Search for Double Beta Decay with GERDA

Carla Macolino on behalf of the GERDA collaboration

INFN, Laboratori Nazionali del Gran Sasso

Les rencontres de physique de la Vallée d'Aoste
La Thuile 25.02.2013

Outline

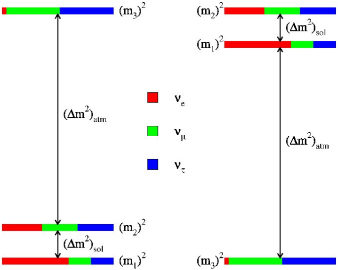
- Probing the nature of neutrino with double-beta decay
- The GERDA experiment: design and detection principle
- The GERDA first physics results: $2\nu\beta\beta$ decay half-life
- Status and future plans for Phase II

The GERDA collaboration

112 physicists, 19 institutions, 7 countries

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

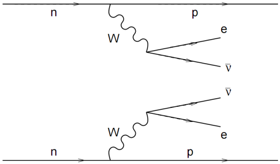
- $0\nu\beta\beta \rightarrow$ Majorana nature of neutrino
- Lepton number violation
- Shed lights on effective neutrino mass
- Shed lights on neutrino mass hierarchy



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

$2\nu\beta\beta$

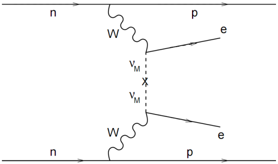
$$(Z,A) \rightarrow (Z+2,A) + 2e^- + 2\overline{\nu}_e$$



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

$0\nu\beta\beta$

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



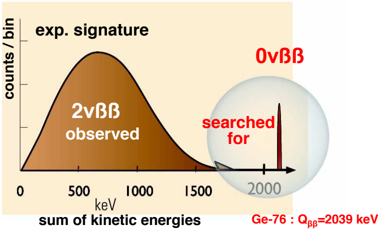
$\Delta L = 2 \Longrightarrow$ Prohibited by s.m.

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.



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

$$(T^{0\nu}_{1/2})^{-1} = G^{0\nu} |M^{0\nu}|^2 \frac{m^2_{\beta\beta}}{m^2_e}$$

$$m_{\beta\beta} \equiv |\sum_{i=1}^{3} U^2_{ei} e^{i\beta} m_i|$$

$\equiv$ effective mass of electron neutrino

$\rightarrow$ information on the absolute mass scale!

GERDA detectors

Sensitivity

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

ϵ	detection efficiency	$\gtrsim 85\%$
A	isotopic abundance	high natural or enrinchment
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)

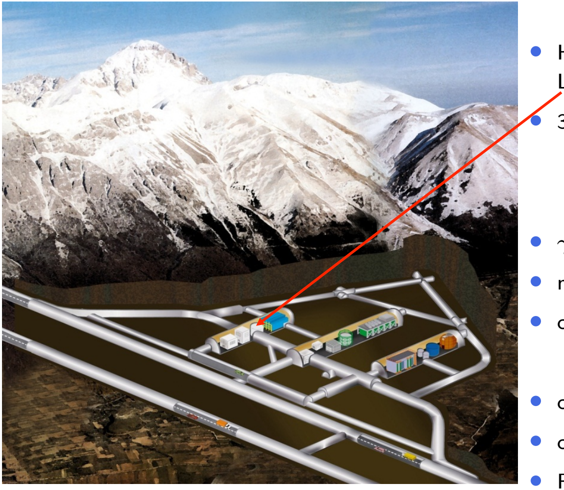
Advantages:

- well established enrichment technique
  $A = 86\%$ 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

Disadvantages:

- Low $Q_{\beta\beta}$ value
  $\rightarrow$ small phase-space factor $G^{0\nu}$
- 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 U chain
- neutrons
- cosmic-ray muons

Internal:

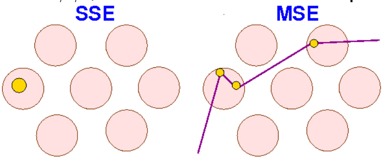
- cosmogenic ^{60}Co ($T_{1/2}$=5.3 yr)
- cosmogenic ^{68}Ge ($T_{1/2}$=271 d)
- Radioactive surface contaminations

Bck reduction and events identification

- Gran Sasso → Suppression of μ-flux$> 10^6$
- Material screening
- Passive shield (H_2O - LAr - Cu)
- Muon veto

- Detector anticoincidence (presently done)
- Pulse-shape analysis (possible)
- LAr scintillation (R&D) (for Phase II)

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



Pulse-shape analysis

e signal: single site energy deposition

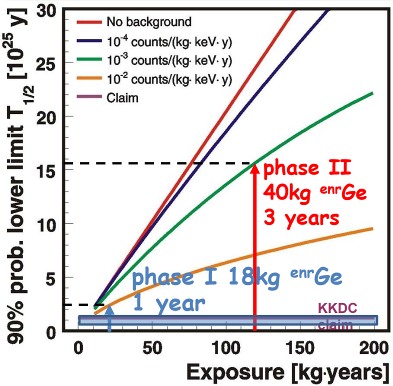
γ signal: multiple site energy deposition

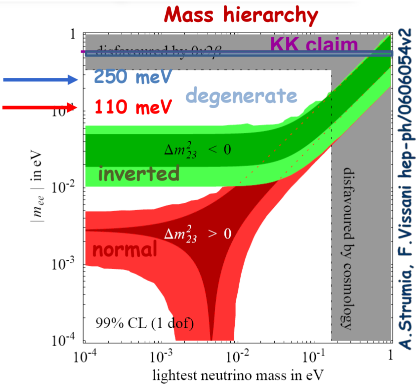
GERDA @ LNGS

GERDA Building

The GERDA collaboration, *arXiv:1212.3210*

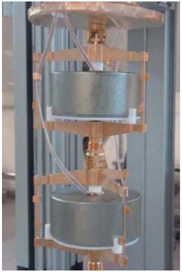
GERDA physics goals





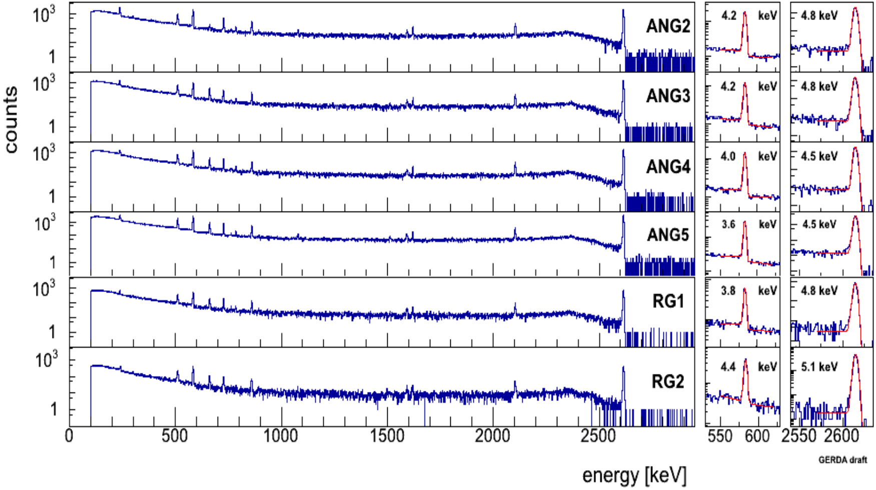
- **Phase I**: existing HdM and IGEX detectors + BEGe detectors
  target sensitivity $T^{0\nu}_{1/2} = 2 \cdot 10^{25}$ yr @ 90% C.L. (requires $\sim$ 20 kg yr exposure)
- **Phase II**: about 20 kg of new ^{76}Ge detectors
  BI $\sim 10^{-3}$ cts/(keV kg yr) and 100 kg yr exposure
- **Phase III**: Gerda + Majorana - BI $\sim 10^{-4}$ cts/(keV kg yr) $\rightarrow \langle m_{ee} \rangle \sim 10$ meV

The GERDA detectors



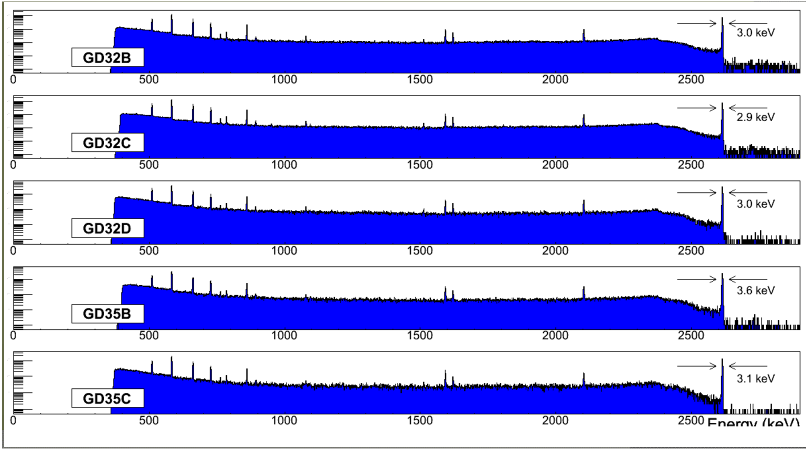
- 3 + 1 strings
- 8 enriched Coaxial detectors: working mass 14.6 kg
  (2 of them are not working due to high leakage current)
- GTF112 natural Ge: 3.0 kg
- 5 enriched BEGe: 3.6 kg
  (testing Phase II concept in the real environment)

Energy calibration - ^{228}Th sources



Coaxials: **Mass weighted average for FWHM at $Q_{\beta\beta} \simeq$ 4.5 keV**

Energy calibration - ^{228}Th sources



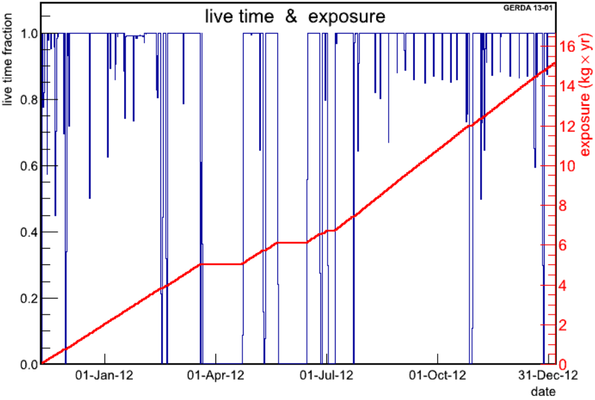
BEGe: **Mass weighted average for FWHM at $Q_{\beta\beta} \simeq 3.0$ keV**

Phase I started on November, 9th 2011

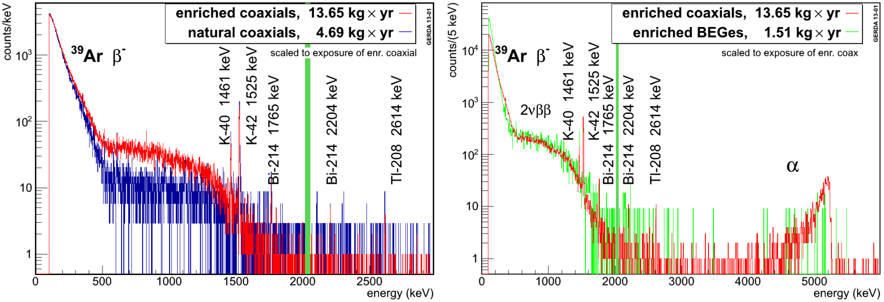
- Exposure by end of 2012:

  15.16 kg yr (enriched)
  4.69 kg yr (natural)

- Average duty cycle: 81%



Natural and Enriched detectors



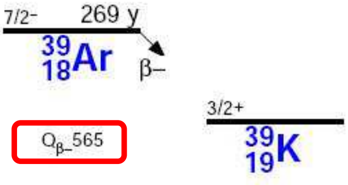
(Spectra normalised to the enriched coaxials spectrum)

^{76}Ge $2\nu\beta\beta$ spectrum clearly visible in enriched detectors

Since Jan. 2012 data at $Q_{\beta\beta} \pm 20$ keV are blinded

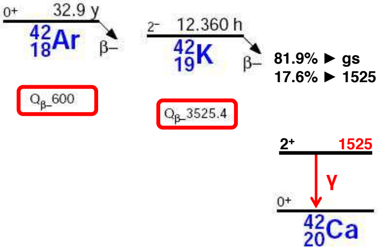
Unblinding in June/July 2013 → @ 20 kg yr exposure

Background from Argon



- ^{39}**Ar**

Published activity of (1.01 ± 0.08) Bq/kg (Benetti et al., *NIM A547 (2007)* 83) fully compatible with our data
Not relevant for BI at $Q_{\beta\beta}$



- ^{42}**Ar**

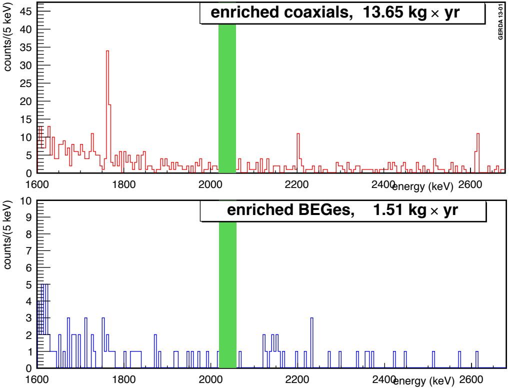
Lower limit of 41 μBq/kg (90% C.L.) (Ashitkov et al., arXiv:nucl-ex:0309001)
Count rate at 1525 keV about 2 times expectation

Convincing evidence that charged ^{42}K ions drift in the E field of Ge-diodes
$\rightarrow$ thin Cu foil (mini-shroud) as electrostatic and physical shield

Background index around $Q_{\beta\beta}$

Average BI in a $Q_{\beta\beta} \pm 100 keV$ window (minus 40 keV blind region)

- $0.022^{+0.003}_{-0.003}$ counts/(keV kg yr) for enriched coaxial detectors ($0.017^{+0.003}_{-0.003}$ counts/(keV kg yr) excluding 1.30 kg yr period of higher background due to detector substitution)
- $0.041^{+0.015}_{-0.012}$ counts/(keV kg yr) for enriched BEGe detectors
- $0.051^{+0.009}_{-0.008}$ counts/(keV kg yr) for natural detectors



BI about 10 times lower than previous experiments

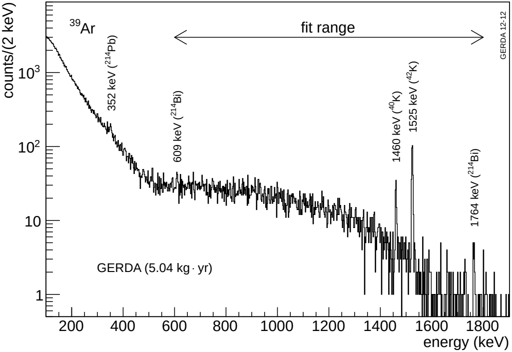
HdM: BI $\gtrsim$ 0.11 counts/(keV kg yr)

IGEX: BI = 0.17 counts/(keV kg yr)

Background contribution at $Q_{\beta\beta}$:

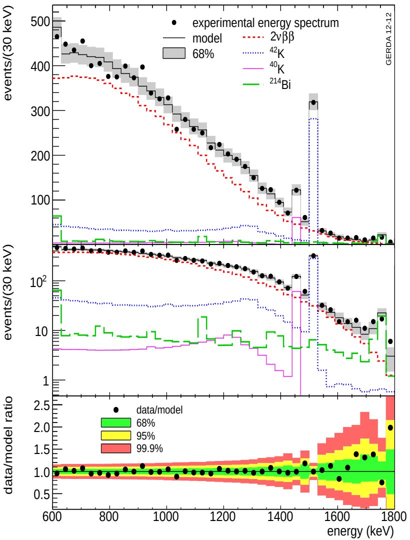
- γ's from ^{214}Bi and ^{208}Tl
- degraded α's from ^{210}Po
- β from ^{42}K

Half-life of $2\nu\beta\beta$ decay of ^{76}Ge



- Data: 8796 events
- Fit range: 600-1800 keV
- 5.04 kg · yr exposure
- Avg. active mass fraction: $(86.7 \pm 4.6(\text{uncorr.}) \pm 3.2(\text{corr.}))\%$
- Avg. enrichment fraction: $(86.3 \pm 2)\%$

Half-life of $2\nu\beta\beta$ decay of ^{76}Ge



Binned maximum likelihood

Parameters:

- Active detector masses (6+1) *nuisance parameter*
- Fraction enrichment in ^{76}Ge (6) *nuisance parameter*
- Background contributions (3x6) *nuisance parameter*
- $T_{1/2}^{2\nu}$ common to all the detectors (1)

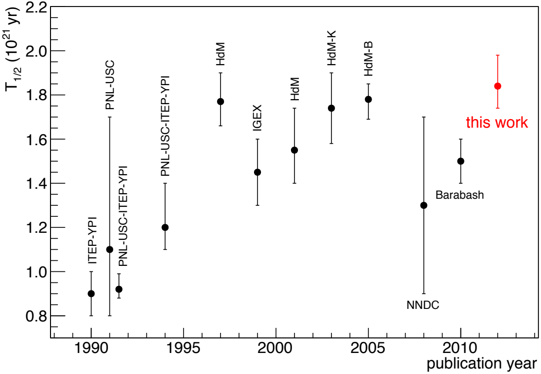
Derive $T_{1/2}^{2\nu}$ after the fit integrating over nuisance parameters

$2\nu\beta\beta$ (80%) ^{42}K (14%)
^{214}Bi (4%) ^{40}K (2%)

$$\mathbf{T_{1/2}^{2\nu} = (1.84^{+0.09+0.11 syst}_{-0.08-0.06 syst}) \cdot 10^{21}\ yr}$$

The GERDA collaboration
J.Phys.G 40 (2013) 035110

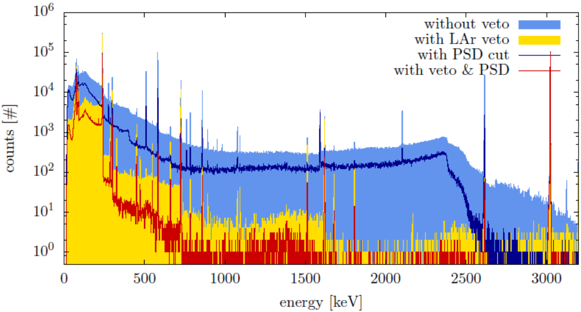
Half-life of $2\nu\beta\beta$ decay of ^{76}Ge



- Uncertainty comparable to best previous experiment (even with lower exposure).
- Such a careful systematic error analysis never done in the past.
- Good agreement with re-analysis of HdM data
  HdM-K: *Nucl. Instr. Meth. A 513, 596 (2003)*
  HdM-B: *Phys. Part. Nucl. Lett. 2, 77/ Pisma Fiz. Elem. Chast. Atom. Yadra 2, 21 (2005)*

Phase II: ^{enr}Ge and liquid Argon instrumentation

- Production of 30 new ^{enr}Ge BEGe detectors ($\sim$20 kg)
- PMT LAr instrumentation for Phase II in LArGe (a smaller GERDA facility)
- Combining PSD of BEGe with LAr veto $\rightarrow$ suppression factor at $Q_{\beta\beta} \sim 5 \times 10^3$ for ^{228}Th calibration source.



Conclusions

- Phase I data taking started on 11.2011
- Data acquisition ongoing. Exposure @ end of 2012 = 15.16 kg yr
- Background from environmental radioactivity much lower than in previous experiments (HdM & IGEX)
- Fit of $2\nu\beta\beta$ spectrum with a model of $2\nu\beta\beta$, ^{42}Ar, ^{40}K and ^{214}Bi in the 600-1800 keV energy window
- Phase I completed in June/July 2013: data unblinding
- Phase II roadmap to get a background 10x lower than Phase I

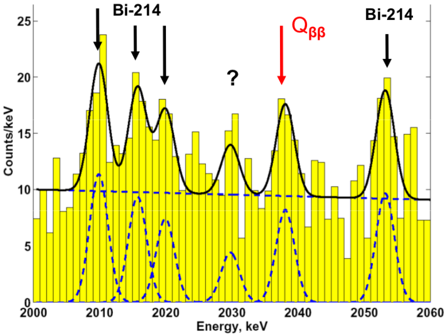
Thank you and have a nice La Thuile Rencontre!

BACKUP SLIDES

The Heidelberg-Moscow claim

HPGe detectors enriched at 86% in ^{76}Ge

Exposure: 71.7 kg yr
Background: 0.11 counts/(keV kg yr) (without pulse shape)



- $T^{0\nu}_{1/2} = 1.2(0.69 - 4.18) \times 10^{25}$ yr
  Phys. Lett. B 586, 198 (2004)
  3σ range
  4.2σ C.L. evidence for $0\nu\beta\beta$
- $T^{0\nu}_{1/2} = 2.23(1.92 - 2.67) \times 10^{25}$ yr
  Mod. Phys. Lett. A 21, 1547 (2006)
  Critized in arXiv:1210.7432
- $m_{\beta\beta}$=(0.24-0.58) eV / (0.29-0.35) eV

IGEX: $T^{0\nu}_{1/2} = 1.57 \times 10^{25}$ yr (90% C.L.)

Radioactivity in argon

$^{39}Ar \xrightarrow{\beta^-, 269yr, Q=565keV} {}^{39}K$

Expected, clearly visible, and not a background for GERDA!

$^{42}Ar \xrightarrow{\beta^-, 32.9yr, Q=600keV} {}^{42}K \xrightarrow{\beta^-, 12.36h, Q=3525keV} {}^{42}Ca$

The 1524.7keV line arises from the ^{42}K decay (BR 17.6%). Rate 2x than expected! These photons are not a concern, but the β emitted in the decay of ^{42}K is a possible background!

Treating the ^{42}K problem

- The initial decay ^{42}Ar $\rightarrow$ ^{42}K produces the daughter in a charged state, which can drift close to the detectors under the action of electric fields.
- Background source only if ^{42}K comes very close to the detectors.
- A string of detetors can be surrounded by a Cu shield, the minishroud, ($\phi = 11.5cm$) to limit the drift of ions

Enriched detectors inside the minishrouds

The mini-shroud

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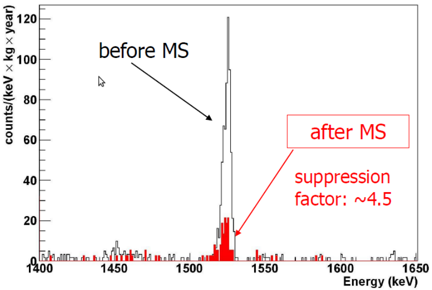
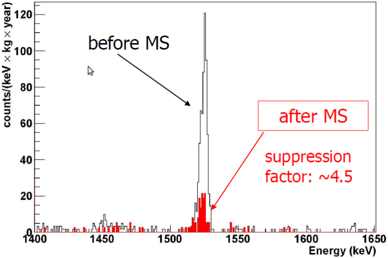


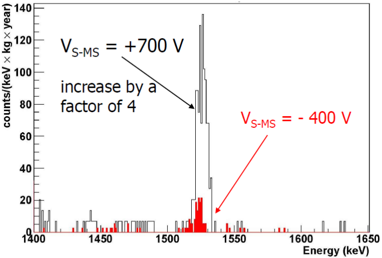
Enriched detectors inside the mini-shrouds

Play with the electric field

Effect of mini-shroud



Effect of voltage configuration



- The initial decay $^{42}Ar \rightarrow {}^{42}K$ produces the daughter in a charged state, which can drift close to the detectors under the action of electric fields
- Background source only if ^{42}K comes very close to the detectors. mini-shrouds limit the drift
- The problem can be strongly mitigated by canceling the electric fields in the surrounding of the detectors or by applying counter-fields to repel ^{42}K ions
- Should not be an issue for the Phase I background goal, but potentially more relevant for Phase II

GERDA and LArGe

GERDA

LArGe

Background lines in GERDA Phase I

isotope	energy [keV]	^{nat}Ge–dets (3.2 kg·y) tot/bck [cnt]	^{nat}Ge–dets (3.2 kg·y) rate [cnt/(kg·y)]	^{enr}Ge–dets (6.1 kg·y) tot/bck [cnt]	^{enr}Ge–dets (6.1 kg·y) rate [cnt/(kg·y)]	HdM rate [cnt/(kg·y)]
^{40}K	1460.8	85 / 15	$21.7^{+3.9}_{-3.1}$	125 / 42	$13.5^{+2.5}_{-2.2}$	181 ± 2
^{60}Co	1173.2	43 / 38	< 5.8	182 / 152	$5.1^{+3.1}_{-3.1}$	55 ± 1
	1332.3	31 / 33	< 3.8	93 / 101	< 3.1	51 ± 1
^{137}Cs	661.6	46 / 62	< 3.2	335 / 348	< 5.9	282 ± 2
^{228}Ac	910.8	54 / 38	$5.0^{+3.0}_{-3.0}$	294 / 303	< 11.1	29.8 ± 1.6
	968.9	64 / 42	$6.7^{+3.8}_{-3.1}$	247 / 230	< 15.2	17.6 ± 1.1
^{208}Tl	583.1	56 / 51	< 6.5	333 / 327	< 7.6	36 ± 3
	2614.5	9 / 2	$2.1^{+1.2}_{-1.0}$	10 / 0	$1.5^{+0.7}_{-0.5}$	16.5 ± 0.5
^{214}Pb	352	740 / 630	$34.6^{+15.2}_{-12.4}$	1770 / 1688	$13.2^{+11.5}_{-7.9}$	138.7 ± 4.8
^{214}Bi	609.3	99 / 51	$14.8^{+4.9}_{-3.5}$	351 / 311	$6.2^{+4.7}_{-4.0}$	105 ± 1
	1120.3	71 / 44	$8.4^{+3.8}_{-3.4}$	194 / 186	< 6.1	26.9 ± 1.2
	1764.5	23 / 5	$5.5^{+2.0}_{-1.6}$	24 / 1	$3.6^{+0.9}_{-0.9}$	30.7 ± 0.7
	2204.2	5 / 2	$0.8^{+0.9}_{-0.7}$	6 / 3	$0.4^{+0.4}_{-0.4}$	8.1 ± 0.5

Systematic uncertainties on $T_{1/2}^{2\nu}$

Source of uncertainty	Uncertainty on $T_{1/2}^{2\nu}$ [%]
1.Not identified background components	$+$ 5.3
2.Energy spectra from ^{42}K, ^{40}K, ^{214}Bi	$\pm$ 2.1
3.Shape of the $2\nu\beta\beta$ decay spectrum	$\pm$ 1
4.Precision of the Monte Carlo geometry model	$\pm$ 1
5.Accuracy of the Monte Carlo tracking	$\pm$ 2
6.Data acquisition and selection	$\pm$ 0.5
Total	**+6.2** **-3.3**

1. ^{60}Co, ^{228}Ac, ^{208}Tl ??
2. Source positions
3. Decay distribution model
4. Dimensions,materials
5. Validation of Geant4 processes