Current experiments on $0\nu\beta\beta$ in Germanium
Gerda and Majorana

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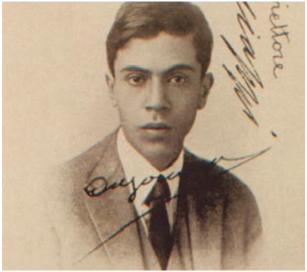
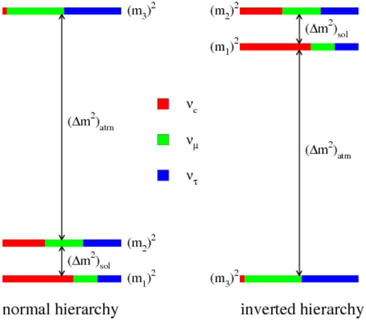
Some open questions we try to shed light on

- What is the mass of the neutrinos?
- Normal or inverted neutrino mass hierarchy?
- Are neutrinos Majorana or Dirac particles?
- What physics is there beyond the Standard Model (SM)?

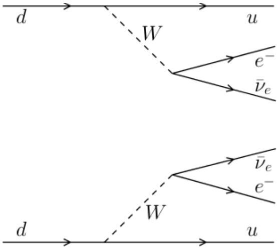




Ingredients for the $0\nu\beta\beta$

$\mathcal{N}$(A,Z) $\rightarrow$ $\mathcal{N}$(A,Z+2) + 2e^- + 2ν_e

- Second order decay: β decay forbidden but lower energetic state exists
- Allowed in the SM experimentally observed in ca. 10 isotopes



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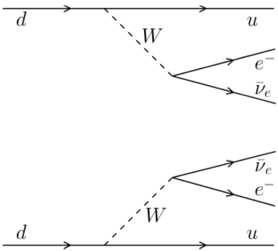
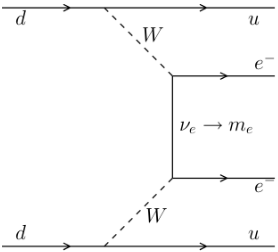


$\mathcal{N}(\mathrm{A,Z}) \rightarrow \mathcal{N}(\mathrm{A,Z+2}) + 2e^{-}$

- Lepton number violating $\rightarrow$ requires a $\Delta L = 2$ operator
  - Can be a Majorana mass but also any other $\Delta L = 2$ process
  - E.g. Higgs triplet, SUSY which gives an important connection to LHC and lepton flavor violation



Ingredients for the $0\nu\beta\beta$

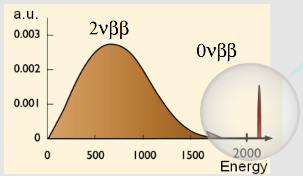
Life time of $0\nu\beta\beta$: $(T^{0\nu}_{1/2})^{-1} = G^{(0)}_{0\nu} g_A^4 |M_{0\nu}|^2 \left(\frac{\langle m_{\beta\beta}\rangle}{m_e}\right)^2$

eff. Majorana ν mass:

$$\langle m_{\beta\beta}\rangle = |U_{e1}|^2 m_1 + |U_{e2}|^2 m_2 \cdot e^{i\Phi^2} + |U_{e3}|^2 m_3 \cdot e^{i\Phi^3}$$

Sensitivity:

$$T^{0\nu}_{1/2} \propto a\epsilon\sqrt{\frac{Mt}{\sigma B}}$$



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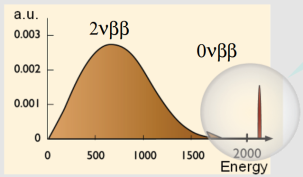

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K.K. claim 2004 [Phys.Lett. B586 198]

- 71.7 kg yr
- 28.75 ± 6.86 signal events
- $T^{0\nu}_{1/2} = 1.9^{+0.37}_{-0.23} \cdot 10^{25}$ yr

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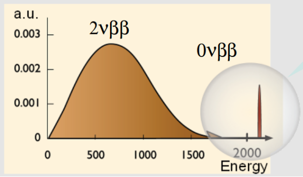

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K.K. claim 2006 [Mod Phys Lett A21]
→ Ann. Phys. 525 (2013) 269

- Missing efficiency of PSD
- Uncentainty on signal counts smaller than poissonian

→ $T_{1/2}^{0\nu}$ central value and errors incorrect

Why using Germanium-76?

Zoo of double beta isotopes:
^{48}Ca ^{76}Ge ^{82}Se ^{96}Zr ^{100}Mo ^{116}Cd ^{128}Te ^{130}Te ^{136}Xe ^{150}Nd ^{238}U

Pros

- Source and detector at the same time $\rightarrow$ detection efficiency about 90%
- Established detector technology
- High purity detectors have a low intrinsic background
- Energy resolution is extraordinary, about $\approx 2‰$
- Pulse shape analysis for background reduction using PPC or BEGe geometry
- Can test K.K. claim without depending on the matrix element

Cons

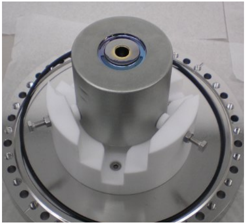
- Rather long and costly process to get a large active detector mass
- Natural abundance of ^{76}Ge is $\approx 8\%$ $\rightarrow$ has to be enriched
- Q-value of 2039 keV is below ^{208}Tl line of 2.6 MeV $\rightarrow$ background from Compton scattered gammas

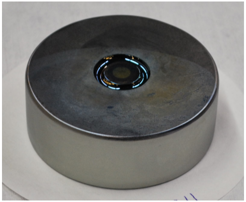
Detector geometries - Coax, BEGe, PPC

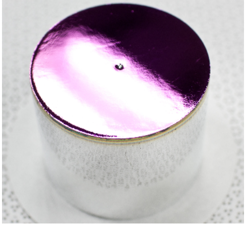
Coax

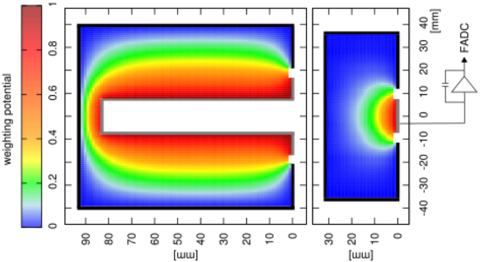
BEGe

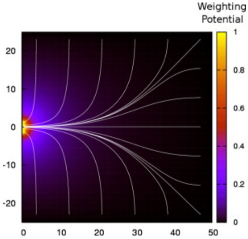
PPC





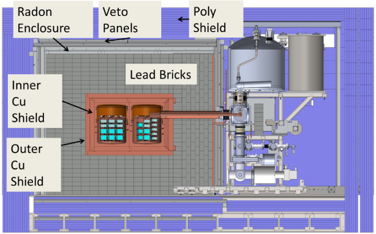






Current $0\nu\beta\beta$ Germanium experiments

MAJORANA DEMONSTRATOR



- Located at SURF (South Dakota, USA)
- 4300 m.w.e
- Status: R&D project under construction

GERDA

- Located at LNGS (Abruzzo, Italy)
- 3500 m.w.e.
- Status: Finished Phase I data taking result puplished last year, currently transition to Phase II

MAJORANA and GERDA are collaborating and are sharing information regarding (hopefully tonne-scale) future experiments.

MAJORANA - R&D goals

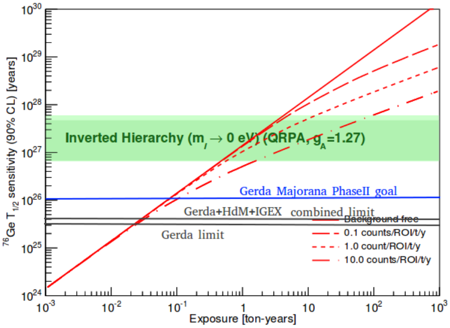
The MAJORANA DEMONSTRATOR is an R&D project for a future tonne-scale Ge experiment

Technical Goals

- Demonstrate achievability of $BI \approx 3\,\mathrm{cts/(ROI\,t\,yr)}$
- Feasibility of constructing and operating Ge modular detector array
- Optimize processes and costs for future tonne-scale experiment

Science Goals

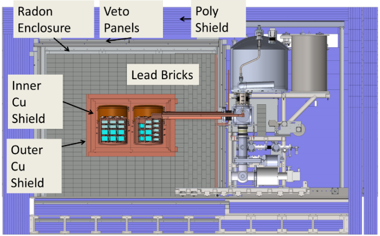
- Exploiting the low energy range to search for Dark Matter and Axions

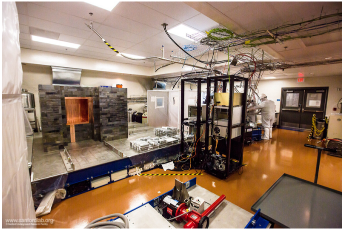


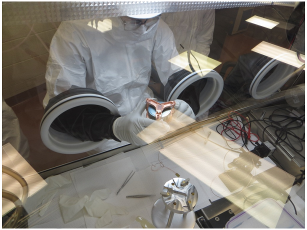
To be sensitive to the whole inverted hierarchy a tonne-scale experiment is needed!

MAJORANA - Setup

- Vacuum cryostats surrounded by a compact shield
- Up to 30 kg of enriched Ge detectors PPC geometry (ORTEC)
- Ultra-pure materials e.g. underground electro-formed copper, material screening







MAJORANA - Experimental phases

Three phases

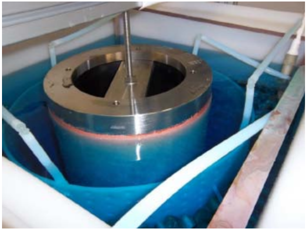
1. Prototype cryostat containing 2 strings of natGe BEGe detectors to test and integrate the different components (In use)
2. Cryostat 1 with 7 strings of enrGe PPC detectors for the commissioning phase (Summer 2014)
3. Cryostat 2 with half natGe and half enrGe completes the setup

Final setup will contain 30 kg of 86% enrGe (Summer 2015)

MAJORANA - Status

Assembly

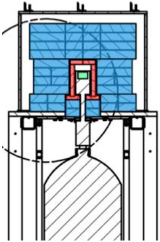
- All components in the lab installed (Shield floor, LN system, assembly table, air bearing system, glove boxes, localized clean space)
- Development of low background front end electronics
- Electro-forming lab in operation since 2011
- ICP-MS (mass spectrometry) sensitivity for U and Th in copper approaching sub μBq/kg level



MAJORANA - Status

Detectors

- Of 42.5 kg enrGe 98% transformed into metal
- 20 kg in 33 detectors natGe BEGe type and 20 kg in 23 detectors PPC type in the UG-lab
- MALBEK - detector R&D: Customized BEGe detector to study optimal point contact geometry, test DAQ, validate background model, exploit low-energy sensitivity of MJD

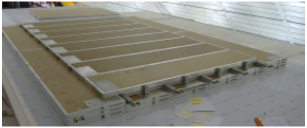


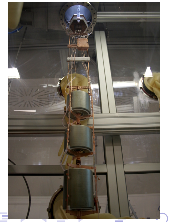
GERDA Phase I - Goals

- Test K.K. $0\nu\beta\beta$ claim without depending on the calculation of the matrix element and the any assumption on the $\Delta L = 2$ operator mediating the decay
  - Higher sensitivity than the Heidelberg-Moscow (HdM) experiment
  - Reach a background index $BI \approx 10^{-2}$cts/(kg keV yr)
  - Get an exposure of about 20 kg yr
- Improve the background suppression using pulse shape discrimination techniques
- Developments for Phase II (e.g. veto using scintillation of LAr)

GERDA - Setup

- Bare Ge detectors (semi-coaxial from HdM and IGEX and BEGe) submerged in 64 m^3 LAr
- Copper lined stainless steel cryostat
- 3 m water shield instrumented with PMTs and used as Water Cerenkov Muon Veto
- Plastic scintillator veto on the roof above the neck (weak spot of the water veto)





GERDA Phase I - Data taking and Data Cuts

Data taking (November 2011 - May 2013)

- Weekly ^{228}Th energy calibration and test pulser stability monitoring
- Duty cycle 88%
- In total 3 coaxial natGe, 8 coaxial enrGe and 5 BEGe enrGe detectors
- Total physics mass: 14.6 kg (coaxial) + 3.0 kg (BEGe)

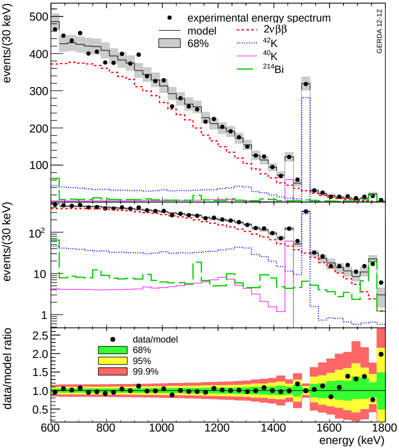
Energy reconstruction and cuts

- Energy is reconstructed with a semi Gaussian filter which is fast and robust
- Detectors with high leakage current and high instabilities were excluded from data analysis
- Cuts: Coincidence with muons, signal in more than one detector and events within 1 ms in one detector (BiPo cut)

GERDA Phase I - $2\nu\beta\beta$ result

- First 5.04 kg yr were used to evaluate the half-life of the $2\nu\beta\beta$ decay
- Data from 6 refurbished semi-coaxial enrGe detectors from the HdM and IGEX experiments
- Binned maximum likelihood approach
- Model contains $2\nu\beta\beta$, ^{42}K (LAr) ^{40}K ^{214}Bi (holders)
- Fit region from 600 – 1800 keV
- $2\nu\beta\beta$ half-life important for understanding of $0\nu\beta\beta$ (e.g. nuclear matrix element)

The GERDA Collaboration et al 2013 J.Phys.G: Nucl.Part.Phys.40 035110 doi:10.1088/0954-3899/40/3/035110

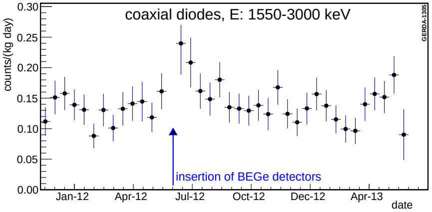


$$T_{1/2}^{2\nu\beta\beta} = 1.84^{+0.14}_{-0.10} \cdot 10^{21}\,\mathrm{y}$$

GERDA Phase I - $0\nu\beta\beta$ result

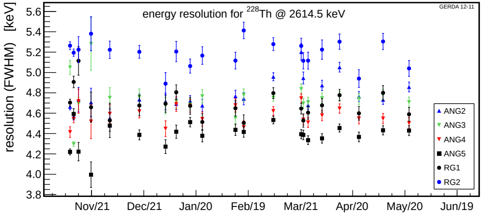
Data selection

- Not considered: natGe, 2 coaxial enrGe (high leakage current), 1 BEGe (instabilities)
- Data split in 3 different sets



BEGe 2.4 kg yr (all BEGe data)
silver coax 1.3 kg yr (20 days from insertion of BEGes)
golden coax 17.9 kg yr (everything else from coaxial)

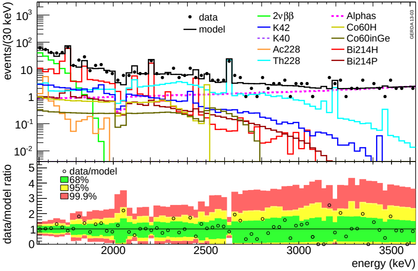
- FWHM: Coaxial 4.8 keV@$Q_{\beta\beta}$
  BEGes 3.2 keV@$Q_{\beta\beta}$
  ca. 10% improvement of resolution with CUSP filter



GERDA Phase I - $0\nu\beta\beta$ result

Data analysis

- All three data sets analyzed unsummed and with independent background and resolution
- Blind analysis: 40 keV window around $Q_{\beta\beta} \rightarrow$ number, energy and waveform unavailable before freezing of parameters
- Validated background model and PSD before unblinding
- Analysis of unblinded data with frozen parameters



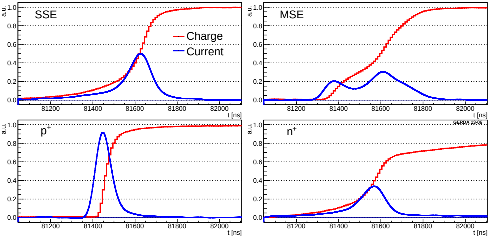
Background model

- Flat around $Q_{\beta\beta}$ (1930 keV-2190 keV) apart from lines at 2104 keV & 2119 keV

GERDA Phase I - $0\nu\beta\beta$ result

BEGe PSD

- A/E vs. Energy cut accepts 0.92 ± 0.02 signal-like and rejects 80% background
- A/E parameter has an exponential time drift which was corrected



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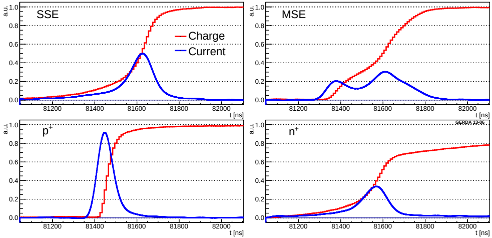


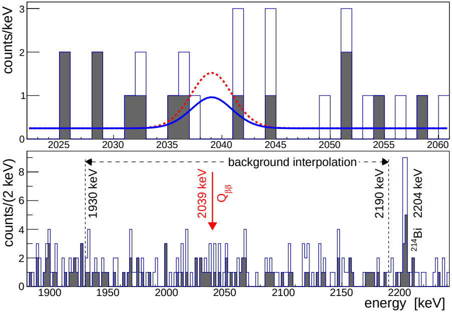
Coaxial PSD

- TMVA neural network with 2 layers of 51 and 50 nods
- Input: time when pulse reaches 1%, 3% ... 99% of maximum
- Two independent cross check analysis performed
- Cuts 45% of background → all rejected by at least one cross check method, 90% by all 3 methods
- Efficiency for DEP $0.90^{+0.05}_{-0.09}$ crosscheck with $2\nu\beta\beta$ effeciency 0.85 ± 0.02

GERDA Phase I - $0\nu\beta\beta$ result

Final result

- Exposure $\rightarrow$ 21.6 kg yr
- Phase I golden + PSD: $BI = (11 \pm 2) \cdot 10^{-3}$ cts/(keV kg yr)
- med. sens. $T_{1/2}^{0\nu\beta\beta} > 2.4 \cdot 10^{25}$ yr
- In ROI $Q_{\beta\beta} \pm 5$ keV: 7 events
  6 coaxial 1 BEGe - in agreement with expected 5.1 ± 0.5
- PSD classifies 3 coaxial and 1 BEGe as background
- Limit (using PSD) disfavours K.K. 2004 claim strongly



$$T_{1/2}^{0\nu\beta\beta} > 2.1 \cdot 10^{25} \text{ yr } 90\% \text{ C.L.}$$

PRL **111**, 122503 (2013) PHYSICAL REVIEW LETTERS week ending 20 SEPTEMBER 2013

Results on Neutrinoless Double-β Decay of ^{76}Ge from Phase I of the GERDA Experiment

GERDA Phase I - $0\nu\beta\beta$ result

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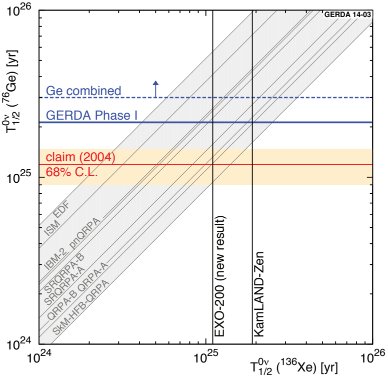

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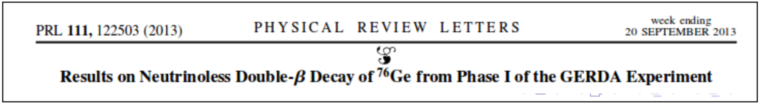
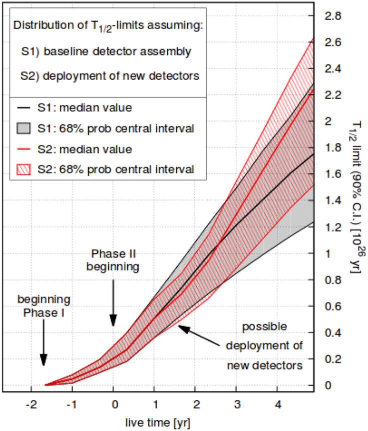


PRL 111, 122503 (2013) PHYSICAL REVIEW LETTERS week ending 20 SEPTEMBER 2013

Results on Neutrinoless Double-β Decay of ^{76}Ge from Phase I of the GERDA Experiment

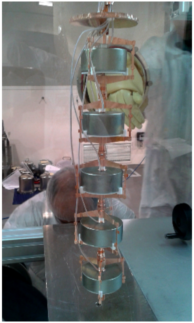
GERDA Phase II - Goals

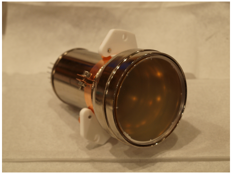
- Improve the sensitivity $T_{1/2}^{0\nu} \propto a\epsilon\sqrt{\frac{Mt}{\sigma B}}$
- Achieve $B = 10^{-3}$ cts/(keV kg yr)
- Augment the detector mass M
- Acumulate $Mt \approx 100$ kg yr of data
- Explore $T_{1/2}^{0\nu\beta\beta} > 10^{26}$yr
- Find $0\nu\beta\beta$ decay!



GERDA Phase II - Current status

- Data taking stopped in July last year
- Preparations for Phase II
  - Augmented detector mass → 30 BEGe detectors ready
  - Exchange the cryostat lock → space for new detectors
  - New front end electronics and cabeling → improved radio purity and lower Rn emanation
  - Use LAr scintillation light as veto → hybrid solution PMTs and fibers+SiPMs
  - Start commissioning ≈ second half 2014





Summary

Majorana

- Majorana still under construction
- Completion of experimental setup in summer 2015

Summary

MAJORANA

- Majorana still under construction
- Completion of experimental setup in summer 2015

GERDA

- Gerda background goal achieved $B \approx 10^{-2}$cts/(kg keV yr)
- Phase I result of Gerda strongly disfavours K.K. claim

Gerda only:	$T_{1/2}^{0\nu\beta\beta} > 2.1 \cdot 10^{25}$ yr 90% C.L.
Gerda+HdM+IGEX:	$T_{1/2}^{0\nu\beta\beta} > 3.0 \cdot 10^{25}$ yr 90% C.L.

- Gerda currently in transition to Phase II
- Similar physics goals of Majorana and Gerda
  - $B \approx 10^{-3}$cts/(kg keV yr)
  - Explore $T_{1/2}^{0\nu\beta\beta} > 10^{26}$yr

THANK YOU FOR YOUR ATTENTION!

GERDA - 0nbb events (L. Pandola)

data set	detector	energy [keV]	date	PSD passed	ANN	A/E	Cut Threshold
golden	ANG 5	2041.8	18-Nov-2011 22:52	no	0.344		0.366
silver	ANG 5	2036.9	23-Jun-2012 23:02	yes	0.518		0.366
golden	RG 2	2041.3	16-Dec-2012 00:09	yes	0.682		0.364
BEGe	GD32B	2036.6	28-Dec-2012 09:50	no		0.750	0.965÷1.070
golden	RG 1	2035.5	29-Jan-2013 03:35	yes	0.713		0.372
golden	ANG 3	2037.4	02-Mar-2013 08:08	no	0.205		0.345
golden	RG 1	2041.7	27-Apr-2013 22:21	no	0.369		0.372

data set	$\mathcal{E}$[kg·yr]	$\langle\epsilon\rangle$	bkg	BI †)	cts	Expected from background only
without PSD						
golden	17.9	0.688 ± 0.031	76	18 ± 2	5	3.3
silver	1.3	0.688 ± 0.031	19	63^{+16}_{-14}	1	0.8
BEGe	2.4	0.720 ± 0.018	23	42^{+10}_{-8}	1	1.0
with PSD						
golden	17.9	$0.619^{+0.044}_{-0.070}$	45	11 ± 2	2	2.0
silver	1.3	$0.619^{+0.044}_{-0.070}$	9	30^{+11}_{-9}	1	0.4
BEGe	2.4	0.663 ± 0.022	3	5^{+4}_{-3}	0	0.1

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