First results on neutrinoless double beta decay from the GERDA experiment

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INFN, Laboratori Nazionali del Gran Sasso

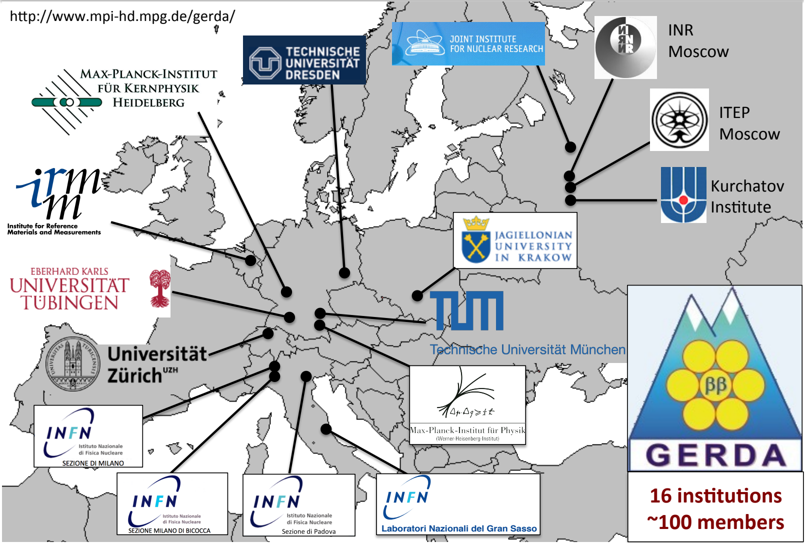
Congresso Nazionale SIF
Trieste, 25.02.2013

Outline

- Probing the nature of neutrino with neutrinoless double-beta decay
- The GERDA experiment: design and detection principle
- The GERDA calibrations and energy spectra
- The background models for GERDA Phase I
- The Pulse Shape Discrimination of GERDA events
- Result on $0\nu\beta\beta$ half-life

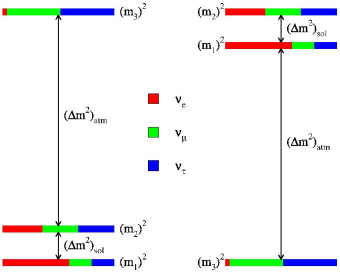
The GERDA collaboration

The GERDA Collaboration



Investigate existence of $0\nu\beta\beta$

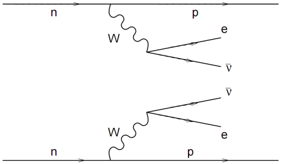
- $0\nu\beta\beta \rightarrow$ Majorana nature of neutrino
- Lepton number violation
- physics beyond Standard Model
- Shed lights on effective neutrino mass
- Shed lights on neutrino mass hierarchy



Search for $0\nu\beta\beta$ decay

$2\nu\beta\beta$

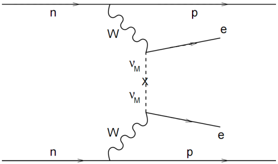
$$(Z,A) \rightarrow (Z+2,A) + 2e^- + 2\overline{\nu}_e$$



$\Delta L = 0 \Longrightarrow$ Predicted by s.m.

$0\nu\beta\beta$

$$(Z,A) \rightarrow (Z+2,A) + 2e^-$$



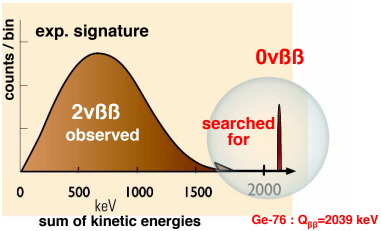
$\Delta L = 2 \Longrightarrow$ Prohibited by s.m.

Light Majorana neutrino exchange

$$Q = M_i - M_f - 2m_e$$

The GERmanium Detector Array

experiment is an ultra-low background experiment designed to search for ^{76}Ge $0\nu\beta\beta$ decay.



$Q_{\beta\beta} = 2039$ keV

Search for $0\nu\beta\beta$ decay

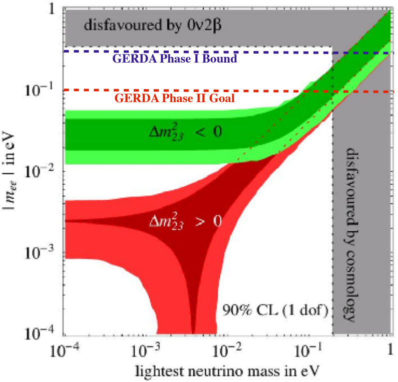
$$(T^{0\nu}_{1/2})^{-1} = G^{0\nu}|M^{0\nu}|^2\frac{\langle m_{\beta\beta}\rangle^2}{m_e^2}$$

with $\langle m_{\beta\beta}\rangle$ = effective electron neutrino mass

$$\langle m_{\beta\beta}\rangle \equiv |U_{e1}|^2 m_1 + |U_{e2}|^2 m_2 e^{i\phi_2} + |U_{e3}|^2 m_3 e^{i\phi_3}$$

m_i=masses of the neutrino mass eigenstates
U_{ei}=elements of the neutrino mixing matrix
$e^{i\phi_2}$ and $e^{i\phi_3}$=Majorana CP phases

$\rightarrow$ information on the absolute mass scale!



- **Phase I result**: BI $\sim 10^{-2}$ cts/(keV kg yr) and $\sim$ 20 kg yr exposure
  $\rightarrow$ limit on $\langle m_{ee}\rangle$ between 0.2 and 0.4 eV
- **Phase II goal**: BI $\sim 10^{-3}$ cts/(keV kg yr) and 100 kg yr exposure
  $\rightarrow$ sensitivity on $\langle m_{ee}\rangle \sim$ 100 meV

Ge detectors

Sensitivity $T_{1/2} \propto \epsilon \cdot \frac{\varepsilon}{A} \cdot \sqrt{\frac{M \cdot T}{b \cdot \Delta E}}$

ϵ	detection efficiency	$\gtrsim 85\%$
ε	enrichment fraction	high natural or enrichment
M	active target mass	increase mass
T	measuring time	
b	background rate (cts/(keV kg yr))	minimize & select radio-pure material
ΔE	energy resolution	use high resolution spectroscopy

Very low background High-Purity Germanium Detectors (HPGe)

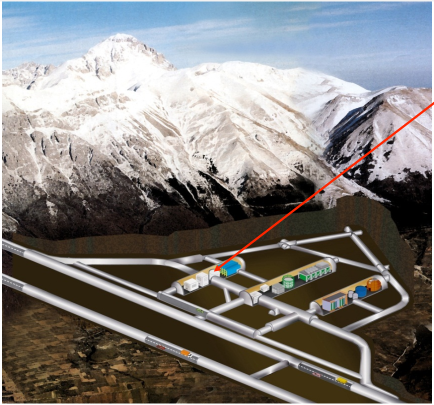
Advantages:

- well established enrichment technique $\varepsilon = 86\%$ for ^{76}Ge
- M and T expandable
- very good energy resolution $\Delta E \sim 0.1\%$ - 0.2%
- very good detection efficiency $\epsilon \sim 1$ (Ge as source and detector)
- high-purity detectors $\rightarrow$ low background b
- higher $M^{0\nu}$ w.r.t. other isotopes

Disadvantages:

- Low $Q_{\beta\beta}$ value (lower than ^{208}Tl 2614 keV) $\rightarrow$ background
- Need enrichment from 7% to 86% $\rightarrow$ it is expensive

GERDA @ LNGS



- Hall A of Gran Sasso Laboratory (INFN)
- 3800 m.w.e.

Background from:

External:

- γ's from Th and Ra chain
- neutrons
- cosmic-ray muons

Internal:

- cosmogenic ^{60}Co ($T_{1/2}$=5.3 yr)
- cosmogenic ^{68}Ge ($T_{1/2}$=271 d)
- Radioactive surface contaminations

Background reduction and events identification

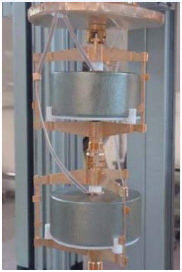
- Gran Sasso suppression of μ flux (10^6)
- Material selection
- Passive shield (H_2O) - LAr - Cu)
- Muon veto
- Detector anticoincidence
- Pulse-shape analysis

GERDA @ LNGS

GERDA Building

The GERDA collaboration, Eur. Phys. Journ. C 73 (2013) arXiv:1212.3210

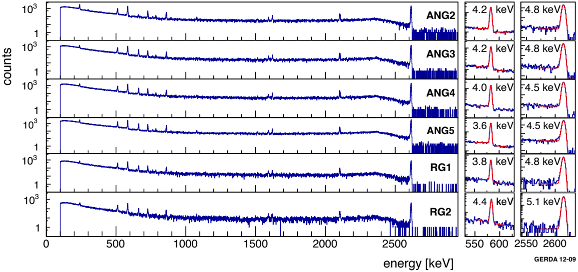
The GERDA detectors

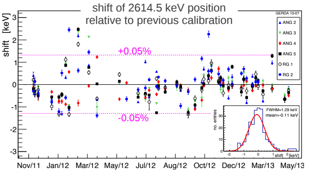


- 3 + 1 strings
- 8 enriched Coaxial detectors: working mass 14.6 kg
  (2 of them are not working due to high leakage current)
- GTF112 natural Ge: 3.0 kg
- 5 enriched BEGe: working mass 3.0 kg
  (testing Phase II concept in the real environment)

Energy calibrations and data processing

- Weekly calibrated spectra with ^{228}Th sources and pulser with 0.05 Hz frequency
- Data useful for resolution and stability over time monitoring
- FWHM at $Q_{\beta\beta}$ is about 4.8 keV for Coaxials and 3.2 keV for BEGes





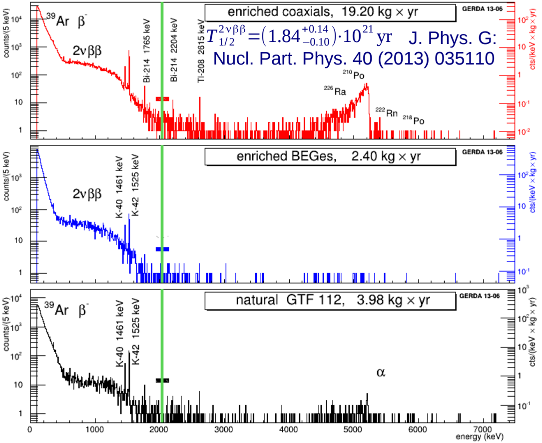
shifts are small compared to FWHM ~ 0.2% $Q_{\beta\beta}$

Data processing: diode→amplifier→FADC→digital filter →energy, pulse shape,...

Data selection: anti coincidence (20% rej.), quality cuts (9% rej.), pulse-shape discrimination (50% rej.)

Energy spectra

- Silver coax: data from coaxial detectors during BEGe deployment (higher BI)
- Golden coax: data from coaxial detectors except Silver coax
- BEGe: data from BEGe detectors

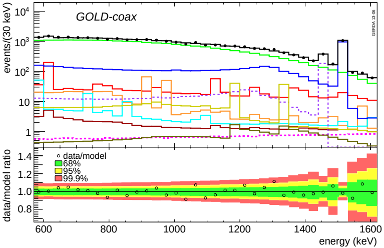


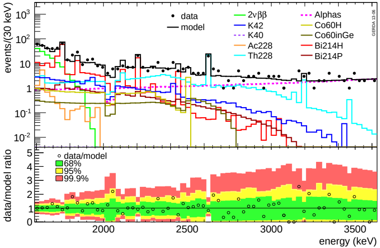
- Events in $Q_{\beta\beta} \pm$ 20 keV kept BLINDED to not bias analysis and cuts
- Phase I data divided in three subsets:
  - Golden coax: 17.9 kg yr exposure
  - Silver coax: 1.3 kg yr
  - BEGe: 2.4 kg yr
- **Background level**:
  - @ 2614 keV: 1.1±0.3 cts/(keV kg yr)
  - @ 1764 keV: 3.3±0.5 cts/(keV kg yr)
  - @ $Q_{\beta\beta}$: 0.018±0.002 cts/(keV kg yr)

Background 10x lower than previous Ge experiments!!

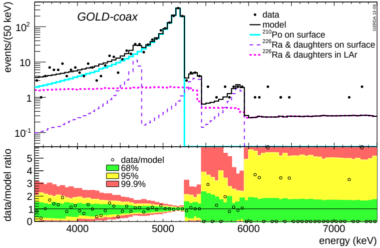
The Background Model of GERDA Phase I

The GERDA collaboration, submitted to Eur. Phys. Journ. C arXiv:1306.5084





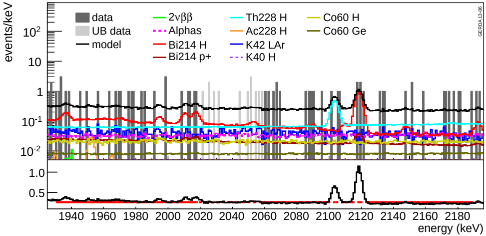
- Simulation of known and observed background
- Fit combination of MC spectra to data from 570 keV to 7500 keV
- Different combinations of positions and contributions tested



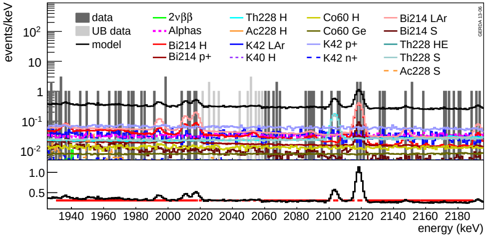
Main contribution from close background sources: ^{228}Th and ^{226}Ra in holders, ^{42}Ar α on detector surface

The Background Model of GERDA Phase I

Minimum model fit



Maximum model fit



- No line expected in the blinded window
- Background flat between 1930 and 2190 keV
- 2140±5 keV and 2119±5 keV excluded
- Partial unblinding after calibration and background model fixed

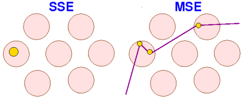
8.6 (minimum model) or 10.3 (maximum model) events expected
while 13 events observed in 30 keV window

Golden coax:
$\mathrm{BI} = 1.75^{+0.26}_{-0.24} \cdot 10^{-2}$ cts/(keV kg yr)

BEGe:
$\mathrm{BI} = 3.6^{+1.3}_{-1.0} \cdot 10^{-2}$ cts/(keV kg yr)

Pulse shape discrimination of GERDA Phase I data

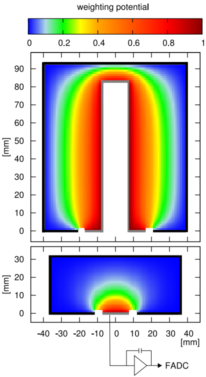
SSE: $\beta\beta$, DEP MSE: Compton



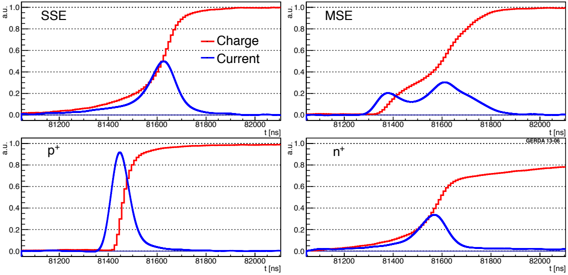
Pulse-shape analysis

e signal: single site energy deposition

γ signal: multiple site energy deposition



Current signal = q · v · ΔΦ
q=charge, v=velocity
(Schockley-Ramo theorem)



$0\nu\beta\beta$ events: 1 MeV electrons in Ge ∼ 1mm
one drift of electrons and holes SINGLE SITE EVENTS (SSE)

Background from γ's: MeV γ in Ge ∼ cm
several electron/holes drifts MULTI SITE EVENTS (MSE)

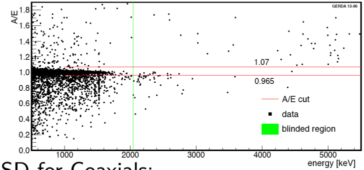
Surface events: only electron or hole drift

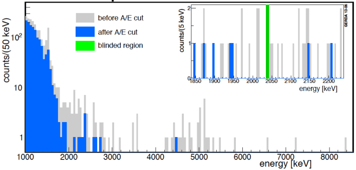
Pulse shape discrimination of GERDA Phase I data

The GERDA collaboration, accepted by Eur. Phys. Journ. C arXiv:1307.2610

PSD for BEGe:

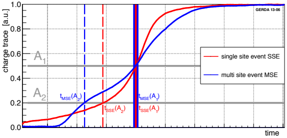
- A over E parameter (A/E) between 0.965 and 1.07
- Double escape peak of 2615 keV γ in ^{228}Th from calibrations → SSE for $0\nu\beta\beta$
- $0.92\pm2\%$ efficiency for $0\nu\beta\beta$ - 7/40 events kept in 400 keV window

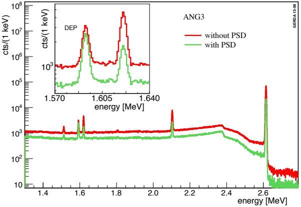




PSD for Coaxials:

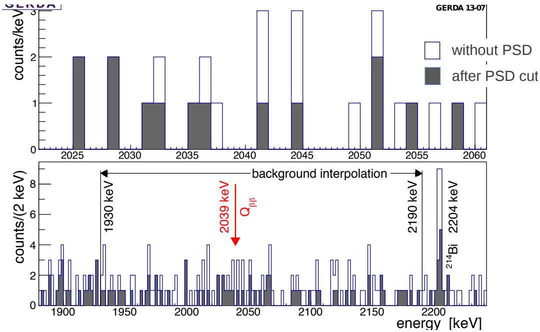
- Artificial Neural Network **ANN**
- Trained on signal SSE: ^{208}Tl (2614 keV) DEP at 1592 keV
- $0.90^{+0.05}_{-0.09}\%$ efficiency for $0\nu\beta\beta$ - 50% rej.





Results on $0\nu\beta\beta$ decay

- Sum spectrum **21.6 kg yr**
- Unblinding after calibration finished, data selection frozen, analysis method fixed and PSD selection fixed
- Consider the 3 data sets separately in the analysis
- 7 events observed in 10(8) keV window - 5.1 expected
- 3 events observed after PSD - 2.5 expected



data set	$\mathcal{E}$[kg·yr]	$\langle\epsilon\rangle$	bkg	BI †)	cts
without PSD					
golden	17.9	0.688 ± 0.031	76	18 ± 2	5
silver	1.3	0.688 ± 0.031	19	63^{+16}_{-14}	1
BEGe	2.4	0.720 ± 0.018	23	42^{+10}_{-8}	1
with PSD					
golden	17.9	$0.619^{+0.044}_{-0.070}$	45	11 ± 2	2
silver	1.3	$0.619^{+0.044}_{-0.070}$	9	30^{+11}_{-9}	1
BEGe	2.4	0.663 ± 0.022	3	5^{+4}_{-3}	0

†) in units of 10^{-3} cts/(keV·kg·yr).

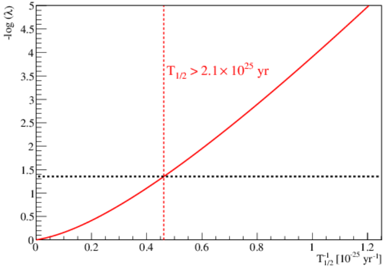
data set	detector	energy [keV]	date	PSD passed
golden	ANG 5	2041.8	18-Nov-2011 22:52	no
silver	ANG 5	2036.9	23-Jun-2012 23:02	yes
golden	RG 2	2041.3	16-Dec-2012 00:09	yes
BEGe	GD32B	2036.6	28-Dec-2012 09:50	no
golden	RG 1	2035.5	29-Jan-2013 03:35	yes
golden	ANG 3	2037.4	02-Mar-2013 08:08	no
golden	RG 1	2041.7	27-Apr-2013 22:21	no

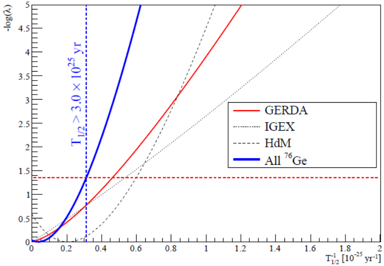
No peak in spectrum observed, number of events consistent with expectation from background

Results on $0\nu\beta\beta$ decay

The GERDA collaboration, Phys. Rev. Lett. 111 (2013) 122503

arXiv:1307.4720





- Frequentist analysis
- Maximum likelihood spectral fit (3 subsets, $1/T_{1/2}$ common)
- Bayesian analysis also available

- **Profile likelihood result**: $T^{0\nu}_{1/2} > 2.1 \cdot 10^{25}$ yr at 90% C.L.
- **Bayesian analysis result**: $T^{0\nu}_{1/2} > 1.9 \cdot 10^{25}$ yr at 90% C.I.
- Best fit: $N^{0\nu} = 0$

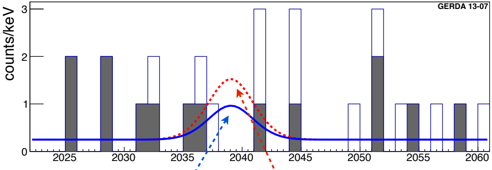
- GERDA+HdM+IGEX: $T^{0\nu}_{1/2} > 3.0 \cdot 10^{25}$ yr at 90% C.I. and Best fit: $N^{0\nu} = 0$

Results on $0\nu\beta\beta$ decay

Comparison with Phys. Lett. B 586 198 (2004) claim

Compare two hypotheses:

- H_1: $T^{0\nu}_{1/2} = 1.19^{+0.37}_{-0.23} \cdot 10^{25}$ yr
- H_0: background only



- **GERDA only**:
  Profile likelihood
  $P(N^{0\nu}{=}0|H_1) = 0.01$
  Bayes factor
  $P(H_1)/P(H_0) = 0.024$
- **GERDA+HdM+IGEX:**
  Bayes factor
  $P(H_1)/P(H_0) = 0.0002$

Compatible with no signal events
$T^{0\nu}_{1/2} = 2.1 \cdot 10^{25}$ yr

Claim strongly disfavoured!

N.B.: $T^{0\nu}_{1/2}$ from Mod. Phys. Lett. A 21 (2005) 157 not considered because of inconsistencies (missing efficiency factors) pointed out in Ann. Phys. 525 (2013) 259 by B. Schwingenheuer.

Conclusions

- Phase I data taking started on 11.2011 and ended on 05.2013
- Total exposure of GERDA Phase I is 21.6 kg yr
- Very low background 0.01 cts/(keV kg yr) after PSD
- 3 events observed while 2.5±0.3 expected in $Q_{\beta\beta}\pm 5$ keV
- Profile likelihood analysis gives $T^{0\nu}_{1/2} > 2.1 \cdot 10^{25}$ yr (90% C.L.) for ^{76}Ge
- Previous claim signal refuted by GERDA at 99%

Thanks

Grazie per la vostra attenzione e buona conferenza SIF!

GERDA Collaboration Meeting in Dubna, Russia
June 2013