CUPID

Results and studies in the CUPID-Mo and CUPID experiments based on GEANT4 simulations

Léonard IMBERT on behalf of the CUPID-Mo and CUPID collaborations

VIEWS24

26/04/24

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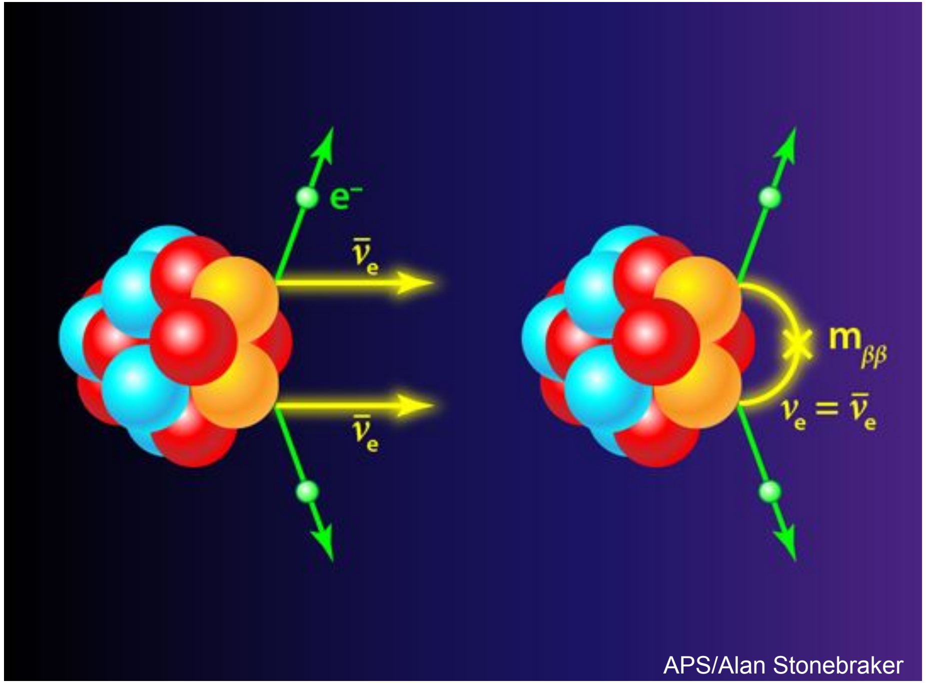
cnrs

Neutrinoless double beta decay

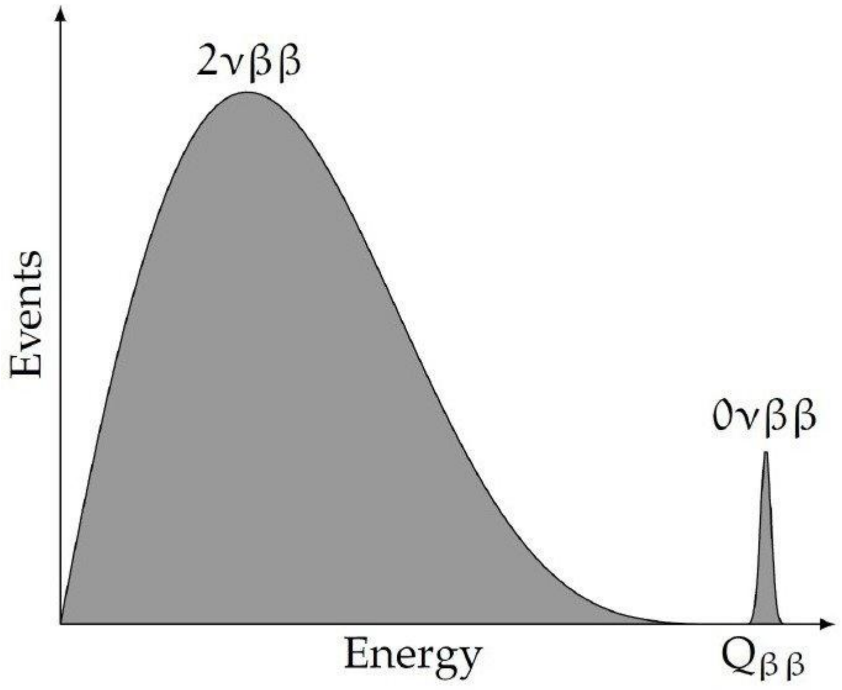
- $2\nu\beta\beta$
  - $2n \rightarrow 2p + 2e^- + 2\bar{\nu}_e$
  - Standard Model process
  - Observed for 14 nuclei
- $0\nu\beta\beta$
  - Hypothetical decay
  - $2n \rightarrow 2p + 2e^-$
  - Violates lepton number $\Delta L = 2$
  - Majorana neutrino $\nu = \bar{\nu}$



Searching for 0νββ

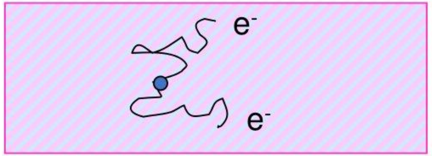
- 0νββ signature:
  - Peak at $Q_{\beta\beta}$ in the sum-energy spectrum of the two electrons
  - Typically $Q_{\beta\beta}$ = 2 ~ 3 MeV

- How to do a good experiment?
  - Low background around the region of interest
  - Good energy resolution
  - High detection efficiency
  - Large mass
  - Long data taking



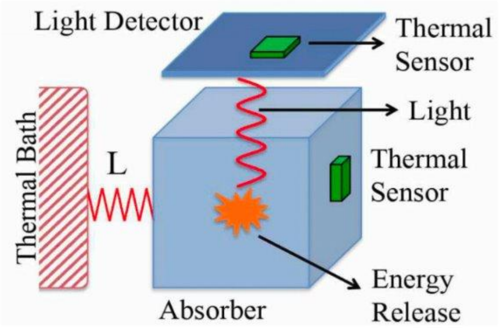
Bolometers

- Crystals cool down to ~ 10 - 20 mK
- Detector = Source
  → High detection efficiency
- Very good energy resolution
  5 - 10 keV FHWM

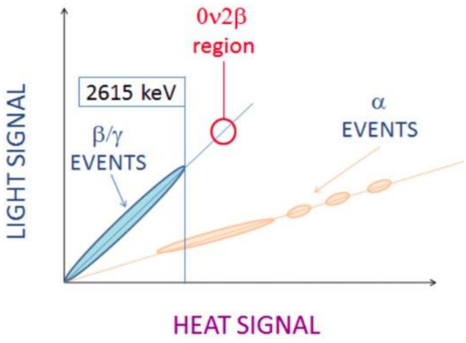


- Scintillating bolometers
  - Heat and Light signals
  - Discrimination between β/ɣ and α

Scintillating Bolometer

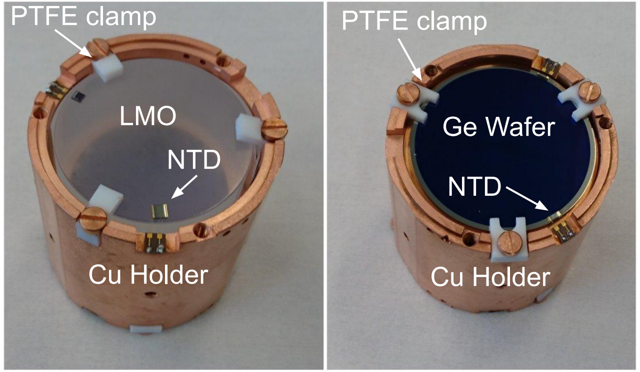


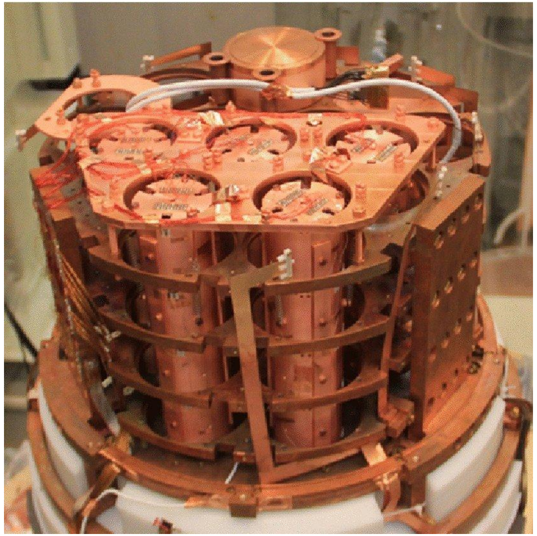
Particle Identification



CUPID-Mo

- Demonstrator for the next experiment CUPID
- Installed in Laboratoire Souterrain de Modane (France) in EDELWEISS cryostat
- Studied 0νββ of ^{100}Mo ($Q_{\beta\beta}$ = 3034 keV)
- 20 $Li_2{}^{100}MoO_4$ scintillating bolometers
  - 0.2 kg cylindrical crystals (ø 44 x 45 mm)
  - ^{100}Mo enrichment ~ 97 %
  - Ge wafers as Light Detectors
  - NTD Ge thermistors to read the signal
  - Reflecting foils to increase light collection





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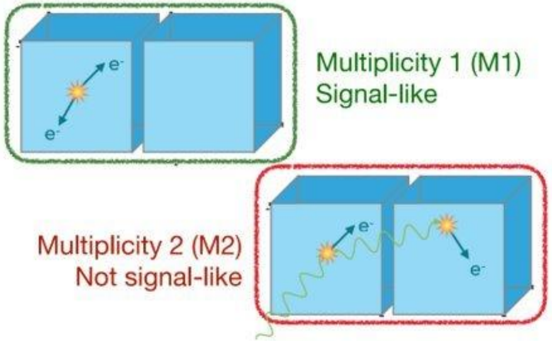
- Set a limit of : **$T_{1/2}$ > 1.8 x 10^{24} yr (90% C.I.)** on the 0νββ of ^{100}Mo

- Corresponds to: **$m_{\beta\beta}$ < (280 - 490) meV**

Experimental Data

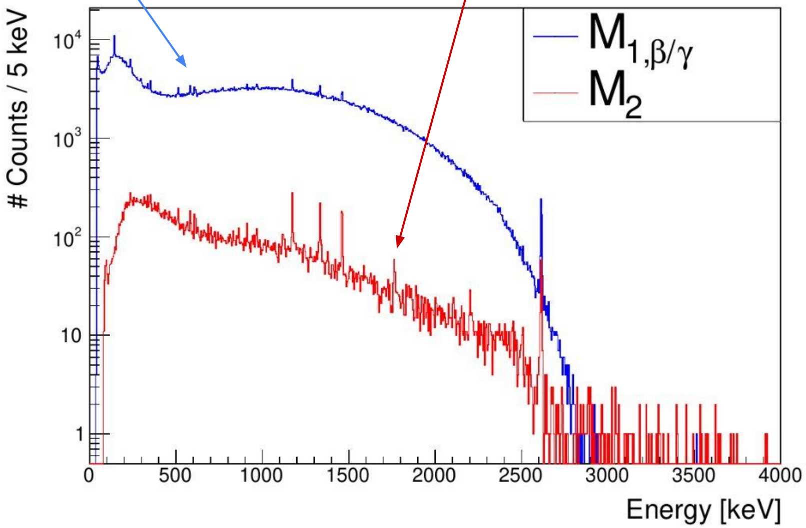


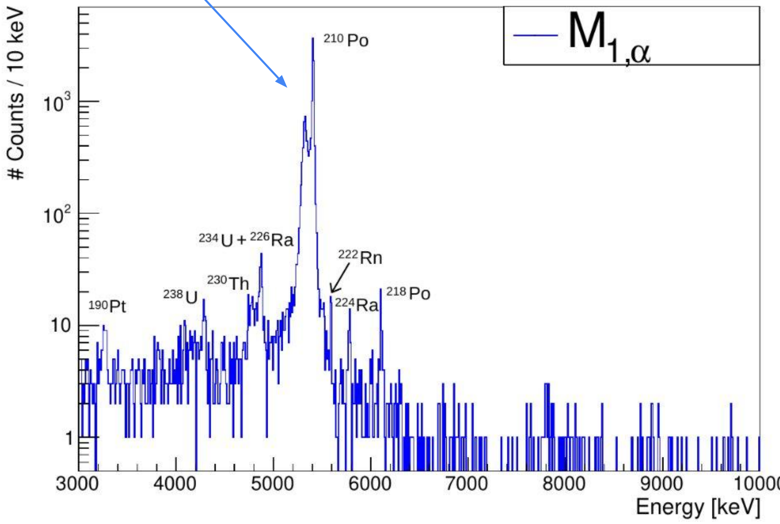
$M_{1,\beta/\gamma}$, M_2 and $M_{1,\alpha}$ spectra

0νββ analysis

Information on γ background

Information on crystal radiopurities





GEANT4 Geometry

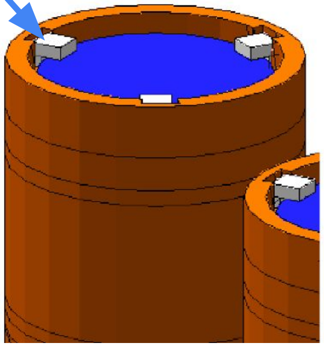
- Based on the program developed by EDELWEISS dark matter experiment
- Detailed geometry of the CUPID-Mo towers
- Reproduced the size of each crystal
- Geometry includes:

Crystals

Ge Light Detectors

PTFE clamps

Reflecting foils



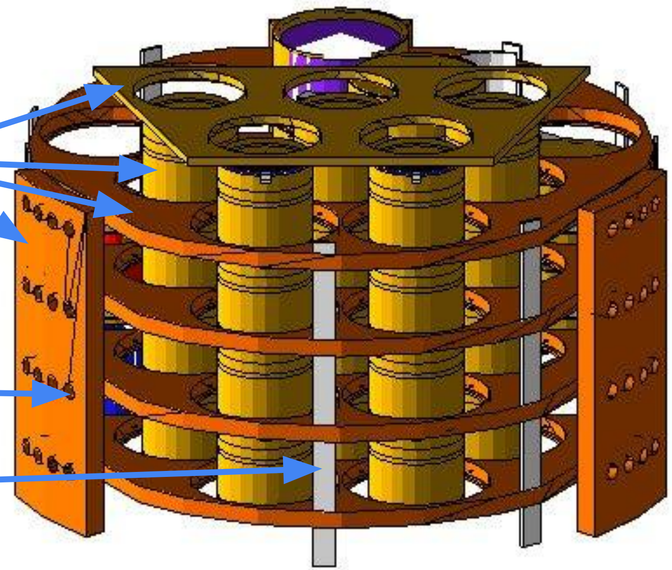
Copper structure

Springs

Screws

Readout cables

EDELWEISS detectors and readout



GEANT4 Geometry

- Based on the program developed by EDELWEISS
- Detailed geometry of the CUPID-Mo towers
- Reproduced the size of each crystal
- Geometry includes:

Copper screens (10mK, 1K, 50K, 100K, 300K)

Internal Polyethylene shielding

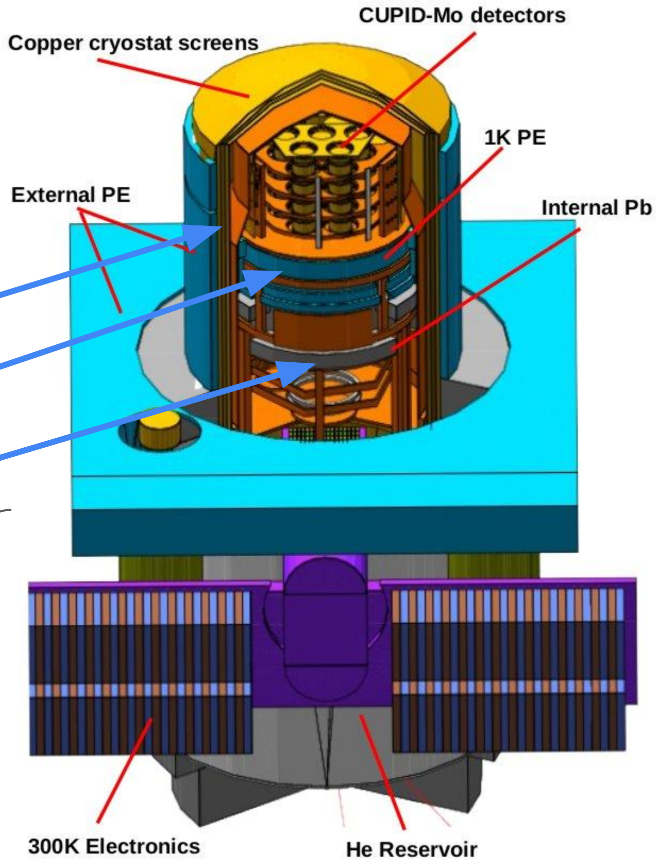
Lead shielding

Dilution unit

300K electronics

Pumps

He Reservoir



GEANT4 simulations

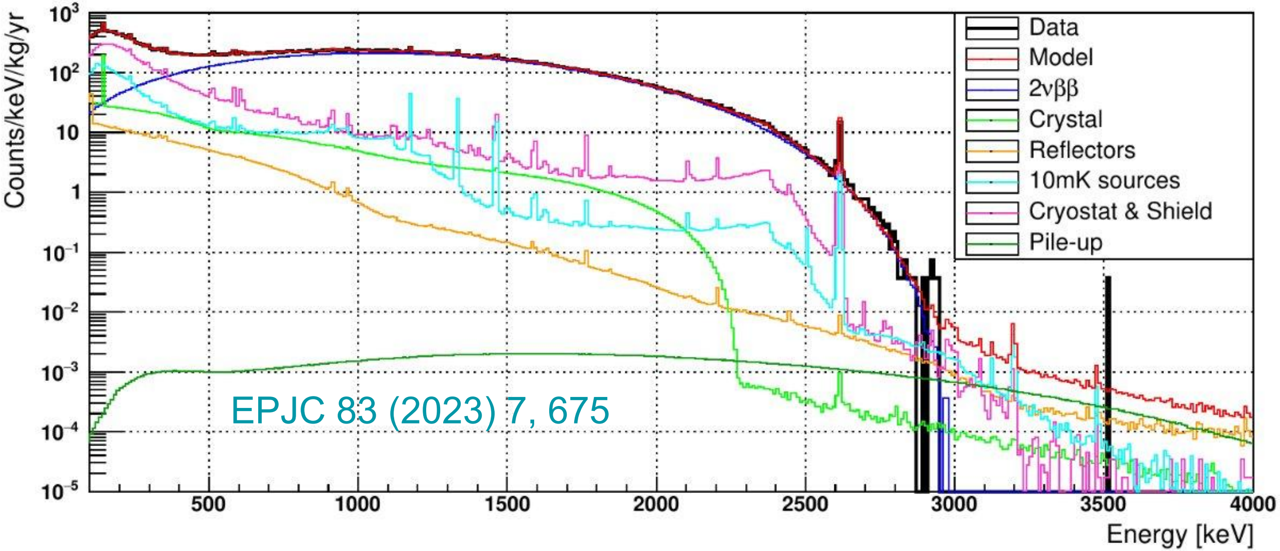
- G4RadioactiveDecay
  - Used for close sources to generate decay chains considering break in secular equilibrium
    - ^{232}Th • ^{228}Ra to ^{228}Th • ^{228}Th to ^{208}Pb
    - ^{238}U to ^{234}U • ^{234}U • ^{230}Th • ^{226}Ra to ^{210}Pb • ^{210}Pb to ^{206}Pb
  - Allows to register the time of event needed for the modelisation of the detector response
- Decay0
  - Used for all the other decays (not directly facing the crystals)
  - Read input files in the PrimaryGeneratorAction class to set particle type and momentum
- $2\nu\beta\beta$
  - Sampled from theoretical two-dimensional single electron energy spectrum

GEANT4 simulations

- Surface contaminations
  - Used for the crystals and the reflecting foils
  - Modelled with an exponential density profile $e^{-x/\lambda}$
  - We did simulations with λ = 10 nm and 10 μm for crystals and reflectors
- Livermore Physics list
- Production cuts: 1 μm for e^-/e^+ and 10 μm for γ's
  - It corresponds to 1 keV for both e^-/e^+ and γ's in the crystal
  - Using a production cut corresponding to 250 eV was giving comparable spectra

Background Model

- Describe the experimental data by a linear combination of the GEANT4 simulation spectra
- Simultaneous fit of $M_{1,\beta/\gamma}$, M_2 and $M_{1,\alpha}$ spectra
- Done with the JAGS software based on Monte-Carlo Markov Chains
- We used 67 sources in the fit



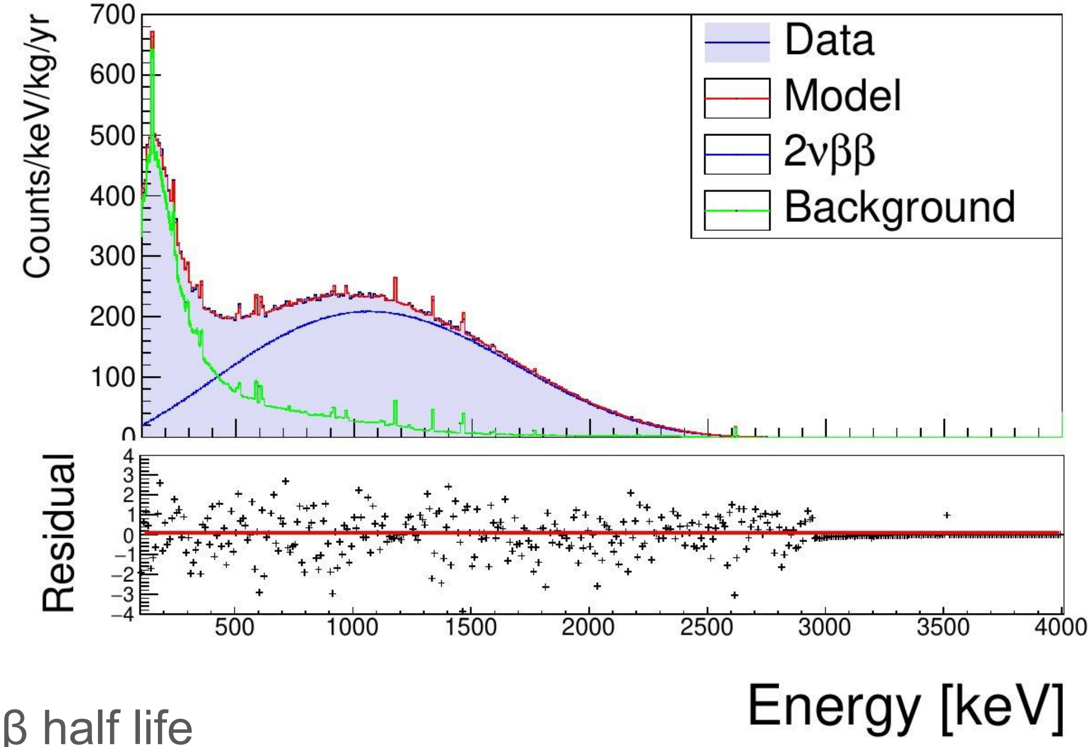
Background index

=

$2.7^{+1.3}_{-0.8}$ x 10^{-3} cts/keV/kg/yr

EPJC 83 (2023) 7, 675

2νββ spectrum



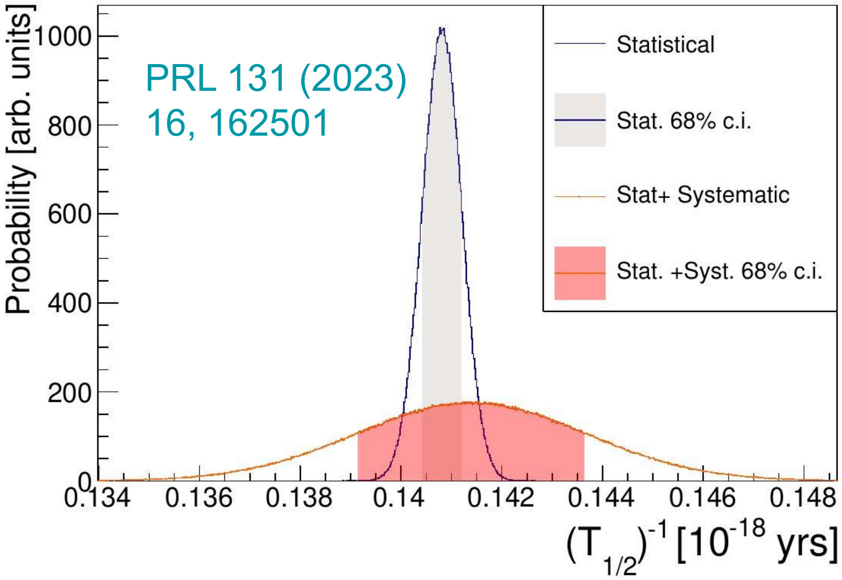
Excellent signal to background ratio

Allows for:

- Precise measurement of the 2νββ half life
- Studies of the 2νββ spectral shape

2νββ half life

- Measurement comes directly from the background model fit
- Systematics evaluated by varying assumptions on the background model



PRL 131 (2023) 16, 162501

Related to the background model

We vary in GEANT4 the bremsstrahlung cross section by +/- 10 %

Systematic test	Uncertainty $T_{1/2}$ [%]
Binning	+/- 0.37
Energy Bias	$^{+0.11}_{-0.16}$
Bremsstrahlung	$^{+0.13}_{-0.22}$
MC statistic	+/- 0.11
Source location	+/- 0.83
Minimal model	+/- 0.24
^{90}Sr + ^{90}Y	+ 1.0 (uniform distribution)
Efficiency	+/- 1.2
Isotope abundance	+/- 0.2

PRL 131 (2023) 16, 162501

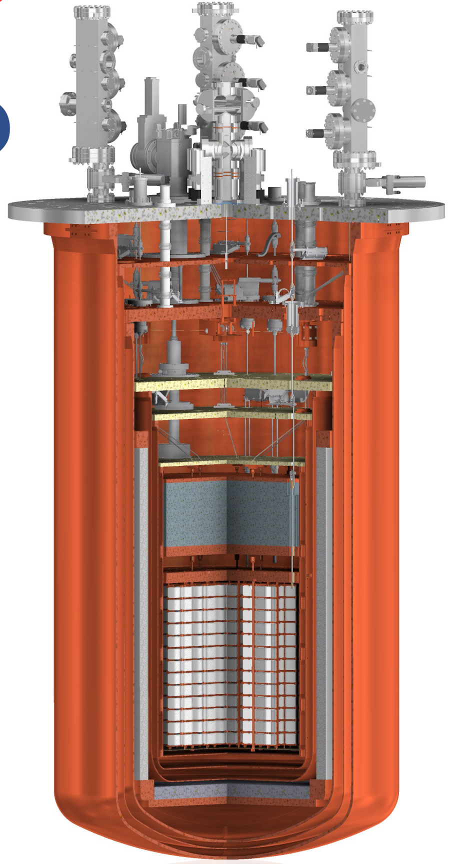
$$T_{1/2} = 7.07 \pm 0.11 \times 10^{18}\ \text{yr}$$

CUPID

- Next generation bolometric 0νββ experiment
- To be installed at LNGS in the CUORE cryostat
- Focus will be a search for 0νββ of ^{100}Mo with $Li_2{}^{100}MoO_4$ crystals
  - Enriched at ~ 95 % in ^{100}Mo
  - Cubic crystals: 45 x 45 x 45 mm
  - 1596 crystals: 240 kg of ^{100}Mo
  - Ge Light Detectors with Neganov-Luke amplification for α's and pile-ups rejection
- Goals
  - Background Index = 10^{-4} cts/keV/kg/yr
  - Energy resolution = 5 keV FWHM @ 3034 keV

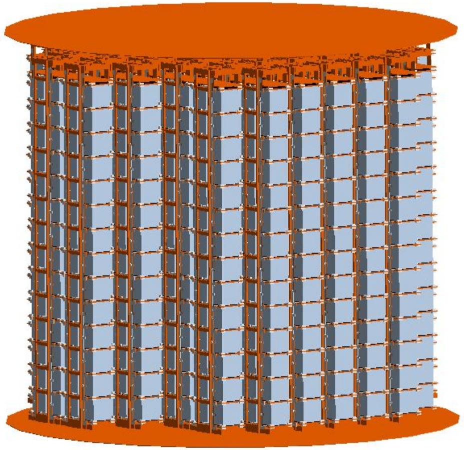
0νββ 3σ discovery sensitivity

- **$T_{1/2} = 10^{27}$ yr**
- **$m_{\beta\beta}$ = 12 - 20 meV**



CUPID simulations

- CUPID detector geometry implemented in the geometry of the CUORE cryostat
- G4RadioactiveDecay
- Livermore Physics list
- The geometry includes:



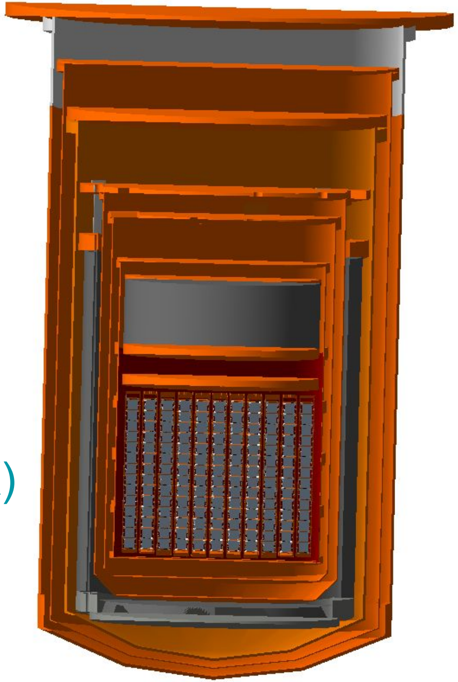
Crystals
Light Detectors

PTFE pieces
CuPEN readout
Copper holders

10mK Screen
10mK Tiles
10mK Plate

Cryostat screens
(50mK, 600mK, 4K, 300K)

Lead shieldings

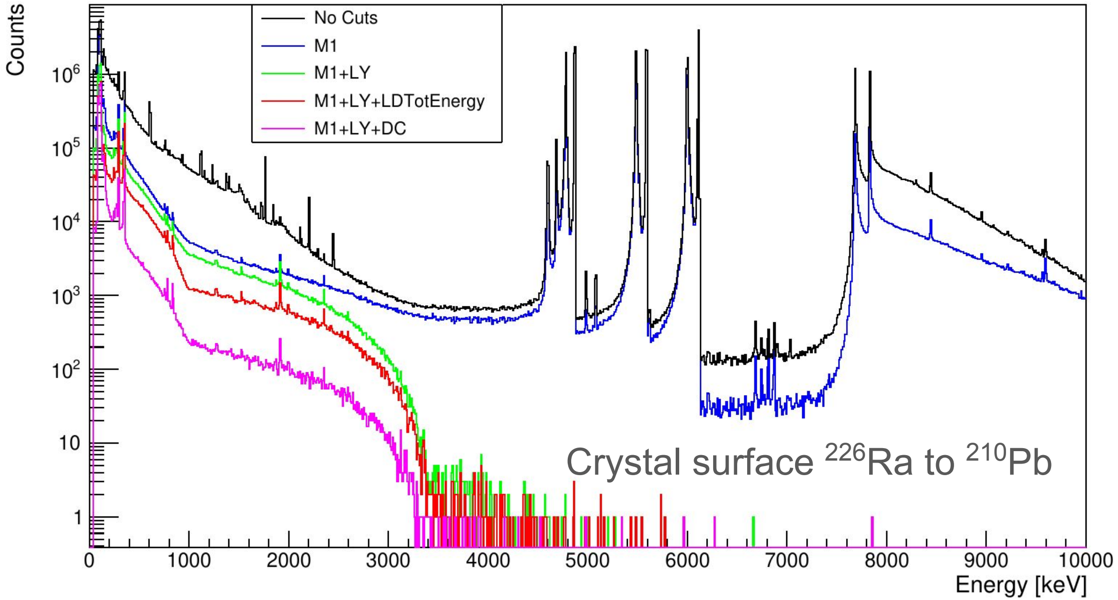


CUPID Background projections

- Detector effects are convolved into MC spectra

- We generated a total of 85 simulations of the various components of the set-up

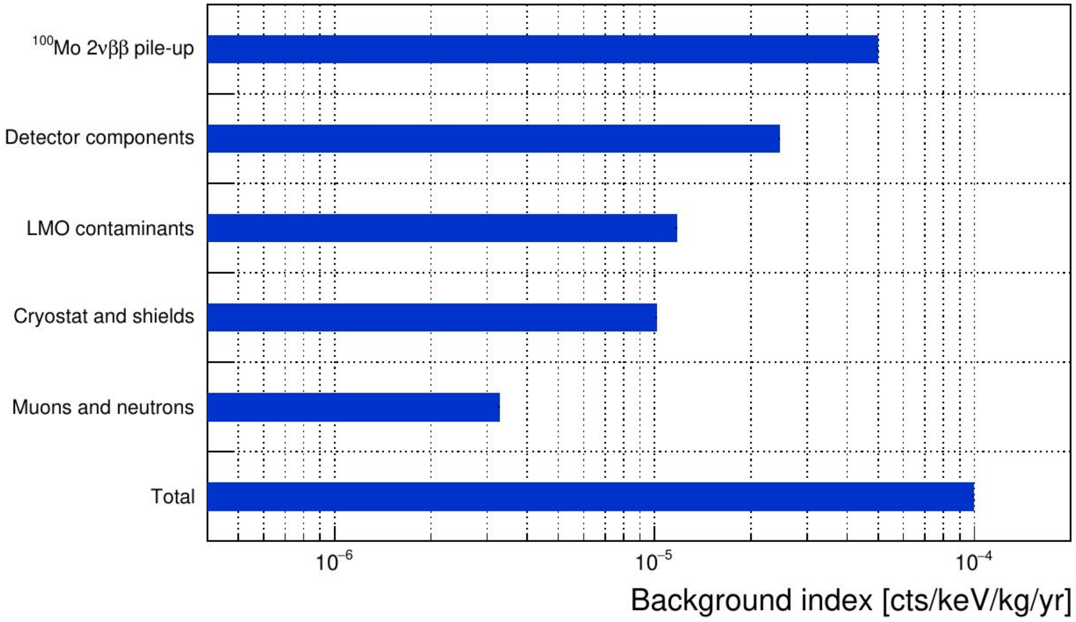
- We used input activities from the CUPID-Mo (crystals) and the CUORE background model



CUPID Background budget

CUPID background budget is based on results from precursor experiments (CUORE and CUPID-Mo) and on improved new design

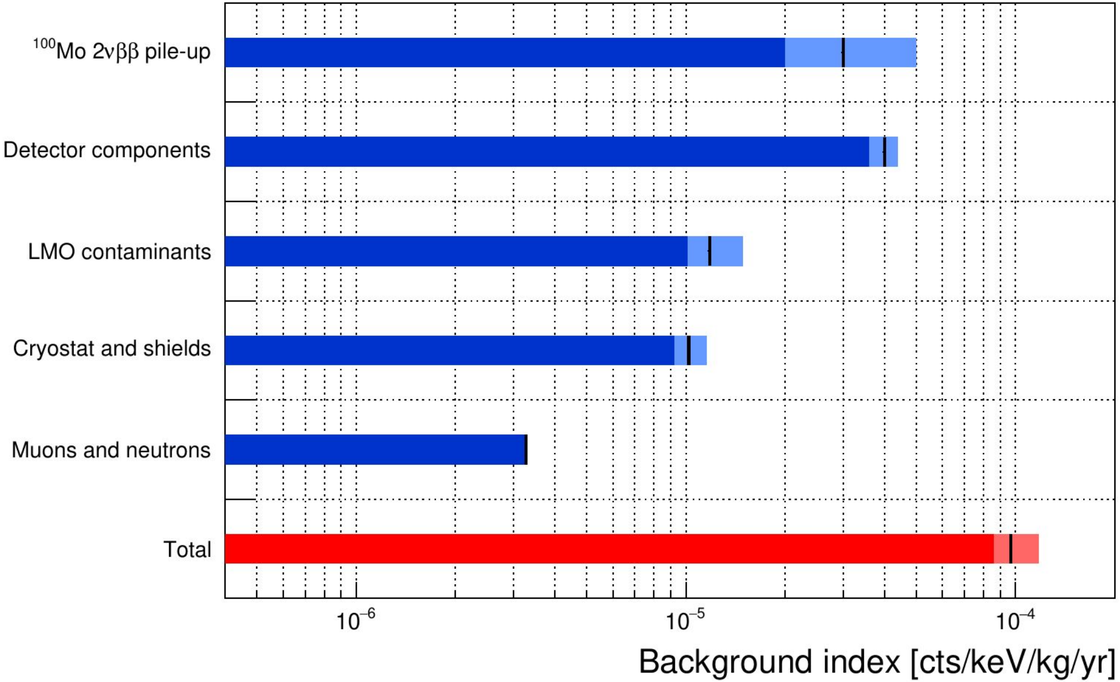
- LMO ^{100}Mo pile-up:
  - Demonstrated performance on baseline NTL detectors
- Detector components:
  - Surface driven
- LMO contaminants:
  - Surface driven
- Cryostat & shields:
  - Bulk
- Muons and neutrons



CUPID Background projections

Backgrounds come from:

- Pile-up
    - random coincidence between two $2\nu\beta\beta$ events
    - extrapolated from measured performances of NTL light detectors
- Detectors components
    - driven by surface of copper holders
- LMO crystal contaminants
    - surface driven
    - includes bulk and cosmogenic
- Cryostat & shields
- Muons and neutrons
    - based on initial design and MC simulation



Total projected background:

$BI = 0.97^{+0.21}_{-0.11} \times 10^{-4}$ cts/keV/kg/yr

Work continues on further improvements in the overall background level

Importance Biasing

- Simulate the environmental background
  - External lead shield of 25 cm

- Simulate the internal contaminations of the lead shieldings

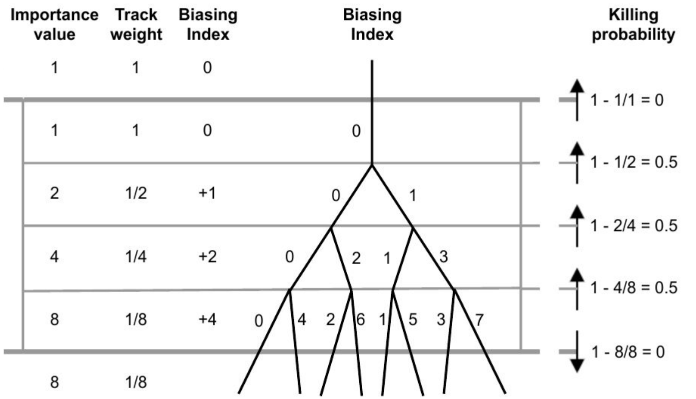
- Importance biasing is implemented in a separate code based on example extended/biasing/B01

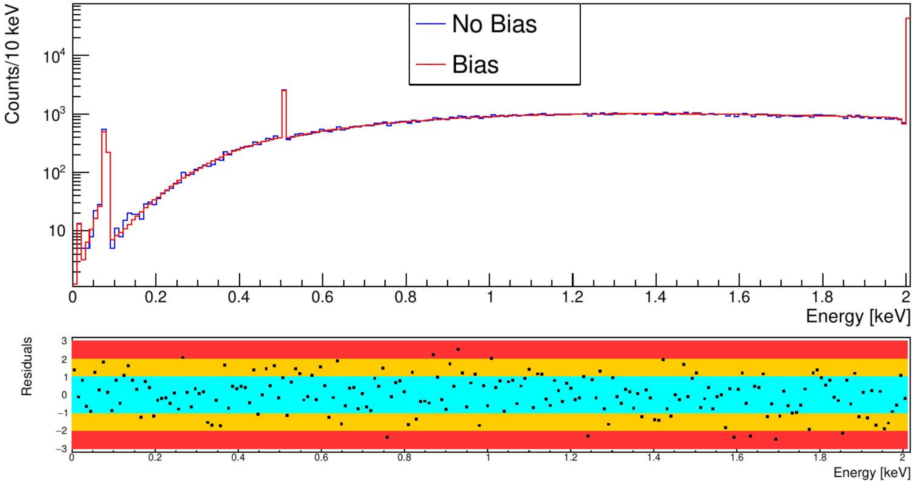
- We then use the output of this code as an input in the main CUPID code

- Validation was done with 2 MeV γ going through 10 cm of Lead

Thanks to the help of Birgit Zatschler

See her presentation for details on importance biasing





Conclusion

- In CUPID-Mo, GEANT4 simulations permitted the construction of the Background Model, leading to:
  - Evaluation of the Background Index EPJC 83 (2023) 7, 675
  - Evaluation of Crystal contaminations → Important for CUPID EPJC 83 (2023) 7, 675
  - Most precise measurement of the 2νββ half-life of ^{100}Mo PRL 131 (2023) 16, 162501
  - First measurement of spectral shape theoretical parameters of the 2νββ of ^{100}Mo PRL 131 (2023) 16, 162501

- In CUPID, GEANT4 simulations are used for background projections
  - We find that background estimations agree with CUPID goals

BACK-UP

Neutrinoless double beta decay

- 2vββ
  - $2n \rightarrow 2p + 2e^- + 2\nu_e$
  - Standard Model process
  - Observed for 14 nuclei

- 0vββ
  - Hypothetical decay
  - $2n \rightarrow 2p + 2e^-$
  - Violates lepton number ΔL = 2
  - Majorana neutrino v = v

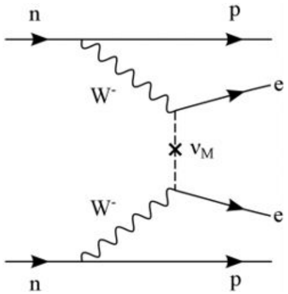
Phase space factor:
- Known and calculated to good accuracy

Nuclear Matrix Element:
- Differences between various nuclear models

$$\left(T^{0\nu}_{1/2}\right)^{-1} = G^{0\nu} \left(g_A^{0\nu}\right)^4 \left(M^{0\nu}\right)^2 \left|\frac{m_{\beta\beta}}{m_e}\right|^2$$

Weak axial-vector coupling strength:
- Question of possible gA quenching under study

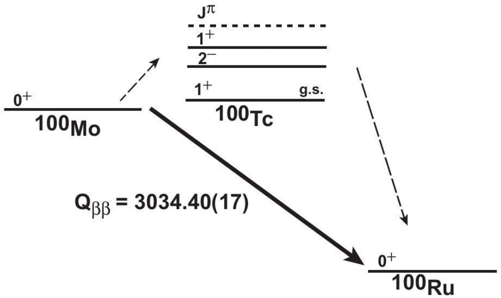
Effective Majorana mass:
- $m_{\beta\beta} = \left|\, |U_{e1}|^2 m_1 + e^{i\alpha_1} |U_{e2}|^2 m_2 + e^{i\alpha_2} |U_{e3}|^2 m_3 \right|$



CUPID-Mo Detector Response Model

- We processed the MC simulations to account for:
    - Energy resolution
    - Energy threshold of 40 keV
    - Event Multiplicity
    - Scintillation Light and Light Detector (LD) resolution
        - We parameterised the scintillation light and the resolution measured by the LD as a function of the energy, the crystal, and the LD (which have different performances)
        - We then generated a random scintillation light for each event
    - Cut efficiencies
    - Inactive periods of detectors
    - Pile-up and delayed coincidences in decay chains

2vββ spectral shape measurement



- Measuring the 2vββ spectral shape constrains nuclear models for Nuclear Matrix Element calculations
- We implemented an improved description of the 2vββ in our fit:

Phase space factors

$$\frac{d\Gamma}{dE} = \left(g_A^{\mathrm{eff}}\right)^4 |M_{GT-1}^{2\nu}|^2 \left(\frac{dG_0^{2\nu}}{dE} + \xi_{31}\frac{dG_2^{2\nu}}{dE} + \frac{1}{3}\xi_{31}^2\frac{dG_{22}^{2\nu}}{dE} + \left(\frac{1}{3}\xi_{31}^2 + \xi_{51}\right)\frac{dG_4^{2\nu}}{dE}\right)$$

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Spectral shape parameters

- We used a gaussian prior on ξ_{51}/ξ_{31} based on theory
- We obtained ξ_{31} = 0.45 +/- 0.06 and g_A(pn-QRPA) = 1.0 +/- 0.2

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