m_{\beta\beta} \rangle = \left| \sum_j m_j U_{ej}^2 \right|$



The low background **GER**manium **D**etector **A**rray





Setup and background shielding:

- Overburden of 3500 m w.e. at Hall A of LNGS
  $\rightarrow$ Cosmic-muon flux reduced by 10^6
- Water tank and plastic scintillator
  R=5 m, h=9.0 m, 590 m^3 of ultra-pure water
  $\rightarrow$ water: neutron moderator/absorber
  $\rightarrow$ both components: active muon veto
- Large volume cryostat:
  R=2 m, h=5.9 m, 64 m^3 of LAr
  $\rightarrow$ cooling medium for diodes
  $\rightarrow$ attenuation of external radiation
- Germanium detector array:
  $\rightarrow$ Operation of bare diodes in LAr using low-mass holders
  $\rightarrow$ Ge enriched in ^{76}Ge: from 8% to ~86-88%

$0\nu\beta\beta$ **source = detector**

Phase I: 1-string & 3-string arm, each string up to 3 detectors
Phase II: Up to 12 strings + 'upgrade'

GERDA Phase I: ^{76}Ge enriched detectors

Detector technology and stability

- Mix of detectors:

  - Reprocessed semi-coaxial HPGe detectors ('coax'): 8×:
    - **Enriched** (^{76}Ge: ∼86%): ANG1-ANG5 from HdM; RG1, RG2 from IGEX

  - New broad energy HPGe detectors ('BEGe'): 5×:
    - **Enriched** (^{76}Ge: ∼88%): GD32B, GD32C, GD35B-GD35D

- Long-term stability: Beside for ANG1 and RG3, no sign. increase of leakage current. GD35C: other instabilities.

  → The 3 detectors not considered for the analysis; partly in coincidence modus.
  → Remaining enr. det. mass: 17.6 kg

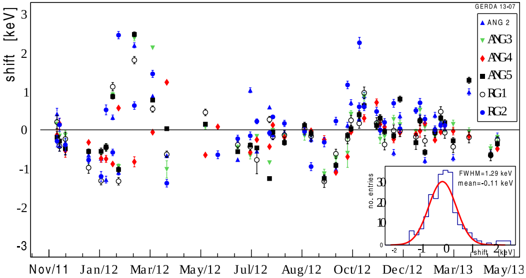
GERDA Phase I: data collection and calibrations

Data collection:

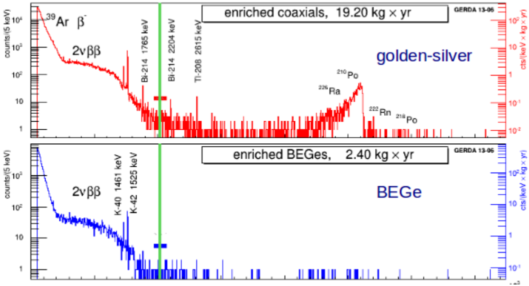
- Periods: 2010-2011 Commissioning
  2011-2013 Physics data with coax; add. BEGe since 2012
- Blinding: automatic blinding of $Q_{\beta\beta}$ region in (2039±20) keV region applied

Calibrations: ^{228}Th sources (bi-weekly), + pulser (0.05 Hz)

- Mean energy resolution (FWHM) at $Q_{\beta\beta}$: coax: 4.8(2) keV, BEGe: 3.2(2) keV
- Energy scale: drift of 2615 keV gamma-line small compared to FWHM

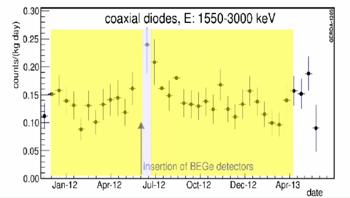


Blinded physics spectrum



Division in 3 data sets:

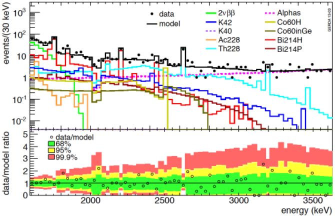
1. 'BEGe' = 2.4 kg·yr
2. 'silver coax' = 1.3 kg·yr: four weeks when BEGe inserted
3. 'golden coax' = 17.9 kg·yr: all coax data but four weeks

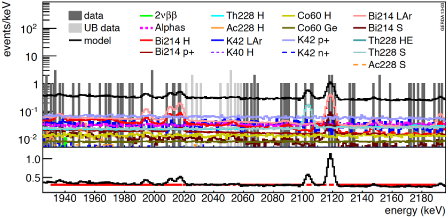


Background identification strategy:

1. Identification of main components: $2\nu\beta\beta$, γ-rays from ^{39}Ar, ^{40}K, ^{214}Bi (U), ^{208}Tl (Th), α-particles (U), β-particles from ^{42}K (^{42}Ar)
2. Background modeling via MC, then prediction of background in blinded region.

Full background decomposition in (570-7500) keV region





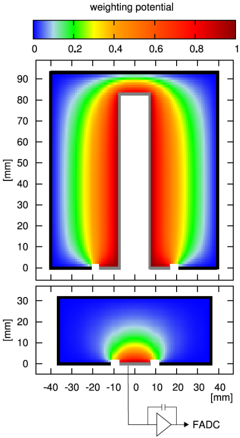
MC-based model of background

- Simulation: known (from material screening prior GERDA construction) and observed background components (from detector operation in GERDA Phase I)
- Fit of 2 extremes: Minimal (all known components) vs. maximal (many possible c.)

Results:

- Achieved background index (BI): 0.02 cts/(keV·kg·yr); only 2× about spec's (w/o PSD)
- Expected background at $Q_{\beta\beta}$: flat continuum and no γ-line

Active background suppression via pulse shape discrimination



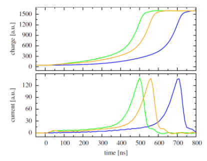
Current signal $= q \cdot v \cdot \nabla\Phi$

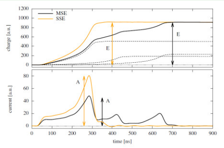
$q =$ charge
$v =$ velocity
$\Phi =$ weighting potential

Particle identification:

- $0\nu\beta\beta$ events: free path of 1 MeV electrons in Ge is $\approx$1 mm. So, only one single energy deposition $\rightarrow$ single site event (SSE).
- Gamma-rays: free path of 1 MeV of γ-rays in Ge is $> 10\times$ larger, Compton scattering. So, charge pulse consists of several time-spread energy depositions $\rightarrow$ multi-site events (MSE)
- Surface events: peculiar behavior distinguishable from SSE (fast/slow risetime)

Example: Charge and current signal for a BEGe





Survival vs. rejection fraction:
BEGe: SSE survival: (92 ± 2)%, bkgr. rej.: $>$80%
coax: SSE survival: (90^{+5}_{-9})%, bkgr. rej.: $>$45%

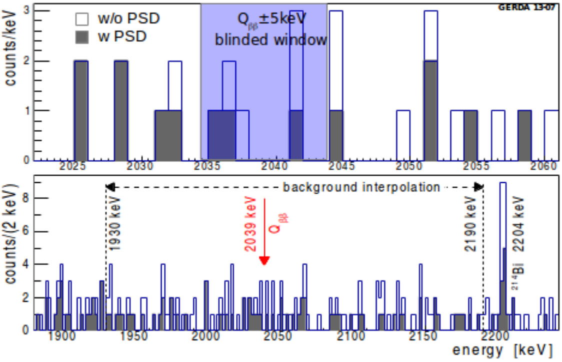
Unblinding

GERDA Collaboration Meeting in Dubna (RUS), June 12-14, 2013

Final steps prior unblinding:

- Freeze analysis cuts (event generation and quality cuts, energy calibration)
- Freeze data periods (golden, silver, BEGe) used for physics analysis
- Freeze background model
- Decide if PSD will be applied or not
- Decide about statistical method to be applied

Unblinded spectrum



Cts in $Q_{\beta\beta}\pm5$ keV	golden	silver	BEGe	total
expected, w/o PSD	3.3	0.8	1.0	**5.1**
observed, w/o PSD	5	1	1	**7**
expected, w PSD	2.0	0.4	0.1	**2.5**
observed, w PSD	2	1	0	**3**

Spectrum agrees with flat background expectation, no hint for gamma-line at $Q_{\beta\beta}$!

From counts to a half-life limit

$T^{0\nu}_{1/2}$, exposure, efficiencies and fitting procedure

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

Dataset	M·t	f_{76}	f_{av}	ϵ_{fep}	ϵ_{psd}
golden	17.9 kg·yr	0.86	0.87	0.92	0.90
silver	1.3 kg·yr	0.86	0.87	0.92	0.90
BEGe	2.4 kg·yr	0.88	0.92	0.90	0.92

- Fit 3 data sets in (1930-2190) keV with 4 free parameters: 3× constant background, 1× Gauss with $(T_{0\nu})^{-1} > 0$
- Gaussian parameters fixed: μ=(2039.06±0.2) keV, σ=(2.0±0.1) keV for coax, (1.4±0.1) keV for BEGe
- Systematic uncertainties on f, ϵ, μ, σ: Monte Carlo sampling and averaging

$T^{0\nu}_{1/2}$ limit: results

- Frequentist: profile likelihood fit → best fit $N^{0\nu} = 0$, $T^{0\nu}_{1/2} > 2.1\times10^{25}$ yr (90% C.L.)
- Bayes: flat 1/T prior 0-10^{-24} yr → best fit $N^{0\nu} = 0$, $T^{0\nu}_{1/2} > 1.9\times10^{25}$ yr (90% C.L.)

Global picture of ^{76}Ge experiments

Frequentist approach

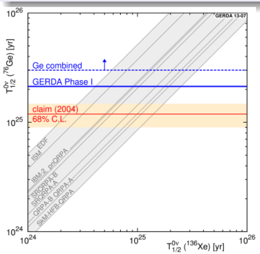
GERDA Phase I alone: $T^{0\nu}_{1/2} > 2.1\times10^{25}$ yr (90% C.L.)

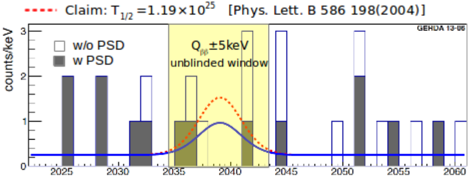
GERDA Phase I combined with HdM [1] and IGEX [2]: $T^{0\nu}_{1/2} > 3.0\times10^{25}$ yr (90% C.L.)

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

Implications

- Klapdor claim of 2004: $T^{0\nu}_{1/2} = (1.19^{+0.37}_{-0.23})\times10^{25}$ yr (90% C.L.)
  → Probability for 0 signal events in the GERDA spectrum, if claim is correct:
  $p(N_{0\nu}{=}0|\text{H1}{=}\text{signal}{+}\text{bckg}) = 0.01$
- Limit for effective neutrino mass: $(T_{1/2})^{-1} = G^{0\nu}\,|M^{0\nu}|^2\,\langle m_{\beta\beta}\rangle^2$
  → For 'Ge combined': $\langle m_{\beta\beta}\rangle < (0.2\text{-}0.4)$ eV





Towards a higher sensitivity

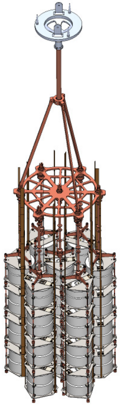
Goal:

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

GERDA's strategy for sensitivity improvement

$$T_{1/2} \propto f_{76} \cdot \epsilon \cdot \sqrt{\frac{M \cdot T}{\Delta E \cdot B}}, \quad \text{(if background is present)}$$

- **M** (Mass): → new Ge detectors
- f_{76} (Enrichement): → ^{76}Ge enrichment from 8% to 90%
- ϵ (Detector efficiency): → detailed characterisation tests
- **T** (DAQ livetime): → larger DAQ period, higher duty cycle
- **ΔE** (Energy resolution): → novel detector technologies with better ΔE (BEGe vs. coax)
- **B** (Background suppression):
  → Minimize exposure to cosmogenic radiation
  → Novel active background suppression strategies (PSD,..)



GERDA Phase II preparation: detector production and characterisation

1. 2005: Ge enr. at 88% in ^{76}Ge at ECP, Zelenogorsk, RUS
2. 2010: Purification via zone-refinement at PPM GmbH, Langelsheim, GER
3. 2011/12: Crystal pulling at Canberra Industries Inc., Oak Ridge, USA
4. 2012: BEGe Diode production at Canberra Semiconductors NV, Olen, BEL;

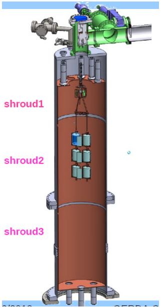
- Production of 30 new BEGe detectors: high mass yield (20.2 kg), all operational
- BEGe detector properties: fully characterized
- Exposure to cosmic radiation: minimized and tracked

GERDA Phase II preparation: LAr scintillation light instrumentation

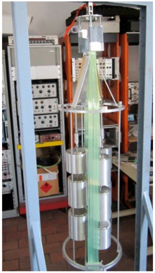
- Idea: Operate germanium diodes in coincidence with scintillation light instrumentation in liquid argon (λ=128 nm) in order to reject background
- Experience with PMTs in the LArGe test facility: background induced from ^{60}Co and ^{228}Th sources deployed in LAr rejected by $\mathcal{O}(1000)$.
- Realisation in GERDA: Combination of:
  - 9 × 3" PMTs at the top, 7 × 3" PMTs at the bottom
  - Wavelength-shifted glass-fibres with SiPM read-out

PMT teststand

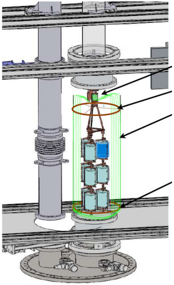
PMT Design



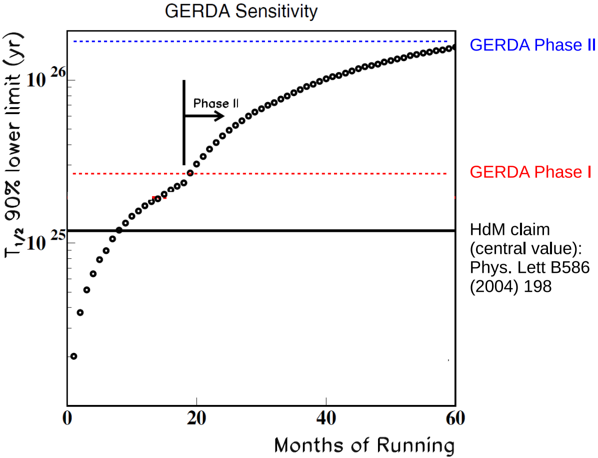
Glass-fibre teststand



Glass-fibre design



GERDA Phase II: sensitivity prediction



$T^{0\nu}_{1/2}$ >(1.5-2.0)×10^{26} yr (90% C.L.)
→ $\langle m_{\beta\beta} \rangle$ <(0.08-0.12) eV

Summary and outlook

GERDA Phase I (2011-2013)

- Design spec's: 21.6 kg·yr, BI$\sim 10^{-2}$ cts/(kg·yr·keV) incl. PSA (unprecedented)
- Physics results:
  - $\mathbf{T^{0\nu}_{1/2} > 2.1 \times 10^{25}}$ **yr (90% C.L.)** (first blind analysis)
    → HdM claim (2004) rejected at 99% level by GERDA alone
    → Combined Ge experiments: $\langle m_{\beta\beta} \rangle$ <(0.2-0.4) eV
  - Some additional results:
    - Published: $T^{2\nu}_{1/2}=(1.88\pm0.10)\times10^{21}$ yr (best S/B ratio among Ge)
    - Next: $2\nu\beta\beta$ and $0\nu\beta\beta$ decays to excited states of ^{76}Se (**talk by T. Wester, T65.3**)

GERDA Phase II (start scheduled in 2014)

- New detectors available: 20.2 kg, fully characterized
- Integration tests ongoing: new contacting, new read-out electronics
- Major upgrade of infrastructure ongoing: lock system, glove box, calibration system
- Active veto techniques for background suppression under preparation
  - LAr scintillation light instrumentation: PMT and fiber solution;
    R&D study: extinction of the scintillation light (**talk by B. Schneider, T65.2**)
  - ^{42}K background mitigation strategies (**talk by A. Lubashevskiy, T65.4**)

Bibliography and further reading

Before unblinding of GERDA Phase I data:

- Pulse shape discrimination for GERDA Phase I data: EPJC 73 (2013) 2583
- The background in the neutrinoless double beta decay experiment GERDA: arXiv:1306.5084
- Measurement of the half-life of the two-neutrino double beta decay of 76Ge with the GERDA experiment: J. Phys. G: Nucl. Part. Phys. 40 (2013) 035110
- The GERDA experiment for the search of $0\nu\beta\beta$ decay in 76Ge: Eur. Phys. J. C 73 (2013) 2330

After unblinding of GERDA Phase I data:

- Results on neutrinoless double beta decay of 76Ge from GERDA Phase I: Phys. Rev. Lett. 111 (2013) 122503