Search for Two-Neutrino Double-Beta Decay of ^{130}Te to Excited States of ^{130}Xe with CUORE

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CUORE collaboration

23 April 2021

Berkeley
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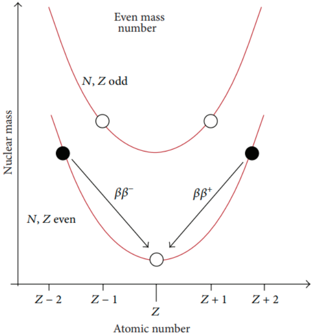
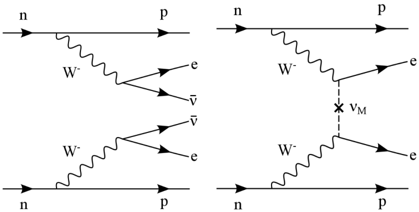
Double Beta Decay



Rare radioactive decay, found in even-even nuclei where single-beta decay is energetically forbidden (e.g. ^{130}Te)

- Two-neutrino ($2\nu\beta\beta$) $\Rightarrow$ Observed, $T_{1/2} > 10^{18}$ years
  $(A, Z) \rightarrow (A, Z+2) + 2e^- + 2\bar{\nu}_e$
- Neutrinoless ($0\nu\beta\beta$) $\Rightarrow$ Expected $T_{1/2} > 10^{25}$ years
  $(A, Z) \rightarrow (A, Z+2) + 2e^-$

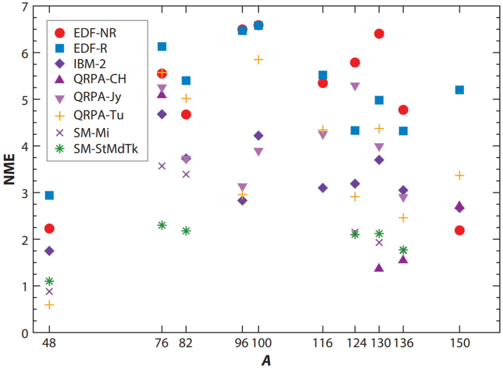


Observation of $0\nu\beta\beta$ is a critical tool to study neutrinos:

- Majorana ($\nu = \bar{\nu}$) or Dirac ($\nu \neq \bar{\nu}$) nature
- Lepton number violation ($\Delta L = 2$)
- ν mass scale and ordering

Measuring neutrino mass with $0\nu\beta\beta$

Nuclear matrix elements (M) are a major source of uncertainty



Ann. Rev. Nucl and Part.Sci. 69 (2019)

$$\Gamma_{0\nu} = (T^{0\nu}_{1/2})^{-1} = G_{0\nu}\ |M_{0\nu}|^2\ \langle m_{\beta\beta}\rangle^2$$
$$\langle m_{\beta\beta}\rangle = |U^2_{ei} m^2_i|$$

KamLAND-Zen:
$T_{1/2}\ >\ 1.07 \times 10^{26}$ yr
$m_{\beta\beta} <$ 61 - 165 meV
Physical Review Letters. 117 (8): 082503

Measurements of $2\nu\beta\beta$ and $0/2\nu\beta\beta$ to excited states contribute to understanding of NME, which in turn contributes to neutrino mass measurements.

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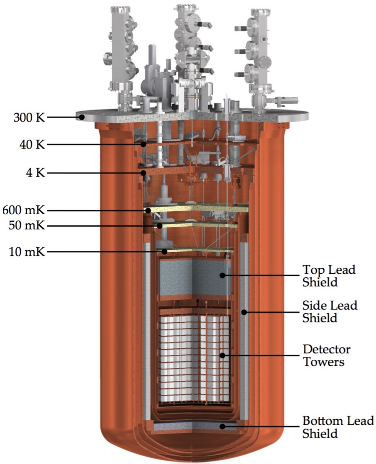
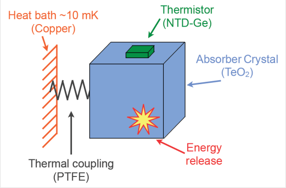
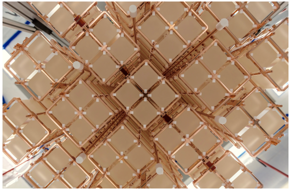
Cryogenic Underground Observatory for Rare Events (CUORE)





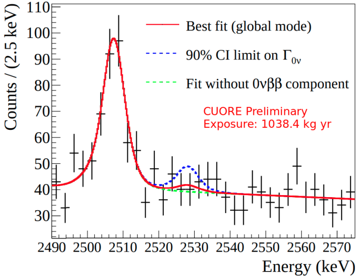


$$^{130}\text{Te} \rightarrow \; ^{130}\text{Xe} + 2\text{e}^-$$

- 988 TeO_2 bolometers (206 kg ^{130}Te) instrumented with NTD thermistors
- Detector array cooled to operating temperature of ~10mK.
- Stringent radiopurity control on materials and assembly
- Target $\Delta E = 5$ keV at Q-value
- Target $b = 10^{-2}$ ct/keV/kg/yr

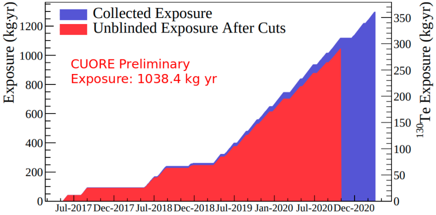
Expected sensitivity to $T_{1/2}$ of $0\nu\beta\beta$ in ^{130}Te (5 yr livetime):
9.5×10^{25} yr (90% CL)
($m_{\beta\beta} \leq$ (50-130) meV)

The Latest from CUORE NEW RESULTS ::: arXiv: 2104.06906



$T_{1/2} > 2.2 \times 10^{25}$ yr (90 %CI)
$m_{\beta\beta} \leq$ (90-305) meV
1038.4 kg yr exposure

$\Delta E < 8.0$ keV FWHM at Q-value (2527.5 keV)
$b = 1.49(4) \cdot 10^{-2}$ ct/keV/kg/yr

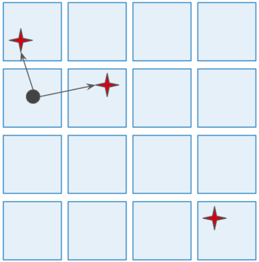


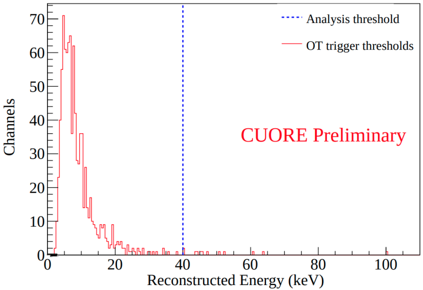
- Newest analysis includes pulse shape discrimination method based on principle component analysis (PCA) where the average pulse is treated like a leading principal component. $\Rightarrow$ increase in efficiency and similar background rejection power across all energies compared to the previous method.
- Bayesian Analysis using BAT (MCMC)
- Systematics: repeat fits with nuisance parameters, allow negative rates (<0.8% impact on limit).

A note on CUORE events:

Multiplicity (M):
The number of crystals engaged in a single event.

- This depends in part on:
  - energy threshold (40 keV*),
  - a distance cut (150 mm, 3 crystals wide), and
  - timing resolution (events within $\pm$ 5 ms)
- Most $0\nu\beta\beta$ events are M=1, and M$\leq$2 are the main priorities for $0\nu\beta\beta$ search analyses.



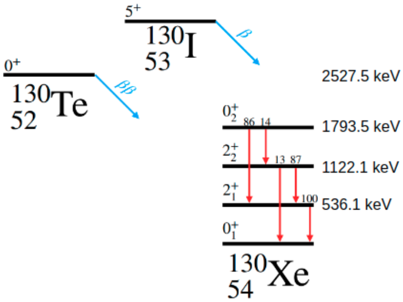


* This is an analysis threshold, set manually. The bolometric threshold depends on the channel, and 97% of channels have thresholds beneath this value.

^{130}Te Double Beta Decay to Excited States ::: Status

new article! — Adams et.al. *Search for Double-Beta Decay of ^{130}Te to the 0^+ States of ^{130}Xe with CUORE* (2021) — submitted to EPJ C ::: arXiv:2101.10702

Pattern	**BR [%]**	**Energy γ_1**	**Energy γ_2**	**Energy γ_3**
A	86%	1257 keV	536 keV	-
B	12%	671 keV	586 keV	536 keV
C	2%	1122 keV	671 keV	-



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The published analysis requires full containment of final state gammas in the crystals.

Published analysis avoids events where

- gamma energy lost in non-active detector material
- scattered gammas appear in more than one crystal.

These events will have the cleanest signature, and allow for peak fitting at the appropriate gamma emission energies. For example, in this paper we define signature “3A0” as

$$E_1 \sim 1257 \text{ keV} \qquad E_2 \sim 536 \text{ keV} \qquad E_3 = \beta\beta$$

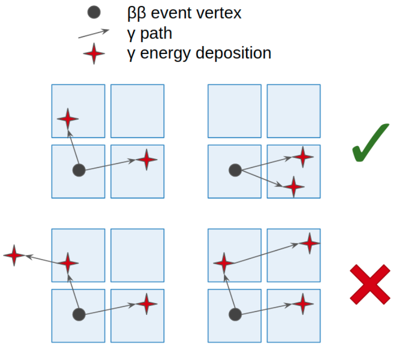

image adapted from G. Fantini

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2A0 - 2B1	**1270**	1257		
2A1-2B2-2C1	1794	**734**		
2A2-2B3	**1991**	536		
3A0	1257	**734**	536	
2B0 - 2C0	**1856**	671		
2B4	**1320**	1207		
2B5	**1941**	586		
2B6 - 2C0	**1405**	1122		
3B0	**1270**	671	586	
3B1-3C0	1122	**734**	671	
3B2	1257	**734**	536	
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3B5	**1405**	586	536	
4B0	**734**	671	586	536

G. Fantini et al. *Sensitivity to double beta decay of ^{130}Te to the first 0+ excited state of ^{130}Xe in CUORE.* J. of Phys.: Conference Series, 1468, 02 2020.

Assigning patterns to energy deposits that contribute to the overall sensitivity of this search leads to **15 distinguishable signatures** across the three patterns.

Some signatures are combined as they are indistinguishable:

2A0

$$E_1 = 536 + \beta\beta(734) \text{ keV}$$
$$E_2 = 1257 \text{ keV}$$

2B1

$$E_1 = 536 + \beta\beta(734) \text{ keV}$$
$$E_2 = 671 + 586 \text{ keV}$$

(Left) Distinguishable signatures of $0\nu\beta\beta$ to excited states. ($2\nu\beta\beta$ signatures differ by how the $\beta\beta$ event is identified: a peak, not a spectrum)

^{130}Te Double Beta Decay to Excited States ::: Status

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Monte Carlo simulations were used to identify the strongest contributions to sensitivity.

Signal simulations

- Produced separately for each pattern
- Gammas monochromatic, w/ no angular correlations*
- Beta energies extracted from appropriate spectrum (not sensitive to $2\nu\beta\beta$ spectral shape).

Background simulations

- CUORE background model
- Cosmic muon flux
- $2\nu\beta\beta$ of ^{130}Te to ground state

5 keV FWHM resolution.

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$$\epsilon = \epsilon_s \times (\epsilon_{cut})^M \times \epsilon_{acc}$$

Containment efficiency, ϵ_s
Probability that energy released by the decay matches the topology of the signature.

$$\epsilon_s = \sum_p BR_p \cdot \frac{[N^{(sel)}]_p^{(s)}}{[N^{(tot)}]_p}$$

Analysis efficiency, ϵ_{cut}
(per dataset) Includes trigger, reconstruction, pile-up and PSA cut efficiencies.

Accidentals efficiency, ϵ_{acc}
(per dataset) Efficiency of properly identifying events while avoiding accidental coincideneces.

Green signatures were identified to have the highest overall efficiencies after accounting for background in their respective ROI.

^{130}Te Double Beta Decay to Excited States ::: Status

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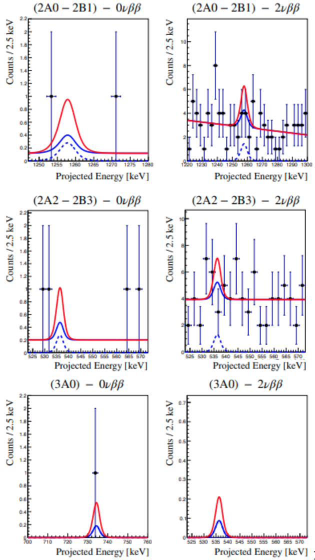
$0\nu\beta\beta$

	2A0-2B1	2A1-2B2	3A0
Containment	4.6(2)	2.9(1)	2.5(1)
Cut	78.7(2)		69.8(3)
Accidentals	98.7(1)		
Total	3.5(2)	2.3(1)	1.7(1)

$2\nu\beta\beta$

	2A0-2B1	2A1-2B2	3A0
Containment	4.2(2)	2.4(1)	0.19(1)
Cut	78.7(2)		69.8(3)
Accidentals	98.7(1)		
Total	3.2(1)	1.9(1)	0.13(1)



- Dominated strongly by containment efficiency ⋆
- Unbinned Bayesian fit with MCMC using BAT
- This analysis fits specifically the event peak which has the highest sensitivity over background (for 2A0, for example, the 1257 keV peak).
- Systematic uncertainty evaluated to have a <0.4% effect, dominated by uncertainty in modeling the detector response function.

^{130}Te Double Beta Decay to Excited States ::: Status

arXiv:2101.10702

new article! — Adams et.al. *Search for Double-Beta Decay of ^{130}Te to the 0^+ States of ^{130}Xe with CUORE* (2021) — submitted to EPJ C ::: arXiv:2101.10702

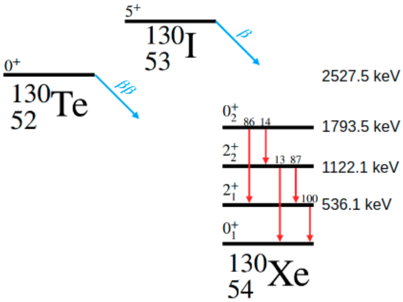
Bayesian lower bound at 90% C.I. on the decay half-lives:

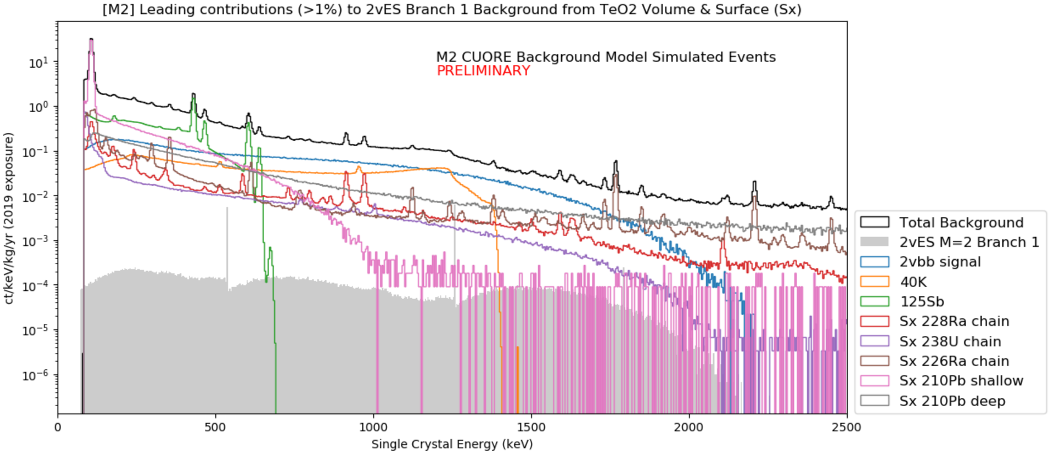
$0\nu\beta\beta$ to 0_2^+ $\quad (T_{1/2})^{0\nu}_{0_2^+} > 5.9 \times 10^{24}$ year

$2\nu\beta\beta$ to 0_2^+ $\quad (T_{1/2})^{2\nu}_{0_2^+} > 1.3 \times 10^{24}$ year

372.5 kg·yr TeO_2 exposure

(5x improvement over previous best limit, set by a combination of Cuoricino and CUORE-0)

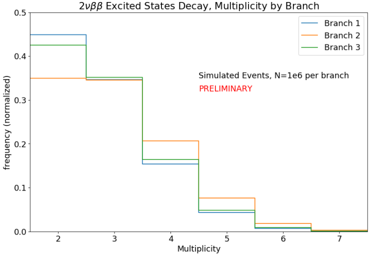


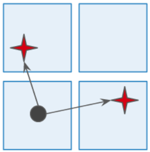


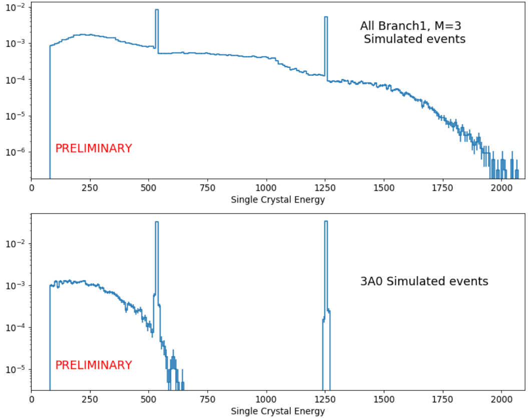
$2\nu\beta\beta$ excited states spectra adjusted to EPJC preprint lower bound.

We must look for ways in which $2\nu\beta\beta$ excited states signals will manifest that will be identifiable beyond looking at peaks...

^{130}Te $2\nu\beta\beta$ to Excited States ::: Status







Looking specifically at $2\nu\beta\beta$ decay to excited states, we see that they have a large M>2 component. The only M>2 pattern in the published analysis is **3A0**, defined to be

$$E_1 \sim 1257 \text{ keV} \qquad E_2 \sim 536 \text{ keV} \qquad E_3 = 0 - 734 keV$$

This is clearly missing a large portion of the data, even just in M=3... so what is happening?

Expanding the Search by Exploiting Detector Geometry & Response

We must relax the requirement for full containment & clean gamma depositions.

The events where gammas scatter between or out of crystals are particularly interesting and compose a non-negligible fraction of the total. We can look at these scattered events specifically by

- performing a spectral search
- seeking out events whose partial sums equal the gamma energies

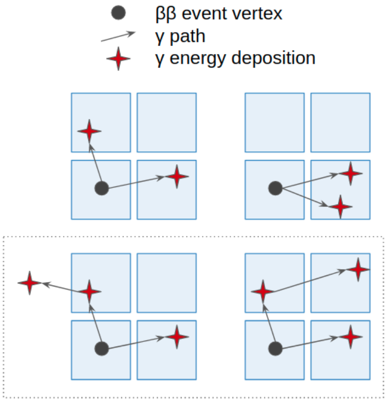
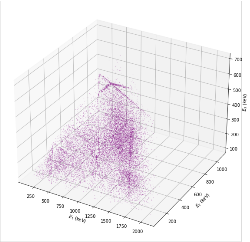


image adapted from G. Fantini

^{130}Te $2\nu\beta\beta$ to Excited States ::: Search in a wider Energy Space

tag	1257 keV	536 keV	Spectral	Population
M3-01-00	E_1	E_2	E_3	0.10
M3-01-11	$E_1 + E_2$	E_3		0.01
M3-01-12	E_1	$E_2 + E_3$		0.01
M3-02-00	E_1		E_2, E_3	0.11
M3-02-11	$E_1 + E_2$		E_3	0.17
M3-02-21	$E_1 + E_2 + E_3$			0.01
M3-03-00		E_1	E_2, E_3	0.16
M3-03-12		$E_1 + E_2$	E_3	0.08
M3-03-22		$E_1 + E_2 + E_3$		0.00
No peak			E_1, E_2, E_3	0.35

Population fraction as a function of tag in 100k simulated $2\nu\beta\beta$ Branch 1 events, ideal resolution; no analysis cuts.



Simulated M3 $2\nu\beta\beta$ Branch 1 events. Single channel energies on each axis. (PRELIMINARY)

Create a sorting ("tagging") system for identifying gamma + spectral events, including the case where two or more crystals sum to a single gamma energy.

This technique *significantly* improves access to the energy space.

^{130}Te $2\nu\beta\beta$ to Excited States ::: Search in a wider Energy Space

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M3-01-12	E_1	$E_2 + E_3$		0.01
M3-02-00	E_1		E_2, E_3	0.11
M3-02-11	$E_1 + E_2$		E_3	0.17
M3-02-21	$E_1 + E_2 + E_3$			0.01
M3-03-00		E_1	E_2, E_3	0.16
M3-03-12		$E_1 + E_2$	E_3	0.08
M3-03-22		$E_1 + E_2 + E_3$		0.00
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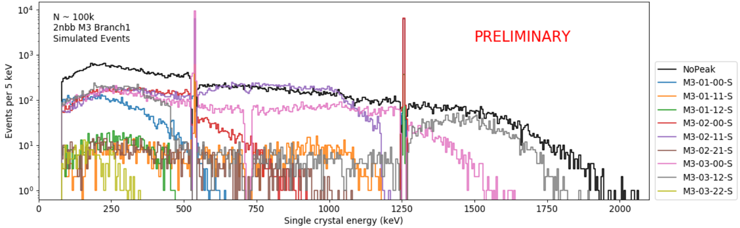

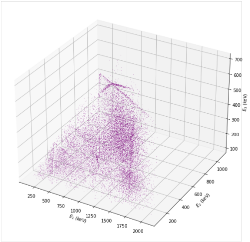

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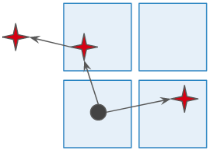
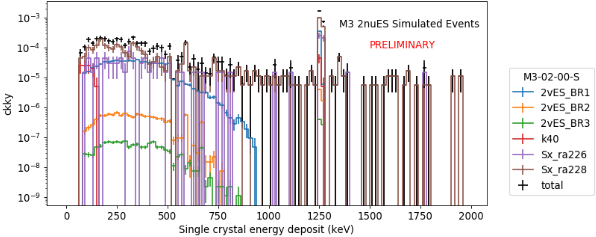
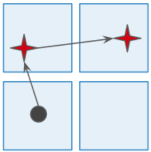
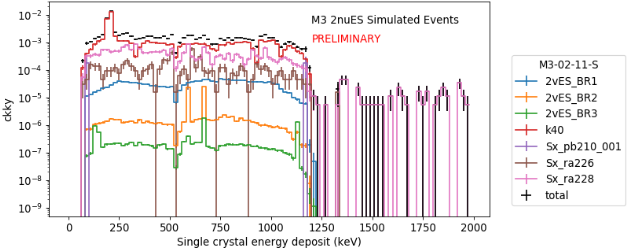
^{130}Te $2\nu\beta\beta$ to Excited States ::: Search in Energy Space

Theoretically, identifying signal signatures can decrease background in the signature regions of interest.

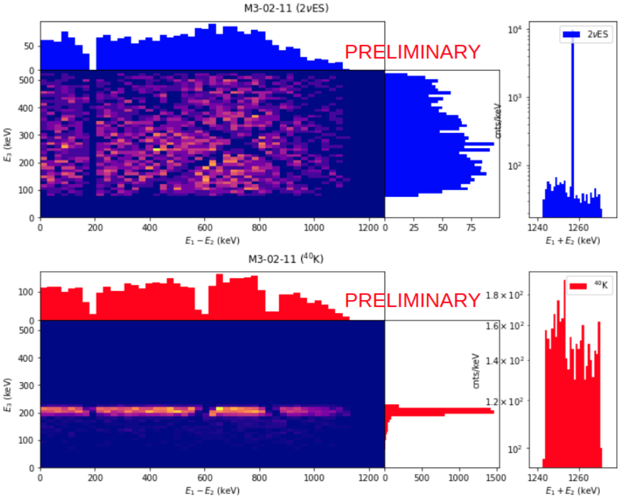








^{130}Te $2\nu\beta\beta$ to Excited States ::: Search in Energy Space



* simulated events

Example: **M3-02-11**:

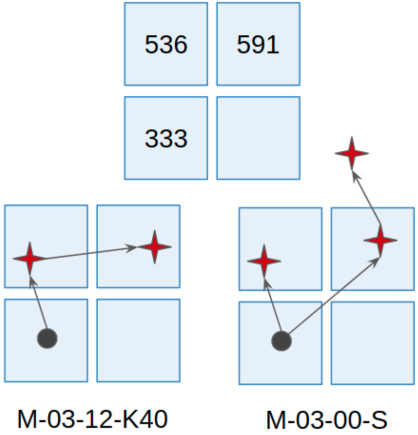
- $E_1 + E_2 = 1257$ keV
- E_3 = spectral

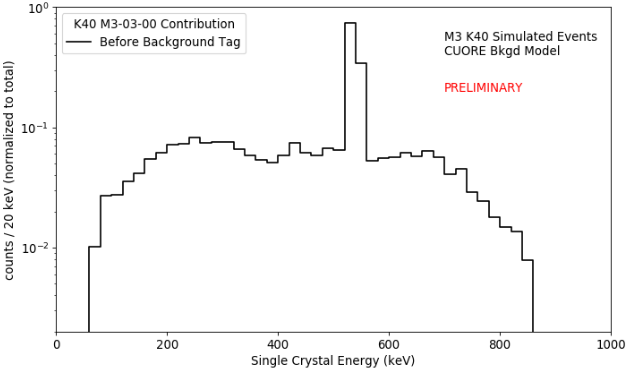
Spectral channel could be the $\beta\beta$ signal, a scattered 536 keV gamma, or a combination of the two.

Background (e.g. ^{40}K, ^{210}Pb) sorted through the same tagging system produces significantly different spectra, which can be fed into a global fit. Such backgrounds may also have accompanying tags (single & summed gammas) which can lower their contamination into signal spectra.

^{130}Te $2\nu\beta\beta$ to Excited States ::: Search in Energy Space

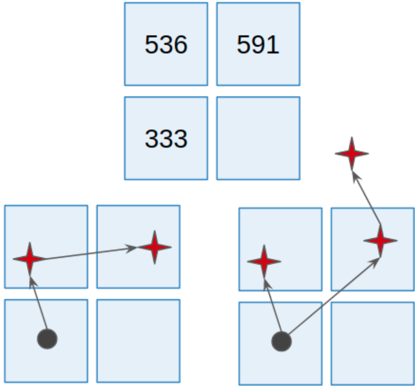
We can remove some background events by tagging their summed energy as well. ^{40}K has a characteristic 1460 keV gamma line, which can be split between crystals, resulting in energies that may appear like signal tags. $\Rightarrow$ If, instead, we create a tag to look for events that prioritize a 1460 keV summation, that can remove events that could contaminate signal spectra.

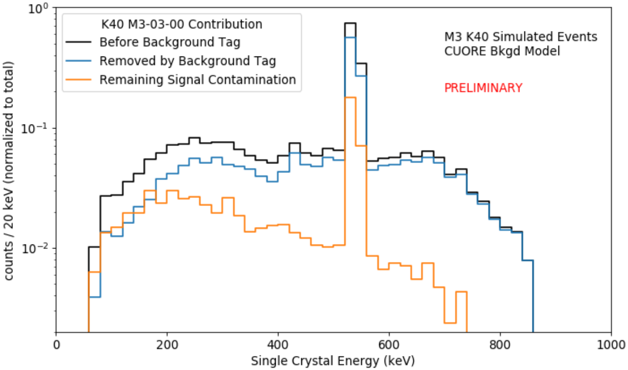




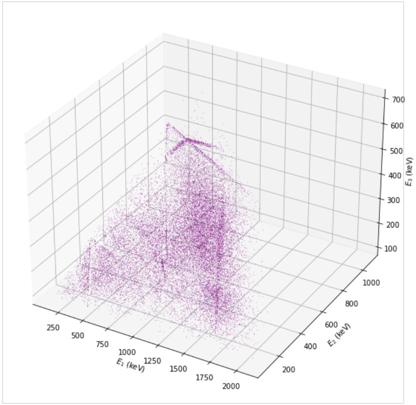
^{130}Te $2\nu\beta\beta$ to Excited States ::: Search in Energy Space

We can remove some background events by tagging their summed energy as well.
^{40}K has a characteristic 1460 keV gamma line, which can be split between crystals, resulting in energies that may appear like signal tags. $\Rightarrow$ If, instead, we create a tag to look for events that prioritize a 1460 keV summation, that can remove events that could contaminate signal spectra.





^{130}Te $2\nu\beta\beta$ to Excited States ::: Search in Energy Space



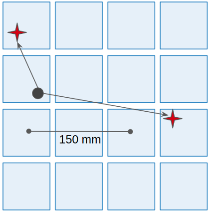
Simulated M3 $2\nu\beta\beta$ Branch 1 events.
Single channel energies on each axis.

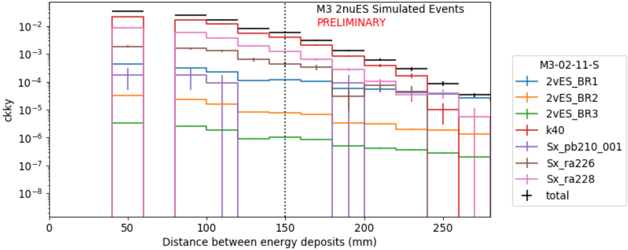
- Tagging energy deposits, namely their sums, creates additional access to the energy space.
- There is additional background rejection power in tagging summed gammas which will not occur, in ^{40}K for example, in the normal peak.
- Tags have been designed for all Branches of $2\nu\beta\beta$ excited states, as well as K40, and modules to apply them to CUORE Monte Carlo data.
- Working now to build modules for applying to data.

^{130}Te $2\nu\beta\beta$ to Excited States ::: Search in Crystal Space

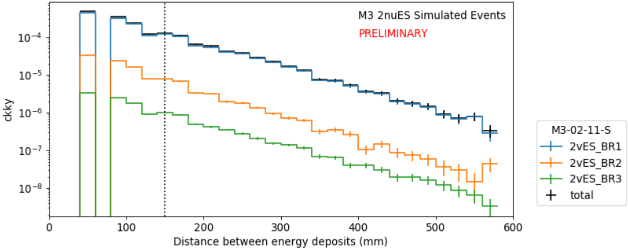
Another non-traditional analysis path we are exploring is how events are spread in crystal-space.

- Default distance cut is 150mm. Roughly 40-45% of $2\nu\beta\beta$ to excited states events pass this cut.
- Relaxing this cut gives access to space that is not dominated by traditional backgrounds.

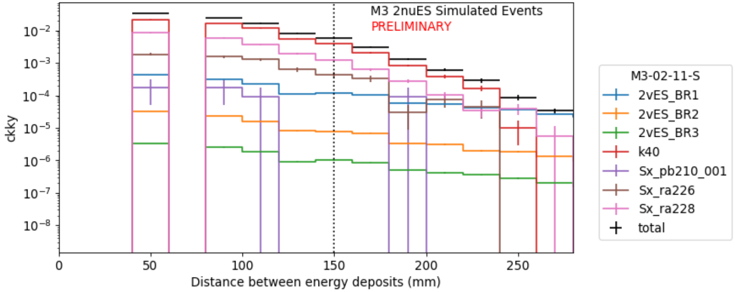




(Above) Includes background with traditional cut. (black dotted)
(Below) Signal only with no distance cut.



^{130}Te $2\nu\beta\beta$ to Excited States ::: Search in Crystal Space

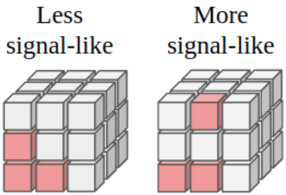


Distances between crystals is discrete and for events with a small footprint (or where the distance cut is enforced), average distance is not a good discriminator.

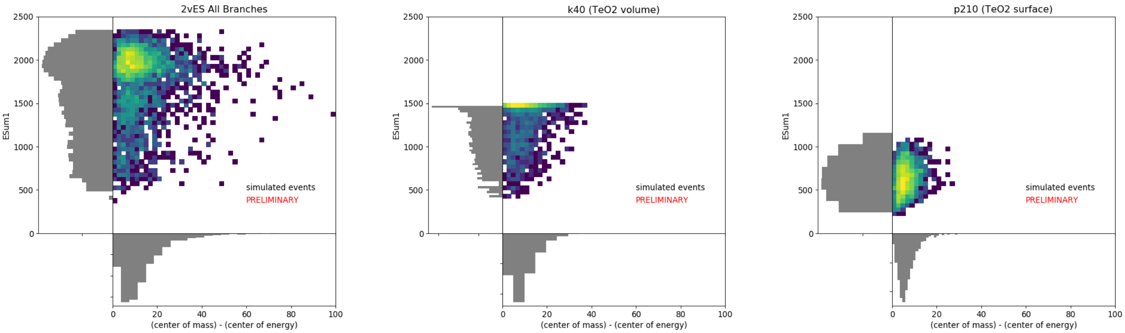
A naive look at which crystals close to a primary vertex were included in a multiplet showed a correlation with events and their "nearest neighbors".

Simple BDT with inputs of "side-", "edge-", "corner-", "no-" neighbors identified patterns that were more likely to be signal (example at right).

*This analysis was performed before angular correlation validation, which will be taken into account in the final result.



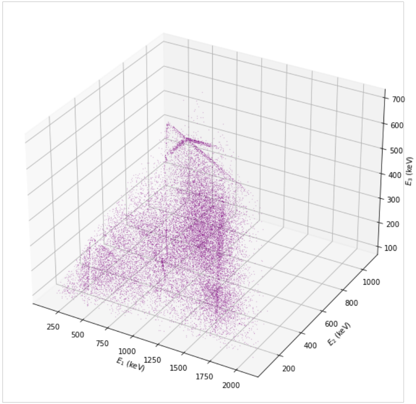
^{130}Te $2\nu\beta\beta$ to Excited States ::: Search in Crystal Space



- (Above) Three sources of events ($2\nu\beta\beta$ excited states, ^{40}K on TeO_2 volume, ^{210}Pb on TeO_2 surface) in this analysis comparing total event energy (Y) vs the displacement of the center of the event when weighted by crystal energy (X)
- Widening the distance over which a multiplet is evaluated (traditional cut is 150mm, or roughly 3 crystals) can improve this discriminator

Crystal topology is an encouraging angle to look at higher multiplicity events.

Looking Forward



Simulated M3 $2\nu\beta\beta$ Branch 1 events.
Single channel energies on each axis.

- Applying this analysis to the newly released 1-tonne-year data will increase sensitivity by a factor of ∼4.
- We are aiming for a factor of ∼10 increase, which we think we can reach with signal efficiency, tagging backgrounds, & topological cuts.
- Next analysis rollout will likely include events in which a gamma scatters over two or more crystals, but will still fit only over peak regions.
- Machine-learning algorithms can help to separate signal-like event topologies from background-like topologies.
- A Bayesian MCMC is under development to fit both signal- and background-like components (∼dozen components over ∼30 event signatures)

New results from CUORE: arXiv: 2104.06906

Search for decay to excited states in CUORE is very active!

- Article submitted to EPJ C ::: arXiv:2101.10702 [nucl-ex]
- The search will be extended by analyzing advanced topologies in position- and energy-space.
    - Events where a single gamma scatters across multiple crystals will be included.
    - The distribution of the event multiplet across the detector may provide additional sensitivity.

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