Results of CUPID-0

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for the CUPID-0 collaboration

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ELECTROWEAK INTERACTIONS AND UNIFIED THEORIES

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CUPID-0 for CUPID (Cuore Upgrade with Particle ID)

CUPID is a proposed bolometric $0\nu DBD$ experiment which aims at a sensitivity to the $m_{\beta\beta}$ on the order of 10 meV

Technical challenges:

- **Detector mass in the range of several hundred kg to a ton of the isotope**
- **Background close to zero at the ton · year exposure scale**
- **Region Of Interest (RoI) of a few keV** around $0\nu DBD$ transition energy

Five steps beyond the present technology:

- **Isotopic enrichment**
- **Active alpha rejection**
- **Improved material selection**
- **Reduced cosmo-activation**
- **Better energy resolution**

CUPID-0 is the first demonstrator, of a series, of the new technologies that will be implemented in CUPID and, at the same time, it is also a competitive $0\nu DBD$ search in its own right.

Scintillating bolometers

A bolometer is a highly sensitive calorimeter operated at cryogenic temperature (~10 mK)

Energy deposits are measured as temperature variations of the absorber

If the absorber is also an efficient scintillator the energy is converted into heat + light

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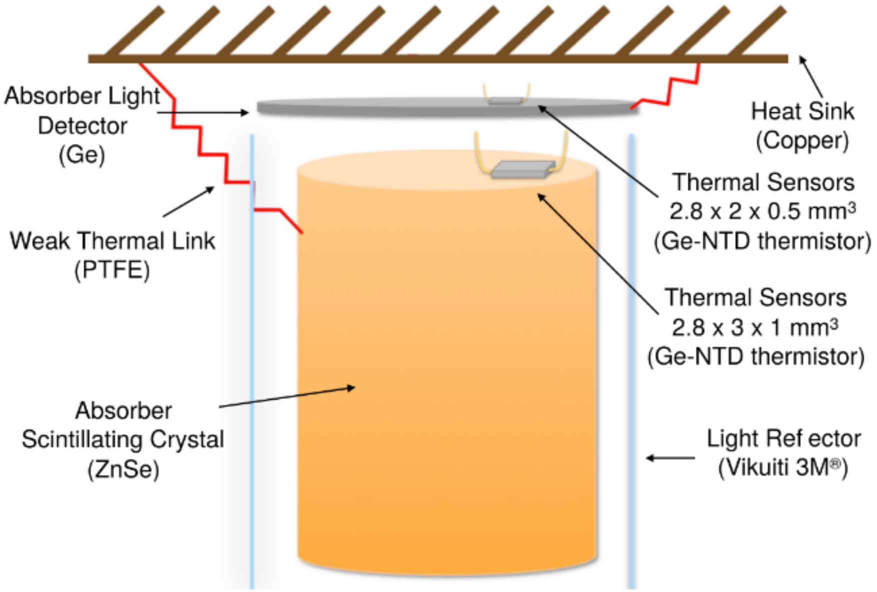


Scintillating bolometer features:

- high energy resolution O(1/1000)
- high detection efficiency (source = detector)
- **particle IDentification**

A **close-to-zero background** experiment is feasible:

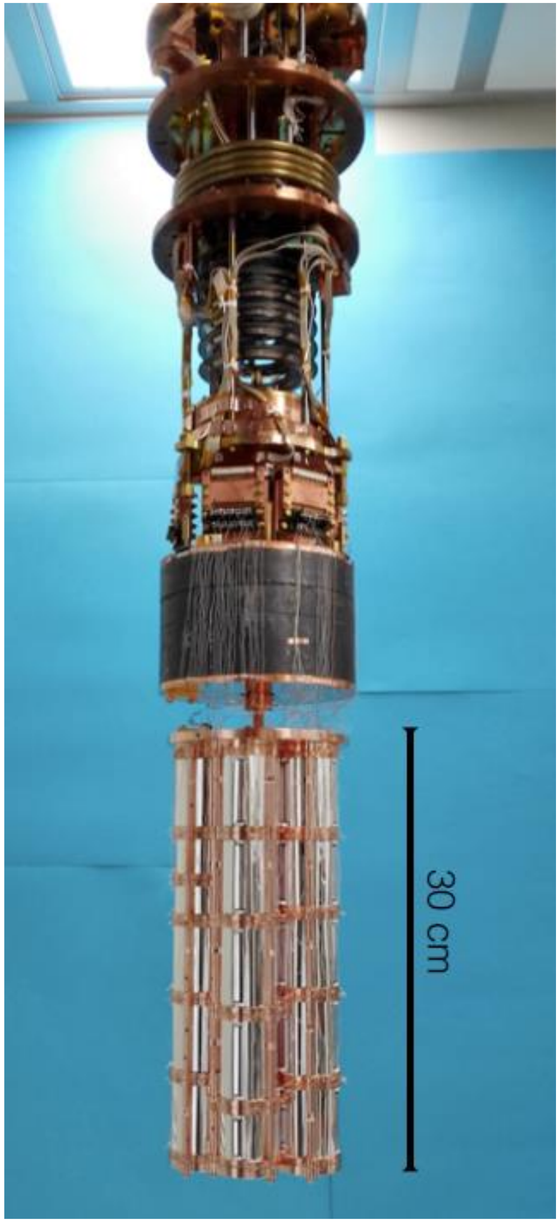
α background: identification and rejection

γ/β background: ββ isotope with large Q-value

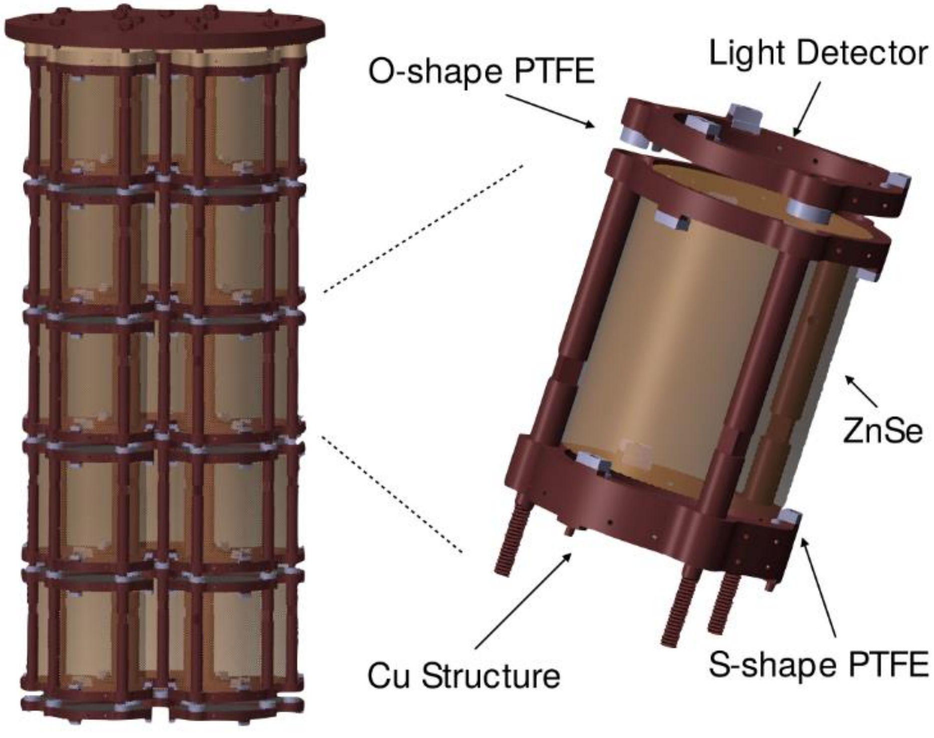
CUPID-0 - The detector

CUPID-0 is the first array of scintillating bolometers for the investigation of ^{82}Se 0vDBD

- Q-value 2998 keV
- 95% enriched Zn^{82}Se bolometers
- Installed in the underground laboratories at Gran Sasso
- 10.5 kg of ZnSe, 5.17 kg of ^{82}Se ($3.8 \cdot 10^{25}$ $\beta\beta$ nuclei)
- Background goal ~10^{-3} c/keV/kg/y also thanks to discrimination capabilities (light yield and pulse shape)



CUPID-0 - The detector



26 ZnSe (24 enriched + 2 nat)

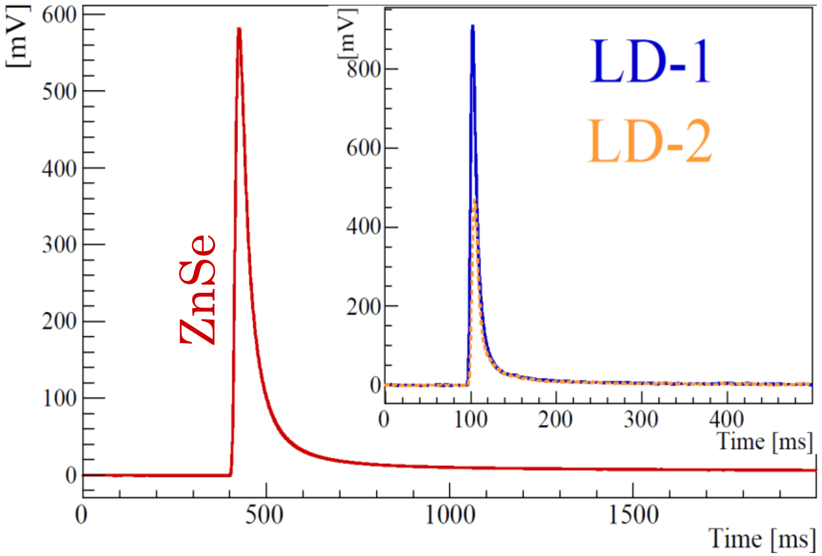
+

31 Light Detectors (LD)

arranged in 5 towers

Simplest modular detector:

- Copper structure
- PTFE holders
- Reflecting foil (VIKUITI 3M)

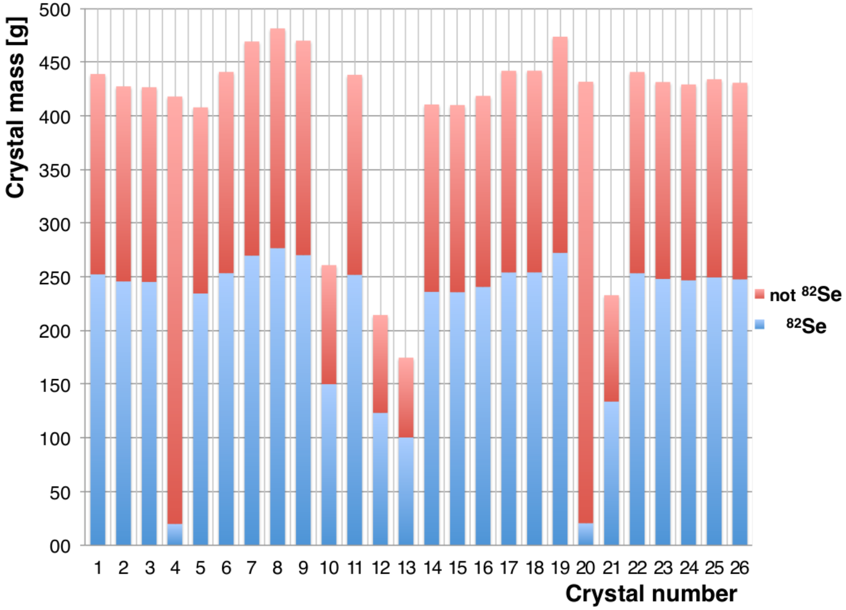


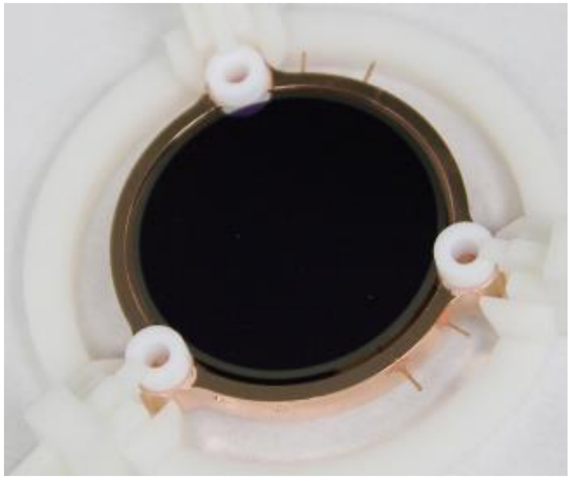
CUPID-0 - The detector

$Zn^{82}Se$ crystals

- The enriched $Zn^{82}Se$ crystals were produced starting from highly pure raw materials
- The crystal is grown using the Bridgman technique. The final crystal is then shaped and optical polished

Crystal masses



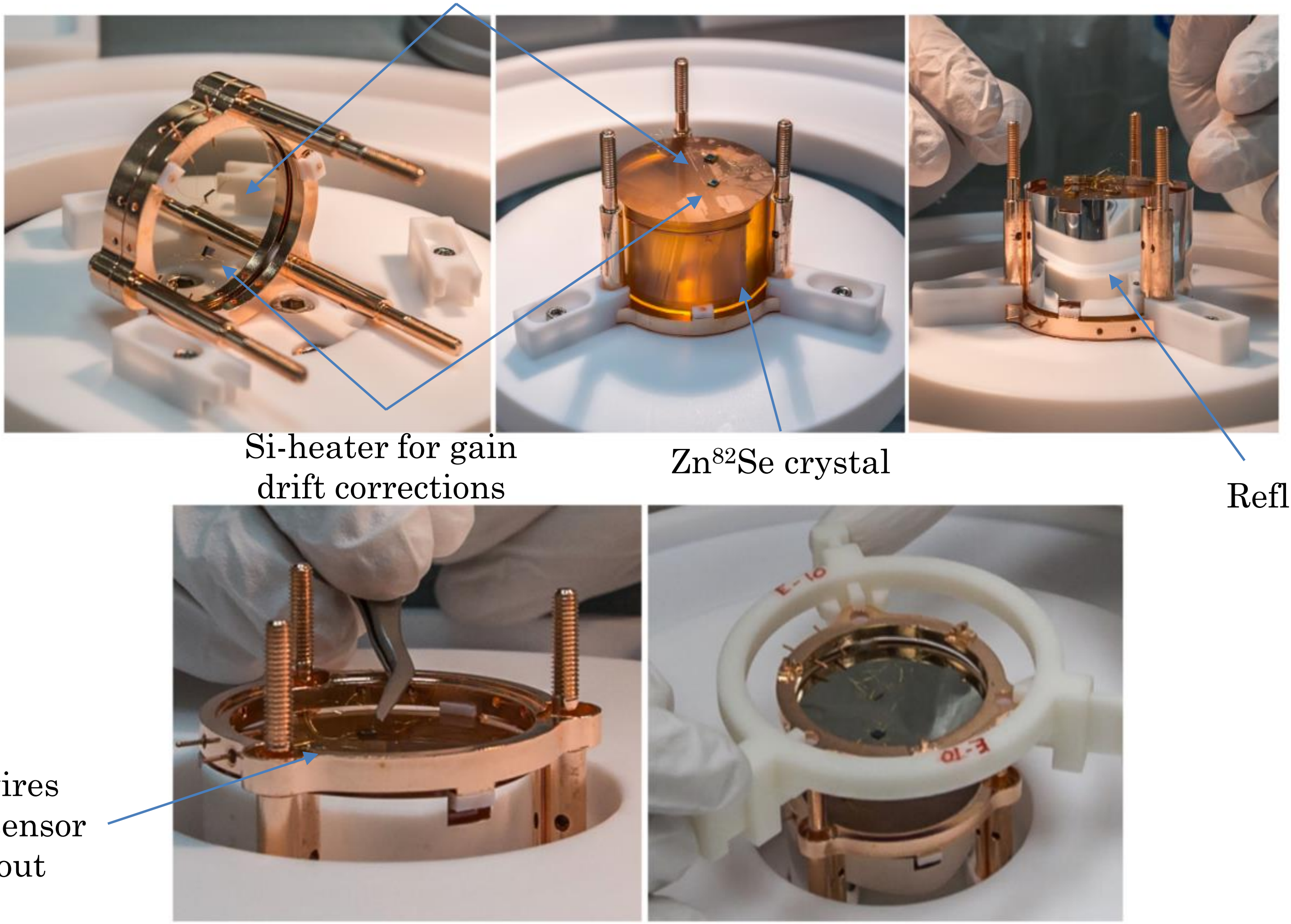


Ge light detectors

- Well established technology for bolometric LDs
  - Ge disk (44.5 x 0.17 mm) with NTD thermal sensor
- LD performance are crucial for background suppression
  - Light vs Heat: possible α leakage in β/γ ROI
  - PSA of Light: highly efficient particle-ID

CUPID-0 - The assembly

- All activities for the construction were carried out in an underground Rn-suppressed clean room
- Assembly started on October, 2016
- Complex assembly: crystals have all different shapes and heights



Ge-NTD thermal sensor

Si-heater for gain drift corrections

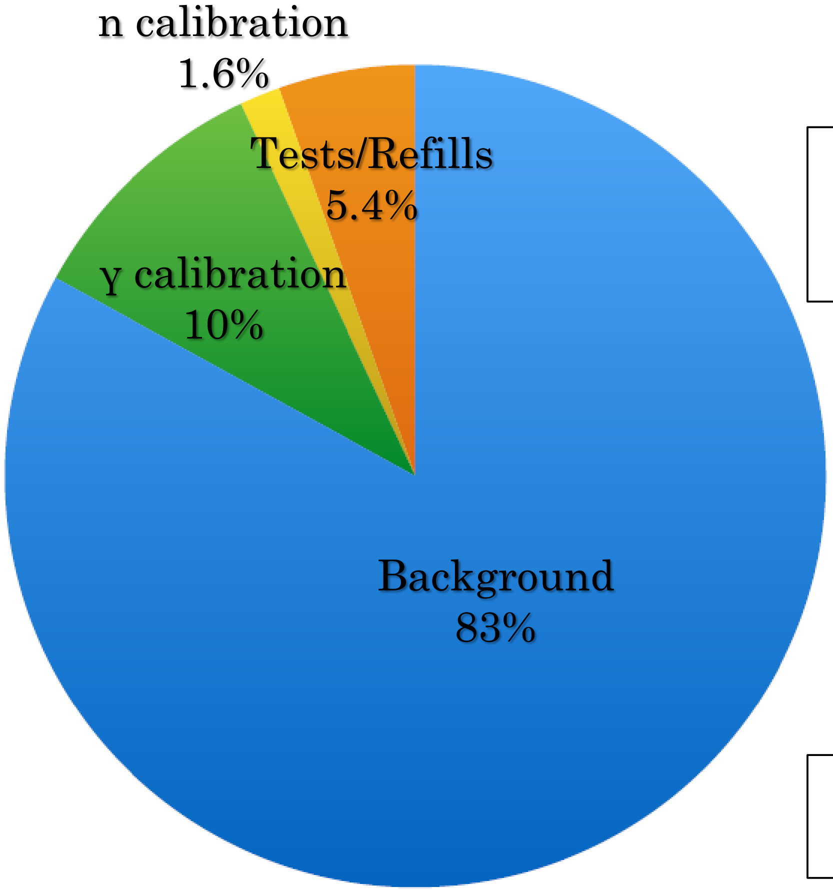
$Zn^{82}Se$ crystal

Reflecting foil

gold wires for the sensor read-out

Data Taking

- Data taking started on March 17th, 2017
- Data presented here were collected between June and December 2017
- 3.44 kg·y ZnSe exposure (background measurements) → 1.83 kg·yr ^{82}Se exposure



Energy calibration
Detector performance

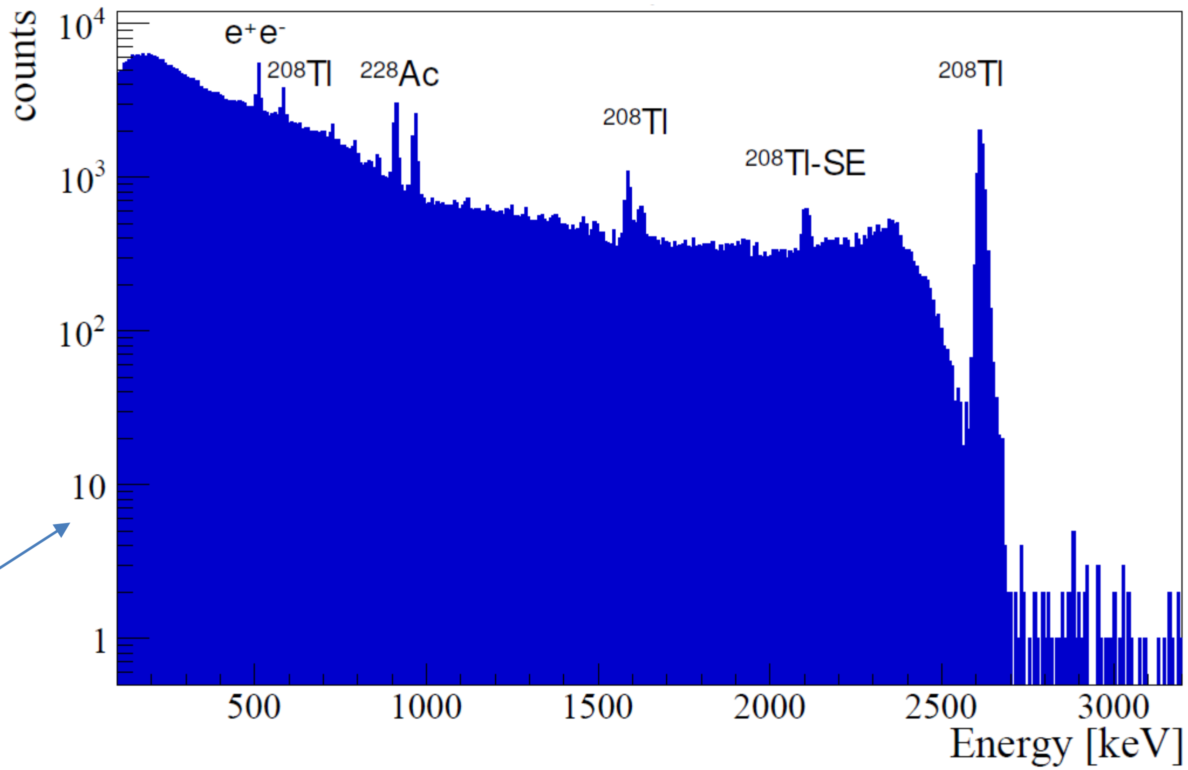
Characterization of
β/γ shape parameters
at RoI

0vDBD
Physics

Maintenance
cryogenic system

Detector performance

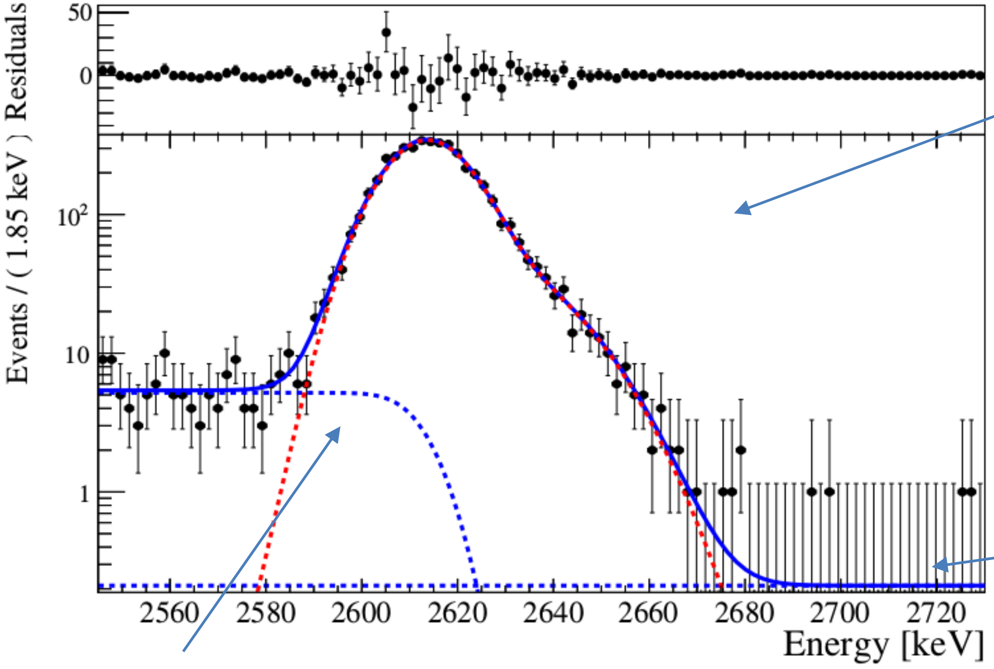
The detector performance were investigated using ^{232}Th sources placed outside the cryostat



Energy spectrum obtained summing all the ZnSe channels in a calibration run

- Major contribution to the energy resolution is the crystal quality (average baseline FWHM 3.5 keV)
- Excellent scintillating performance
- Total signal detection efficiency: **(75 ± 2)%**

Detector response function



Double gaussian

- Simplest model which well reproduces the detector response function over the entire spectrum
- Deviations from the single gaussian model already observed in other bolometric experiments

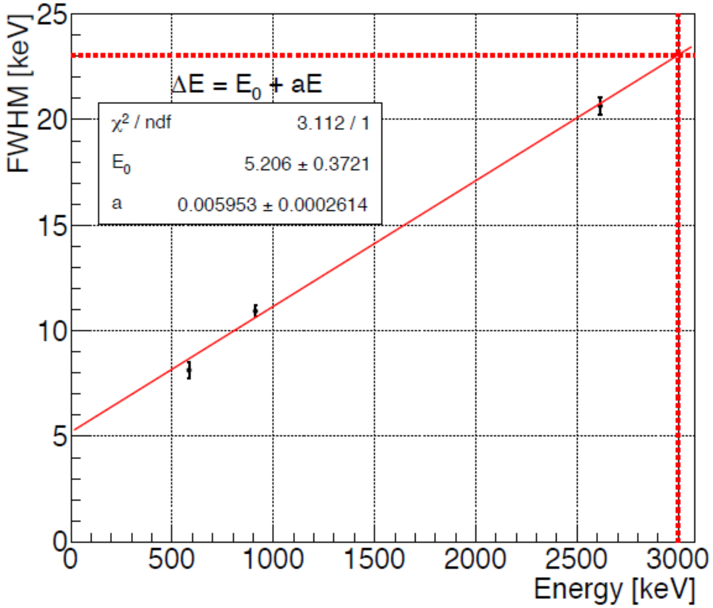
flat background

multi-Compton continuum

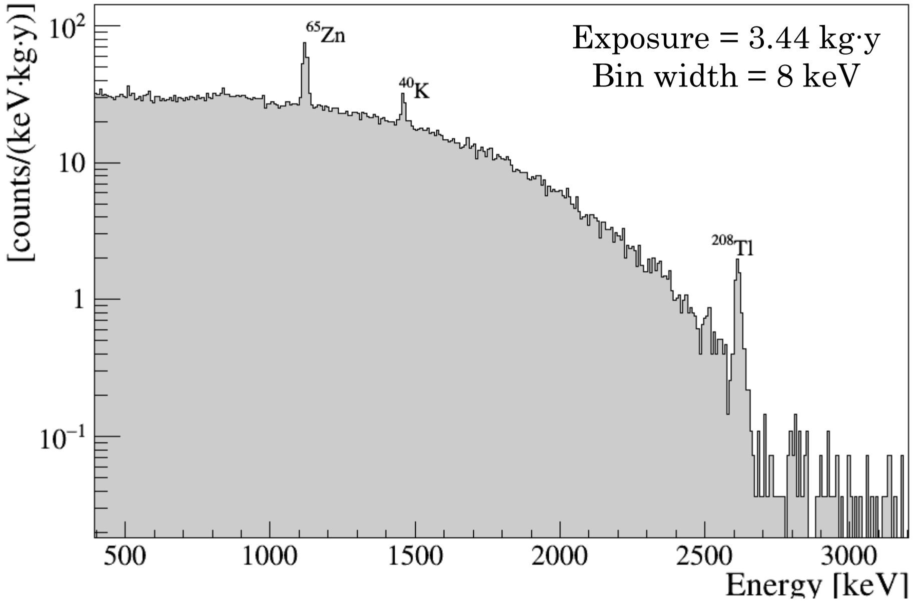
We linearly extrapolate the width of the primary peak at $Q_{\beta\beta}$.

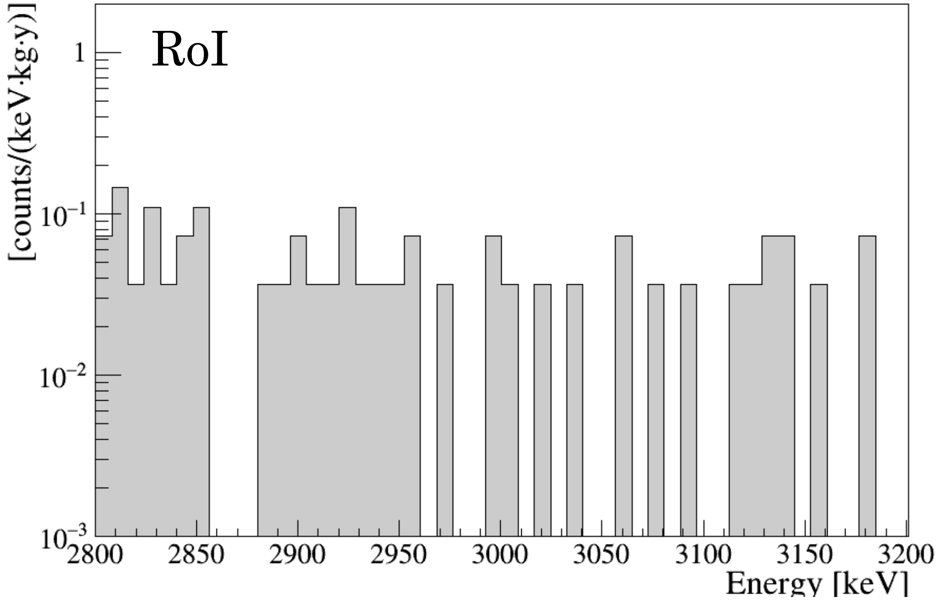
The exposure-weighted harmonic mean FWHM energy resolution at the $Q_{\beta\beta}$ results to be

$$\mathbf{(23.0 \pm 0.6)}\ \boldsymbol{keV}$$



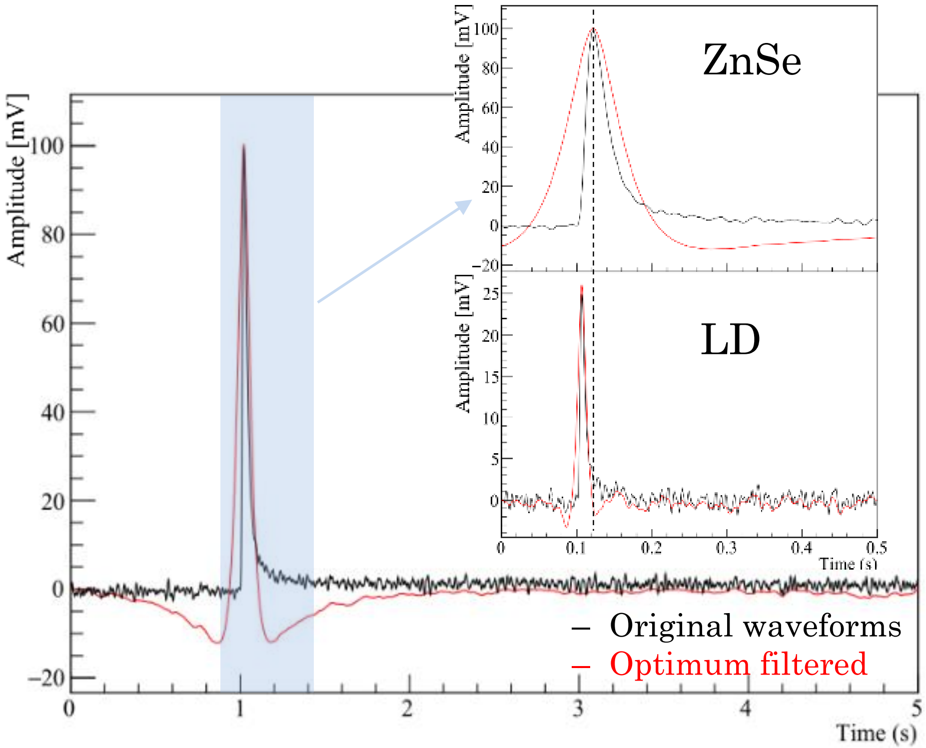
Background - Total energy spectrum





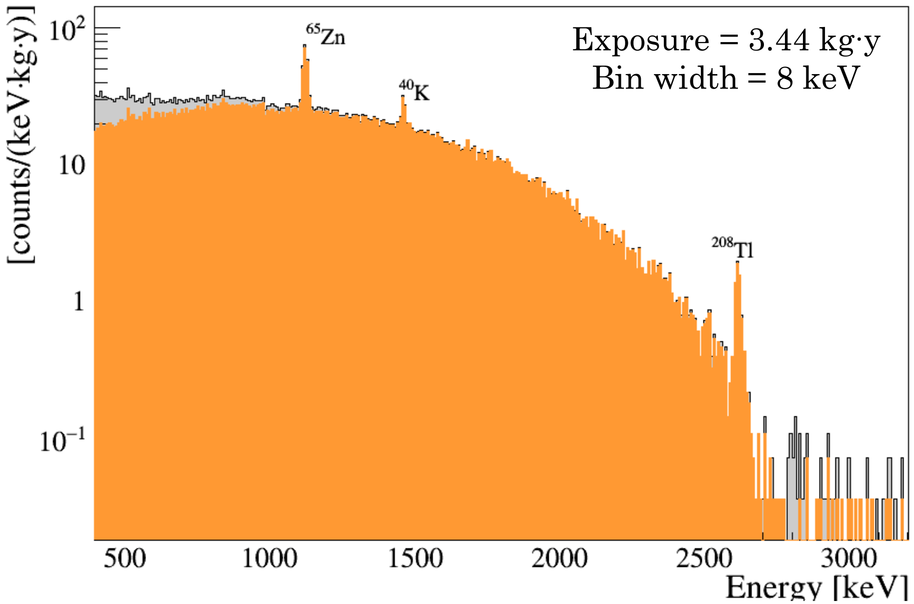
First level data analysis:

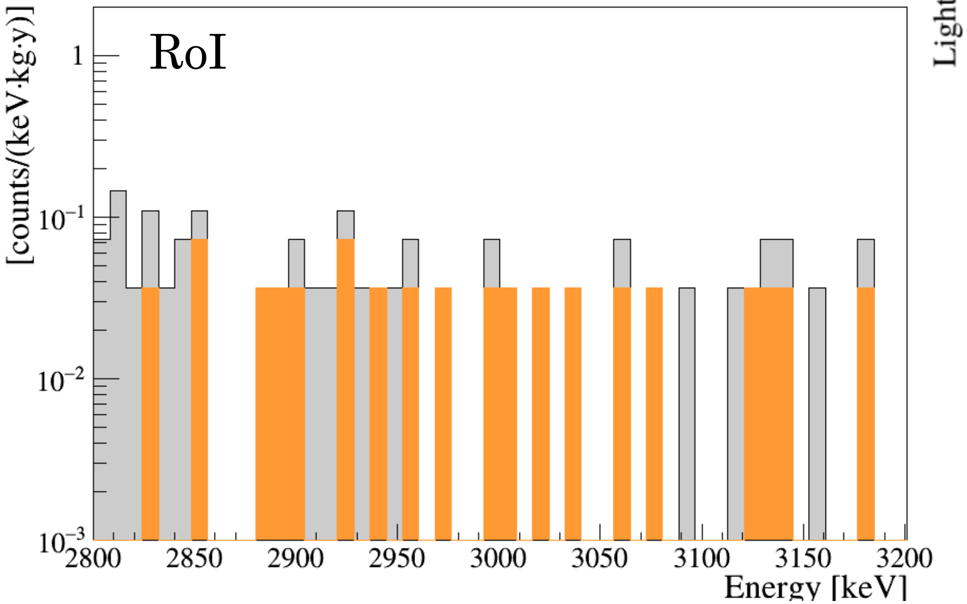
- Optimum filtering
- Gain stability corrections
- Synchronization Heat-Light



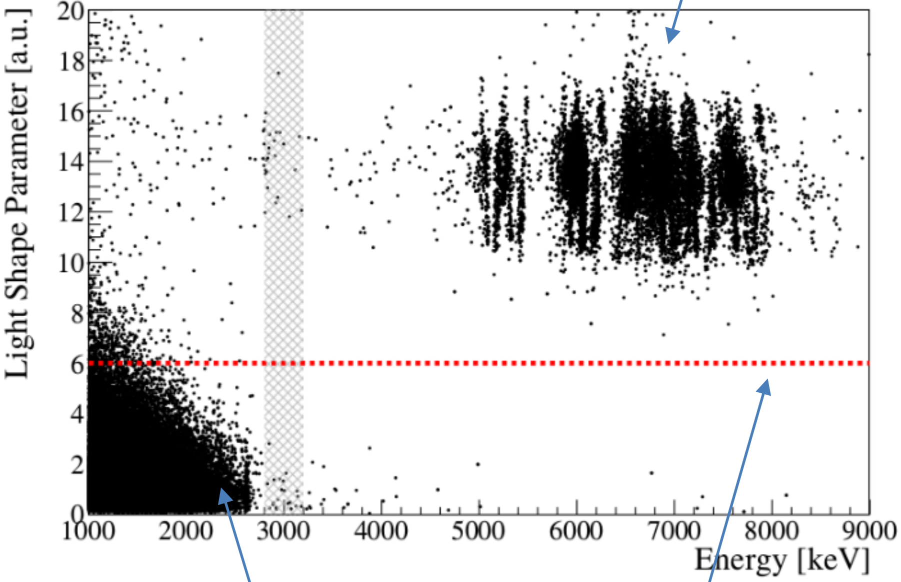
- Rejection of “non-particle-like” events through pulse shape on thermal pulses
- Anti-coincidence between crystals ($\Delta T = 20ms$)

Background – Data selection





Alpha rejection with light-shape variable



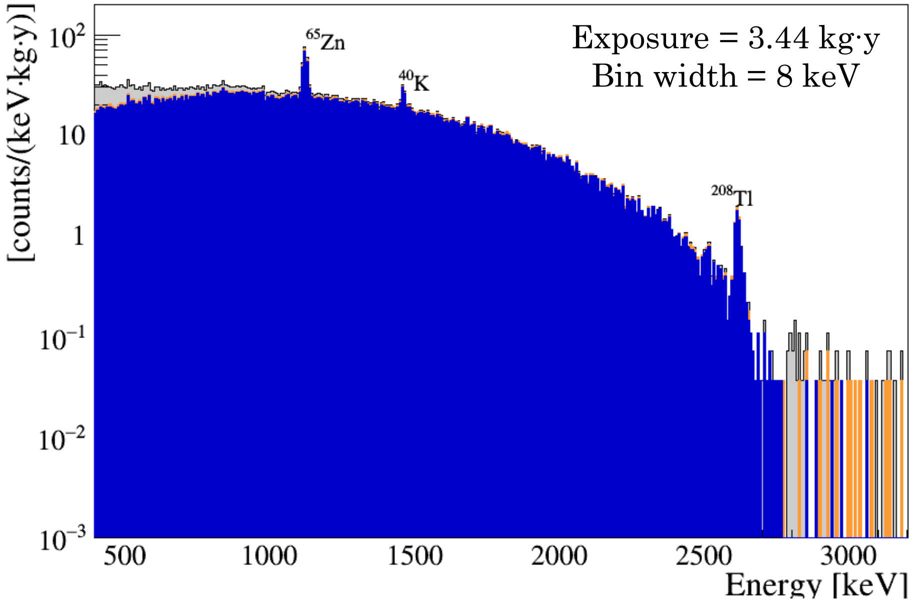
alpha events

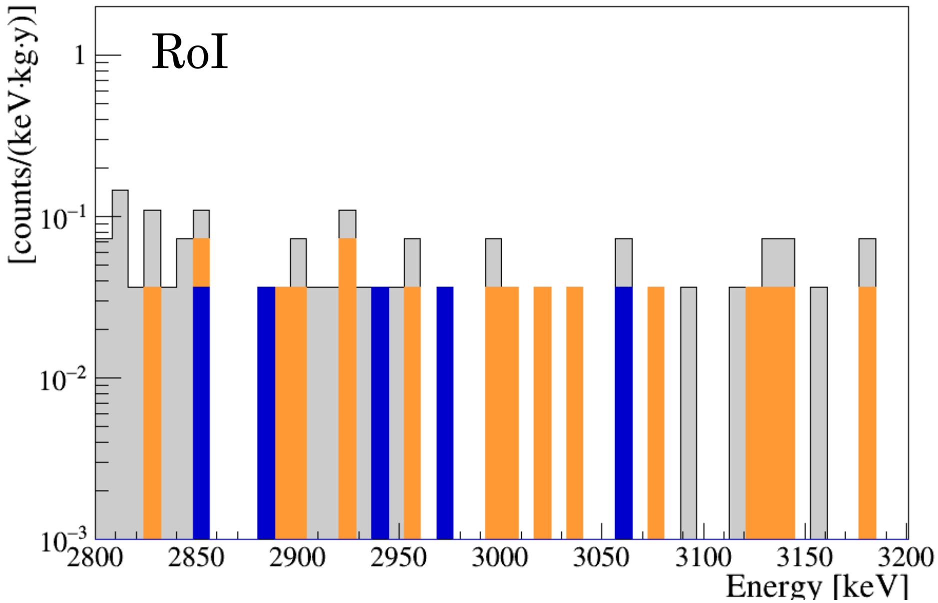
beta/gamma events

acceptance threshold

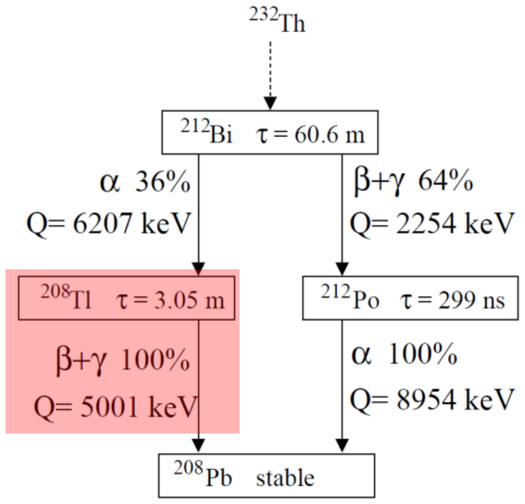
For E>4500 keV
mis-identification
probability <10^{-6}

Background – Data selection





Delayed alpha coincidence ^{212}Bi-^{208}Tl rejection



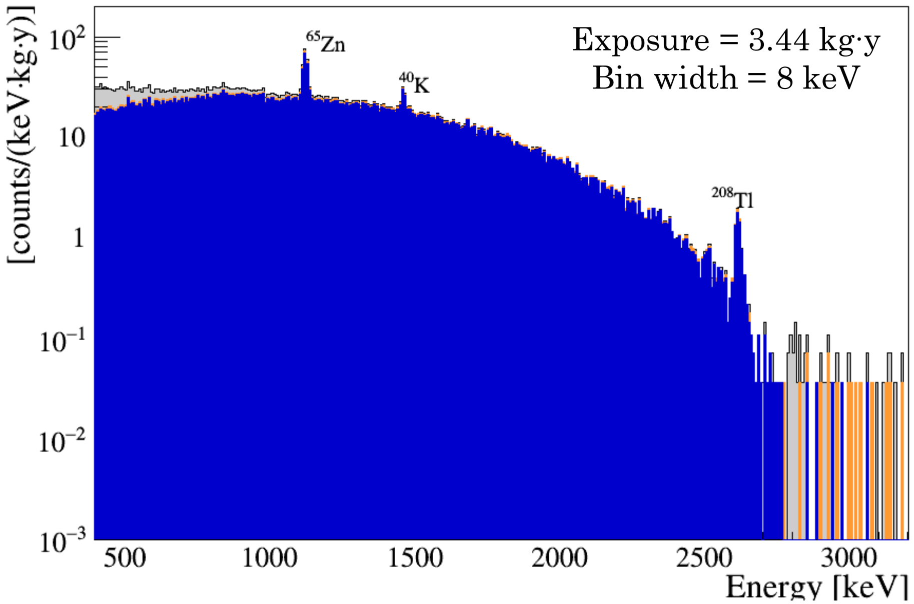
We veto any event succeeding a primary ^{212}Bi α event in a window corresponding to three times the half-life.

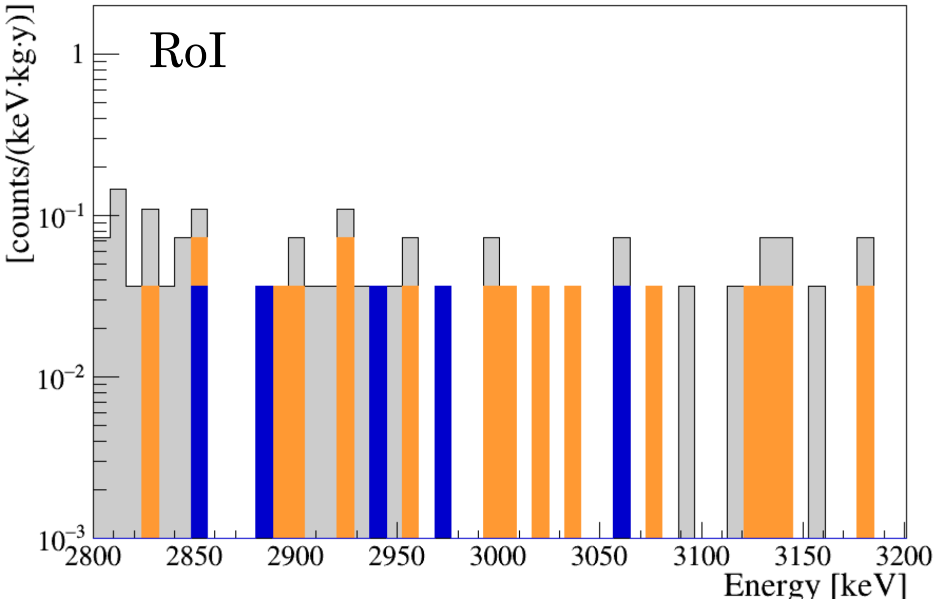
If the contamination is close to the surface and the α escapes the crystal, only part of the energy of the decay is collected

↓

α pulse shape of the primary event and energy in the range (2.0-6.5) MeV

Background – Data selection





Background index in the RoI

$$(3.6^{+1.9}_{-1.4}) \cdot 10^{-3} \text{ cts/(keV} \cdot \text{kg} \cdot \text{yr)}$$

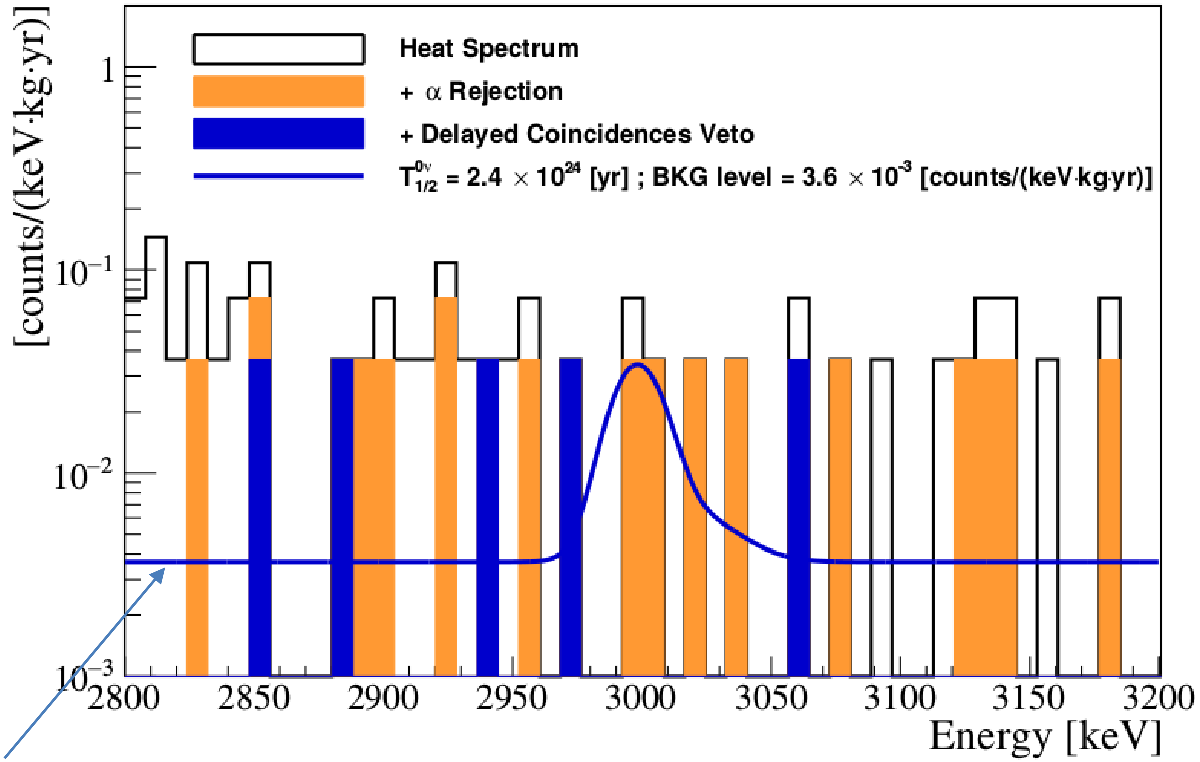
Thanks to the simultaneous heat-light readout we reached the lowest background achieved with bolometric experiments.

CUPID-0 Results: half life and neutrino mass

$$T_{1/2}^{0\nu} > 2.4 \cdot 10^{24} \text{ yr (90\% C.I.)}$$

$$m_{\beta\beta} < 376 - 770\ meV$$

range due to the nuclear matrix element calculations



fitted spectrum together with a hypothetical signal corresponding to the 90% C.I. limit

Previous NEMO limit $T_{1/2}^{0\nu}(^{82}Se) > 3.6 \cdot 10^{23}$ yr (exposure ~3.5 kg · y)

Conclusions

- CUPID-0 is the first large array of enriched scintillating bolometers
- Data taking is smoothly going on since March 2017
- Excellent background index in the region of interest

  - we reach the lowest background level achieved with bolometric experiments of

$$(3.6^{+1.9}_{-1.4}) \cdot 10^{-3}\ \text{cts/(keV} \cdot \text{kg} \cdot \text{yr)}$$

- Acquired data allowed to establish the best half-life limit on ^{82}Se 0vDBD

$$T^{0\nu}_{1/2} > 2.4 \cdot 10^{24}\ yr\ \text{(90\% C.I.)}$$

- Studies on the background model are in progress (higher statistics is needed)
- Goal: run until 10 kg · y of Zn^{82}Se exposure

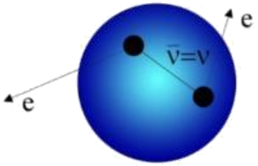
BACKUP

SLIDES

Neutrinoless Double Beta Decay (0νDBD)

0νDBD

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



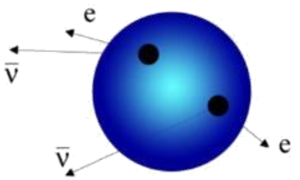
- Not allowed in Standard Model (ΔL=2)
- The decay occurs only if neutrinos are Majorana particles
- Requires neutrino is a massive particle
- The decay rate $T^{0\nu}_{1/2}$ depends on the “effective Majorana mass” $m_{\beta\beta}$

$$\left(T^{0\nu}_{1/2}\right)^{-1}=G_{0\nu}|M_{0\nu}|^2 m^2_{\beta\beta}$$

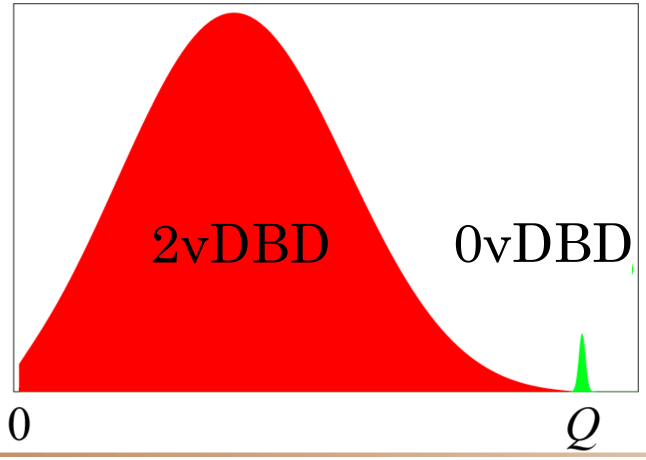
$G_{0\nu}$ - phase space factor
$M_{0\nu}$ - nuclear matrix element

2νDBD

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



- Allowed in Standard Model
- Already observed for several nuclei (half-lives of the order $10^{18}-10^{21}$ y)



Neutrinoless Double Beta Decay (0νDBD)

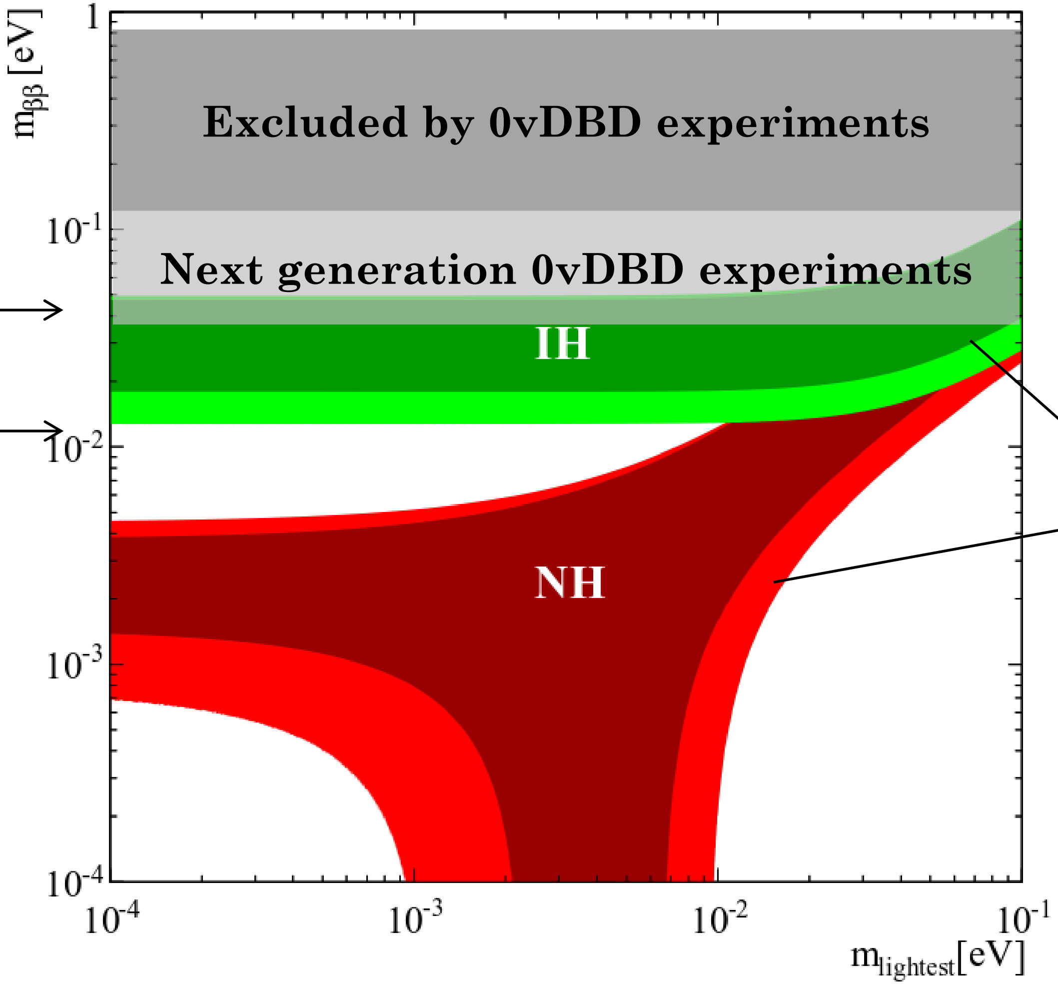
- Possible for ~35 nuclei, only ~10 really interesting
- Extremely rare process ($T^{0\nu}_{1/2} > 10^{24}$ -10^{25} y)

$T^{0\nu} \sim 10^{26}$-10^{27}y →

$T^{0\nu} \sim 10^{27}$-10^{28}y →

↓

Experiments able of measuring such low rate are a technological challenge!!!

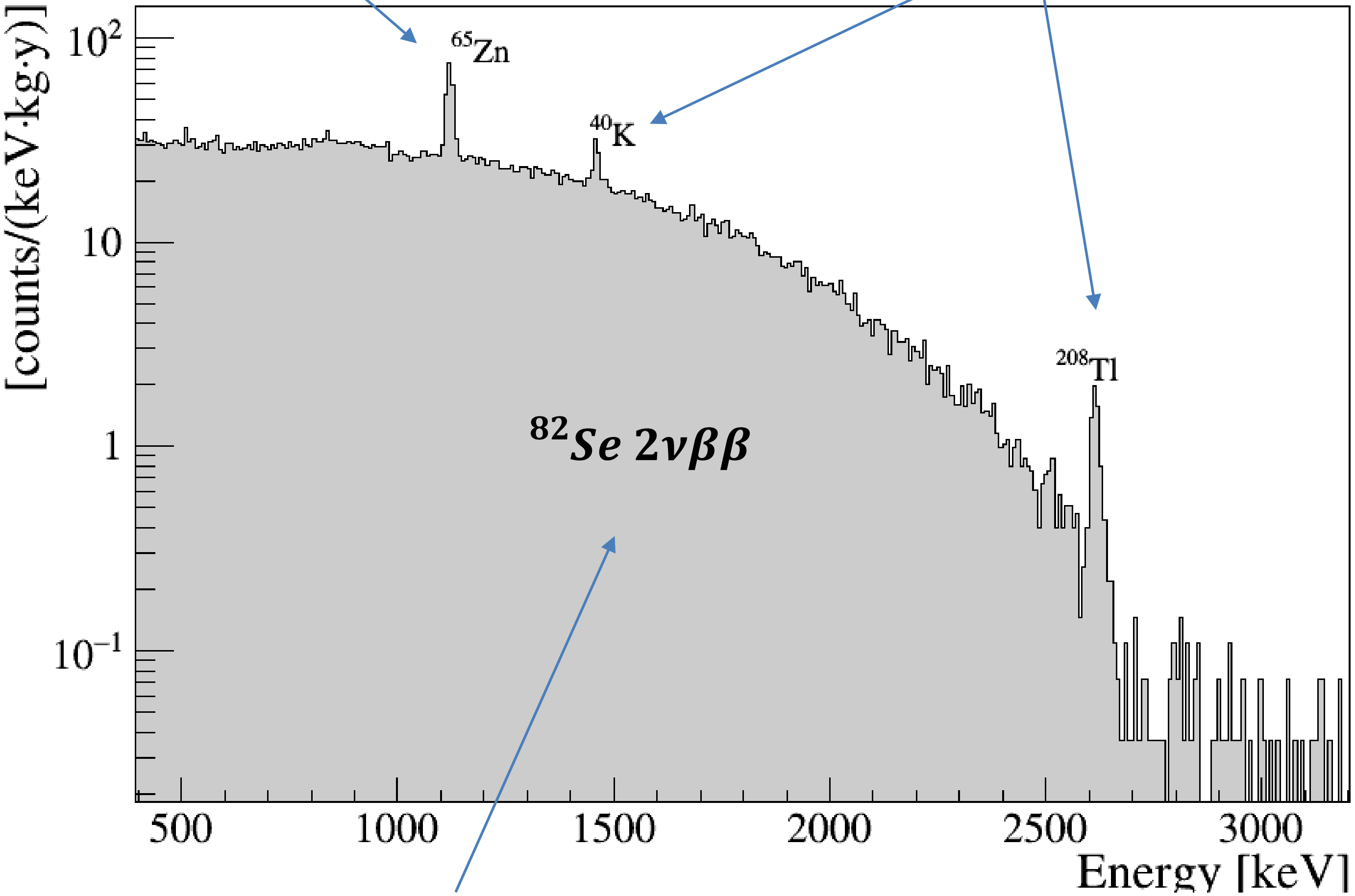


Neutrino oscillations constrains

Background energy spectrum components

cosmogenically activated

natural radioactivity



continuous spectrum generated by the 2vDBD decay of ^{82}Se

$$T_{1/2}^{2\nu} = (9.2 \pm 0.7) \cdot 10^{19}\ \text{yr}$$

Detector sensitivity for 0νDBD searches

Sensitivity: the process half-life corresponding to the maximum signal that could be observed at a given statistical C.L..

n = confidence level

$N^{eff}_{\beta\beta} = N_{\beta\beta} \cdot \varepsilon$

$N_{\beta\beta}$ = isotope number

ε = detector efficiency

$$N_{\beta\beta} = \frac{N_A \cdot M \cdot x \cdot \eta}{A}$$

T = live time [y]

M = detector mass [kg]

B = background [c/keV/kg/ y]

Δ = energy resolution [keV]

A = atomic mass

x = isotopic ab.

$\eta = N_{\beta\beta}$ per molecule

$$\boldsymbol{S = \ln 2 \cdot N^{eff}_{\beta\beta} \cdot \frac{T}{N}}$$

‘Zero’ background experiments

$$M \cdot T \cdot B \cdot \Delta \approx 0$$

$$\downarrow$$

$$n = 2.8 \ \ (68\% \text{ C.L.})$$

$$\boxed{S_{0B} = \ln 2 \cdot N^{eff}_{\beta\beta} \cdot \frac{T}{2.8} \propto M \cdot T}$$

Experiments with background

$$M \cdot T \cdot B \cdot \Delta >> 0$$

$$\downarrow$$

$$n = \sqrt{M \cdot T \cdot B \cdot \Delta} \ \ (68\% \text{ C.L.})$$

Assumption: B∝M

$$\boxed{S_{B} = \ln 2 \cdot N^{eff}_{\beta\beta} \cdot \sqrt{\frac{T}{M \cdot B \cdot \Delta}} \propto \sqrt{\frac{M \cdot T}{B \cdot \Delta}}}$$

Critical experimental parameters: M, T, B, Δ

Neutrino mass

$$T_{1/2}^{0\nu} > 2.4 \cdot 10^{24} \text{ yr (90\% C.I.)}$$

$$\left(T_{1/2}^{0\nu}\right)^{-1} = G_{0\nu}|M_{0\nu}|^2 m_{\beta\beta}^2$$

$$m_{\beta\beta} < 376 - 770\ meV$$

$G_{0\nu}$ - Phase space factor

J. Kotila and F. Iachello, Phys. Rev. C 85, 034316 (2012).
S. Stoica and M. Mirea, Phys. Rev. C 88, 037303 (2013).

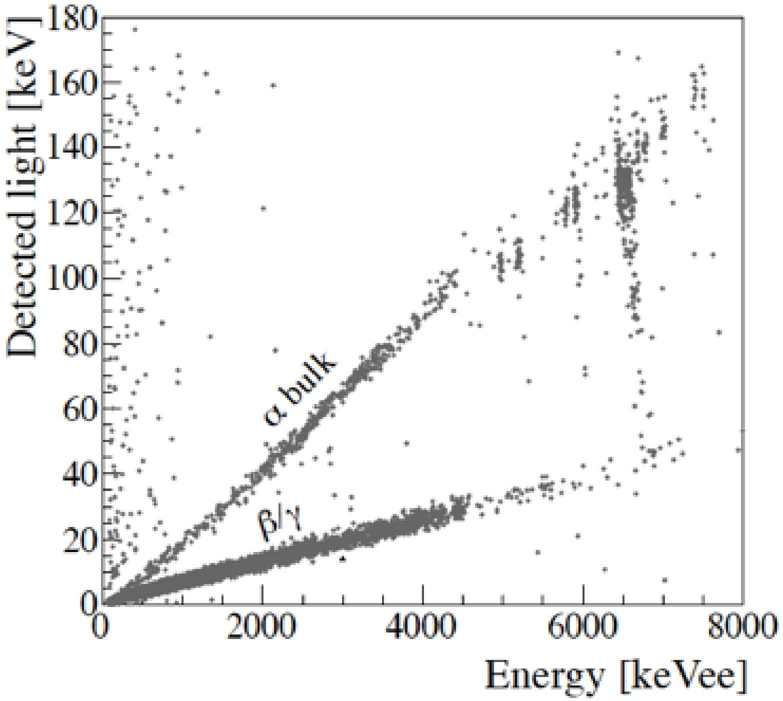
$M_{0\nu}$ - Nuclear matrix element

J. Engel and J. Menendez, Rept. Prog. Phys. 80, 046301 (2017)
J. M. Yao, L. S. Song, K. Hagino, P. Ring, and J. Meng, Phys. Rev. C 91, 024316 (2015)
J. Menendez, A. Poves, E. Caurier, and F. Nowacki, Nucl. Phys. A 818, 139 (2009)
F. Simkovic, V. Rodin, A. Faessler, and P. Vogel, Phys. Rev. C 87, 045501 (2013)
T. R. Rodriguez and G. Martinez-Pinedo, Phys. Rev. Lett. 105, 252503 (2010)
A. Meroni, S. T. Petcov, and F. Simkovic, JHEP 02, 025 (2013)

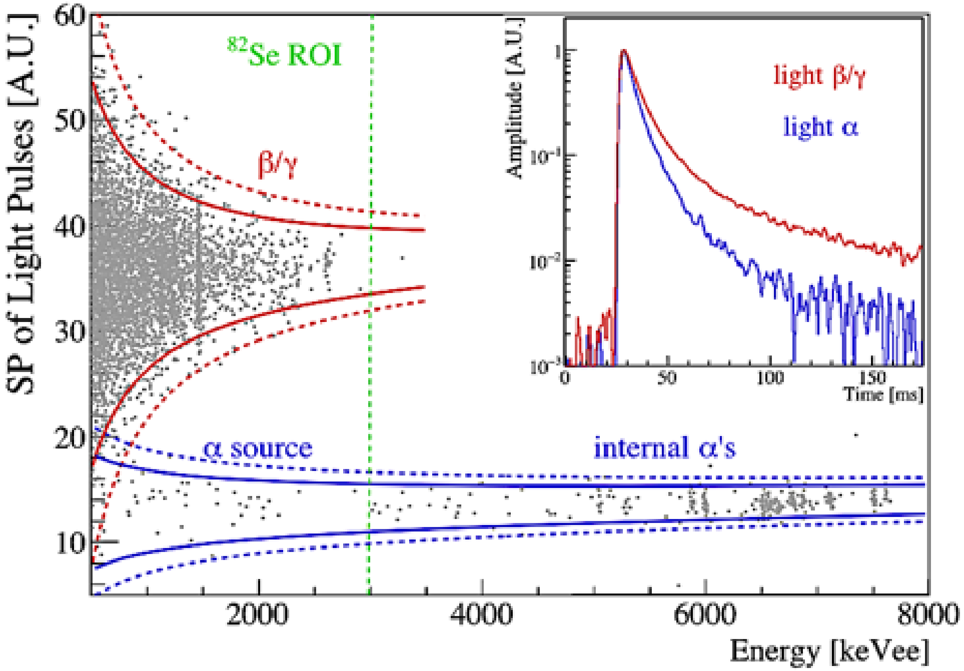
$g_a = 1.269$ – Axial coupling constant

Particle Identification

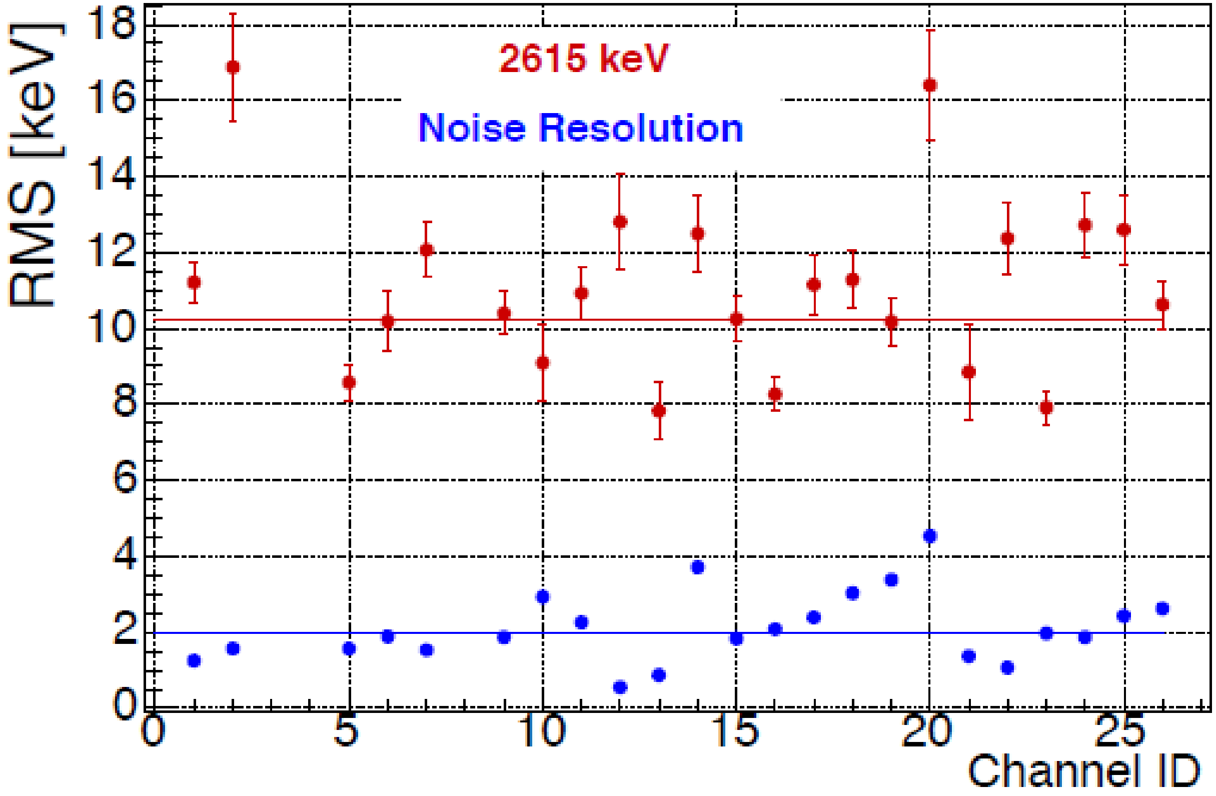
ZnSe Light Yield



Pulse shape

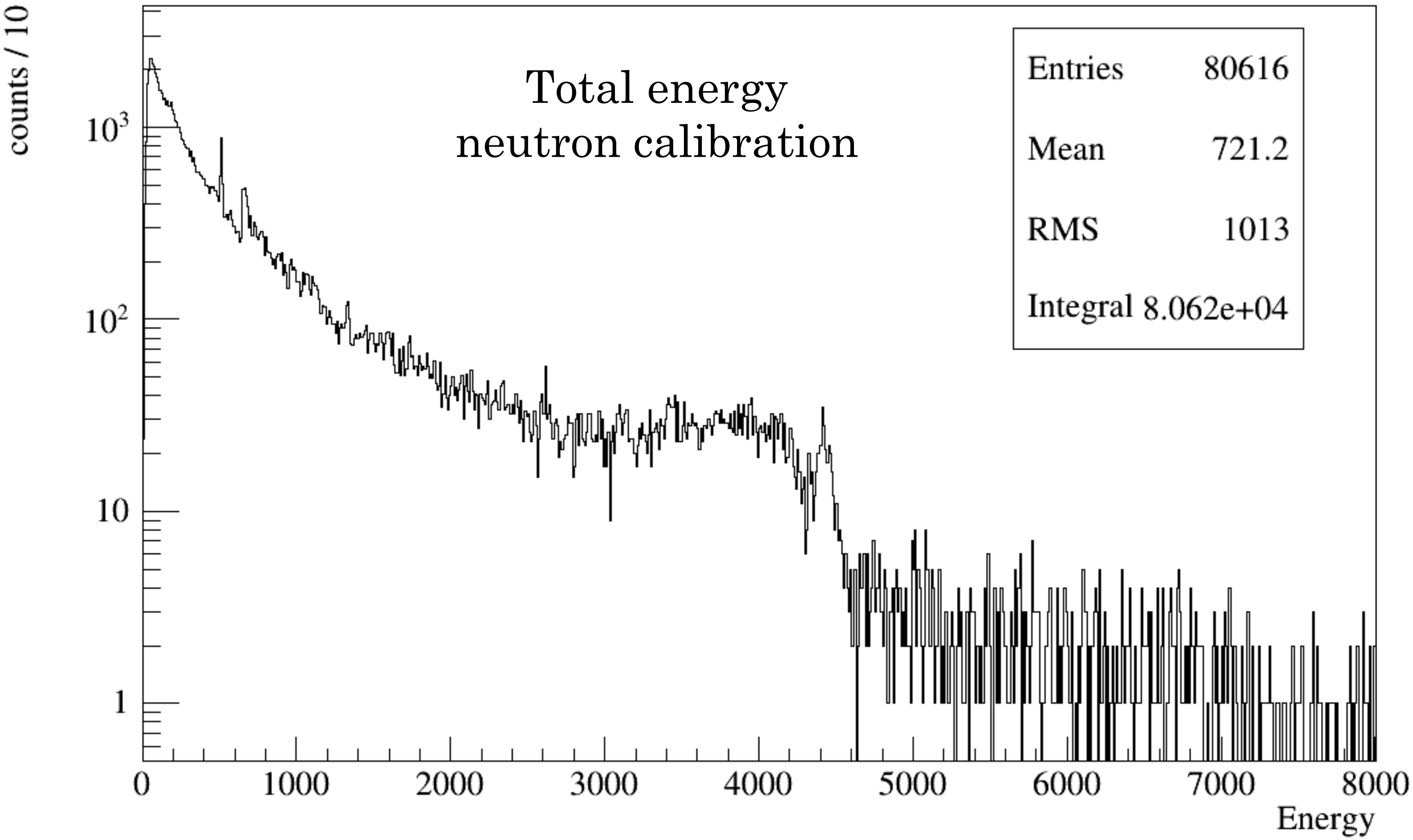


Detector performances



Neutrons calibration

We used neutron calibration in order to have gamma events also in the 3-4 MeV energy region



0nDBD fit

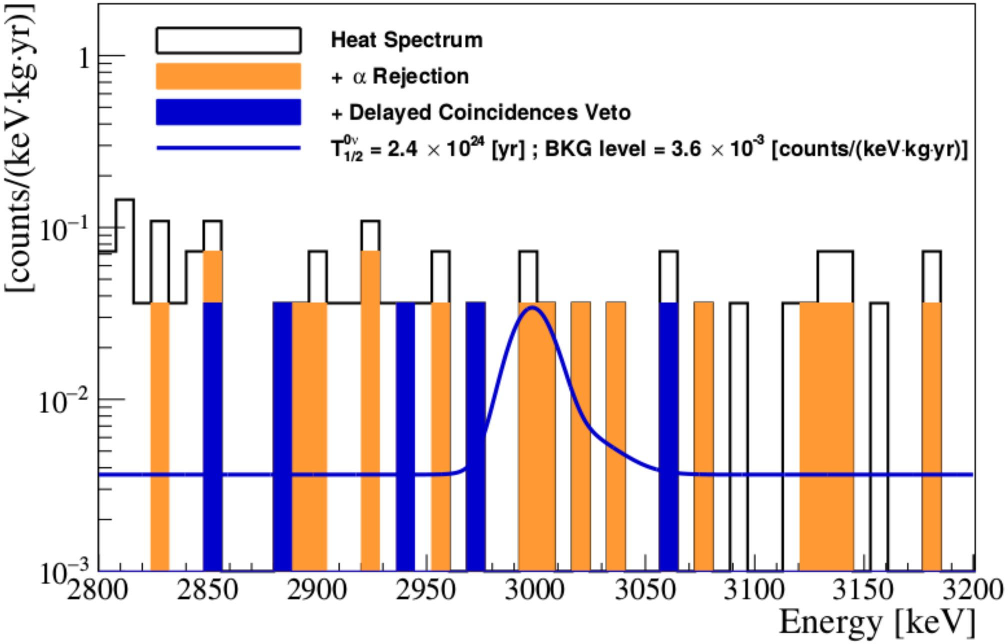
We estimate the systematics due to the uncertainty on the absolute energy scale, the detector response function, the efficiency and the exposure. For each influence parameter we weight the likelihood with a gaussian p.d.f. with mean and width fixed to the best estimated values and uncertainties respectively. We then integrate the likelihood via numerical integration.

We set a 90% credible interval (C.I.) Bayesian upper limit on $\Gamma^{0\nu}$ using a uniform prior in the physical region of $\Gamma^{0\nu}$ and marginalizing over the BI nuisance parameter: $\Gamma^{0\nu} < 0.285 \cdot 10^{-24} yr^{-1}$. This corresponds to a lower limit on the half-life of

$$T^{0\nu}_{1/2} > 2.4 \cdot 10^{24} \text{ yr (90\% C.I.)}$$

We evaluate the median 90% C.I. lower limit sensitivity from toy MC experiments to be: $T^{0\nu}_{1/2} > 2.3 \cdot 10^{24}$ yr.

With the accumulate exposure, the probability to obtain a limit greater than the one report is 44%.



Signal detection efficiency

We have evaluated the signal detection efficiency taking into account:

- the probability that a 0νDBD event is fully confined inside a single crystal (GEANT4 simulation)

  (81.0±0.2)%

- the trigger efficiency + the correct energy reconstruction (estimated on flagged heater pulses)

  (99.44±0.01)%

- that the signal survives the selection criteria (anticoincidence, heat and light pulse shape, delayed coincidences)

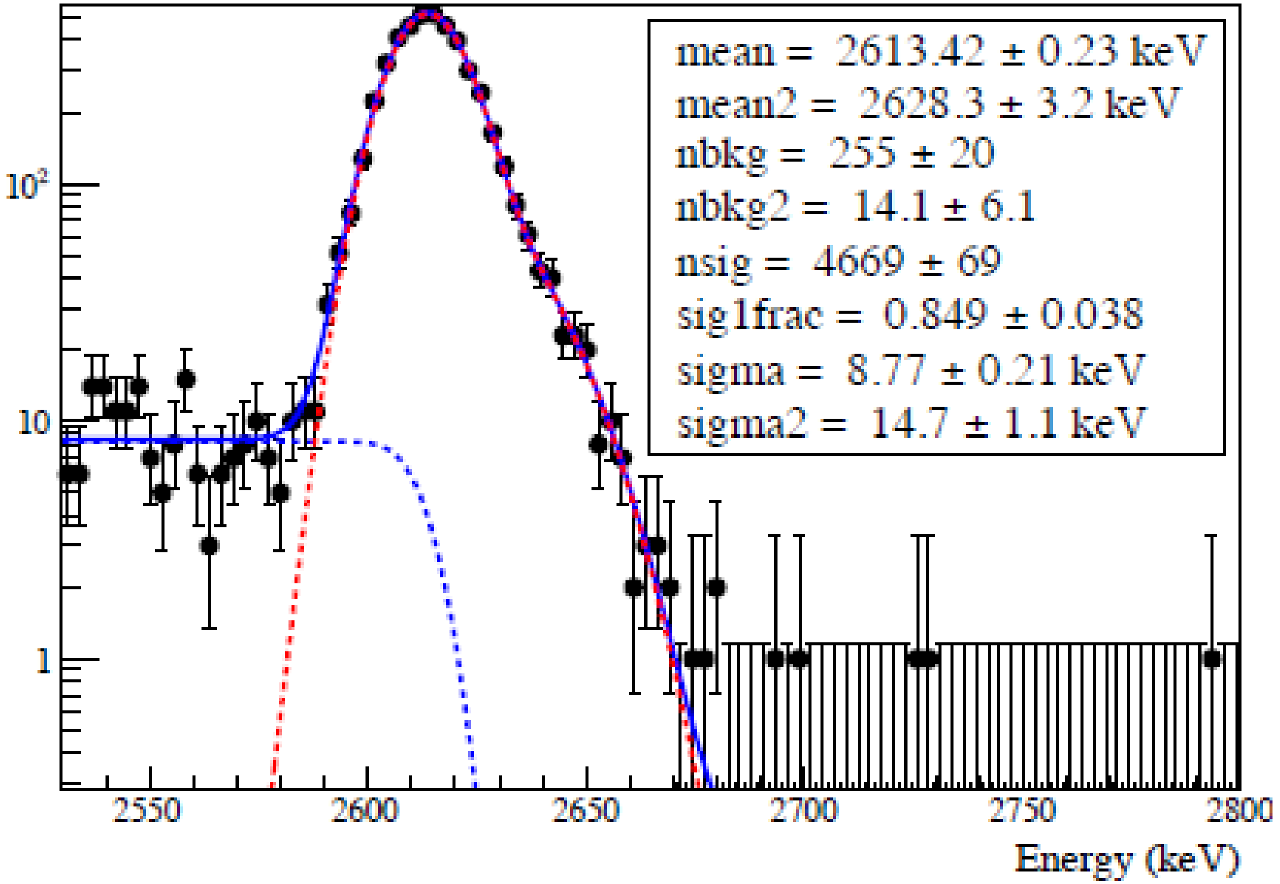
  (93±2)%

The total signal detection efficiency is:

(75 ± 2)%

Detector response function

We parametrize the line shape of the 2615 keV line with a double gaussian



Optimum filtering

The basic concept is to build a filter that, when applied to the raw-pulse, produces a pulse with the best signal to noise ratio. The filtered pulse is then used to evaluate the signal amplitude. It can be proven that in the frequency domain the OF transfer function H(ω) is given by

$$H(\omega) = K \, \frac{S^*(\omega)}{N(\omega)} \, e^{-j\omega t_M}$$

where S(ω) is the Fourier transform of the ideal thermal signal (reference pulse in the absence of noise), N(ω) is the noise power spectrum, t_M is the delay of the current pulse with respect to the reference pulse and K is a proper normalizing factor usually chosen in order to obtain the correct event energy.

Crystals radiopuruty

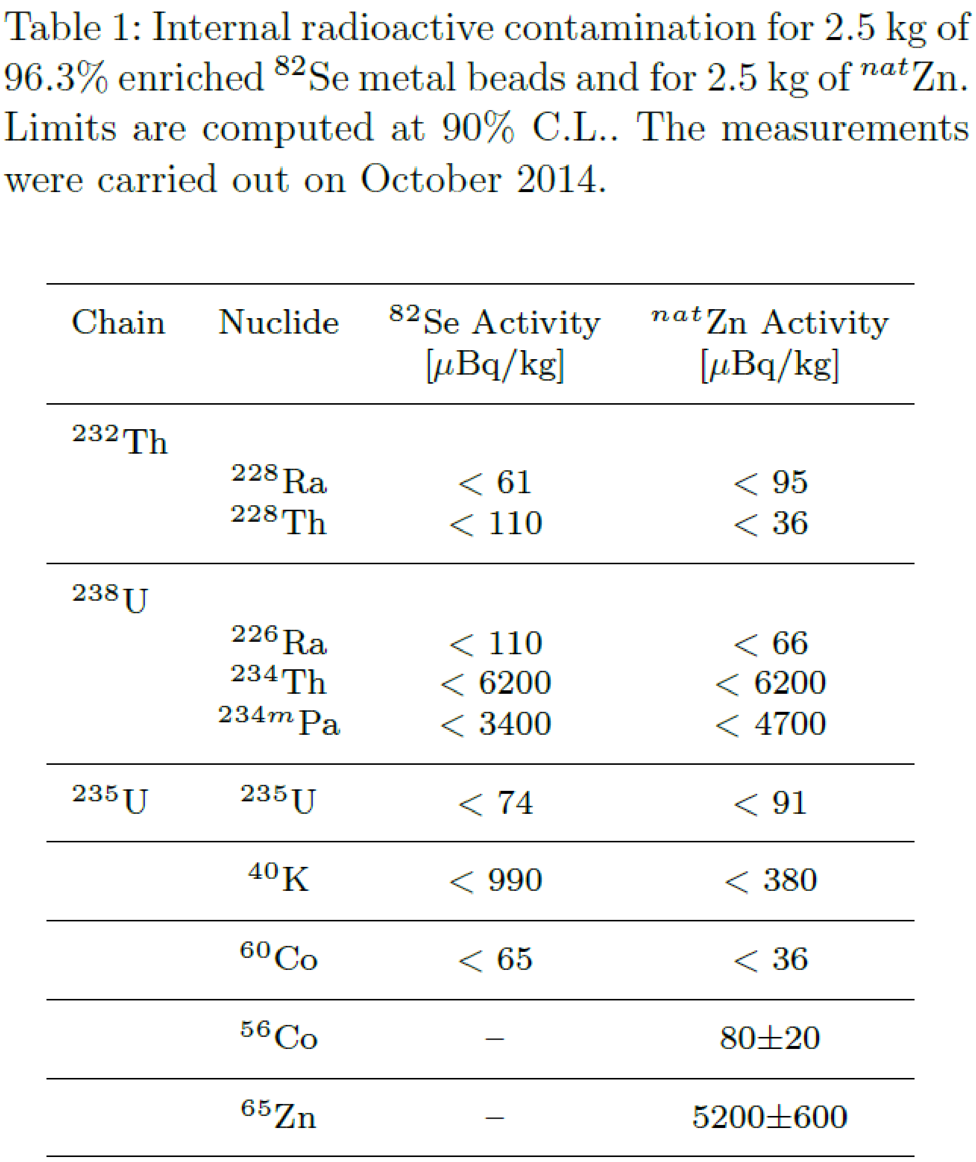


Table 1: Internal radioactive contamination for 2.5 kg of 96.3% enriched ^{82}Se metal beads and for 2.5 kg of ^{nat}Zn. Limits are computed at 90% C.L.. The measurements were carried out on October 2014.

Chain	Nuclide	^{82}Se Activity [μBq/kg]	^{nat}Zn Activity [μBq/kg]
^{232}Th			
	^{228}Ra	< 61	< 95
	^{228}Th	< 110	< 36
^{238}U			
	^{226}Ra	< 110	< 66
	^{234}Th	< 6200	< 6200
	^{234m}Pa	< 3400	< 4700
^{235}U	^{235}U	< 74	< 91
	^{40}K	< 990	< 380
	^{60}Co	< 65	< 36
	^{56}Co	–	80±20
	^{65}Zn	–	5200±600

Signal detection efficiency

We have evaluated the signal efficiency taking into account:

- the probability that a 0νDBD event is fully confined inside a single crystal (GEANT4 simulation)
- trigger efficiency as the ratio of triggered to tagged heater pulses + the energy reconstruction efficiency as the probability of the mono-energetic heater pulse to be reconstructed within three gaussian standard deviations.
- Finally we estimate the selection efficiency from a simultaneous fit on both the spectra of accepted and rejected events in the 1115 keV ^{65}Zn peak in the sample not used for the optimization. We sum all channels due to the limited statistics and derive a selection efficiency of (93±2)%. We cross-check the selection efficiency as a function of the energy selecting double-hit events; these are vey likely a sample of true particle events since spurious coincidences are negligible. The ratio of events before and after applying the selection criteria is compatible with the efficiency computed on the peak of ^{65}Zn in a range up to 2.6 MeV.