UNIVERSITY OF SOUTH DAKOTA

Experimental Study of $^{13}C(\alpha,n)^{16}O$ Reactions in the MAJORANA DEMONSTRATOR Calibration Data

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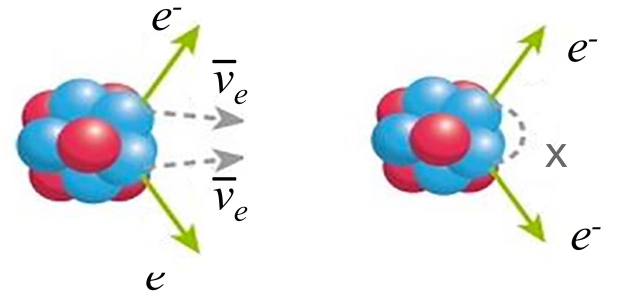
Neutron captures and delayed decays of reaction products are common sources of background in ultra-rare event searches. One common source of neutrons is (α,n) reaction that might occur within the detector materials. A statistical model such as TALYS can be used to estimate the reaction cross sections when the precise measurement is sparse in the relevant α-particle energy. In this work, we studied 6129-keV isomeric photons following $^{13}C(\alpha,n)^{16}O$ reaction in the calibration data. Measurements and predictions were found to be consistent, albeit with large statistical uncertainties, which support for background projections from (α,n) reactions in low-background experiments.

The MAJORANA DEMONSTRATOR

Searching for neutrinoless double-beta decay of ^{76}Ge in HPGe detectors, probing additional physics beyond the standard model, and informing the design of the next-generation LEGEND experiment



^{76}Ge and Double-Beta Decay

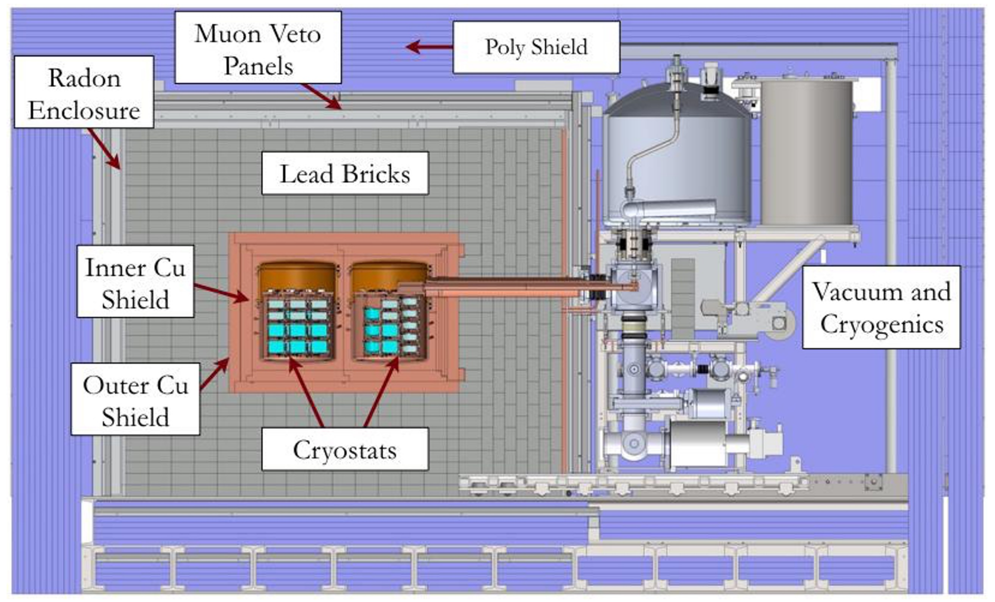
$$(T^{0\nu}_{1/2}) \propto \begin{cases} a\,M\,\varepsilon\,t & \text{Background free} \\ a\,\varepsilon\sqrt{\dfrac{M\,t}{B\,\Delta E}} & \text{With background} \end{cases}$$

Half-life sensitivity

Cosmogenic background: R. Massarczyk (Friday 9:40 am)

Background Modeling for MAJORANA: C. Haufe (Friday 11:45 am)

Operating at the 4850' level of the Sanford Underground Research Facility (SURF)



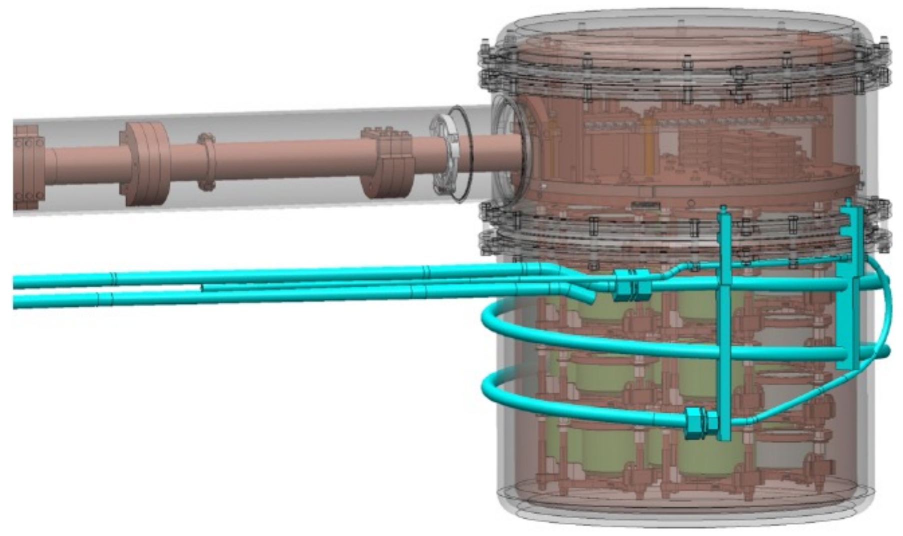
Germanium Detectors:

- Enriched to 87% in ^{76}Ge, from 7% natural abundance
- Ultra-pure, low radioactive material
- Simultaneously source and detector material
- P-type point contact design:
  - Excellent Energy resolution, 2.5 keV FWHM at $Q_{\beta\beta}$
  - Pulse-shape analysis background rejection

44.1 kg of Ge detectors:

- 29.7 kg enriched Ge
- 14.4 kg of natural Ge
- 6.7 kg of enriched Ge inverted coaxial point contact design in the final run period
- Enclosed in two independent vacuum cryostats
  - Made of underground electroformed Cu

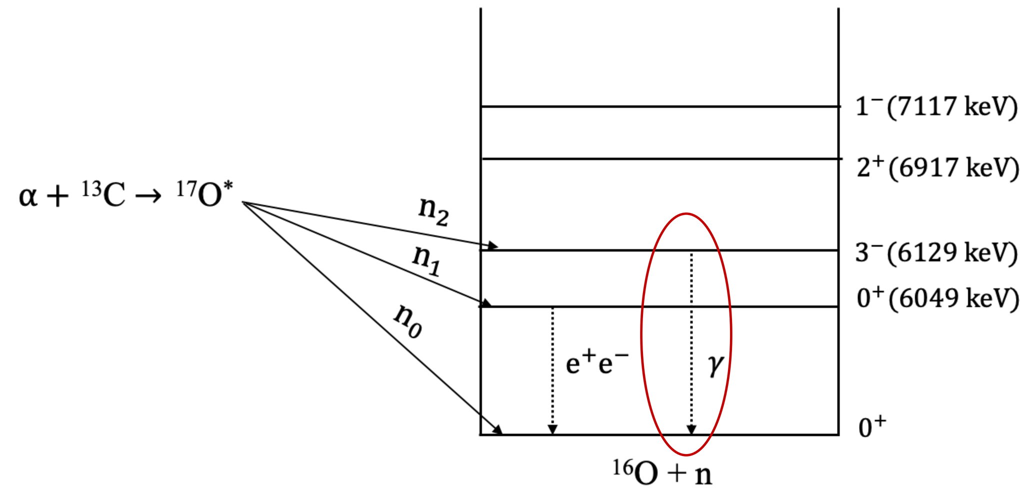
Calibration Source



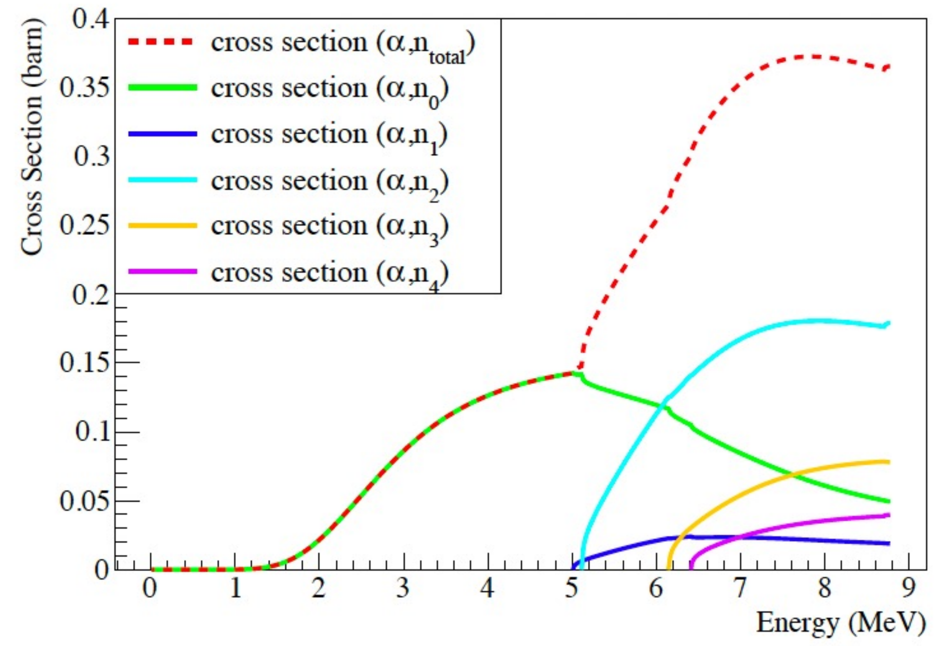
A diagram that shows one module, the detector string within, and the calibration track (highlighted) through which a line source is deployed during calibrations

- Calibration data is taken on a weekly basis using ^{228}Th line sources
- Sources are made of thoriated epoxy, a carbon-rich material, encapsulated in a tube made of PTFE
- ^{228}Th decay chain produces several γ-rays that are used for the energy calibration and detector characterization
- The decay chain also produces several α-emitters along the way until it reaches to ^{208}Pb and α-particles with energies 5.34 MeV to 8.79 MeV are produced

$^{13}C(\alpha,n)^{16}O$ Reaction



The level scheme of ^{16}O as populated in the $^{13}C(\alpha,n)^{16}O$ reaction (energy not to scale). The numerical index of emitted neutrons n_0, n_1, n_2 represent which final state is populated. The 3^- decays via 6129 keV γ-ray emission.



Total cross section and partial cross sections for the $^{13}C(\alpha,n)^{16}O$ reaction as a function of incident α-particle energy generated by TALYS-1.95.

- Precise measurement of cross section of $^{13}C(\alpha,n)^{16}O$ reaction over the entire α-particle energy is sparse
- A statistical modeling approach using the nuclear reaction code such as TALYS is often used to study the radiogenic neutron background in low-background experiments
- Such a model however lacks resonance structure

Data Quality Check and Benchmarking Simulation

Data quality check was performed based on the most prominent 2615-keV γ-peak in the calibration data. If the 2615-keV event rate in a run deviates more than 3.5 σ from the mean value in the dataset, the run is excluded from the analysis.

Source initial activity

$A_0 = 10.36 \pm 0.6$ kBq, on May 1, 2013

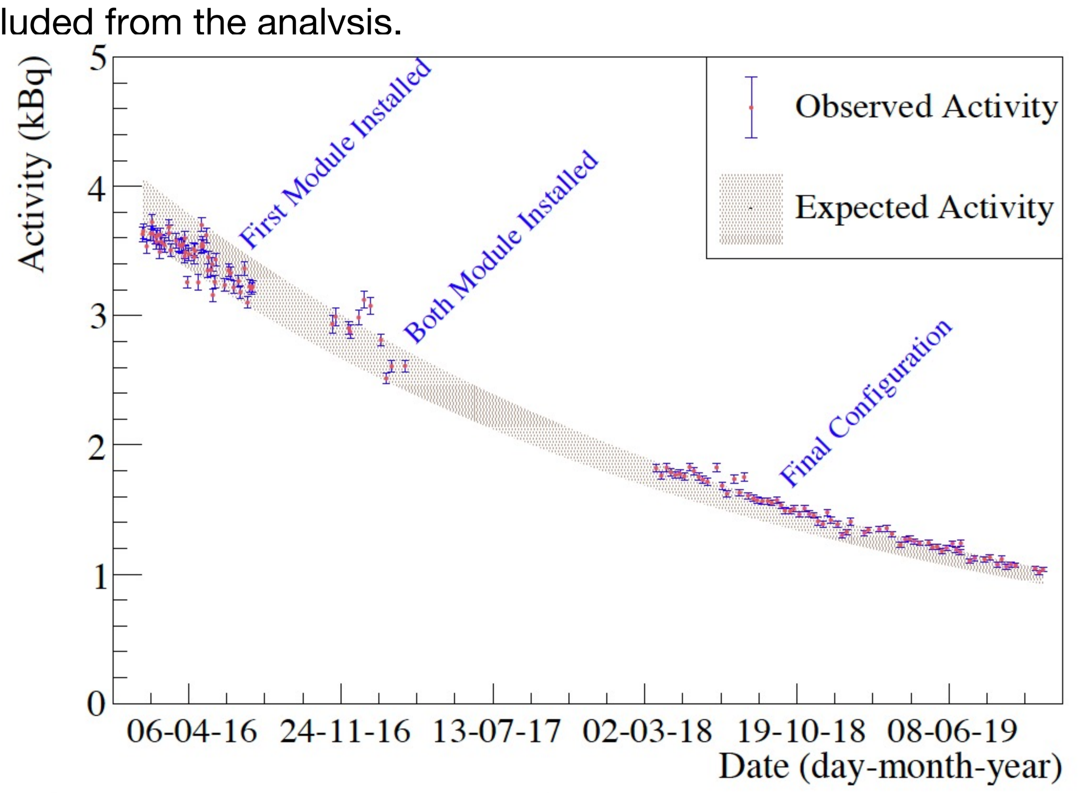
$$A_{observed} = \frac{R}{\epsilon \times b}$$

Rate; Efficiency; Branching ratio

$$A_{expected} = A_0 e^{[-\lambda(t-t_0)]}$$

half-life of ^{228}Th = 1.912 years

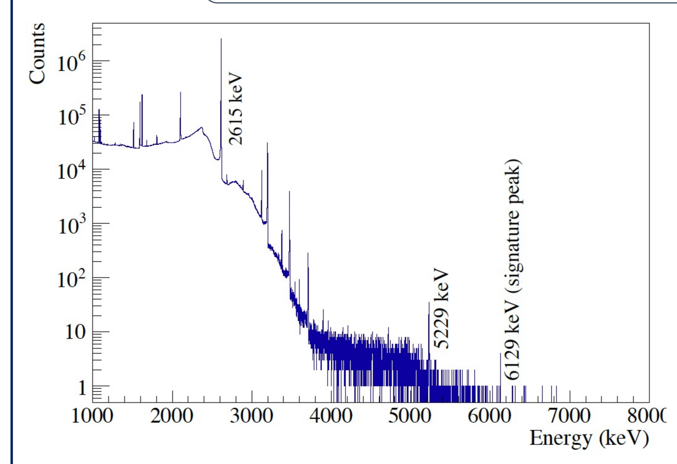
Uncertainty
Observed activity: Statistical
Expected activity: Vendor-reported



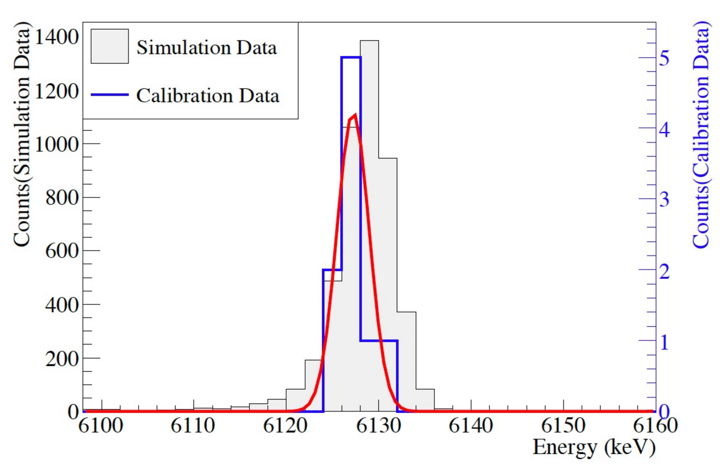
Observed and expected activities of a calibration source used. The gaps in the plot are the periods not used in this analysis when both modules had their sources deployed.

A good agreement was found between expected and observed activities representing that the calibration source measurements are consistent with simulations over various detector configurations throughout multiple years of calibrations. This demonstrates the excellent performance of MaGe simulation, which is a GEANT4-based simulation package used in MAJORANA DEMONSTRATOR.

6129-keV Photon Signature

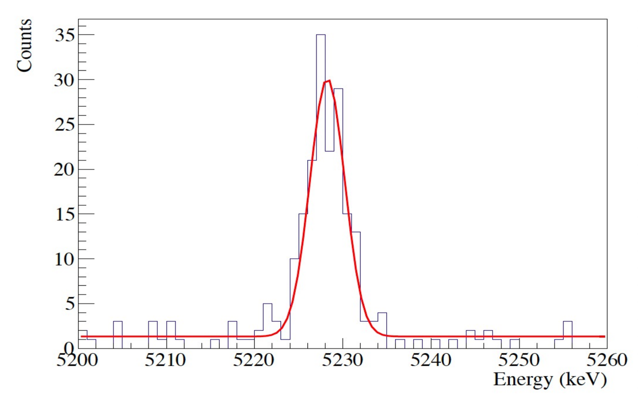


The sum energy spectrum of calibration data selected for the analysis. A clear signature of the 6129-keV peak can be seen.



The zoomed-in plot of the 6129-keV signature peak and the peak shape from the simulation of 1 million such photons from the calibration tracks of the MAJORANA DEMONSTRATOR. The red curve is the fit to the observed data

The signature peak has low statistics and in order to cross-check the fit parameters, we also performed a fit to the more prominent 5229-keV peak



The double coincidence (2 × 2614.5 keV) peak at 5229 keV in the sum energy spectrum.

The signature and the 5229-keV peaks were found to be at expected locations with expected widths in the sum energy spectrum.

The MAJORANA DEMONSTRATOR energy performance is also understood in the higher energy region above 3 MeV.

Comparison with TALYS-based NeuCBOT Predictions

NeuCBOT is a TALYS-based software to estimate the yield of (α,n) reactions. NIMA 875, 57 (2017)

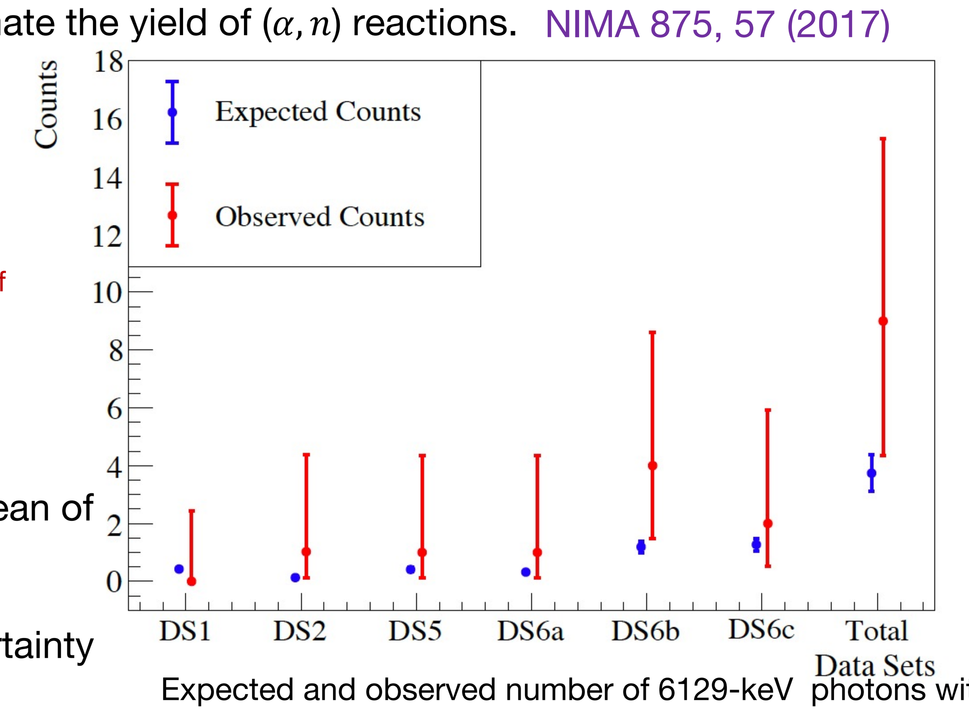
$$N = Y \times \sum_i A_i \times \epsilon_i \times T_i$$

Number of expected events; Yield from NeuCBOT; Source activity; Detection efficiency; Livetime of calibration

Uncertainty

Observed counts: 90% C.L intervals on the mean of Poisson signals (Feldman-Cousins)

Expected counts: combined systematic uncertainty



Expected and observed number of 6129-keV photons with corresponding uncertainties in each dataset and combined data.

The measurement and predictions were found to be consistent, albeit with large statistical uncertainties.

This suggests that the TALYS-based NeuCBOT provides a reasonable estimation of the neutrons from the thorium impurities in carbon-rich materials.

The combination of NeuCBOT with GEANT4 can be valuable for predicting the radiogenic neutron background for the low-background experiments.

The background contribution for the MAJORANA DEMONSTRATOR is less of a concern but future low-background experiments with stringent background requirements should be careful of using alpha sources in carbon-rich materials.

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