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

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IVICFA Friday's: Experimental Physics - 25 Oct 2013 - Valencia, Spain

Outline

- Neutrinoless double beta decay
- The GERDA experiment
- Phase I – prior to data unblinding
- Phase I – $0\nu\beta\beta$ analysis
- Phase II – preparation and plans

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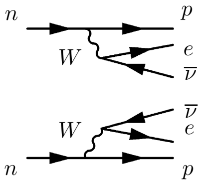
Double beta decays

Second order nuclear transitions $\rightarrow$ decay of two neutrons into two protons:

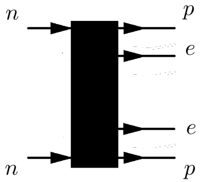
2-neutrino final state ($2\nu\beta\beta$):

- $(A, Z) \rightarrow (A, Z+2) + 2e^- + 2\bar{\nu}_e$
- allowed in the Standard Model
- measured in several isotopes
- $T^{2\nu}_{1/2}$ in the range $10^{19} - 10^{24}$ yr



0-neutrino final state ($0\nu\beta\beta$):

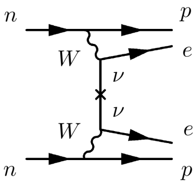
- $(A, Z) \rightarrow (A, Z+2) + 2e^-$
- lepton number violation ($\Delta L = 2$)
- physics beyond the Standard Model (e.g. light Majorana ν, R-handed weak currents, SUSY particles)
- ν Majorana mass component (Schechter-Valle theorem)
- $T^{0\nu}_{1/2}$ limits in the range $10^{21} - 10^{26}$ yr
- claim for a signal (subgroup of HdM experiment, 2004)

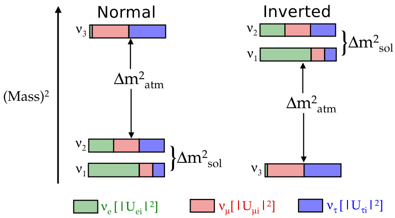


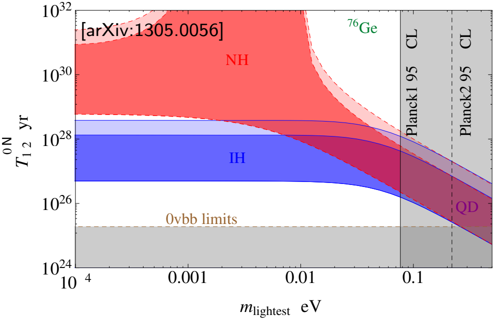
Neutrinoless double beta decay & neutrino physics

Assuming light-Majorana neutrino exchange as dominant $0\nu\beta\beta$ channel:

- $(T_{1/2}^{0\nu})^{-1} = G_{0\nu}(Q_{\beta\beta}, Z)|\mathcal{M}_{0\nu}(A,Z)|^2 \langle m_{\beta\beta}\rangle^2$
- effective Majorana mass: $\langle m_{\beta\beta}\rangle \equiv \left|\sum_i U_{ei}^2 m_i\right| = \left|c_{12}^2\, c_{13}^2\, m_1 + s_{12}^2\, c_{13}^2\, m_2\, e^{i2\alpha} + s_{13}^2\, m_3\, e^{i2\beta}\right|$
- neutrino oscillations: 3 angles, 2 delta mass squared, 1 phase
- ν mass spectrum (inverted/normal hierarchy, absolute mass scale)







Ge-76 and Xe-136 experiments

Ge-76:

- IGEX collaboration
  [Phys.Rev. D65, 092007 (2002)]:
  $T^{0\nu}_{1/2}(^{76}\text{Ge}) \geq 1.6{\cdot}10^{25}\ \text{yr}$ (90% C.L.)

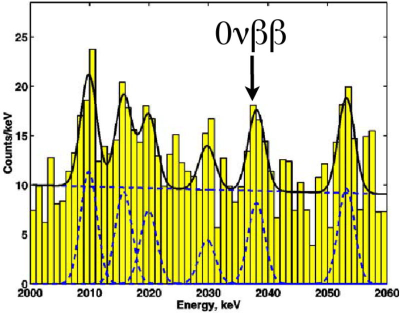
- HdM collaboration
  [Eur. Phys. J. A 12, 147 (2001)]:
  $T^{0\nu}_{1/2}(^{76}\text{Ge}) \geq 1.9{\cdot}10^{25}\ \text{yr}$ (90% C.L.)

- Klapdor-Kleingrothaus et al.
  [Phys.Lett. B586, 198 (2004)]:
  $T^{0\nu}_{1/2}(^{76}\text{Ge}) = 1.19^{+0.37}_{-0.23} \cdot 10^{25}\ \text{yr}$

Xe-136:

- EXO collaboration
  [Phys. Rev. Lett. 109 (2012)]:
  $T^{0\nu}_{1/2}(^{136}\text{Xe}) > 1.6{\cdot}10^{25}\ \text{yr}$ (90% C.L.)

- KamLAND-Zen collaboration
  [Phys.Rev.Lett. 110, 062502 (2013)]:
  $T^{0\nu}_{1/2}(^{136}\text{Xe}) > 1.9{\cdot}10^{25}\ \text{yr}$ (90% C.L.)



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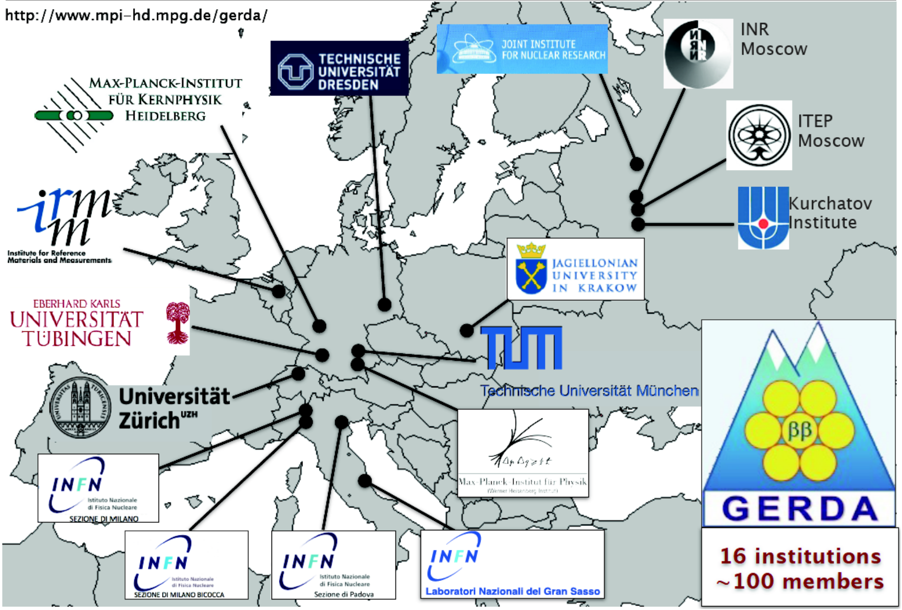
Collaboration

Institutions

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



16 institutions
~100 members

Sensitivity and background goals

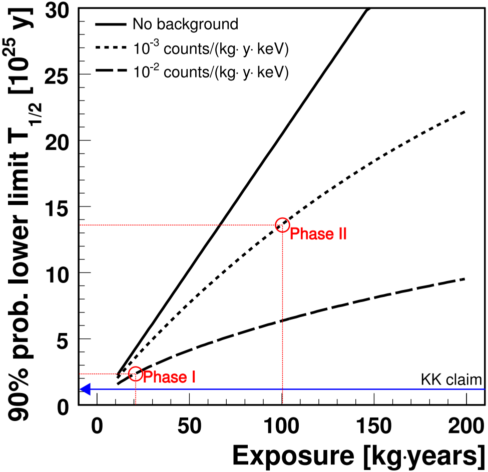
Phase I (Nov 2011 - May 2013):

- 15 – 20 kg of target mass (87% ^{76}Ge)
- bkg $\sim 10^{-2}$ cts/(keV· kg· yr) at $Q_{\beta\beta}$
- exposure 21.6 kg·yr
- sensitivity to scrutinize KK claim

Phase II (migration ongoing):

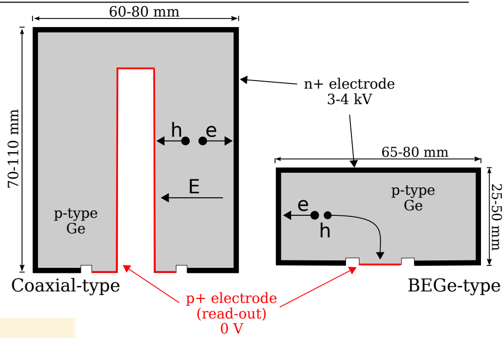
- new custom-produced BEGe detectors (additional 20 kg, 87% ^{76}Ge)
- bkg $\lesssim 10^{-3}$ cts/(keV· kg· yr) at $Q_{\beta\beta}$ (active techniques for bkg suppression)
- exposure $\gtrsim$ 100 kg·yr
- start exploring $T^{0\nu}_{1/2}$ in the 10^{26} yr range

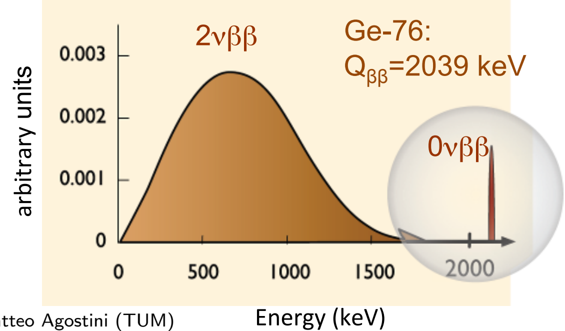
[Phys.Rev.D75, 092003 (2006)]



Detectors

- HPGe detectors from material enriched in ^{76}Ge ($\sim$87%)
- detectors well established technology
- optimal spectroscopy performance:
  - long-term stability
  - $\Delta E \approx 0.1\%$ at $Q_{\beta\beta}$
  - radio purity



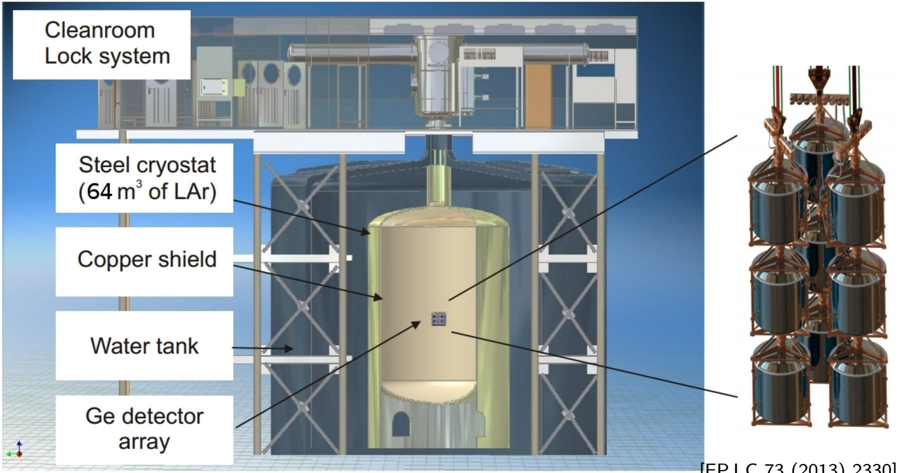


Calorimeter detectors:

- source=detector
- high detection efficiency
- peak at Q-value ($Q_{\beta\beta}$)

Shielding strategy and apparatus

- bare Ge detectors in liquid Argon (LAr)
- shield: high-purity LAr/H_2O
- radio-pure material selection
- deep underground (LNGS, 3800 m.w.e.)



[EPJ C 73 (2013) 2330]

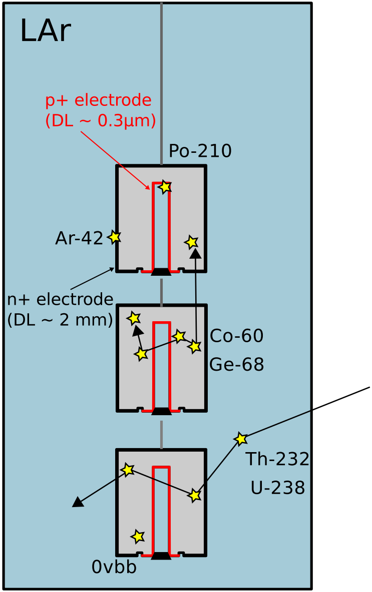
Backgrounds and mitigation techniques

Background sources:

- natural radioactivity (^{232}Th and ^{238}U chains):
  - γ-rays (e.g. ^{208}Tl, ^{214}Bi)
  - α-emitting isotopes from surface contamination (e.g. ^{210}Po) or ^{222}Rn in LAr
- cosmogenic isotopes in Ge decaying inside the detectors (^{68}Ge, ^{60}Co)
- long-lived cosmogenic Ar isotopes (^{39}Ar,^{42}Ar)

Mitigation strategy:

- detector anti-coincidence
- time-coincidence (Bi-Po or ^{68}Ge)
- pulse shape analysis (bulk localized energy deposition)
- LAr-scintillation (in Phase II)



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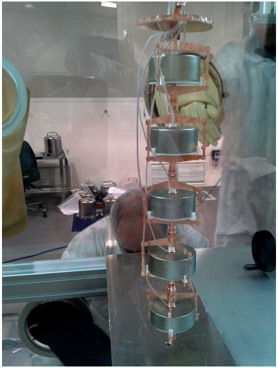
Detector array assembly

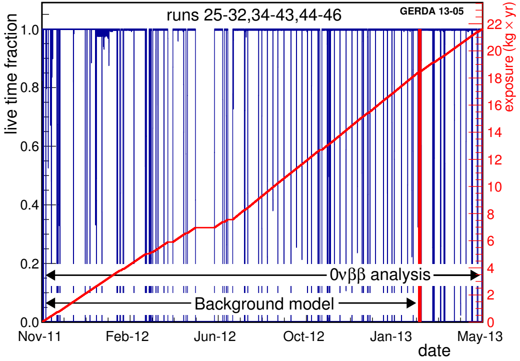


- 3 + 1 strings
- 8 ^{enr}Ge coaxial detectors (2 not considered in the analysis)
- 5 ^{enr}Ge BEGe detectors (1 not considered in the analysis)
- 3 ^{nat}Ge coaxial detectors

^{enr}Ge mass for physics analysis: 14.6 kg (coaxial) + 3.0 kg (BEGe)

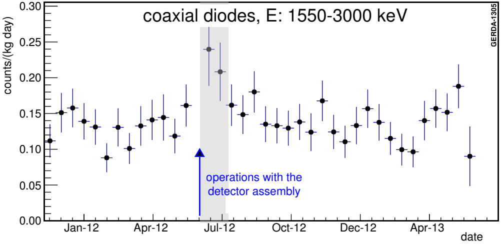
Overview of the data taking

- data taking Nov11 - May13 (492 d)
- average duty cycle 88%
- total exposure 21.6 kg·yr
- (bi)weekly calibration with Th-228 (blue spikes)

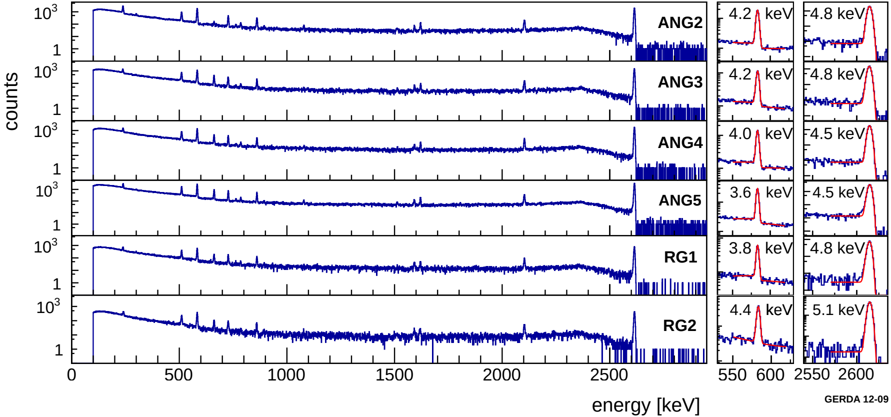


- BEGe detectors from Jul12
- 3 data sets:

dataset	exposure
coaxial (golden)	17.9 kg·yr
coaxial (silver)	1.3 kg·yr
BEGe	2.4 kg·yr



Calibration of the energy scale (^{228}Th)



Energy resolution at 2.6 MeV (FWHM):

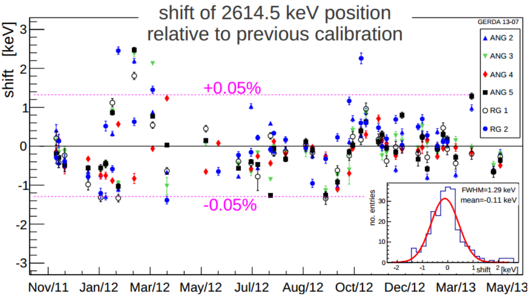
- 4 – 5 keV for coaxial data sets
- ∼ 3 keV for BEGe data set

Phase I – prior to data unblinding

Stability of the energy scale and resolution

Calibration runs:

- calibration every one/two weeks
- off-line energy reconstruction (semi-Gaussian filter)
- energy resolution stable
- energy shift between successive calibrations $\lesssim 1$ keV @ $Q_{\beta\beta}$

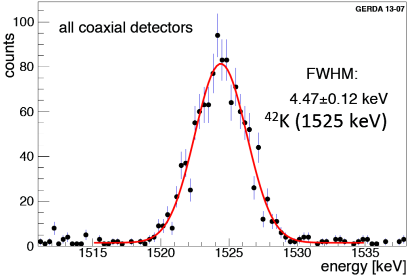


$0\nu\beta\beta$ data set:

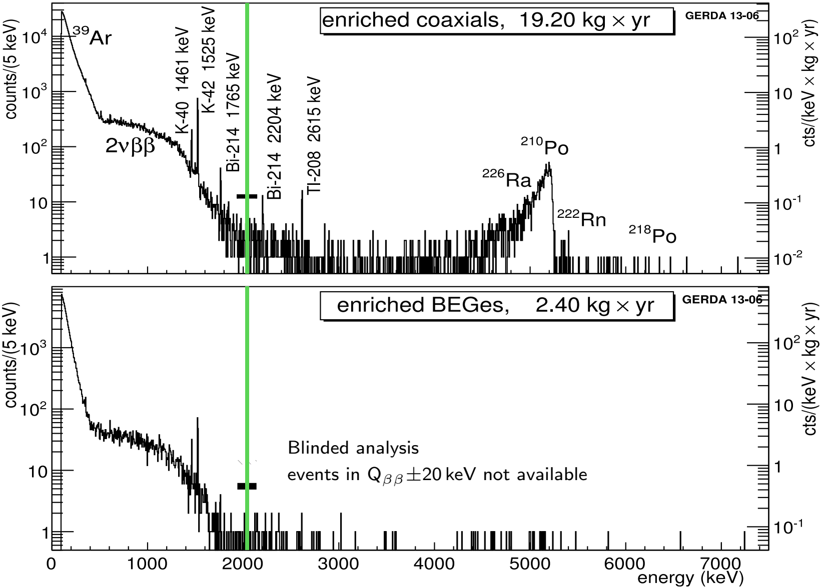
- peak position within 0.3 keV at correct position
- resolution 4% larger than in calibration runs
- mean FWHM at $Q_{\beta\beta}$ (mass/exposure weighted):

  coax —> 4.8±0.2 keV

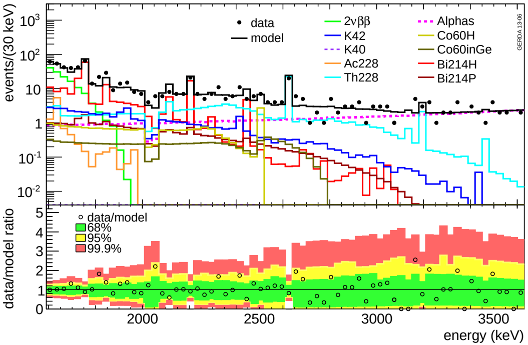
  BEGe —> 3.2±0.2 keV



Prominent structures in the energy spectrum



Phase I – prior to data unblinding
Background modeling

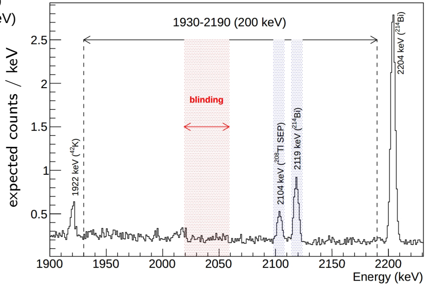


Contribution at $Q_{\beta\beta}$:

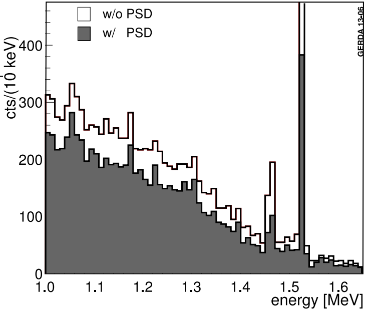
- γ-rays (close sources): Bi-214, Tl-208, K-42
- α- and β-rays (surface decays): Ra-226 daugheter, Po-210, K-42

more details in [arXiv:1306.5084]

- no line expected in the blinded window
- background flat between 1930-2190 keV (excluding peaks at 2104 and 2119 keV)
- extrapolated background level at $Q_{\beta\beta}$ in units of 10^{-2} cts/(keV$\cdot$ kg$\cdot$ yr):
  - coaxial (golden): $1.75^{+0.26}_{-0.24}$
  - BEGe: $3.6^{+1.3}_{-1.0}$



Phase I – prior to data unblinding
Pulse shape discrimination

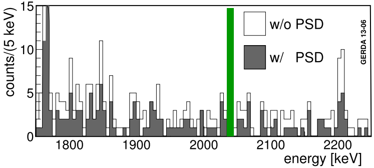


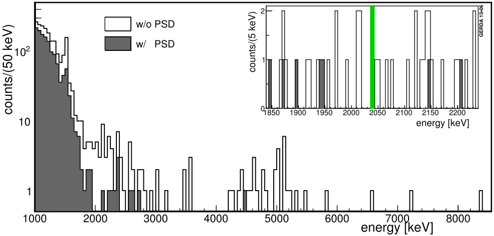
Coaxial detectors:

- artificial neural network TMlpANN
- cut defined using ^{228}Th calibration data
  cut fixed to 90% acceptance of 2.6 MeV DEP
- cross checks:
  - $2\nu\beta\beta$ acc. = (85±2)%
  - 2.6 MeV γ-line compton-edge acc. = 85-94%
  - Co-56 DEP (1576 & 2231 keV) acc. = 83-95%

$\boxed{0\nu\beta\beta \text{ acceptance} = 90^{+5}_{-9}\%}$

$\boxed{\text{background acc at } Q_{\beta\beta} = \sim 45\%}$





BEGe detectors:

- A/E method (mono-parametric PSD)
- $0\nu\beta\beta$ acc (DEP and simulations) (92±2)%
- $2\nu\beta\beta$ acc (91±5)%
- background acc at $Q_{\beta\beta} \leq 20\%$

more details in [Eur.Phys.J C73 (2013) 2583]

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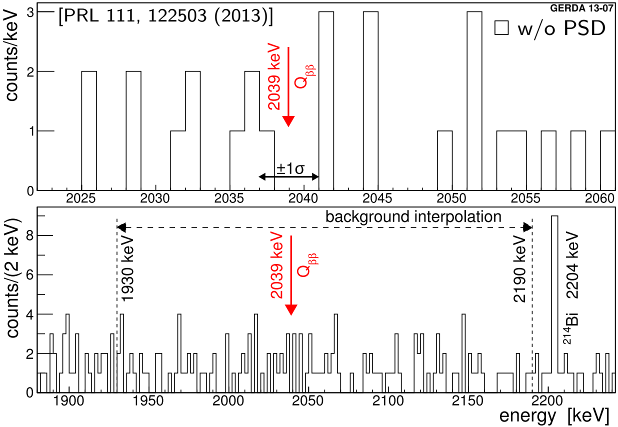
Energy spectra in the region of interest around $Q_{\beta\beta}$



Analysis cuts applied:

1) signals quality cuts
2) detector anti-coincidence
3) muon-veto anti-coincidence
4) single-detectors time coincidence (BiPo cut)
5) PSD

Cut acceptance around $Q_{\beta\beta}$:

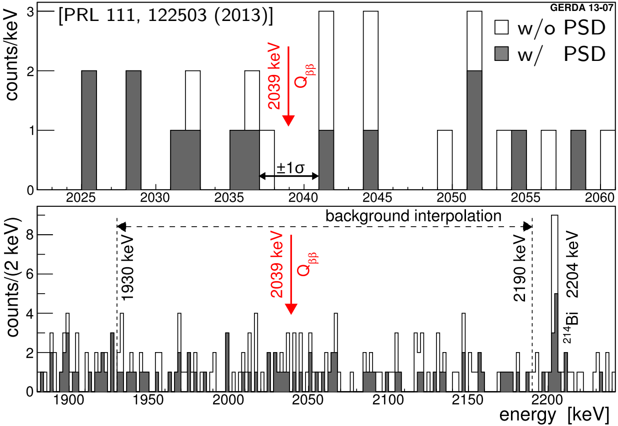
1	~99%
2+3	~60%
4	~100%
5	~50%

w/o PSD

w/ PSD

data set	exposure [kg· 10yr]	background 10^{-2} cts/(keV· kg· yr)	expected cts ($Q_{\beta\beta}\pm5$ keV)	observed cts ($Q_{\beta\beta}\pm5$ keV)
golden	17.3	1.8	3.3	5
silver	1.3	6.3	0.8	1
BEGe	2.4	4.2	1.0	1

Energy spectra in the region of interest around $Q_{\beta\beta}$



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4) single-detectors time coincidence (BiPo cut)
5) PSD

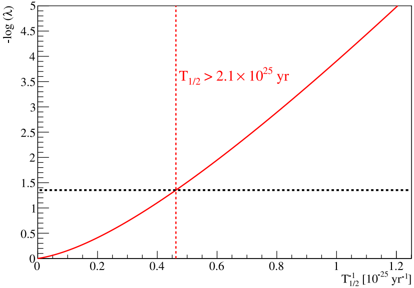
Cut acceptance around $Q_{\beta\beta}$:

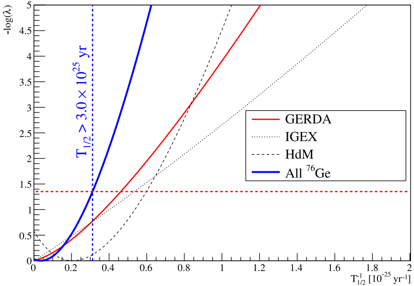
1	∼99%
2+3	∼60%
4	∼100%
5	∼50%

w/o PSD (blue) / w/ PSD (red)

data set	exposure [kg· 10yr]	background 10^{-2} cts/(keV· kg· yr)		expected cts ($Q_{\beta\beta}\pm5$ keV)		observed cts ($Q_{\beta\beta}\pm5$ keV)	
golden	17.3	1.8	1.1	3.3	2.0	5	2
silver	1.3	6.3	3.0	0.8	0.4	1	1
BEGe	2.4	4.2	0.5	1.0	0.1	1	0

Statistical analysis





Baseline analysis (profile likelihood):

- maximum likelihood spectral fit (constant+Gauss in 1930-2190 keV range)
- multiple data sets (common $T^{0\nu}_{1/2}$)
- $T^{0\nu}_{1/2} \geq 0$ (coverage tested)

Results (GERDA only):

- best fit for $N_{0\nu\beta\beta} = 0$ signal cts
- $N_{0\nu\beta\beta} < 3.5$ cts at 90% C.L.
- $T^{0\nu}_{1/2} > 2.1 \cdot 10^{25}$ yr (90% C.L.)
- MC Median sensitivity (for no signal): $T^{0\nu}_{1/2} > 2.4 \cdot 10^{25}$ yr (90% C.L.)

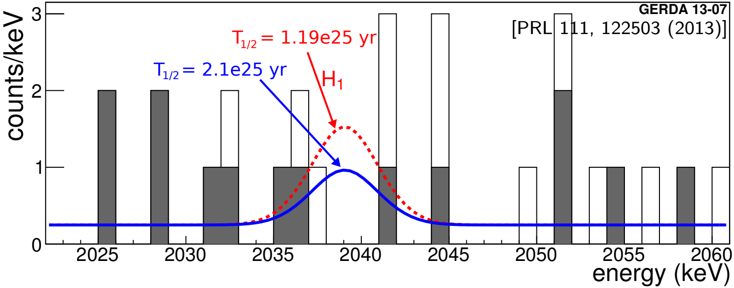
Results (GERDA + IGEX [1] + HdM [2]):

- best fit for $N_{0\nu\beta\beta} = 0$ signal cts
- $T^{0\nu}_{1/2} > 3.0 \cdot 10^{25}$ yr (90% C.L.)

PRL 111, 122503 (2013); [1] Phys.Rev. D65, 092007 (2002); [2] Eur.Phys.J. A12, 147 (2001)

Comparison with Phys.Lett. B586 198 (2004) claim

Hypothesis test: $\boxed{H_1\ (T^{0\nu}_{1/2} = 1.19^{+0.37}_{-0.23} \cdot 10^{25}\ \text{yr} + \text{bkg})}$ vs $\boxed{H_0\ (\text{bkg only})}$



In $Q_{\beta\beta} \pm 2\sigma_E$ (after PSD):

expected 5.9±1.4 signal cts

expected 2.0±0.3 bkg cts

observed 3 cts

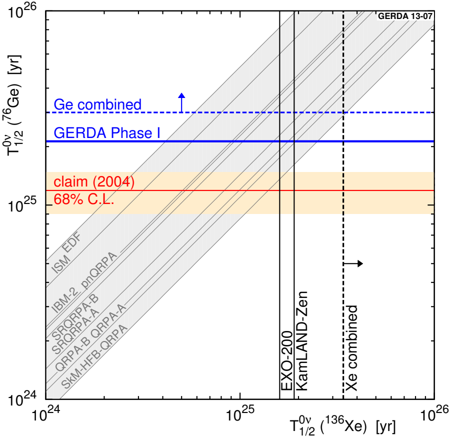
GERDA only:
- ▶ profile likelihood $P(N_{0\nu\beta\beta} = 0|H_1) = 0.01$
- ▶ Bayes factor $P(H_1)/P(H_0)$=$2.4 \cdot 10^{-2}$

GERDA+IGEX+HdM: ▶ Bayes factor $P(H_1)/P(H_0)$=$2 \cdot 10^{-4}$

—> claim strongly disfavoured

$T^{0\nu}_{1/2}$ from Mod. Phys. Lett. A 21 (2006) 1547 is not considered because of inconsistencies (i.e. missing efficiency factors, problem in the conversion from counts to $T^{0\nu}_{1/2}$) pointed out in Ann. Phys. 525 (2013) 269.

Comparison with ^{136}Xe experiments



- GERDA provides a model-independent test of the signal claim
- comparison with ^{136}Xe experiments possible only through:
  - assumptions on the leading channel (e.g. exchange of light Majorana neutrinos)
  - matrix element computations (selection used in the plot is taken from arXiv:1305.0056)

GERDA+EXO+KamLAND-Zen:

Bayes factor $P(H_1)/P(H_0) = 2.2 \cdot 10^{-3}$

(computed for the smallest NME ratio Xe/Ge)

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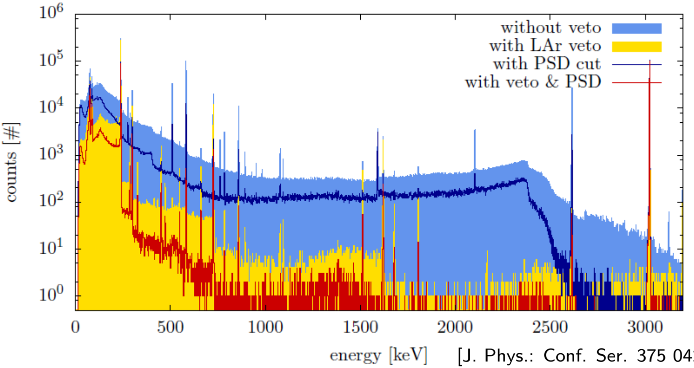
Phase II detectors and liquid argon scintillation

BEGe detectors:

- excellent energy resolution (1.6 keV @ 1.3 MeV)
- enhanced pulse shape discrimination performance
- 30 new ^{enr}Ge detectors ready at LNGS (20 kg)

LAr-scintillation (combined design):

- low-background photo-multipliers
- WLS fibers with Si photo-multipliers



[J. Phys.: Conf. Ser. 375 042009]

Pulse shape analysis combined with LAr-scintillation (in LArGe setup): measured suppression factor of $(5.2 \pm 1.3) \cdot 10^3$ at $Q_{\beta\beta}$ for close Th-228

Conclusions

- GERDA Phase I collected 21.6 kg·yr of exposure

- background order of magnitude lower than previous Ge experiments:

  $\sim$0.01 cts/(keV· kg· yr) at $Q_{\beta\beta}$ (after PSD)

- blind analysis —> no positive $0\nu\beta\beta$ signal:

  $T_{1/2}^{0\nu} > 2.1 \cdot 10^{25}$ yr at 90% C.L. (GERDA only)

  $T_{1/2}^{0\nu} > 3.0 \cdot 10^{25}$ yr at 90% C.L. (GERDA+IGEX+HdM)

- transition to Phase II in preparation (started in summer 2013):
  - major upgrade of many components
  - increased target mass (+20 kg)
  - new active techniques for background reduction down to

    10^{-3} cts/(keV· kg· yr) at $Q_{\beta\beta}$