# Investigating the Radiopurity of Lithium Molybdate for Neutrinoless Double Beta Decay Searches

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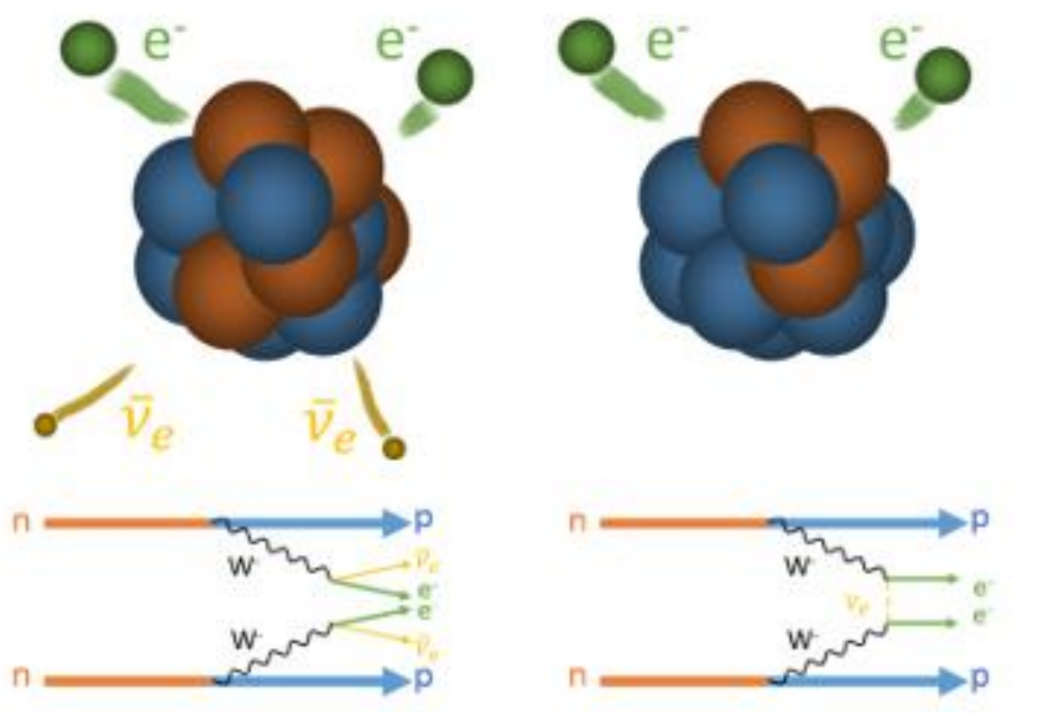
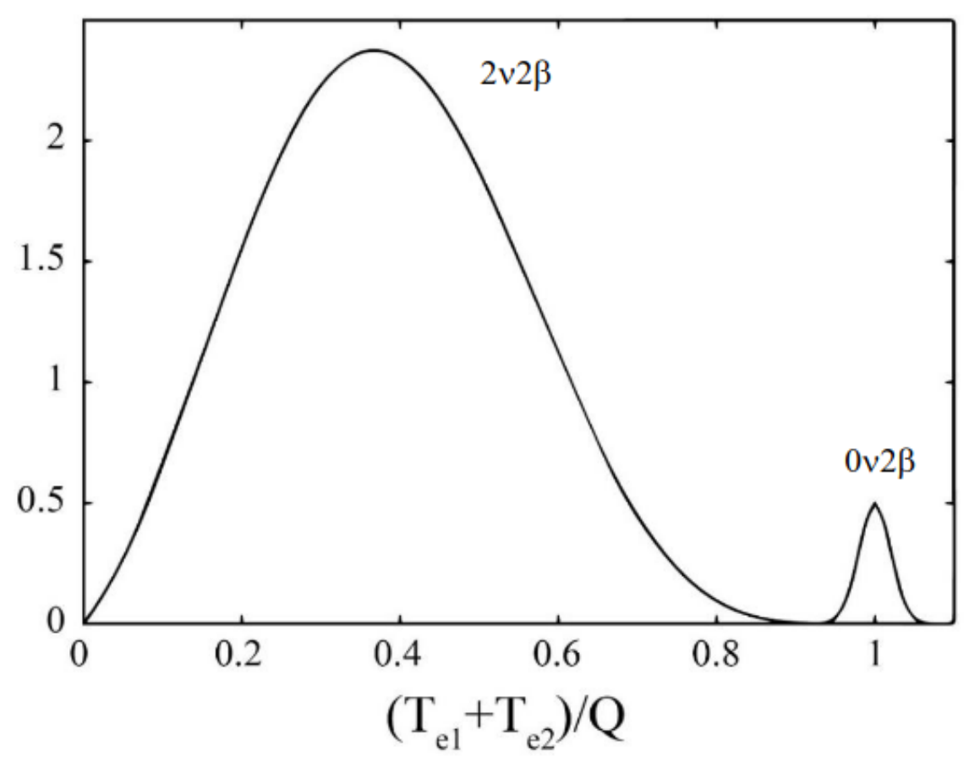
The CUPID project aims to find new physics by detecting neutrinoless double beta decay. Since it is critical to ensure low backgrounds, we analyzed the radioactive spectrum of Lithium Molybdate, placing upper limits on the activity at high energies.

## BACKGROUND

### Beyond the Standard Model - Neutrinoless Double Beta Decay

- The Cryogenic Underground Observatory for Rare Events (CUORE) and the CUORE Upgrade with Particle Identification (CUPID) are the largest projects using cryogenic particle detectors to search for neutrinoless double beta decay.
- Double beta decay (DBD) occurs when a (A Z) parent nucleus decays to a (A Z+2) daughter. In normal modes, two electrons and antineutrinos are released.
- Neutrinos are hypothesized to be Majorana fermions - in neutrinoless DBD, the neutrino acts as its own antiparticle and self-annihilates, releasing only two electrons.
- Since neutrinoless DBD violates lepton number conservation, its discovery would provide powerful evidence for theories beyond the Standard Model. Furthermore, no antileptons are released, making this an important mechanism to study in explaining the matter-antimatter asymmetry.

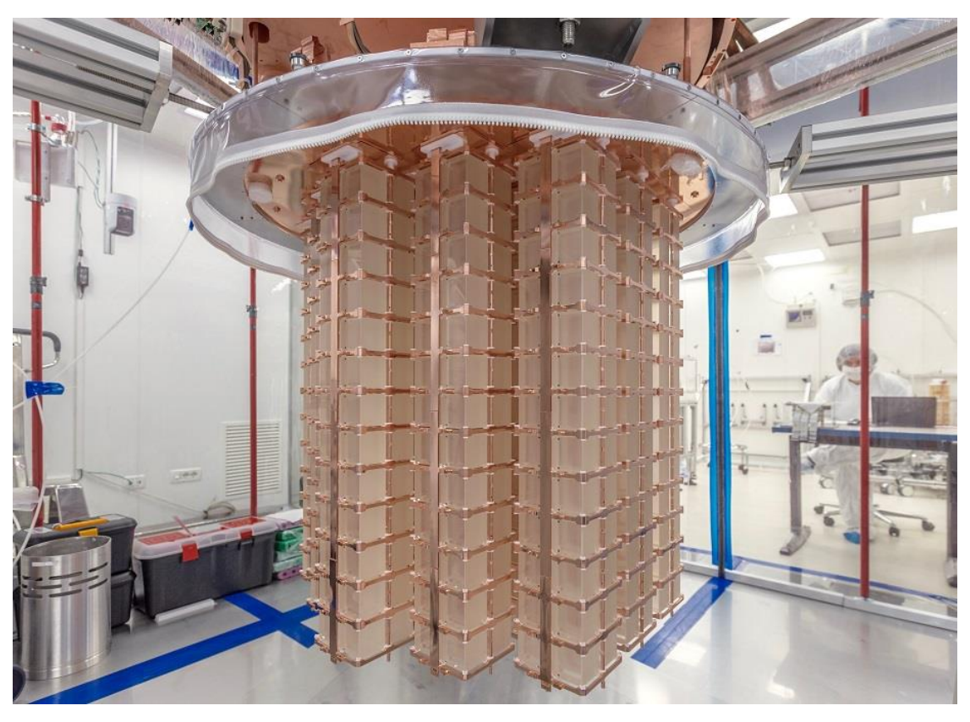


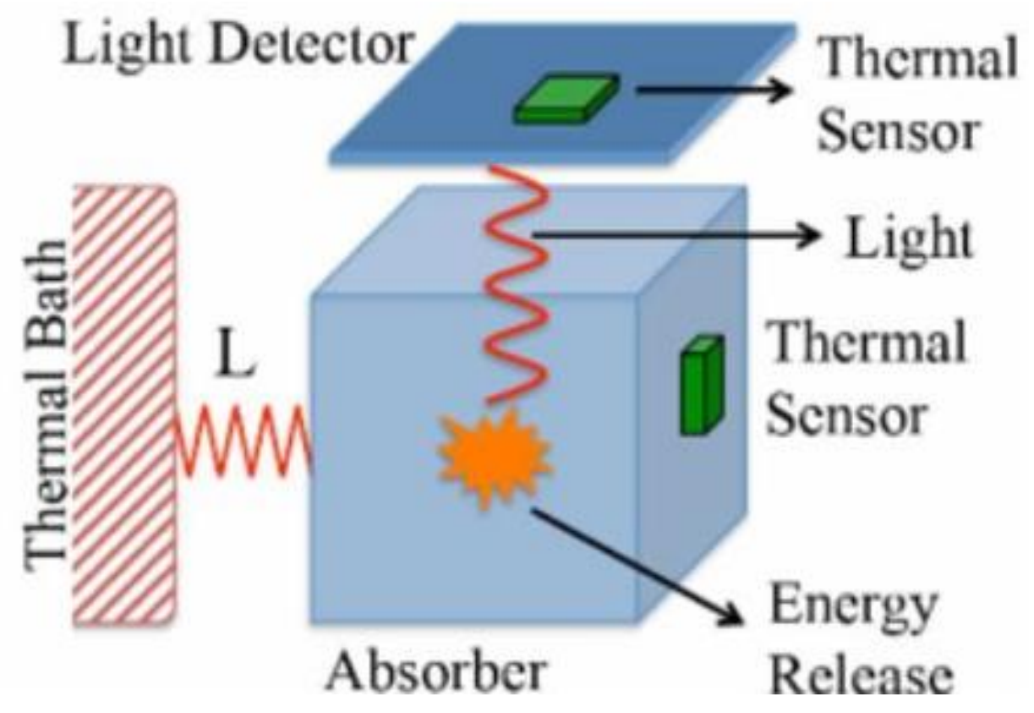


*Left : Neutrinoless DBD, unlike normal DBD, releases only two electrons*
*Right : The electron energy spectrum is marked by a distinct peak for neutrinoless DBD*

### CUORE's search for new physics

- Theoretically, neutrinoless DBD has a clear experimental signature. Since no antineutrinos are released, the transition energy of the nucleus is transferred to the outgoing electrons. Neutrinoless DBD is then marked by a distinct peak in the electron energy spectrum, at the endpoint of the normal DBD spectrum.
- CUORE's challenges are in distinguishing this peak; neutrinoless DBD has a small signal since it occurs extremely rarely, with lifetime limits above $10^{25}$-$10^{26}$ years.
- To achieve the energy resolution and low backgrounds necessary, it is critical to carefully research detector materials. CUORE's solution is **bolometers**, cryogenic particle detectors with high resolutions and efficiencies. Ton-scale arrays of Tellurium dioxide crystals, the DBD source, are coupled with themal sensors to maximize the probability of detecting neutrinoless DBD.





*Left: CUORE tower operates 988 Te-130 bolometers at 10 mK*
*Right: A scintillating bolometer set-up with a DBD crystal coupled to thermal sensors*

## RESEARCH GOALS

### A New DBD Source: Molybdenum-100

- CUPID is investigating molybdenum-100 to further reduce backgrounds by two orders of magnitude.
  - Its high transition energy at 3034 keV minimizes the beta and gamma background from natural radioactive sources.
  - Molybdenum-100 can also be enriched in scintillating **lithium molybdate (LMO)**. The emitted thermal and scintillation signals can be used to identify alpha events, the most prominent source of background above the 2615 keV level.

### Investigating the LMO High Energy Spectrum

- We aim characterize the radioactive spectrum of off-the-shelf LMO. The sample may not be radiopure and must be analyzed for its radio content.
- Furthermore, we examine the activity at high energies. Compton scattering from muon activation can add signal-like events to lower energies and interfere with measurements of molybdenum-100 DBD.

## METHODS

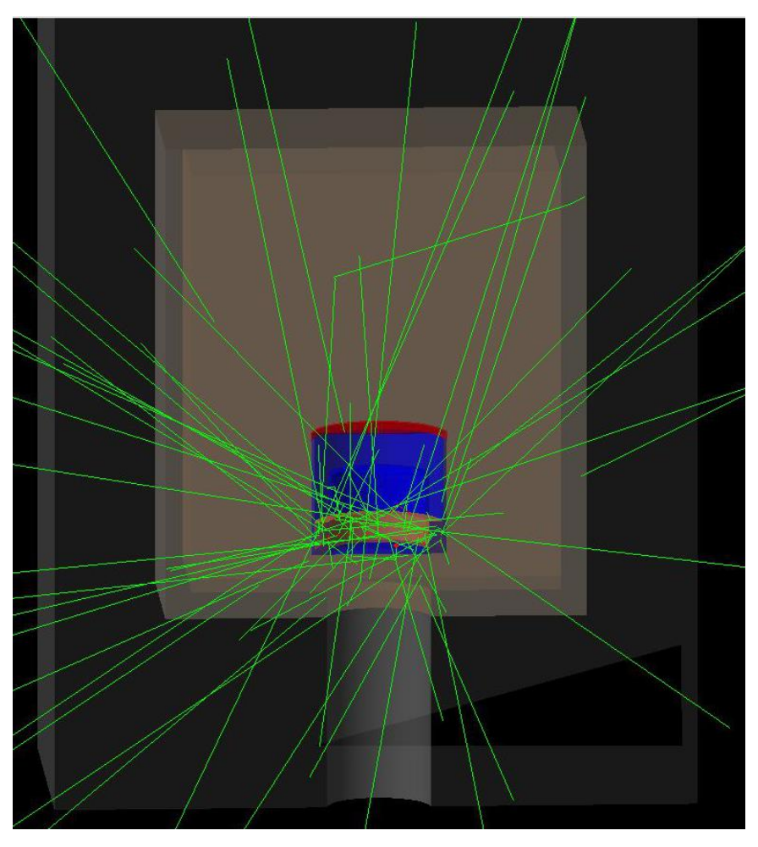
### Gamma-ray Spectroscopy

- We collected data on the radioactive spectrum of a 1 kg sample of off-the-shelf LMO with the "MELISSA" high purity germanium detector.
- Long-lived isotopes, particularly daughters of uranium-238 and thorium-232, contribute to a significant background in our detector.
- The detector's baseline spectrum was therefore first established, being recorded for a live time of 15.6 days. The LMO sample data was then subsequently recorded for a live time of 18 days.

*The "MELISSA" Canberra LB high purity germanium detector inside a copper housing and lead brick shield*

### Geant4 Simulation Toolkit

- With Geant4, we created Monte Carlo simulations of the detector and modeled the activity of radioactive sources.
- We obtain the detector efficiency by comparing activity in simulated and recorded data of calibration sources with known activities.
- The activities recorded in the LMO and background spectrum can then be used to determine the levels of radioactive impurities present.

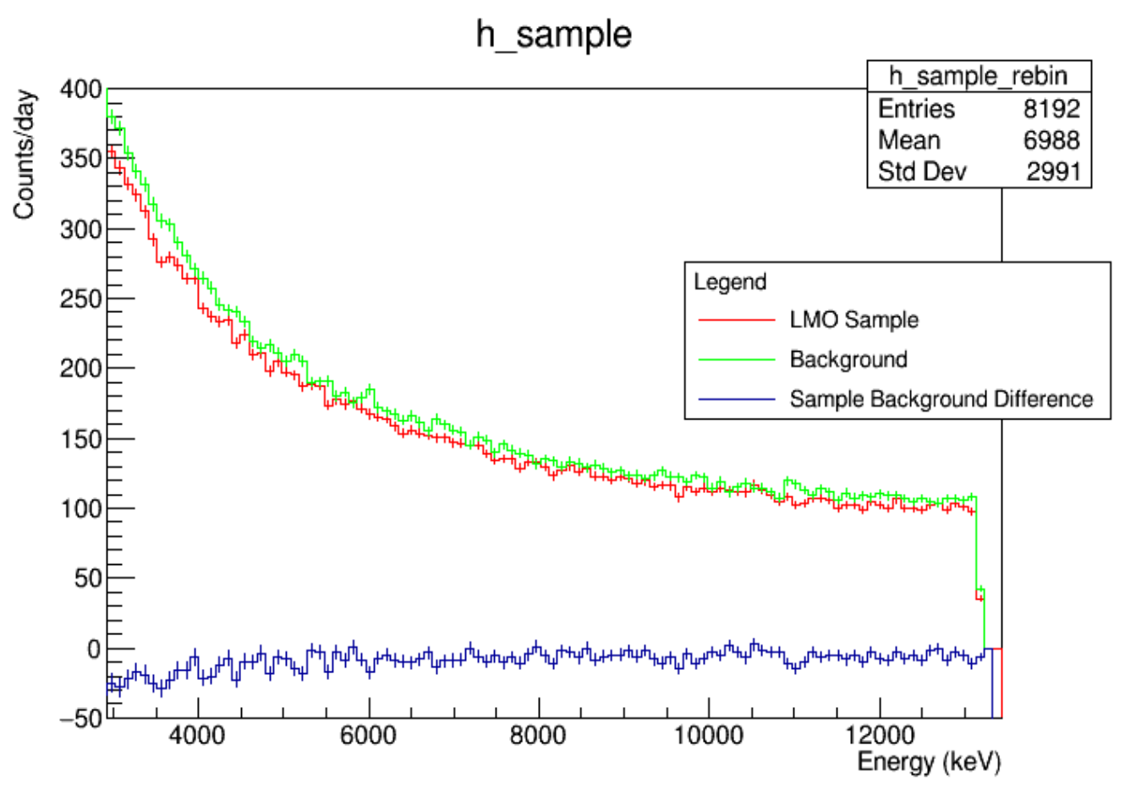


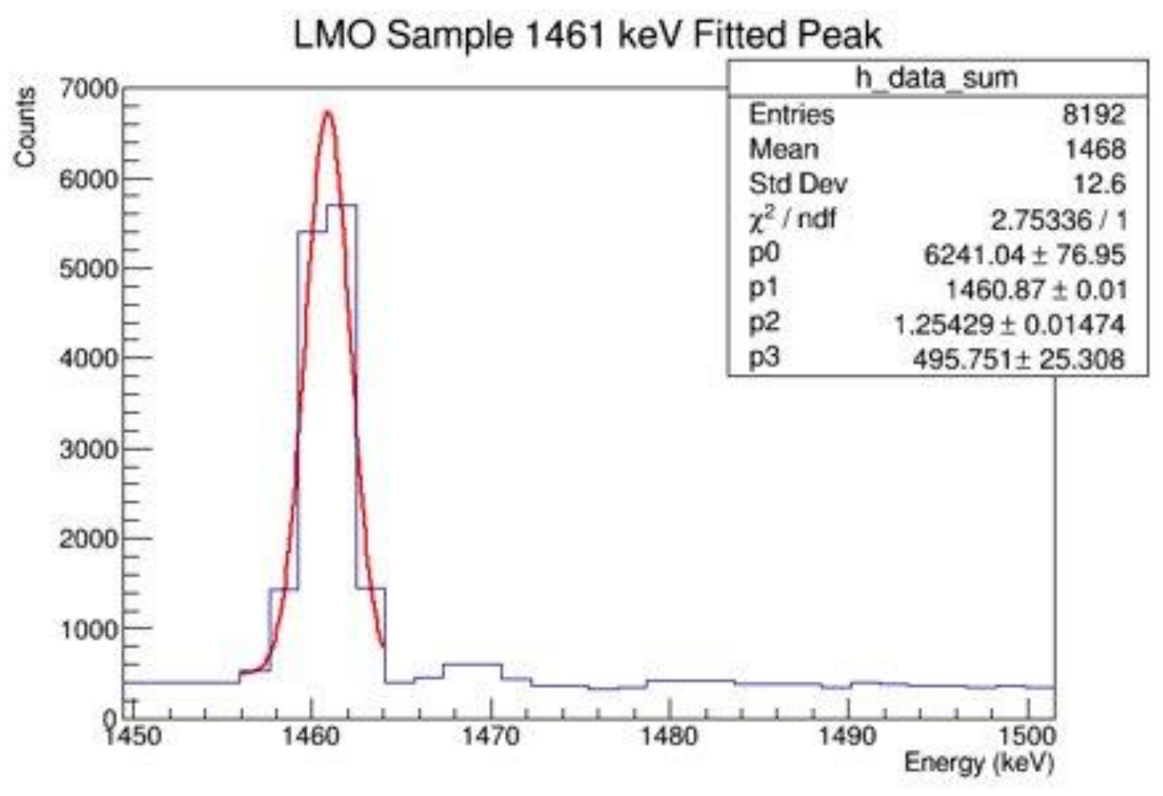
*The detector in Geant4, 100 decays shown from a radioactive sand calibration source*

## RESULTS

### High Energy LMO Spectrum

- We find no statistically significant evidence of excess events in LMO above 3034 keV.
  - At the 90% confidence level, we place an upper limit of 1.0 counts/day on additional activity at 3034 keV.
- However, the high background limits our detector's sensitivity to small signals.
  - Activating the sample under high intensity neutron and proton beams at an accelerator facility will amplify cosmogenic signals. Analysis on this will more conclusively show if significant features in the high energy spectrum exist.

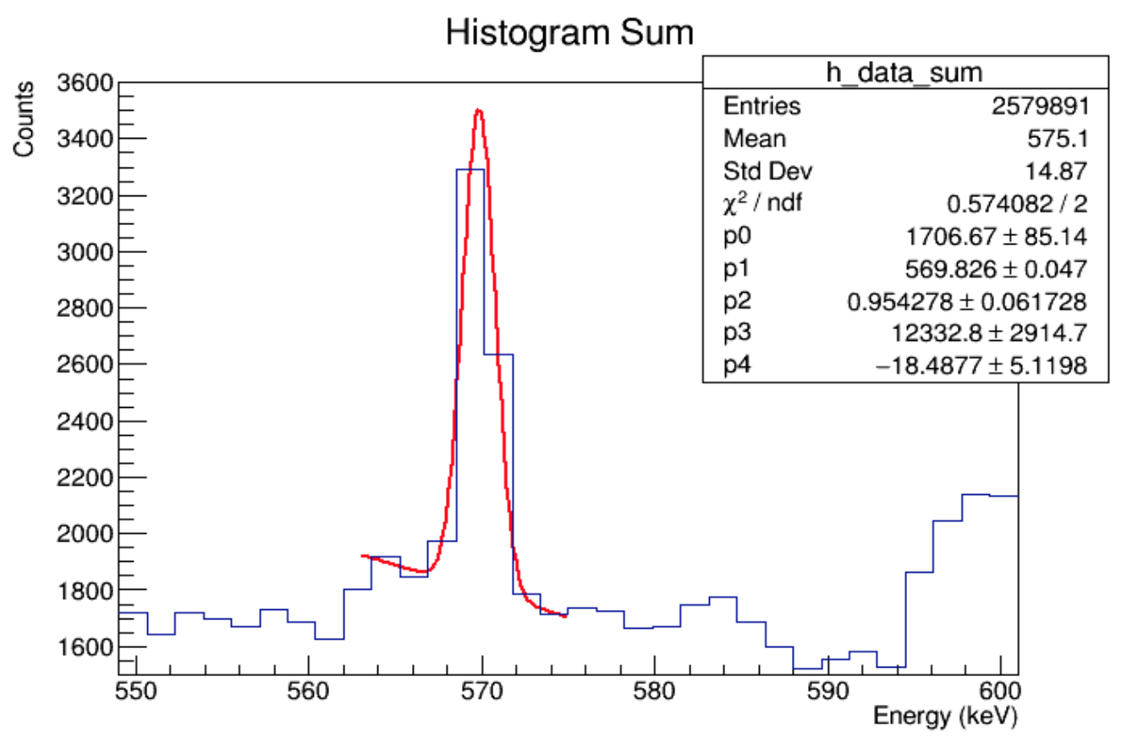


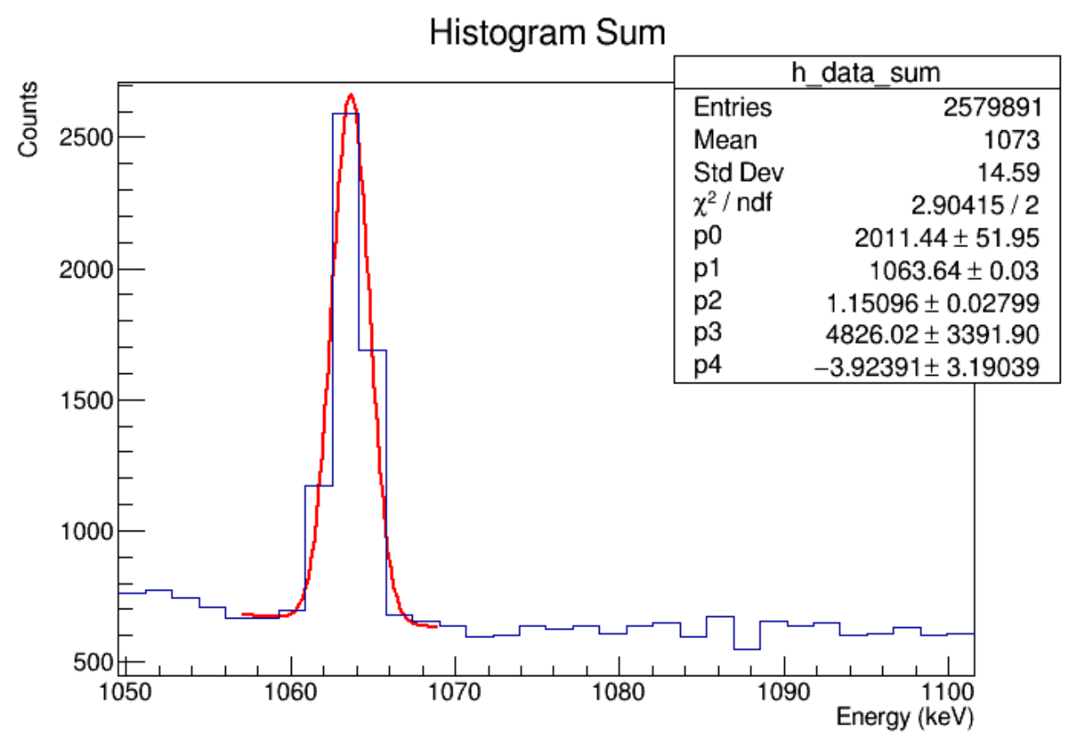


*Left : LMO data rebinned high energy (> 3 MeV) spectrum*
*Right: Fitted 1461 keV peak in LMO data*

### Potassium-40 Impurity

- We observe significant activity at the 1461 keV energy and conclude that the LMO sample contains potassium-40 impurities.
  - Preliminary simulations in Geant 4 place 23.5 ± 5.8 micrograms in the sample.
  - Future work will need to address this; pile-up events from potassium-40 can interfere with measurements of activity at higher energies.





*Left: Fitted 569 keV peak in background data*
*Right: Fitted 1063 keV peak in background data*

### Detector Background Bismuth-207 Peaks

- In the detector background, two peaks at 569 and 1063 keV were noted.
  - These energies are not consistent with decay radiation in uranium-238, thorium-232, or other common radioisotopes and are attributed to bismuth-207.
- The source of bismuth-207 in our experiment is under investigation.
  - Bismuth-207 is not naturally occurring - it could be a product of cosmogenic activation in lead or environmental contamination from nuclear fallout.
  - Simulations in Geant4 of bismuth-207 decay in lead can help determine which is more consistent with the observed activity.

## ACKNOWLEDGMENTS

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