Neutron Transmutation Doping of Germanium for CUPID Thermistors

VIRGINIA TECH

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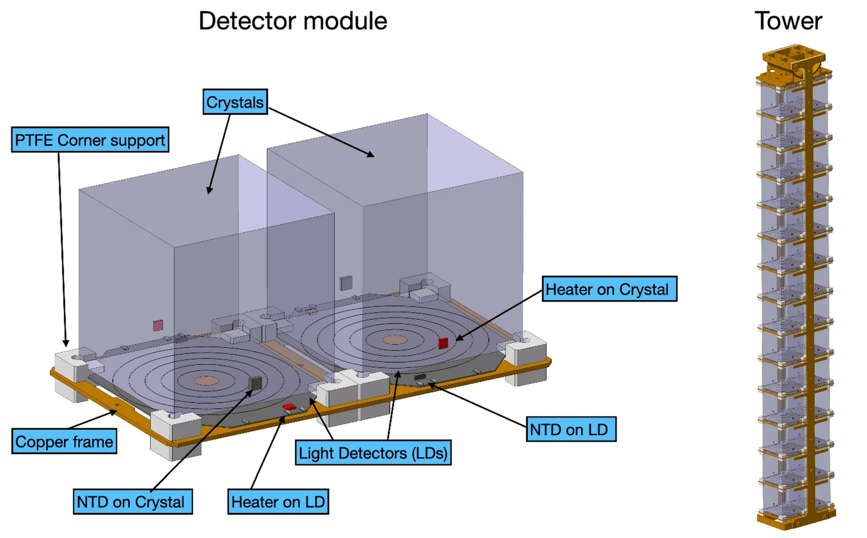
CUPID and NTD-Ge Thermistors

CUORE Upgrade with Particle ID (CUPID)

The CUPID experiment will be deployed underground at the Gran Sasso National Laboratory (LNGS) in Italy, and will use over 1500 Li_2MoO_4 crystals acting as both source and detector for its search for the **neutrinoless double-beta decay** ($0\nu\beta\beta$) of ^{100}Mo [1]. Our goal is to achieve a 3σ discovery sensitivity to the $0\nu\beta\beta$ half-life of ^{100}Mo of **1.0×10^{27} years**. This would correspond to an effective Majorana neutrino mass sensitivity of approximately **12 − 21 meV**, investigating into the inverted neutrino mass hierarchy region.



CUPID detector floor (left) showing Li_2MoO_4 crystals, Ge light detectors, NTD thermistors, heaters, and copper/PTFE frame; full 14-floor detector tower (right) [1].

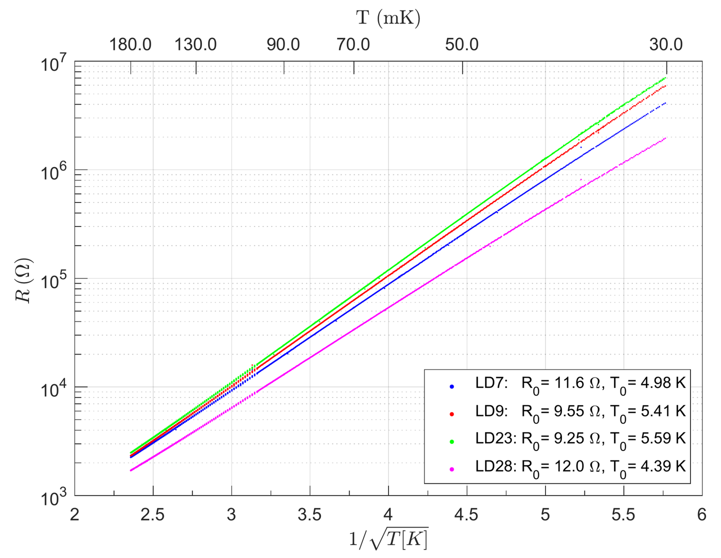
The scintillating properties of the Li_2MoO_4 crystals will enable **particle discrimination**, between α and β/γ events, thus reducing backgrounds in the ROI around the 3 MeV **Q-value** of ^{100}Mo.

NTD-Ge Thermistors

CUPID will use **neutron-transmutation-doped germanium (NTD-Ge) thermistors** to read out its cryogenic bolometers [2]. NTD-Ge sensors were chosen because they have a well-characterized low-temperature response and can be produced with high uniformity via neutron irradiation. The NTD-Ge resistance follows the variable-range hopping form

$$R(T) = R_0 \exp\left[\left(\frac{T_0}{T}\right)^p\right], \qquad p \simeq \frac{1}{2},$$

where R_0 and T_0 can be tuned by adjusting the net dopant concentration [3].



Resistance response of NTD-Ge thermistors irradiated at the HANARO research reactor in South Korea, showing the variable-range hopping behavior used to parameterize NTD-Ge sensors with R_0 and T_0 [4].

The NTD properties are ultimately determined by the reactor **thermal-neutron fluence**, or the time-integrated thermal neutron flux experienced during irradiation. We irradiated Ge wafers and activation monitor foils at the **MIT Research Reactor (MITR)**, then used HPGe γ-ray spectroscopy to extract monitor foil activities in order to determine the delivered fluence to the germanium wafers. In this poster, we present irradiation methodology and HPGe spectroscopy results from the first of the series of planned irradiations for CUPID.

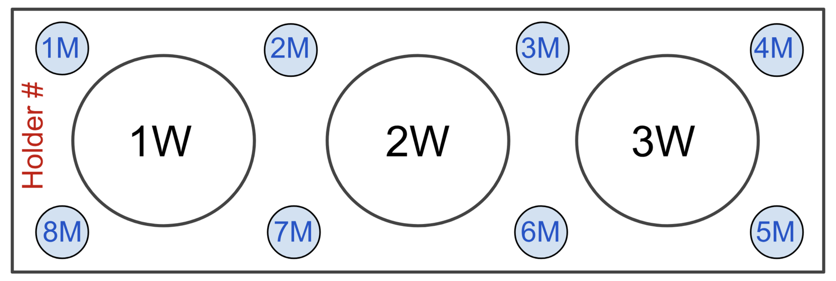
Neutron Transmutation Doping

Ge Transmutation Reactions

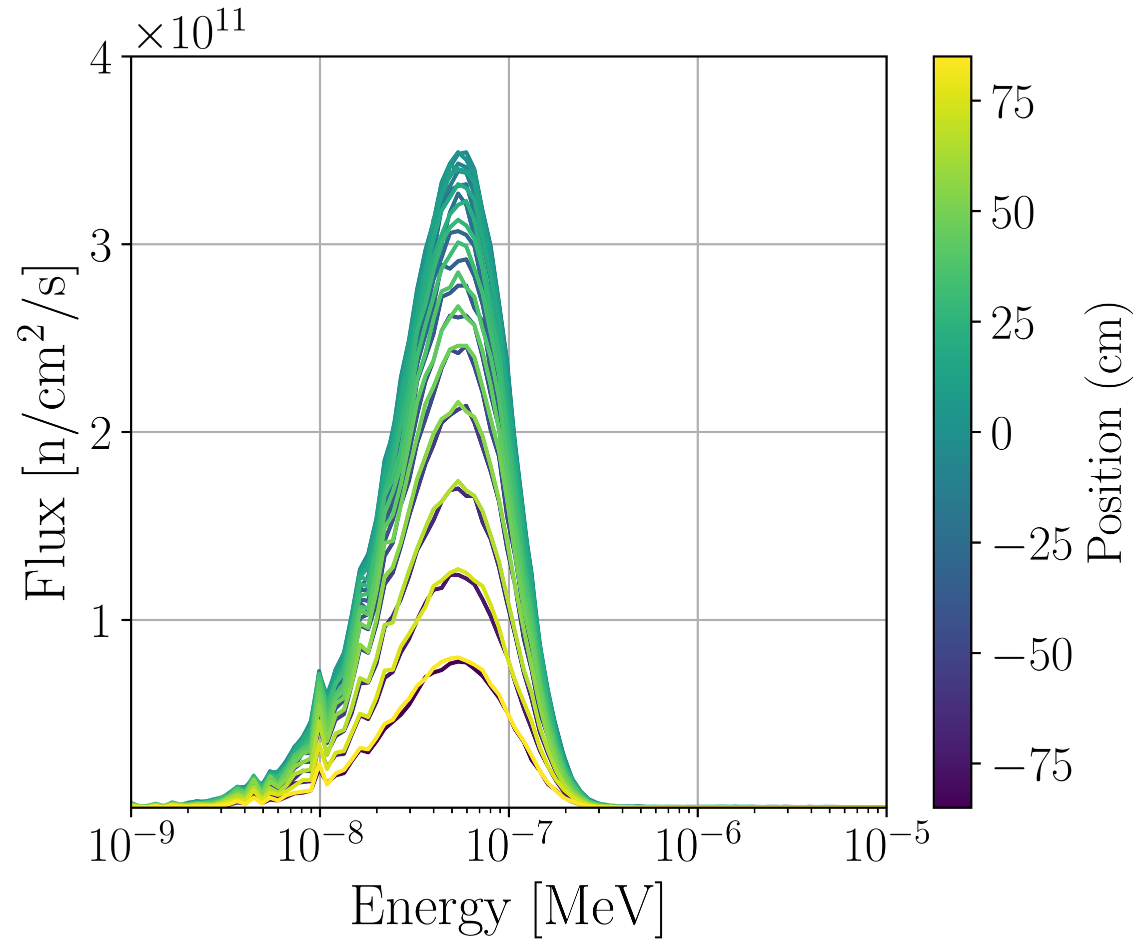
During irradiation, thermal-neutron capture on certain germanium isotopes leads to the creation of charge carrying dopants. The following table summarizes the key reactions:

Reaction	σ_{th} [b]
^{70}Ge$(n,\gamma)^{71}$Ge $\to$ ^{71}Ga (**acceptor**)	3.43
^{74}Ge$(n,\gamma)^{75}$Ge $\to$ ^{75}As (**donor**)	0.52
^{76}Ge$(n,\gamma)^{77}$Ge $\to$ ^{77}Se (**double donor**)	0.16

MITR Neutron Flux Profile



Schematic of the Ge wafer holder. Three wafers (1W–3W) are loaded with monitor foils (1M–8M) at fixed positions surrounding them.



Neutron flux spectra at axial positions spanning ±75 cm in the MITR irradiation tube, colour-coded by position (blue = −75 cm to yellow = +75 cm). Flux peaks near 10^{-7} MeV; magnitude decreases at larger axial displacements.

Activation Monitor Foil Counting

Thin foils irradiated alongside the Ge wafers serve as **neutron fluence monitors** [5]. Key activation products and their principal γ-ray lines:

Isotope	Reaction	E_γ [keV]	$t_{1/2}$
^{60}Co	^{59}Co(n,γ)	1173, 1332	5.27 yr
^{59}Fe	^{58}Fe(n,γ)	1099, 1292	44.5 d
^{95}Zr	^{94}Zr(n,γ)	724, 757	64.0 d

After a month-long cooldown, foils were sent to multiple **HPGe γ-spectroscopy facilities**. Background-subtracted peak areas were extracted and converted to thermal neutron fluence via:

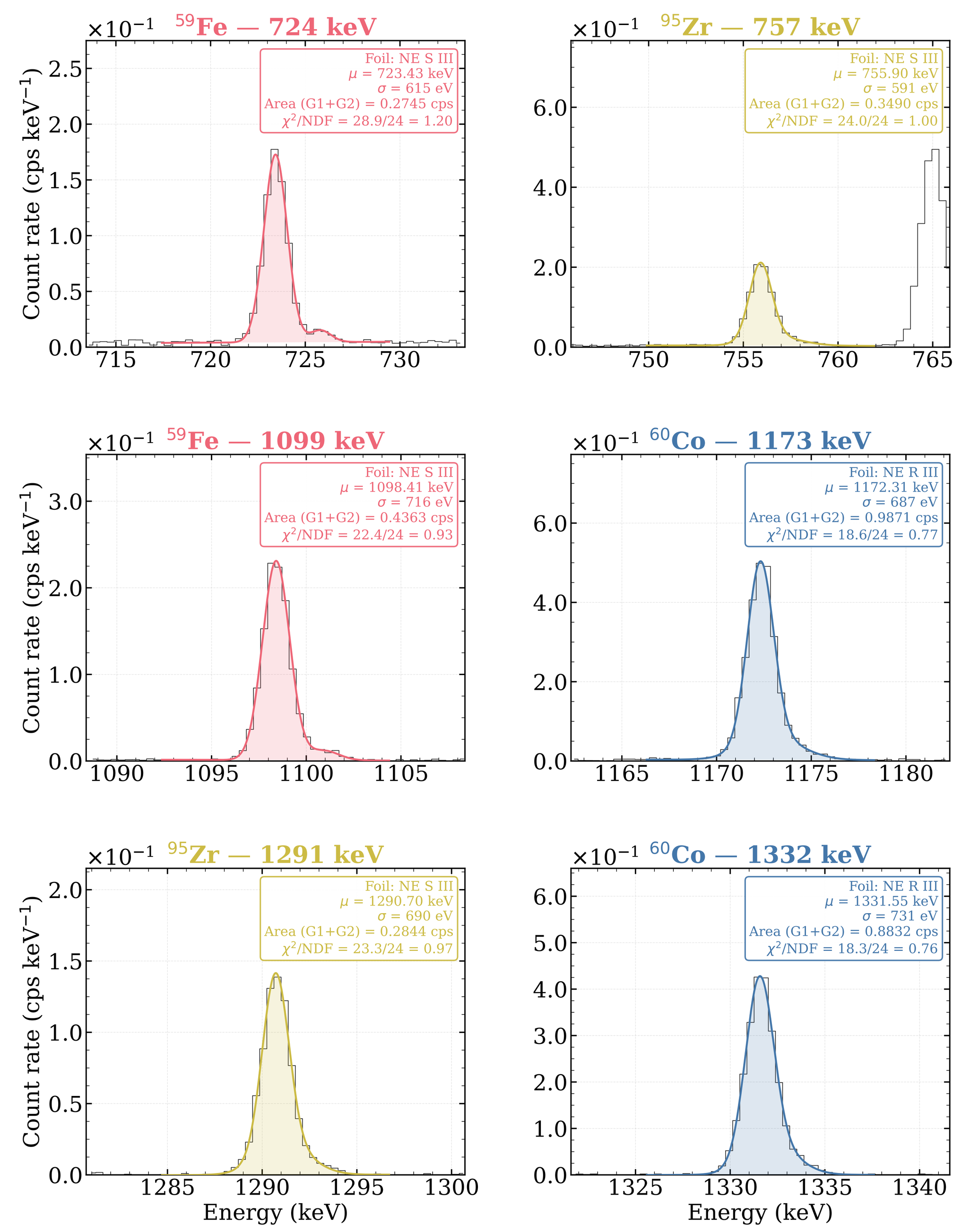
$$\Phi_{th} = \frac{A \cdot t_{irr}}{N\sigma_{th}(1-e^{-\lambda t_{irr}})e^{-\lambda t_{cool}}}$$

A — detected count rate
N — number of target atoms
σ_{th} — thermal cross section
$t_{irr/cool}$ — irradiation/cooling time
λ — radioactive decay constant

HPGe Spectroscopy

Measured γ-Ray Spectra

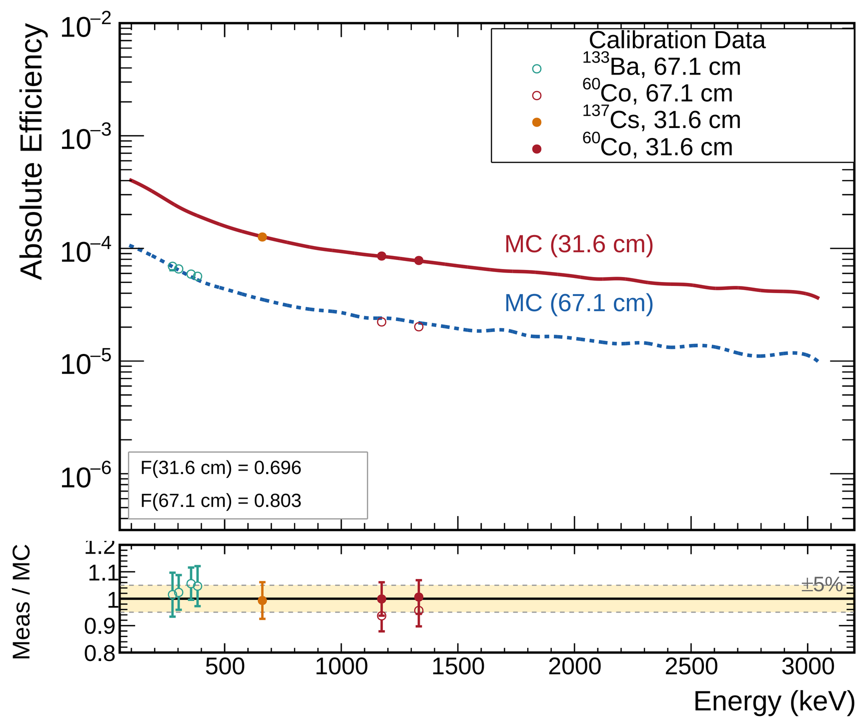
- Virginia Tech's low background HPGe facility used an **Ortec Gem30** HPGe detector to count the γ-ray spectra of the irradiated monitor foils.
- Two different distances (31.6 cm and 67.1 cm) were used to mitigate **coincidence-summing** effects for the high-activity foils.



Background-subtracted γ-ray spectra with **2-Gaussian** fits at all 6 activation γ-ray energies across the 8 foil positions in the cylinder.

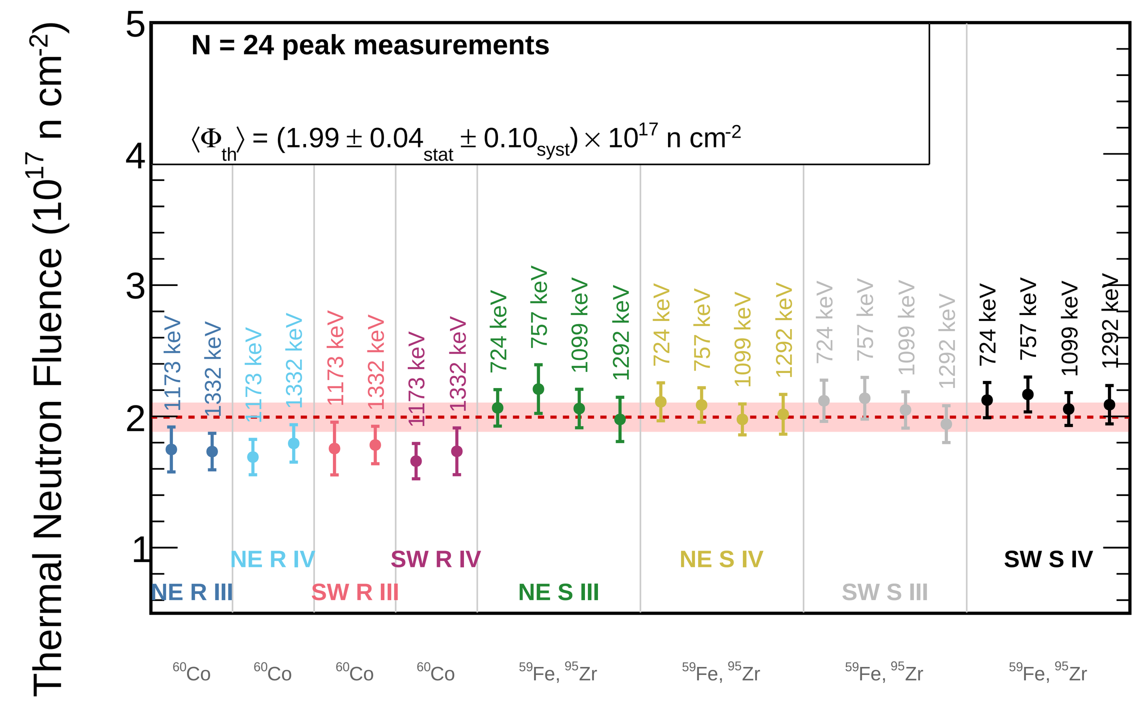
Detector Efficiency Calibration

- Absolute detection efficiency was calibrated using *^{133}Ba, ^{137}Cs, and ^{60}Co* sources at multiple source-detector distances.
- The efficiency curve was fitted with a **semi-empirical** function $F(d)$ that accounts for discrepencies between measured and simulated data.



Results & Analysis

Fluence Map



Thermal neutron fluence per foil and γ-line ($N = 24$). Points are each photopeak measurement; the dashed line is the weighted mean and red band gives the 1-σ error band $\langle\Phi_{th}\rangle = (1.99 \pm 0.11)\times10^{17}\ \mathrm{n\,cm^{-2}}$.

Uncertainty Budget

Source	Type	σ/Φ (%)
Calibration-source activity	systematic	5.0
Isotopic abundance	systematic	1.3
Foil-to-foil spread	systematic	1.8
Gamma Counting	statistical	0.9
Total		**5.6**

Overview

- CUPID aims to achieve a 3σ discovery sensitivity to the $0\nu\beta\beta$ half-life of ^{100}Mo of 1.0×10^{27} years, corresponding to an effective Majorana neutrino mass sensitivity of $12-21$ meV.
- Achieving this sensitivity requires a large, **low-background detector** with excellent energy resolution and particle identification.
- NTD production for stage-1 CUPID has started and aims to produce around **1,200 NTD sensors**.
- The first irradiation campaign at MITR has been completed with a thermal neutron fluence of $\Phi_{th} = 1.99\times10^{17}\,\mathrm{n/cm^2}$.
- The second irradiation campaign is underway, with the goal of producing the targeted fluence for the CUPID NTD-Ge thermistors.

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CUPID — CUORE UPgrade with Particle IDentification