Monte Carlo Simulations in CUORE

Michinari Sakai on behalf of the CUORE collaboration

Monte Carlo Tools for Beyond the Standard Model Physics 2018
Institute for Particle Physics Phenomenology - Durham University
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CUORE UCLA NSF

CUORE (Cryogenic Underground Observatory for Rare Events)

- Objective:

  Search for Majorana neutrino ($\nu = \bar{\nu}$) through neutrinoless double beta ($0\nu\beta\beta$) decay of ^{130}Te

- Detector:

  Array of 988 TeO_2 bolometers

- Mass:

  742 kg of TeO_2
  206 kg of ^{130}Te (34.2 % natural abundance in Te)

- Operating temperature:

  ∼15 mK

- Energy resolution goal:

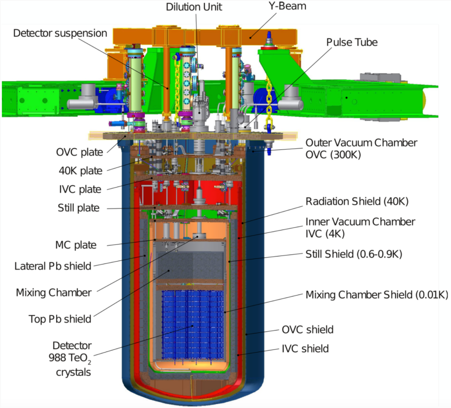
  5 keV FWHM @ 2615 keV

- $T_{1/2}$ sensitivity goal:

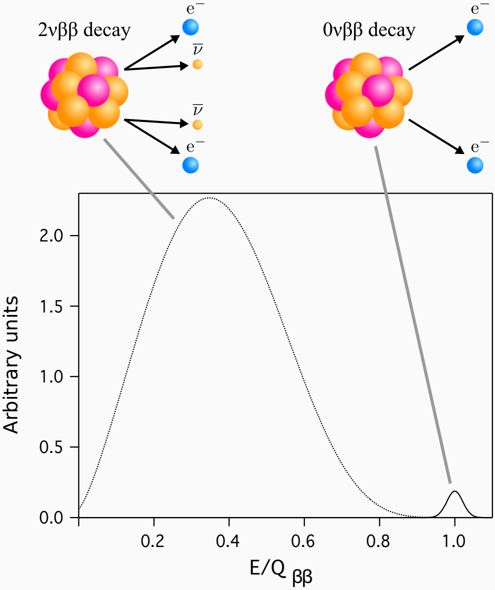
  $\sim 9 \times 10^{25}$ yr (90 % C.L.) in 5 years of data taking

- Background goal:

  0.01 counts/(keV · kg · yr) in energy region of interest

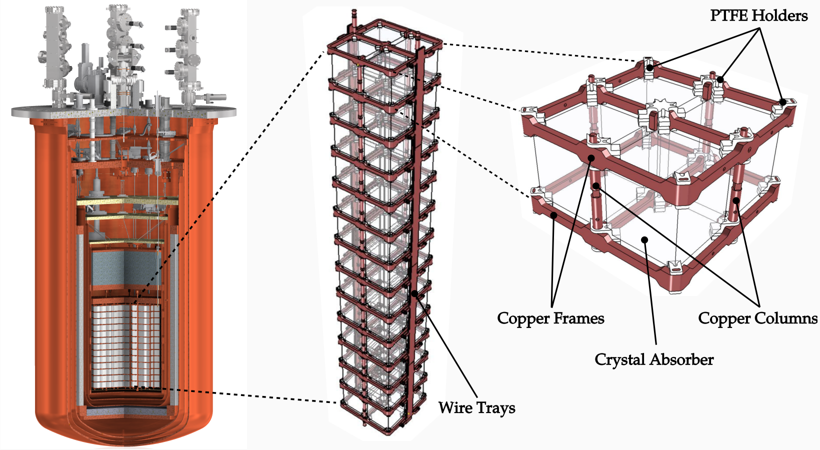


DOUBLE BETA ($\beta\beta$) DECAY SIGNATURE

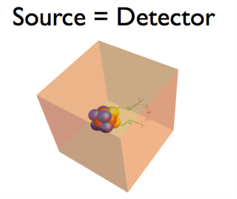


- $^{130}\mathrm{Te} \to {}^{130}\mathrm{Xe} + 2\beta^-$ decay
  Q value $= 2528$ keV
- Region of Interest (ROI) $\approx [2470, 2570]$keV
- $0\nu\beta\beta$ decay signature: Faint mono-energetic decay peak at Q value smeared only by detector resolution if βs deposit full energy in detector
- $2\nu\beta\beta$ decay signature: Broad peaked continuum up to decay Q value with neutrinos carrying away energy across phase space

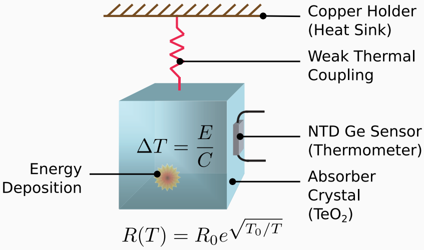
DETECTOR GEOMETRY



- Closely packed array of 988 TeO_2 thermal detectors are housed in 19 towers
- Each tower holds 13 floors with 4 detectors on each floor
- Detector: $5 \times 5 \times 5\,\text{cm}^3$, 0.75 kg each
- Detectors are mechanically held in place only by polytetrafluoroethylene (PTFE) holders
- Entire structure is held together by copper frames

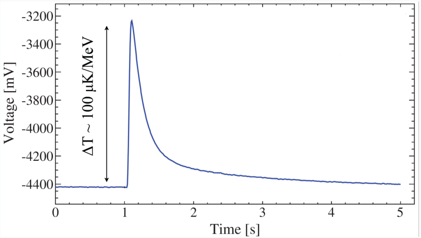


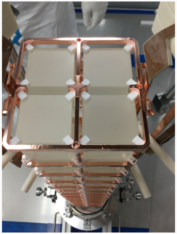
- Electron events from $\beta\beta$ decay mostly contained in bulk (88.4 % containment efficiency)
  $\Longrightarrow$ Anti-coincidence cuts backgrounds
- Detector only sensitive to temperature change
  $\Longrightarrow$ No active background rejection



$C(T) \propto T^3$

Slow ($\sim$ 1 s) signal pulse
suitable for rare event searches





Sources Near Detectors

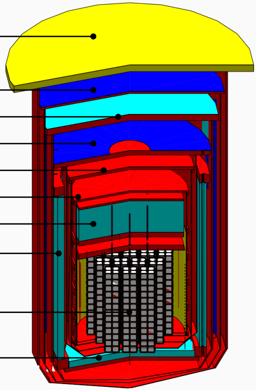
- ^{238}U, ^{232}Th and decay products on surface and in bulk of TeO_2 crystals and nearby materials
- Multi-Compton events from 2615 keV γ from ^{208}Tl (from ^{232}Th chain)*
- Both bulk and surface contaminations are significant and unique backgrounds

Sources Far from Detectors

- Cu and Pb shields
- Background contribution from bulk/surface contaminations degenerate $\implies$ only simulate bulk

Modeling backgrounds is important part of CUORE!

*This is the only environmental γ line with B.R. $> 1\,\%$ with energy $> Q_{\beta\beta}$



Based on GEANT4 with geometries:

- Array of 988 TeO_2 crystals
- PTFE supports, NTD Ge thermistors
- Cu frame structure holding crystals, wire trays
- Thermal shields
- Pb shields, steel rods supporting Pb shields
- Calibration source guiding tubes
- External Pb and polyethylene shields

2 step detector simulation

1. Propagate particles from nuclear decay chains down to $\sim$ keV energies and record energy depositions in TeO_2 thermal detectors
2. Important observables are saved and further processed applying detector response and readout features mimicking real data

GEOMETRY ELEMENTS†

Region	Element	Mass (g)	Surface Area (cm^2)
Near TeO_2 detectors	TeO_2 crystals	7.42×10^5	148 200
	Si heaters	6.8	158
	NTD Ge thermistors	42	228
	PEN-Cu cables	389	1200
	Cu wire pads	57	1140
	PTFE crystal supports	5500	29 800
	NOSV Cu parts	9.4×10^5	278 900
Far from TeO_2 detectors	OFE Cu parts	7.0×10^6	—
	Superinsulation layers	17×10^3	—
	Roman Pb shield	4.5×10^6	—
	Modern Pb shield	2.1×10^6	—
	Stainless steel rods	15.2×10^3	—
	300 K steel flange	1.9×10^6	—

- Surface contamination is simulated only for parts near TeO_2 detectors*

*The projected background for the CUORE experiment , Eur.Phys.J. C77 (2017) no.8, 543

†Elements are geometrical volumes made of the same material with similar production history and contamination levels.

PARTICLE PROPAGATION

Physics

- Variable physics list that defaults to Livermore for accurate low energy (0—10 TeV) physics relevant in underground applications

Sources

- Arbitrary sub-chains of decaying isotopes

  $\Longrightarrow$ Useful for studying breaks in secular equilibrium within one chain
- $\beta\beta$ decays with/without νs from the ground or excited states of ^{130}Te

Source Positions

- Bulk of detector parts
- Surface of detector parts (uniform distribution up to some depth into surface, or exponential profile)

FURTHER CONVOLVING WITH DETECTOR RESPONSE

Detector Response

- Timing resolution:

  Sum energy depositions occurring in same crystal in time window of $\pm 5\,\mathrm{ms}$
- Energy resolution:

  $\mathrm{FWHM}(E) = a + b \cdot E(\mathrm{keV})$
- Define coincidences:

  Events between multiple bolometers within $\pm 5\,\mathrm{ms}$ window

Accidental Coincidences

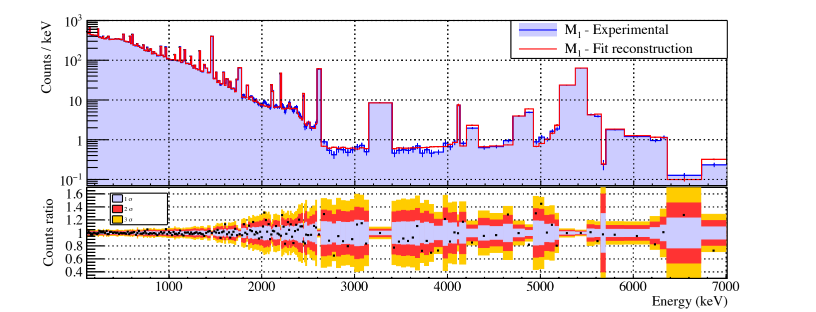
- In real data, particles from different decay chains can hit multiple detectors simultaneously in time (e.g. during calibration using high activity sources)

  $\implies$ Decay rate of progenitor nucleus of decay chain can be set retroactively

Particle Quenching

- E.g. αs exhibit negative quenching factor ($\sim 1\,\%$) that can be modeled

M_1 Spectrum JAGS Reconstruction (Simulation vs Data)



- Fit residuals have a Gaussian-like distribution compatible with mean = 0 and standard deviation = 1σ
- Reconstruction of similar quality also obtained with M_2, Σ_2 spectra

*arXiv:1610.04518v1 [nucl-ex]

CUORE-0 BULK CONTAMINATION MODEL

Bulk Contamination of TeO_2 and Cu Frame (90 % C.L.)*

Material	Source	Activity (Bq/kg)
TeO_2	^{210}Po	$(2.39 \pm 0.11) \times 10^{-6}$
	^{210}Pb	$(1.37 \pm 0.19) \times 10^{-6}$
	^{230}Th only	$(2.8 \pm 0.3) \times 10^{-7}$
	^{232}Th only	$(7 \pm 3) \times 10^{-8}$
	^{228}Ra to ^{208}Pb	$< 3.5 \times 10^{-8}$
	^{238}U to ^{230}Th	$< 7.5 \times 10^{-9}$
	^{226}Ra to ^{210}Pb	$< 7 \times 10^{-9}$
Cu frame†	^{238}U	$< 1.2 \times 10^{-5}$
	^{232}Th	$< 2.1 \times 10^{-6}$

*Alduino, C., Alfonso, K., Artusa, D.R. et al. Eur. Phys. J. C (2017) 77: 543

†Cu frame includes all other small detector parts that have degenerate spectral contribution

CUORE-0 SURFACE CONTAMINATION MODEL

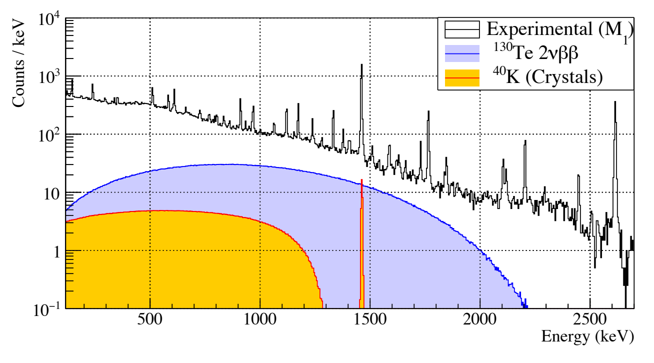
Surface Contamination of TeO_2 and Cu Frame (90 % C.L.)*

Material	Contamination	Depth (μm)	Activity (Bq/cm^2)
TeO_2	^{210}Pb	0.001	$(6.02 \pm 0.08) \times 10^{-8}$
	^{210}Pb	1	$(8.6 \pm 0.8) \times 10^{-9}$
	^{226}Ra to ^{210}Pb	0.01	$(3.14 \pm 0.10) \times 10^{-9}$
	^{228}Ra to ^{208}Pb	0.01	$(2.32 \pm 0.12) \times 10^{-9}$
	^{238}U to ^{230}Th	0.01	$(2.07 \pm 0.11) \times 10^{-9}$
	^{230}Th only	0.01	$(1.15 \pm 0.14) \times 10^{-9}$
	^{210}Pb	10	$< 2.7 \times 10^{-9}$
	^{232}Th	10	$(7.8 \pm 1.4) \times 10^{-10}$
	^{232}Th only	0.01	$(3 \pm 1) \times 10^{-10}$
	^{238}U	10	$< 3.3 \times 10^{-11}$
Cu frame†	^{210}Pb	0.1	$(4.3 \pm 0.5) \times 10^{-8}$
	^{210}Pb	0.01	$(2.9 \pm 0.4) \times 10^{-8}$
	^{238}U	10	$(1.38 \pm 0.16) \times 10^{-8}$
	^{210}Pb	10	$< 1.9 \times 10^{-8}$
	^{232}Th	10	$(5.0 \pm 1.7) \times 10^{-9}$

*Alduino, C., Alfonso, K., Artusa, D.R. et al. Eur. Phys. J. C (2017) 77: 543

†Cu frame includes all other small detector parts that have degenerate spectral contribution

Fitted Contribution of $2\nu\beta\beta$ and ^{40}K Background in Crystals (Simulation) to M_1 Spectrum (Data)



- $2\nu\beta\beta$ decay of ^{130}Te produce ∼10 % of events in γ region [118, 2700]keV
- $\Gamma_{2\nu} = (3.43 \pm 0.09) \times 10^5$ Bq/kg
  $\implies T_{1/2}^{2\nu} = [8.2 \pm 0.2\,(\text{stat.}) \pm 0.6\,(\text{syst.})] \times 10^{20}$ yr

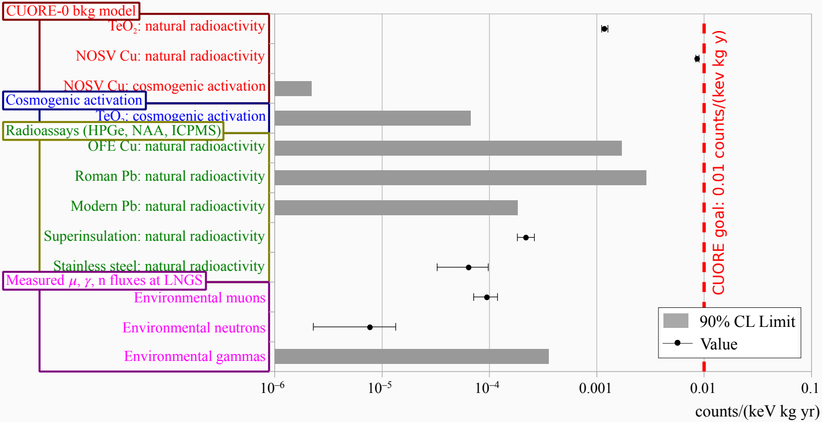
*arXiv:1610.04518v1 [nucl-ex]

CUORE-0 BACKGROUND FIT PROCESS

- Energy spectra for 57 contamination sources and distribution profiles created
- The activities of the sources are fitted to the experimental M_1, M_2, and Σ_2 spectra through a linear combination of the simulated spectra
- Fits are done using a Bayesian approach using JAGS* exploiting Markov Chain Monte Carlo simulations to sample the joint posterior PDF of source activities
- Priors:
  - Gaussian (or half-Gaussian) priors used when activity of source (or upper limits) known
  - Otherwise, uniform non-informative priors from 0 to upper limits compatible with data
- Fit allows for disentangling of contamination sources and study of secular equilibrium violations in radioactive decay chains

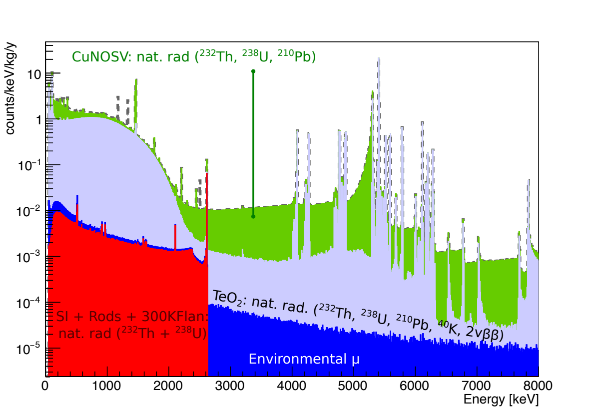
*Just Another Gibbs Sampler (JAGS), `http://mcmc-jags.sourceforge.net/`

CUORE BACKGROUND EXPECTATION*



*The projected background for the CUORE experiment, Eur. Phys. J. C (2017) 77:543

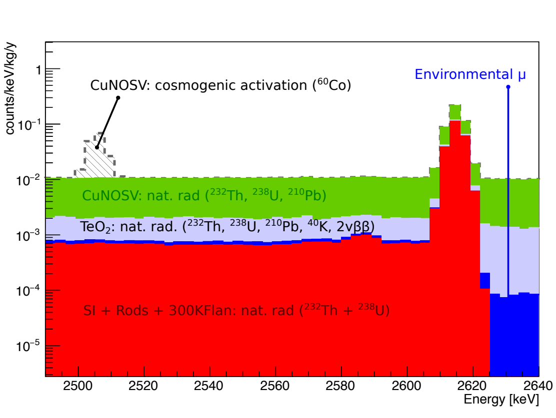
Full Spectrum $[0, 8000]$keV



- Anti-coincidence spectrum recorded by the 988 bolometer array
- ^{60}Co contamination in CuNOSV set at 90 % C.L. upper limit
- Additional sources set at values from CUORE-0 ($2\nu\beta\beta$, ^{40}K)

*The projected background for the CUORE experiment, Eur. Phys. J. C (2017) 77:543

Region of Interest [2490, 2640]keV



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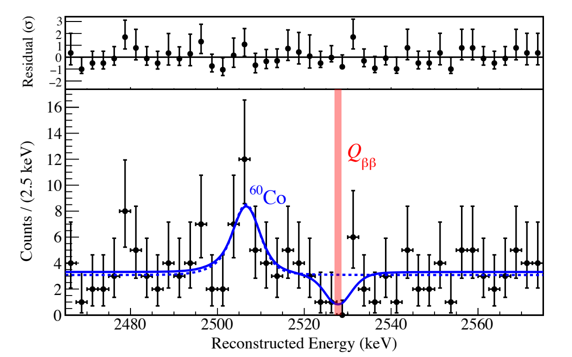
*The projected background for the CUORE experiment, Eur. Phys. J. C (2017) 77:543

$0\nu\beta\beta$ Peak Fit in ROI [2465, 2575]keV around ^{130}Te $Q_{\beta\beta} = 2528$ keV



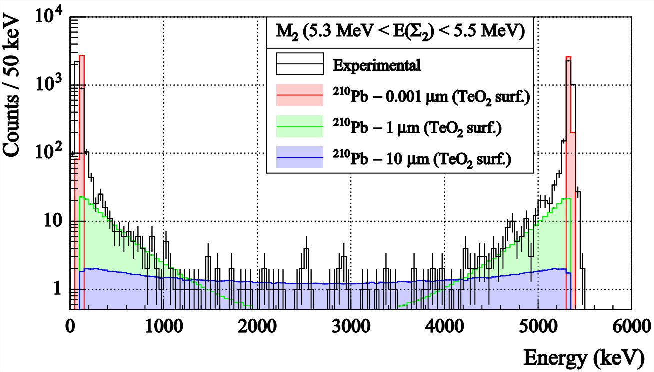
Best fit from unbinned extended maximum likelihood fit:

- Flat background in ROI $= (0.014 \pm 0.002)$ counts/(keV · kg · yr)
- Peak at $Q_{\beta\beta} = 2528$ keV fitted with variable rate
- Best fit decay rate (90 % C.L.): $\Gamma_{0\nu} < 0.52 \times 10^{-25}\,\text{yr}^{-1} \implies T^{0\nu}_{1/2} > 1.3 \times 10^{25}\,\text{yr}$

*First Results from CUORE: A Search for Lepton Number Violation via $0\nu\beta\beta$ Decay of ^{130}Te, CUORE Collaboration,Phys.Rev.Lett. 120 (2018) no.13, 132501

α BACKGROUND MODELING

CUORE-0 ^{210}Po α decay*



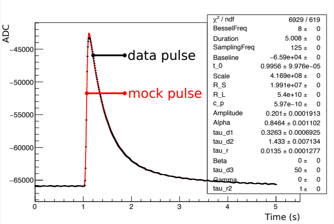
- Comparison between the experimental and the Monte Carlo M_2 spectra with Σ_2 energy equal to the Q value of ^{210}Po α decay.
- MC spectra with different TeO_2 surface contamination average depths 0.001, 1, 10 µm can be combined to fit shape of data

*Measurement of the two-neutrino double-beta decay half-life of ^{130}Te with the CUORE-0 experiment, Eur. Phys. J. C (2017) 77:13

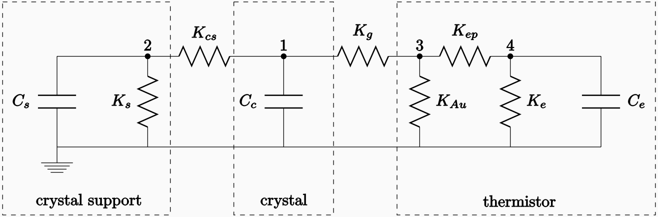
SIGNAL PULSE MODEL

- Rise time $\sim 0.05\,\mathrm{s}$
- 2 decay times: $\tau_1 \sim 0.2\,\mathrm{s}, \tau_2 \sim 1.5\,\mathrm{s}$
- Mock signal pulses can be reverse engineered from data based on thermal model circuit of bolometers
- Can be useful to test/optimize analysis steps or for pulse shape analysis by using “realistic” data

Real/Simulated Bolometer Pulse



Thermal model circuit*



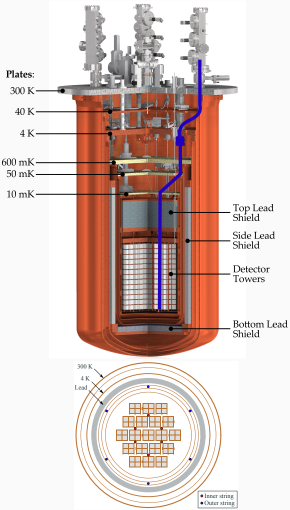
*M. Carrettoni and M. Vignati, 2011 JINST 6 P08007

SUMMARY

- Detector simulations and background modeling were successfully demonstrated in pilot experiment CUORE-0
- Framework was updated to model backgrounds in CUORE and first analysis results further confirm accuracy of software
- Additional R&D efforts are underway to better understand backgrounds and improve our understanding of the detector

Backup Slides

DETECTOR CALIBRATION (IN-SITU)*



- Sources are put on 12 Kevlar strings and lowered under their own weight; a series of tubes in the cryostat guide the strings
- ^{232}Th γ sources (thoriated tungsten) are outside cryostat during physics data-taking and lowered into cryostat and cooled to base temperature for calibration
- Heat from sources is removed with:
  - A pair of copper blocks that mechanically squeezes on the sources at 4 K
  - Contact between the sources and their guide tubes, which are thermalized to different cryostat stages
- Temperature stabilization of the Mixing Chamber is able to compensate for the power dissipated during the deployment
- 6 inner strings: $\sim$4 Bq
- 6 outer strings: $\sim$20 Bq

*NIM A 844, 32-44 (2017). arXiv:1608.01607

CUORE BACKGROUNDS IN REGION OF INTEREST (ROI) (BACKUP)

Most Common Background Sources

- Long-lived radioactive nuclei: ^{40}K, ^{238}U, ^{232}Th
- Anthropogenic radioactive isotopes: ^{60}Co, ^{137}Cs, ^{134}Cs
- Cosmogenically-produced radioactive isotopes by n activation in Cu/Te

$$^{60}\mathrm{Co} \xrightarrow[\tau_{1/2}\,=\,5.27\,\mathrm{yr}]{Q\,=\,2.82\,\mathrm{MeV}} {}^{60}\mathrm{Ni} + \mathrm{e}^{-} + \gamma\mathrm{s}$$

$$^{110m}\mathrm{Ag} \xrightarrow[\tau_{1/2}\,=\,250\,\mathrm{days}]{Q\,=\,3.01\,\mathrm{MeV}} {}^{110}\mathrm{Cd} + \mathrm{e}^{-} + \gamma\mathrm{s}$$

- Environmental n, μ, γ

Main Background Contributors to ROI

- multi-Compton events from 2615 keV γ from ^{208}Tl (from ^{238}U chain)*
- ^{238}U, ^{232}Th and decay products on surface of TeO_2 crystals
- ^{238}U, ^{232}Th and decay products on surface of materials close to TeO_2 crystals

Modeling backgrounds is important part of CUORE!

*This is the only environmental γ line with B.R. $> 1\,\%$ with energy $> Q_{\beta\beta}$

PARTICLE PROPAGATION (BACKUP)

- Program interface uses the standard UNIX command line options convention (e.g. `<executable> -<option> [argument]`) instead of using messenger classes derived from `G4UIMesseger` with macro files

  $\Longrightarrow$ Easy storage of simulation settings in output data files for future reference

- Variable physict list that defaults to Livermore for accurate low energy (0—10 TeV) physics relevant in underground applications
- Variable material dependent tracking cuts used to balance simulation detail and speed, e.g.
  - 1 mm in TeO_2/Cu close to bolometers
  - 1 cm for high Z Pb and outer shields
- Particle sources:
  - Single particles: $\mathrm{e}^{\mp}$, $\mu^{\mp}$, γ, α, n
  - Arbitrary sub-chains of decaying isotopes

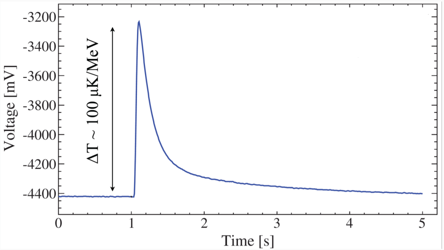
    $\Longrightarrow$ Useful for studying breaks in secular equilibrium within one chain

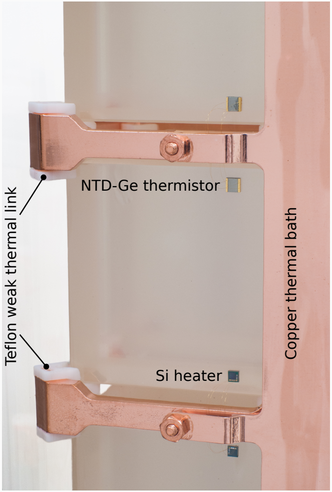
  - $\beta\beta$ decays with/without νs from the ground or excited states of ^{130}Te
  - Thermal neutrons
  - Cosmic ray μ with zenith angle dependent flux
- Source positions:
  - Geometrically shaped distributions
  - Bulk of detector parts
  - Surface of detector parts (uniform distribution up to some depth into surface, or exponential profile)

DETECTOR PRINCIPLE (BACKUP)

Ultra-cold TeO_2 crystals function as very sensitive bolometer

- Energy response calibrated using known γ source
- Slow ($\sim 1\,s$) pulses suitable for rare event searches





OUTPUT SAVED FROM PARTICLE PROPAGATION (BACKUP)

Save important simulation output in 2 Trees

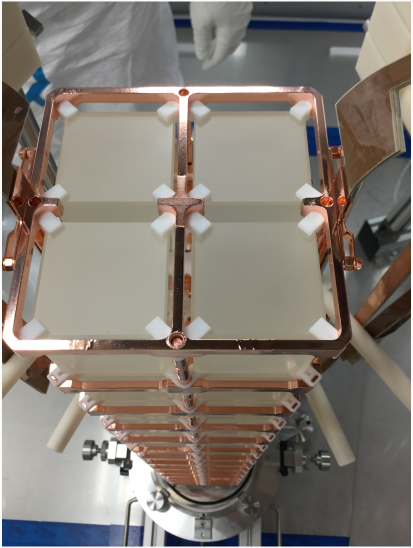
Tree 1

- Command line used to run simulation (with all options)
- Number of simulated events
- Number of simulated decay chains

Tree 2

- Channel number of TeO_2 bolometer
- Decay chain number
- Time of energy deposition
- Deposited energy (total)
- Deposited energy by particle (γ, $e^{\pm}$, $\overset{(-)}{p}$, $\overset{(-)}{n}$, α, ion, $\mu^{\mp}$)
- Energy deposited in surrounding copper material
- Parent ion of event
- Initial energy of parent ion
- Topological information of parent ion
    - x-position
    - y-position
    - z-position
    - x-direction
    - y-direction

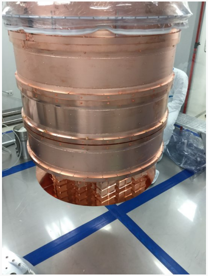
BACKGROUND FROM SOURCES NEAR TeO_2 DETECTORS (BACKUP)



- Both bulk and surface contaminations are significant and unique backgrounds from near sources
  - $\because$ Closest to TeO_2 detectors, so radiation is not hindered
  - ^{40}K contamination significantly affects energy region of $2\nu\beta\beta$ spectrum
- Measured in CUORE-0
  - Single CUORE-like tower in Cuoricino cryostat
  - Saw reductions in α backgrounds due to improvements in construction process compared to predecessors

BACKGROUND FROM SOURCES FAR FROM TeO_2 DETECTORS (BACKUP)

10 mK Shield



Roman Pb Shield

4 K Insulation Foil

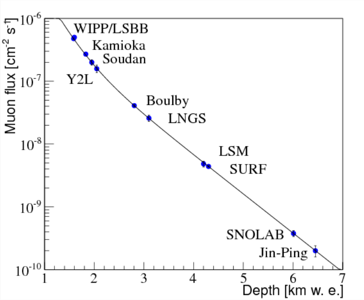
300 K Shield

- Background contribution from bulk/surface contaminations degenerate
- Contaminations in shields act as background sources
- 4.5 t Roman lead
- 2.1 t modern lead
- Largest contributor: Roman Pb extracted from ancient shipwreck
    - $T_{1/2} = 22.3\,\mathrm{yr}$

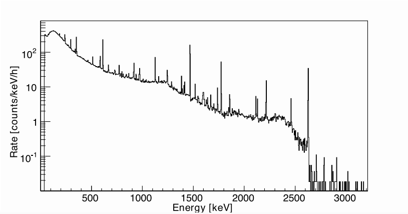
BACKGROUND FROM EXTERNAL SOURCES (BACKUP)

- Cosmic ray muons
  - Overburden 3600 m.w.e.
  - Flux $\sim 3 \times 10^{-8}$ /s/cm^2
  - Average Energy $\approx$ 270 GeV
- Natural rock radioactivity
  - Gamma: ~ 0.73 /s/cm^2, energy $\lesssim$ 3 MeV
  - Neutron: $\sim 4 \times 10^{-6}/(\mathrm{s} \cdot \mathrm{cm}^2)$, energy $\lesssim$ 10 MeV

Underground Lab Depths



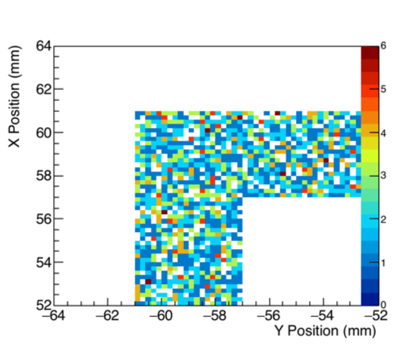
γ Spectrum in CUORE Hall*



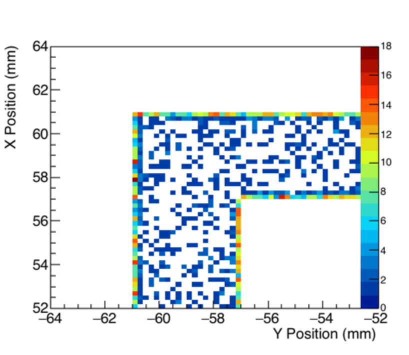
*Bellini, F., et al. Monte Carlo evaluation of the external gamma, neutron and muon induced background sources in the CUORE experiment. Astroparticle Physics 33.3 (2010): 169-174.

CONTAMINATION PROFILE (BACKUP)

Bulk Contamination*



Surface Contamination†



- Bulk contamination is assumed to be spatially uniform

- Surface contamination is modeled with exponential density profile
- $\rho = \rho_0 \times \exp\left(-x/\lambda\right)$, where

  x = penetration depth into surface
  ρ_0 = impurity density
  λ = mean depth, 0.001—30 µm

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*K. Alfonso
†K. Alfonso

SIMULATED BULK CONTAMINATION PARTS

TeO2-pt190
TeO2-ra226-pb210
TeO2-ra228-pb208
TeO2-sb125
TeO2-2nu
TeO2-2nu
TeO2-ag110m
TeO2-co60
TeO2-th230only
TeO2-k40
TeO2-th232only
TeO2-pb210
TeO2-u238-th230
TeO2-po210
NTD-th232
NTD-u238

CuNOSV-u238
CuNOSV-co60
CuNOSV-th232
CuNOSV-k40
CuNOSV-mn54
PTFE-th232
PTFE-u238
PbRCu-th232
PbRCu-u238
PbR-ag108m
PbR-bi210
PbR-th232
PbR-u238
CuUpStdPbPlug-th232
CuUpStdPbPlug-u238
TopPb5cm_210Bi
ExtPb5cm_210Bi
StdPbPlug-th232
StdPbPlug-u238
SI-2615
SI-2615
SI-tl208

mu-R5m
SteelRods-th232
300K-2615
300KFlan-2615
40K-2615
4K-th232
4KTot-co60
600mK-bi210
600mK-co60
600mKFlan-th232
600mKFlan-u238
600mK-th232
600mK-u238
50mK-th232
50mK-u238

SIMULATED SURFACE CONTAMINATION PARTS

TeO2Sx-pb210-.001
TeO2Sx-pb210-10
TeO2Sx-pb210-1
TeO2Sx-ra226-pb210-.01
TeO2Sx-ra228-pb208-.01
TeO2Sx-th230only-.01
TeO2Sx-th232-10
TeO2Sx-th232only-.01
TeO2Sx-u238-10
TeO2Sx-u238-th230-.01
PTFESx-pb210-5
PTFESx-th232-5
PTFESx-u238-5
CuNOSVSx-pb210-.01
CuNOSVSx-pb210-10
CuNOSVSx-pb210-.1
CuNOSVSx-th232-.01
CuNOSVSx-th232-10
CuNOSVSx-u238-.01
CuNOSVSx-u238-10
CuNOSVTowerSx-pb210-1
CuNOSVTowerSx-th232-.01
CuNOSVTowerSx-th232-10
CuNOSVTowerSx-u238-.01
CuNOSVTowerSx-u238-10
CuNOSVTowerSx-pb210-.01
CuNOSVTowerSx-pb210-10
CuNOSVTowerSx-pb210-.1
CuNOSVOthersSx-u238-10
CuNOSVOthersSx-u238-.01
CuNOSVOthersSx-th232-10
CuNOSVOthersSx-th232-.01
CuNOSVOthersSx-pb210-1
CuNOSVOthersSx-pb210-.1
CuNOSVOthersSx-pb210-10
CuNOSVOthersSx-pb210-.01
600mKSx-pb210-.01