Measurements of Neutron-Induced Gamma Ray Background of ^{100}Mo for CUPID

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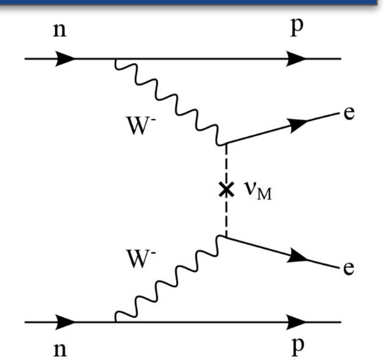
Background

Neutrinoless double beta decay (0νββ) is a theoretically predicted radioactive decay process, which has not yet been observed. In 0νββ, two neutrons concurrently decay into two protons inside an atomic nucleus, emitting two electrons and no neutrinos. The observation of 0νββ is thought to be the most feasible approach to determine the Majorana nature of the neutrino: whether the neutrino is its own antiparticle.



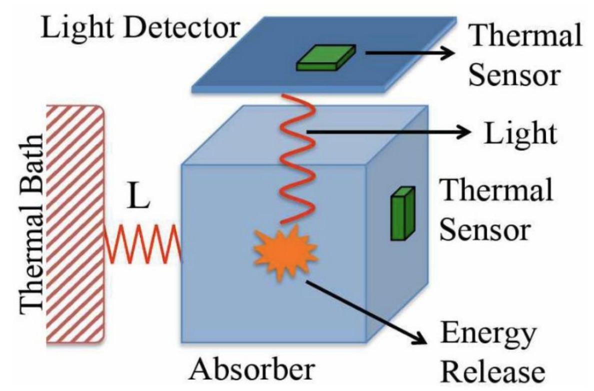


Fig 1: CUPID Detector Cartoon (courtesy CUPID)

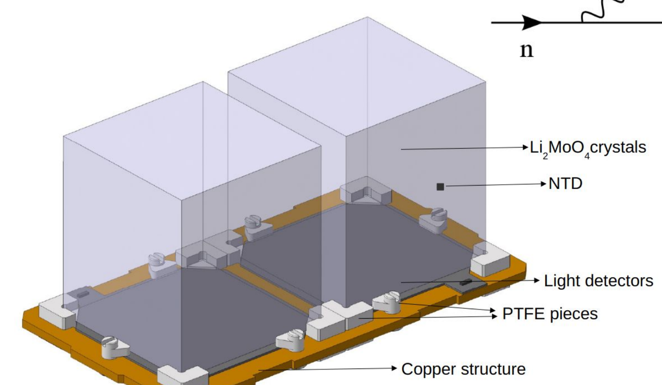


Fig 2: CUPID Module CAD Drawing (courtesy CUPID)

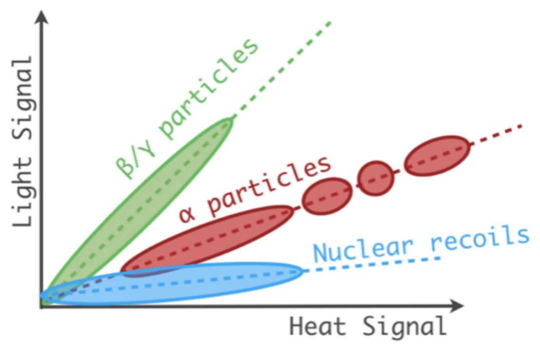


Fig 3: Light-to-heat Signal Ratio for Different Radioactive Decays (courtesy CUPID)

The CUPID experiment [1], designed to detect 0νββ, will operate Li_2MoO_4 cryogenic scintillators; these detectors examine two modes of energy deposition: heat as phonons and light as scintillation photons. When the electrons emitted by 0νββ are absorbed, a heat signal is detected by the crystal, and the corresponding scintillation light is detected by an auxiliary detector.

The ratio of energy-readout of the two signal types depends on the type of radioactive decay occurring inside the crystal: β and γ particles give much higher light yield compared to an α particle with the same total energy. CUPID is expected to be able to isolate 0νββ signals from signals due to background α-events (as shown by [2,3]).

Motivation

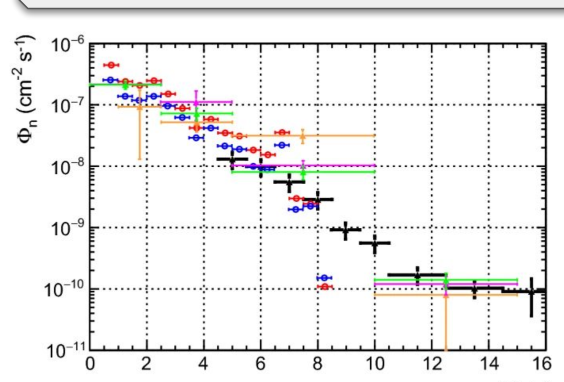


Fig 4: Neutron flux at LNGS (from [5] and references therein)

Neutron scattering with ^{100}Mo in CUPID creates a poorly understood background that could resemble the signal created by neutrinoless double beta decay. There 3 main sources of neutrons interacting with the CUPID experiment

- Muon induced neutrons produced inside the detector → easy to ignore using high efficiency muon vetoes [4]
- Muon induced neutrons produced inside rock around the detector
- Actinide contamination inside the detector & surrounding material

The latter two processes are of primary concern since they are not as easy to account for. To deduce the expected background resulting from these processes, it is important to understand the cross section between neutrons and ^{100}Mo at different energy levels. For this purpose, an experiment was conducted at TUNL.

Citations

[1] CUPID Interest Group, CUPID pre-CDR, arXiv preprint (2019), arXiv:1907.09376 [physics.ins-det].
[2] O. Azzolini et al. (CUPID-0), Final Result of CUPID-0 Phase-I in the Search for the Se-82 Neutrinoless Double-β Decay, Physical Review Letters 123, 032501 (2019),arXiv:1906.05001 [nucl-ex].
[3] E. Armengaud et al. (CUPID-Mo), New Limit for Neutrinoless Double-Beta Decay of Mo 100 from the CUPID-Mo Experiment, Physical Review Letters 126, 181802 (2021),arXiv:2011.13243 [nucl-ex].
[4] Tornow, W., Finch, S. W., and Kidd, M. F., Potential neutron-induced γ-ray background on natural tellurium relevant to 130Te 0νββ decay searches at the CUORE and SNO+ detectors. United States: N. p., 2021. doi:10.1103/physrevc.103.044612.
[5] Bruno, G., Fulgione, W., Flux measurement of fast neutrons in the Gran Sasso underground laboratory. Eur. Phys. J. C 79, 747 (2019)
[6] M. F. Kidd, W. Tornow, and S. Finch, "Investigation of neutron-induced backgrounds in isotopes of Molybdenum for 0νββ decay searches," presented at the APS Division of Nuclear Physics Fall Meeting 2020
[7] Mike Richman. "Histlite" (2022) GitHub repository. https://github.com/zgana/histlite.
[8] Matthew Gooden. "GoodFit" (2021) Personal Communication
[9] Beyer et.al. Inelastic scattering of fast neutrons from excited states in ^{56}Fe, Nuclear Physics A,Volume 927,2014,Pages 41-52, ISSN 0375-9474,

Acknowledgements

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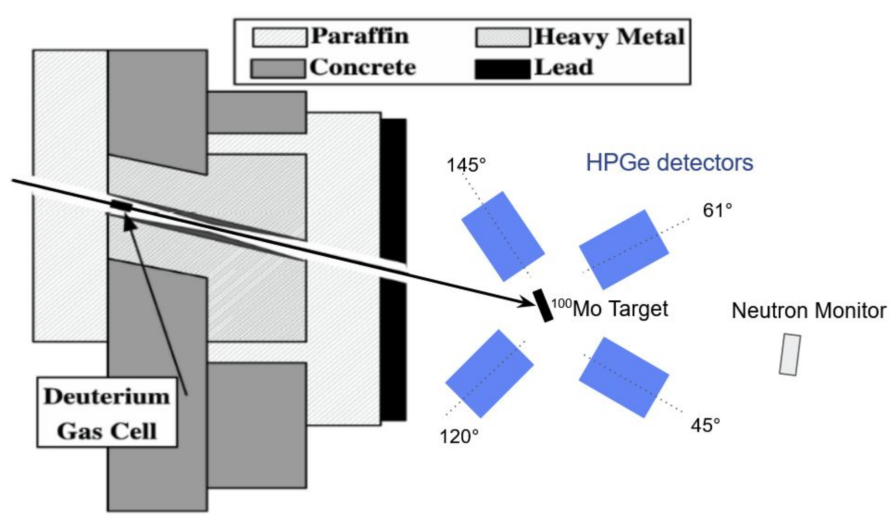
This research used resources of the National Energy Research Scientific Computing Center (NERSC). We thank Matthew Gooden (LANL) for use of his gamma-peak fitting software GoodFit.

Datataking at TUNL

Experimental Setup



	Target Sample	
Material	% enriched	Uncertainty
100 Mo	96.33	0.96
98 Mo	3.07	0.15
96 Mo	0.16	0.01
97 Mo	0.13	0.01
95 Mo	0.13	0.01
92 Mo	0.11	0.01

Fig 5 (left): Experimental set up for TUNL data collection, adapted from [6]
Fig 6 (right): Ge detectors with sample
Table 1 (above): Composition of the target used

The data used for this analysis was taken at TUNL (Triangle Universities Nuclear Laboratory) using the set up shown in Fig 5. Tandem beams of ranging from 4-8 MeV were targeted at varying samples of Mo enriched in ^{100}Mo, Fe, and Cu. Germanium detectors were used to measure the resulting gamma decays.

Preprocessing

We utilized the pulsed-beam structure of the accelerator in order to determine the neutron-^{100}Mo cross sections. Time of Flight (TOF) tells us which events are neutron-induced (as they are coincident with the neutron beam) and which are random coincidences from ambient background sources.

- Examples of these cuts are shown via the graph in Fig 7.
- The TOF correction was necessary in order to start the process of peak hunting.

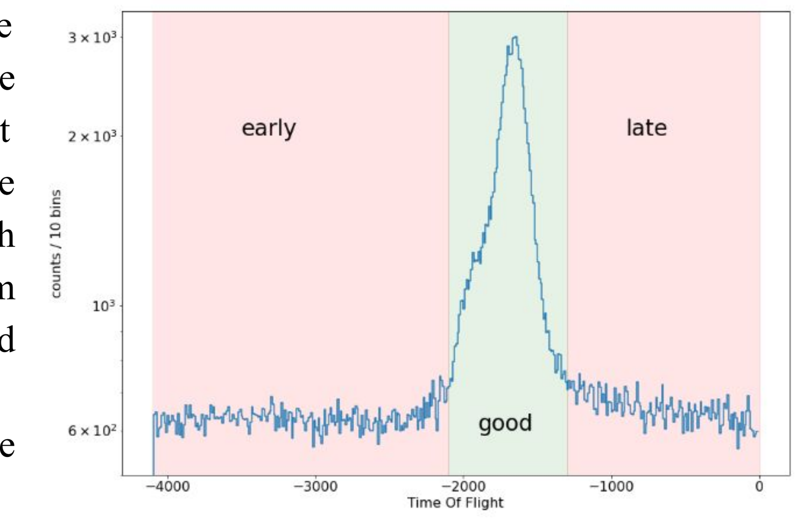


Fig 7: Depicts the cuts needed for scaling by the appropriate energy

Data Analysis

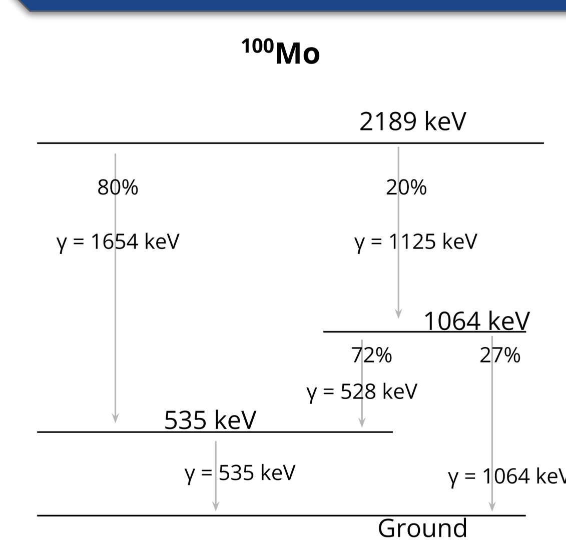


Fig 8: De-excitation scheme for ^{100}Mo that has been excited to 2189 keV

Analysis began with a thorough examination of possible decay paths for ^{100}Mo excited up to 6 MeV.

At left, Fig 8: an example of a de-excitation scheme for ^{100}Mo

- Neutron scattering excites ^{100}Mo from ground state to 2189 keV
- ^{100}Mo de-excites to ground state in one of the 3 following ways, emitting corresponding gammas along the way
  - (80%) 2189 keV → 535 keV → ground state
  - (14%) 2189 keV → 1064 keV → 535 keV → ground state
  - (5%) 2189 keV → 1064 keV → ground state

The 1125 keV gamma emitted during the transition from 2189 keV to 1064 keV results in a peak we can observe in the data.

With this list of gammas we began developing of peak hunting analysis for 6 MeV ^{100}Mo data:

- The peak hunting was conducted by looking through the collected data in the forms of histograms.
- The histograms were compiled and examined using histlite [7]. And via a python script, The different peaks were found and recorded on a custom spreadsheet along with relevant information about their relative heights and frequency.

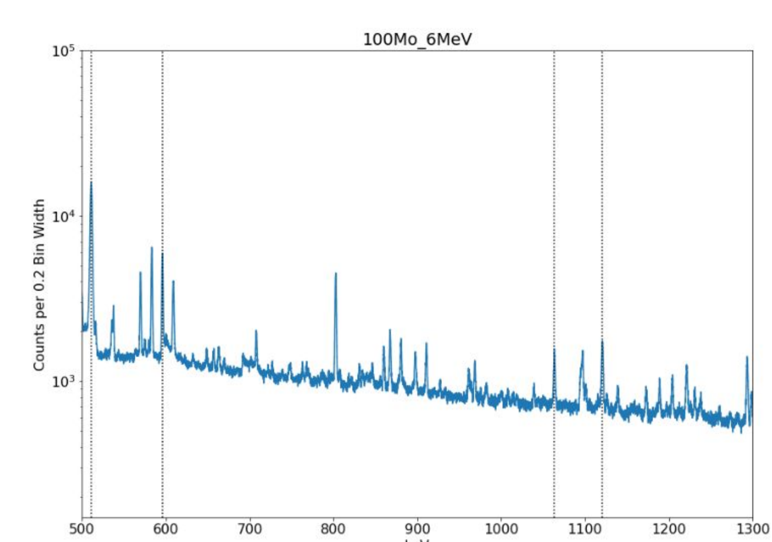


Fig 9: 6 MeV ^{100}Mo histograms with expected peaks indicated by dashed lines

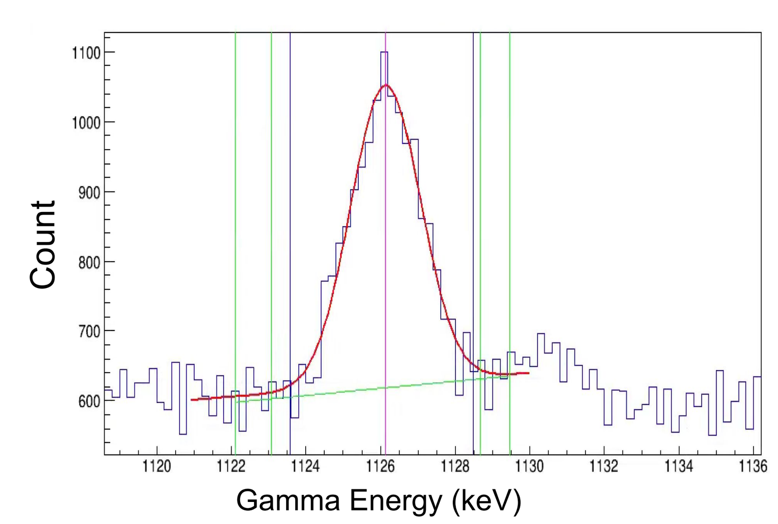


Fig 10: GoodFit plot for the 1126 keV photopeak

We used the LANL program GoodFit [8] to calculate the strength of each photopeak. At left, Fig 10: example of GoodFit plot for the 1126 keV photopeak with the following characteristics:

- Bin size used: 0.2 keV
- Data shown is from a single detector
- Legend: background (green lines), range of peak (dark purple lines), location of peak (red line)
- Output:
  - Integrated area: 5094 ± 152 counts
  - Fitted area: 5026 ± 204 counts
  - Width of fitted curve: 2.20 ± .80 keV

Preliminary Results

In order to make a preliminary estimate of the cross-section of 6 MeV neutron inelastic scattering on ^{100}Mo based on our resultant photopeak intensities, we need the following pieces of information:

- σ_{Fe} → cross-section of 847 keV photopeak of ^{56}Fe @ 6 MeV neutron beam energy (σ_{Fe} = 1.52 ± 0.09 b at 6 MeV from [9])
- n_{Mo} → area under that peak of ^{100}Mo photopeaks, as measured by this analysis
- n_{Fe} → area under the 847 keV ^{56}Fe peak, as measured by this analysis
- BCI (Beam Current Integration) → proportional to the total neutron flux during TUNL runs
- ϵ → Ge detector efficiency dependent on detector and incident gamma energy
  - Determined using a mixed gamma source at the conclusion of datataking
- N → number of nuclei in the target, determined by target mass and enrichment

Cross sections vary slightly based and on the channel. After determining cross-sections and their corresponding error by channel we averaged this information by gamma energy (reported in the table below).

$$\sigma_{\rm Mo} = \sigma_{\rm Fe} \cdot \frac{n_{\rm Mo}}{n_{\rm Fe}} \cdot \frac{\rm BCI_{Fe}}{\rm BCI_{Mo}} \cdot \frac{\epsilon_{\rm Fe}}{\epsilon_{\rm Mo}} \cdot \frac{N_{\rm Fe}}{N_{\rm Mo}}$$

Fig 11: Formula used in order to calculate the cross section of ^{100}Mo

E_Gamma (keV)	Cross Section (barns)	Cross Section Error
600	0.170	0.020
1063	0.059	0.008
1126	0.154	0.014

preliminary

Table 2: Current results of cross section analysis

Conclusions

We have completed the necessary peak hunting and curve fitting to start the next phase of work which consists of refining our error analysis and peak hunting.

Future Work

- The next phase of work consists of fine-tuning the error analysis; this includes more precisely propagating the error terms for detector efficiency, BCI, and σ_{Fe}
- Additionally, we also need to determine if there are any possible missing peaks:
  - Corrections to the calculations done in the TOF process resulted in the elimination of many previously identified peaks of ^{100}Mo
  - We intend to take a closer look at the peaks to make sure the elimination of those "missing" peaks is indeed valid.
- We also anticipate some level of correlation analysis as was done in [6] to determine gammas that should appear together within the same decay scheme.