

Search for a heavy neutral lepton with the MAGNETO- ν experiment using ^{241}Pu β^- decays

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(Received 31 August 2025; revised 20 November 2025; accepted 13 January 2026; published 26 February 2026)

The MAGNETO- ν experiment searches for keV-scale heavy neutral leptons (HNLs) through precise measurements of the β^- -decay spectrum of ^{241}Pu . We present spectra comprising a total of 194 million β^- decays recorded using decay energy spectrometry with metallic magnetic calorimeters, representing the most statistically precise measurement of ^{241}Pu β^- decay to date. The β -endpoint energy was determined using γ rays and x-rays from an external ^{133}Ba calibration source, yielding $Q_\beta = 22.273(33)$ keV. The measured spectrum shows no statistically significant deviation from the allowed β -decay model. From a subset of the high-statistics data, we set an upper limit on the mixing of an 11.5-keV HNL with the electron neutrino, $|U_{e4}|^2 < 1.31 \times 10^{-3}$ at the 95% confidence level.

DOI: [10.1103/4xt7-mdyv](https://doi.org/10.1103/4xt7-mdyv)

I. INTRODUCTION

High-precision β -decay spectra provide critical insight into nuclear and particle physics, enabling measurements of the neutrino's nonzero mass [1–7], studies of axial-vector coupling (g_A) quenching in nuclear decays [8,9], investigations of the reactor-neutrino anomaly [10], and searches for cosmic relic neutrinos [7,11,12]. Furthermore, β -decay spectra enable searches for new physics beyond the standard model, including hypothetical heavy neutral leptons (HNLs) with right-handed chirality [13–19] and possible scalar or tensor interactions in β decays [20,21].

The MAGNETO- ν experiment searches for HNLs in the 1–20 keV mass range by precisely measuring the β^- -decay spectrum of ^{241}Pu . HNLs within this mass range are viable candidates for warm dark matter [22,23]. With $Q_\beta \approx 22$ keV and a decay spectrum closely resembling that of an allowed decay, ^{241}Pu is a promising isotope for searches. The experiment employs decay energy spectrometry (DES) [24–26]

to measure nuclear-decay energy via temperature increases in the detector. DES offers a nearly unity detection efficiency for β particles across a wide energy range, minimizing systematic uncertainties from dead layers and the need for efficiency corrections. Our DES system uses metallic magnetic calorimeters (MMCs) as a thermometer. MMCs are the most linear cryogenic sensors available, making them ideal for precision β -spectral shape measurements [27–29]. This analysis is based on 194 million ^{241}Pu β^- decays, a statistical sample several hundred times larger than in previous measurements, representing the most precise ^{241}Pu β^- spectrum obtained to date.

This paper is organized as follows: Section II reviews the ^{241}Pu β^- -decay theory. Section III describes the experimental setup and operation. Section IV outlines data processing and analysis. Section V presents the measured ^{241}Pu Q_β value. Section VI reports the ^{241}Pu β^- -decay spectrum and corresponding HNL search based on the 194 million-decay dataset, and Sec. VII summarizes the conclusions.

II. β^- -DECAY OF ^{241}Pu

A. β Decay theory with heavy neutral leptons

Fermi's theory of β decay can be formulated as [9,30]

$$N(E, m_\nu)dw = \frac{G_F^2 \cos^2 \Theta_c}{2\pi^3} |M_{if}|^2 w p w_\nu \sum_\nu |U_{e\nu}|^2 p_\nu(m_\nu) \times F(Z, w) X(w) r(Z, w) C(w). \quad (1)$$

Here E denotes the β -particle kinetic energy, m_ν the neutrino mass eigenstate, G_F the Fermi constant, Θ_c the Cabibbo angle, and M_{if} the elements of the nuclear-transition matrix.

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The β -particle total energy and momentum are normalized to the electron rest mass m_e , with $w = E/m_e + 1$ and $p = (w^2 - 1)^{1/2}$. An antineutrino is emitted with a normalized total energy $w_\nu = w_0 - w$, where $w_0 = Q_\beta/m_e + 1$ defines the normalized endpoint energy. The neutrino mass m_ν modifies the normalized antineutrino momentum, $p_\nu = [w_\nu^2 - (m_\nu/m_e)^2]^{1/2}$. The total rate $N(E, m_\nu)$ is the sum of the degenerate contributions of different m_ν , each weighted by $|U_{e\nu}|^2$, where $U_{e\nu}$ are the elements of the Pontecorvo-Maki-Nagawa-Sakata (PMNS) matrix [31]. The Fermi function $F(Z, w)$ accounts for the Coulomb interaction between the emitted β particle and the daughter nucleus of charge Z [32,33]. The term $X(w)$ corrects atomic-screening and exchange effects arising from the indistinguishability of electrons in quantum mechanics.

Changes in atomic orbitals caused by nuclear decay also affect E ; the corresponding atomic-overlap correction is given by [33]

$$r(Z, w) = 1 - \frac{1}{w_0 - w} \frac{\partial^2}{\partial Z^2} B(G). \quad (2)$$

Together, $X(w)$ and $r(Z, w)$ enhance the low-energy region of the spectrum while suppressing the high-energy tail. The shape factor $C(w)$ reflects nuclear-structure effects and is typically determined experimentally from deviations relative to allowed decays. For ^{241}Pu , $C(w)$ is effectively unity and varies by no more than 0.3% over the relevant energy range [34].

In the massless limit $m_\nu \rightarrow 0$, the antineutrino momentum p_ν converges to w_ν , and Eq. (1) can be rearranged as

$$\sqrt{\frac{N(E, 0)}{pwF(Z, w)X(w)r(Z, w_0)}} \propto K(w_0 - w)\sqrt{C(w)}. \quad (3)$$

A Kurie plot compares the left-hand side of Eq. (3) with w (or equivalently E). For allowed β decays, the Kurie plot forms a straight, descending line with a slope K . The Q_β value is obtained from the intersection of the line with the energy axis.

A hypothetical HNL with a mass m_4 and an admixture $|U_{e4}|^2$ extends Eq. (1), such that the total differential rate R_β is

$$R_\beta(E, m_4, |U_{e4}|^2) = (1 - |U_{e4}|^2)N(E, m_\nu) + |U_{e4}|^2 N(E, m_4). \quad (4)$$

The first term represents the standard β -decay branch emitting active neutrinos, and the second term stands for the HNL-emitting branch. Figure 1 illustrates how a 10-keV HNL affects R_β . A hypothetical branch emitting an HNL has its endpoint shifted by m_4 (dotted line). This branch introduces a distinctive “kink” at $Q_\beta - m_4$ in the combined differential spectrum (solid line). Such a kink should be detectable in a β decay spectrum with high statistics and energy resolution.

B. ^{241}Pu β Decay

^{241}Pu β decay is a first-forbidden, nonunique transition with a measured partial half-life of 14.329 (29) years and a $Q_\beta = 20.78$ (17) keV [17,35,36]. The decay product ^{241}Am undergoes α decay with a half-life of 432.6 (0.6) years, which is much longer than that of ^{241}Pu [37]. Conversion and Auger

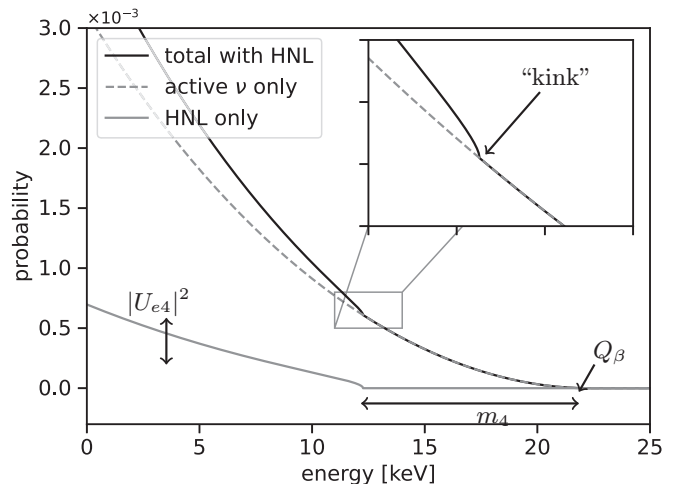


FIG. 1. HNL mixing signature in the ^{241}Pu β decay spectrum. Normal decays emitting active neutrinos terminate at Q_β (dashed), whereas decays emitting hypothetical HNLs with mass $m_4 = 10$ keV end at $Q_\beta - m_4$ (gray solid), near 12 keV. The total spectrum (black solid), given by the sum of both decay modes, exhibits a characteristic kink at the endpoint of the HNL branch. An unusually large admixture, $|U_{e4}|^2 = 0.2$, is used here for illustration.

electrons from ^{241}Am decays constituted major backgrounds in earlier magnetic-spectrometer measurements [17]. Besides the dominant β branch, ^{241}Pu undergoes a rare [0.00245 (1)%] α decay to ^{237}U with $Q_\alpha = 5140.0(5)$ keV. The daughter ^{237}U subsequently emits β particles [37]. ($t_{1/2} = 6.752(5)$ d, $Q_\beta = 518.6(5)$ keV). Figure 2 summarizes the decay scheme of ^{241}Pu .

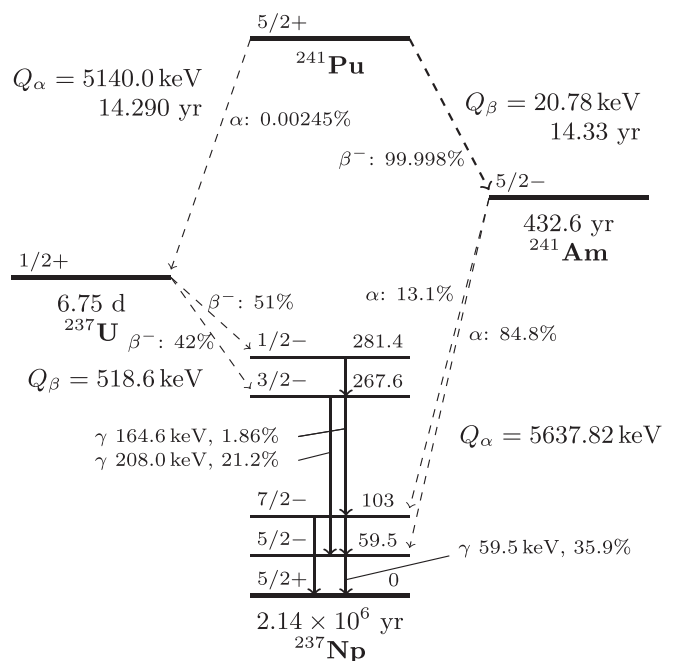


FIG. 2. Decay scheme of ^{241}Pu [35]. Most ^{241}Pu nuclei undergo β decay to ^{241}Am with $Q_\beta = 20.78$ (17) keV [36]. A small fraction undergoes α decay, producing ^{237}U , which subsequently β decays.

High-precision measurements of the ^{241}Pu β spectrum have important implications for fundamental physics:

- (1) The $Q_\beta \approx 20$ keV of ^{241}Pu is especially sensitive to ≈ 10 keV HNLs that could constitute warm dark matter.
- (2) Because its Q_β is among the lowest of known radionuclides, ^{241}Pu is an excellent candidate for direct neutrino-mass measurement: spectral distortion near the endpoint is more pronounced and easier to detect. Background from ^{237}U β decay can be suppressed by identifying and rejecting its coincident γ rays.
- (3) ^{241}Pu is also a promising target for cosmic-background-neutrino detection: its large capture cross section and low Q_β increase sensitivity. Successful detection additionally requires identifying and rejecting the ^{237}U β background.

A comparison with tritium is instructive. Both isotopes have $Q_\beta \approx O(20)$ keV. Like tritium, ^{241}Pu undergoes a single-branch β decay without accompanying γ or x-rays. This simplicity reduces systematic uncertainties and simplifies data interpretation. However, ^{241}Pu β decay differs from tritium in two key ways: (i) The heavy-nucleus recoil is much less energetic, reducing resolution broadening compared with tritium; and (ii) its decay energy arises mainly from rearrangement of atomic electrons rather than nucleon transitions [17]. These differences make ^{241}Pu -based experiments a complementary approach to tritium-based studies. At room temperature, ^{241}Pu is easy to handle in its solid form, whereas tritium typically requires specialized facilities to contain the radioactive gas.

The precise Q_β value of ^{241}Pu remains uncertain. The currently accepted value derives largely from theoretical estimates [38] and measurements of the mean decay energy [39]. Loidl *et al.* measured the ^{241}Pu spectrum with MMC-based DES and reported a Q_β value ≈ 0.8 keV above the accepted value [40]. However, they did not claim a discovery because (i) no calibration source was available above Q_β , and (ii) their model underpredicted data below 3 keV. Mougeot *et al.* later explained the low-energy excess by including atomic-screening and exchange effects [41,42]. The atomic overlap correction, which must be applied together with atomic corrections, implies that Q_β is ≈ 0.2 keV higher than the maximum kinetic energy of the β particle.

We conducted our own calculation of ^{241}Pu β -decay shape factor with the method described in Refs. [9,43,44]. Nuclear structure was determined with the NushellX code [45] using the *khpe* interaction in the *jj67pn* valence space [46]. The latter was restricted to limit computational burden, disregarding the proton $1i_{13/2}$ and neutron $1j_{15/2}$ orbitals. The dominant matrix element corresponds to the zeroth multipole order, making the spectrum weakly sensitive to any variation of the effective value of the axial-vector coupling constant g_A . A linear shape factor similar to that of [34] was found, with a maximum difference of 0.7%.

III. EXPERIMENTAL METHOD

A. Decay energy spectrometry with metallic magnetic calorimeter

DES is a state-of-the-art technique that measures the total energy released in a radioactive decay using cryogenic microcalorimeters [26]. It measures the temperature rise caused by the radioactive decays of a source embedded in a microscopic metallic absorber. The absorber, a thin gold foil, effectively stops charged decay products, including α and β particles and daughter nuclei, and converts their kinetic energy to heat. It provides a powerful method for accurately determining the β -decay spectral shape because of its excellent energy resolution, nearly 100% uniform detection efficiency, and the absence of a detector dead layer, which ensures a consistent response across the entire detection volume. DES is also unaffected by conversion and Auger electrons from ^{241}Am decays, which dominated the background in the magnetic-spectrometer experiment [17]. Electrons emitted in ^{241}Am decay always accompany an α particle and therefore appear as high-energy events near 5.6 MeV.

Among the microcalorimeter sensors for DES, an MMC is particularly well suited to high-precision β spectrometry due to its excellent linearity and reproducibility [28,29,47–49]. An MMC converts deposited decay energy into a change in magnetization: energy deposition heats conduction electrons in the absorber, which alters the spin ordering of paramagnetic Er^{3+} ions in the sensor material [50]. The signal conversion is highly linear over more than two orders of magnitude in energy, making MMCs ideal for mapping β -decay spectra across a broad range.

The best energy resolution achieved with MMCs to date is 1.25 eV full width at half maximum (FWHM) for 5.9 keV photons [51]. The MMCs used in the MAGNETO- ν experiment exhibit lower resolution because their absorbers are several orders of magnitude larger to contain the high-activity source and fully stop α particles. Future detectors with smaller absorbers distributed over many multiplexed pixels could potentially reach eV-scale resolution [52,53].

MMCs also provide comparatively faster response times than other microcalorimeters of similar absorber size. This advantage stems from the fact that decay energy couples to the sensor solely through conduction electrons, which maintain relatively high thermal conductivity at millikelvin temperatures. The rapid response enhances timing resolution and event separation, allowing faster data collection for improved statistical precision.

B. Source and absorber preparation

The ^{241}Pu source (Table I) was originally procured from Oak Ridge National Laboratory in 2009 and prepared at Lawrence Livermore National Laboratory (LLNL). On October 19, 2023, the source was purified using standard anion exchange chemistry to remove ingrown Am. Pu was dissolved in 8 M nitric acid, and the solution was then loaded onto a column packed with Eichrom AG1-X4 resin. The column was sequentially washed with 8 M nitric acid and 10 M hydrochloric acid. Pu was eluted from the column with a 10 M mixture

TABLE I. Isotopic compositions and relative activities of the MAGNETO- ν ^{241}Pu source (decay-corrected from original certification to 2 Jan., 2024).

	^{238}Pu	^{239}Pu	^{240}Pu	^{241}Pu	^{242}Pu
atom%	0.08	6.30	23.96	54.70	14.96
activity %	0.024	0.007	0.096	99.873	0.001

of hydrochloric acid and concentrated hydroiodic acid (10 : 1 volumetric ratio). The purified Pu was converted into nitrate form by evaporating concentrated nitric acid several times, and the resulting nitrate was dissolved in 4 M nitric acid. An aliquot was diluted to 0.09 M nitric acid and deposited onto a 4 mm $\times$ 6 mm $\times$ 25 μm gold foil using a micropipette for DES. The deposited solution, with a total activity of approximately 950 Bq, was evaporated at 80 $^{\circ}\text{C}$ on a hot plate. During the evaporation process, Pu-nitrate microcrystals could form, which temporarily absorb β -particle energy, distorting the β spectrum and degrading the energy resolution. To mitigate this, the gold foil was repeatedly folded and rolled with a jeweler's mill to break down Pu-nitrate crystals. The folding and rolling process was repeated 20 times. This mechanical-alloying technique reduced the crystal size and improved the energy resolution [54,55]. Finally, the foil was encapsulated with an additional 5- μm -thick gold layer to prevent electron and α -particle escape. The typical range of 20-keV β particles in gold is $\approx 1 \mu\text{m}$; thus a 5- μm -thick layer is sufficient to fully stop them. The thin gold layer also blocks $O(5)$ MeV α particles from actinide decays.

The gold foil was then divided into three pieces to reduce heat capacity and radioactivity. One of these pieces, labeled B-3, was then divided into two ≈ 1.6 mg pieces. The two pieces, named B-3.1 and B-3.2, were used for two detector setups, labeled Channel 0 and Channel 1. We measured α decays from the absorbers using an external α detector. The absence of detectable counts ($\ll 1$ cpm) confirmed negligible particle escape from the absorber, consistent with the Monte Carlo simulation presented below. The two samples were wire-bonded to MMC devices fabricated by the Korea Research Institute of Standards and Science (KRISS) in South Korea [56,57]. Table II summarizes the two detector setups used in Run 122.

TABLE II. Run 122 of detector configurations.

	Channel 0	Channel 1
Absorber mass (mg)	1.6 mg	1.6 mg
Trigger rate	90 cts/s	90 cts/s
Total counts	89×10^6	83×10^6
MMC chip	KRISS 1 mm	KRISS 0.5 mm
SQUID chip	Magnicon XS1W & X16W	
Rise time	0.45 ms	0.2 ms
Decay time	3.25 ms	2 ms
Signal size	$0.8 \Phi_0/\text{MeV}$	$0.6 \Phi_0/\text{MeV}$

The Geant4 Monte Carlo framework [58] was used to evaluate energy-loss mechanisms and their impact on the measured energy spectrum. Trajectories of 4×10^6 β particles with kinetic energies between 0.5 and 25.5 keV were simulated in a geometry closely matching the experimental absorber. The simulation employed Geant4's default FTFP_BERT_HP physics list, coupled with radioactive decays. Its standard electromagnetic physics was replaced with LLNL's low-energy electromagnetic models to accurately transport β particles down to 10 eV. This model also included bremsstrahlung via LLNL's Evaluated Electron Data Library (EEDL) [59]. The simulation confirmed that no β particles escaped the absorber. The main energy-loss mechanism was the escape of 9.9 and 11.8 keV Au L_{α} and L_{β} x-rays. The total fractional energy loss was $\approx 10^{-5}$ for 20 keV β particles, a negligible value that did not affect the measured spectrum.

C. Experimental setup

Figure 3 shows a schematic of the MMC-based DES system, comprising a ^{241}Pu -embedded absorber thermally coupled to an MMC sensor. The sensor was thermally linked to both the absorber and the thermal bath through 25- μm -diameter gold wires. An $O(10)$ keV electron emitted in ^{241}Pu decay raised the absorber temperature by approximately $O(10)$ μK at 10 mK. The thermalized energy was subsequently transferred to the Au:Er MMC sensor magnetized by a superconducting Nb coil. This transfer changed the sensor's temperature and magnetization, and the superconducting quantum interference device (SQUID) detected the corresponding change in magnetization. The gold-wire bonds controlled heat flow and shaped the typical DES signals $V(t)$, which follow the form

$$V(t) \propto e^{-t/t_r} - e^{-t/t_d}. \quad (5)$$

Here, t_r and t_d denote the signal rise and decay times, respectively. The lower-left panel of Fig. 3 shows representative α -decay pulses from the setup. The rise time depends on the absorber's heat capacity relative to its thermal conductance to the MMC sensor, and the decay time depends on the same heat capacity relative to its conductance to the heat bath.

The lower-right panel of Fig. 3 shows the experimental assembly. The absorber, MMC sensor, and SQUID chips were mounted on a copper holder with GE-Varnish. The assembly was enclosed in a superconducting Nb can to shield the SQUIDs from stray magnetic fields.

D. Data acquisition

The magnetic-flux signals from the MMC sensors were amplified by two SQUID stages in series, using XS1W and X16W units from Magnicon GmbH, Germany. The SQUIDs were operated in flux-locked-loop (FLL) mode using Magnicon's XXF-1 electronics. Most microcalorimeter experiments use the maximum FLL gain to maximize the signal amplitude relative to postamplifier noise, thereby improving energy resolution. However, this high-gain setting limits the measurable energy range because the output voltage range of XXF-1 is only 10 V. In this work, we prioritized a tenfold

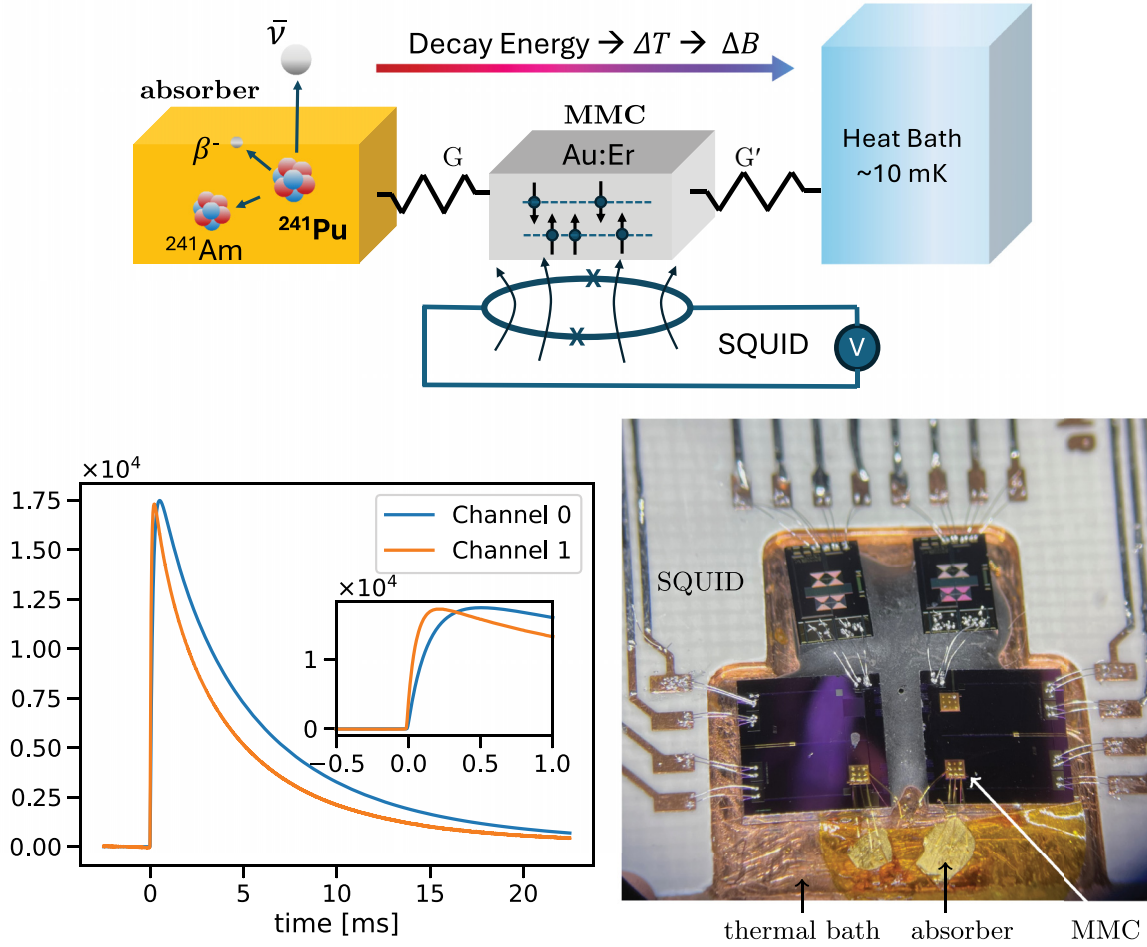


FIG. 3. (top) Principle of MMC-based DES. A ^{241}Pu nucleus embedded in a gold absorber decays, and the decay energy is transferred to the Au:Er MMC sensor, altering its magnetization. (left) Representative α -decay signals from Run 122. Inset shows an enlarged view of the pulse rise. Channel 1 pulses are faster due to the smaller heat capacity of its MMC. The y axis is in arbitrary units. (right) Photograph of the MAGNETO- ν setup.

expansion of the measurable energy range at the cost of lower SQUID gain and correspondingly reduced energy resolution. This compromise enabled simultaneous acquisition of low-energy ^{241}Pu β and high-energy α -decay signals. The α -decay signals were later used to correct sensitivity drifts and to provide background-free energy calibration. The FLL output voltages were fed into SR-560 low-noise preamplifiers [60], which also served as 100 kHz low-pass filters. The filtered waveforms were continuously recorded at 200 kS/s using a 14-bit NI PXIe-5172 oscilloscope unit [61] without hardware triggering to preserve complete data for offline software analysis.

The FLL electronics had limited bandwidth and occasionally lost lock during rapid flux changes following large pulses from α decays. Such losses produced sudden, discrete shifts in the FLL output voltage. These flux jumps modified the FLL feedback current, inducing subtle changes in the DES unit's temperature and sensitivity that required correction during analysis. The occurrence rate of SQUID flux jumps varied from once every few minutes to once every few hours, depending on the specific SQUID unit, bias conditions, and input signal amplitudes.

This study focuses on two datasets collected during the first phase of the MAGNETO- ν experiment. The ^{241}Pu β -spectrum shape and a preliminary HNL limit were derived from Run 122, which was acquired between December 25, 2023 and January 9, 2024 at 9 mK. The Q_β of ^{241}Pu was measured in Run 151 (September 9–13, 2024) at 20 mK using γ rays and x-rays from an external ^{133}Ba calibration source.

IV. DATA PROCESSING AND ANALYSIS

The initial phase of MAGNETO- ν required collecting more than one billion ^{241}Pu β decays, with a target rate of 100 Bq per detector, to achieve optimal sensitivity to $O(10)$ keV HNLs. Recording an unbiased energy spectrum for both β and α decays at such a high trigger rate is particularly challenging in microcalorimetry because of accidental coincidences. Rather than the optimal-filtering method commonly used in microcalorimeters, we employed trapezoidal shaping, which efficiently processes pulses shorter than a single decay time. Figure 4 shows a raw ≈ 18 keV pulse waveform and its two trapezoidally shaped versions: a short pulse for triggering (green) and a long pulse for amplitude

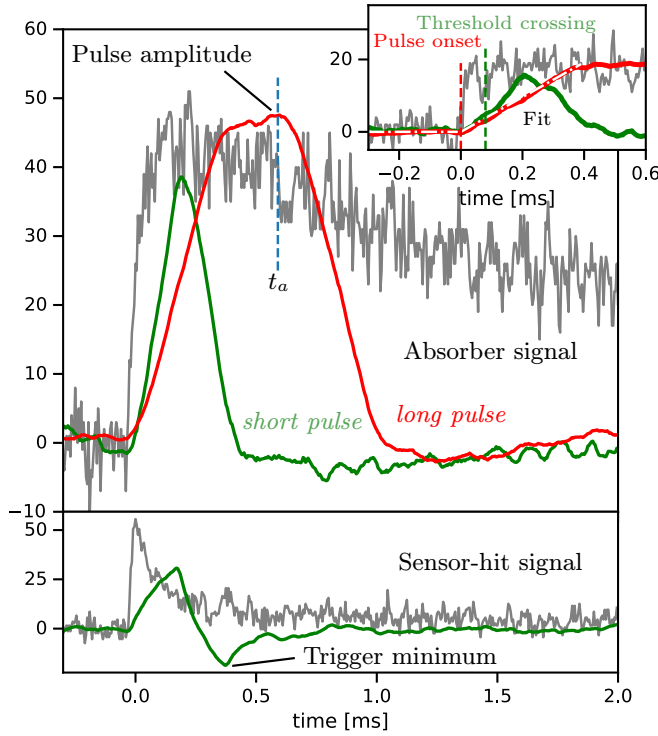


FIG. 4. (top) Raw Channel 1 pulse (gray) with corresponding short- (green) and long- (red) trapezoid-shaped pulses. Pulse amplitude is measured at t_a (blue dashed) on the long pulse. (inset) Enlarged view of a smaller pulse showing that the raw pulse begins (red dashed) 0.08 ms before the short pulse crosses threshold (green dashed); $t = 0$ is defined by linear fits (white dot-dashed) to the long pulse. (bottom) A sensor-hit signal rises and decays faster than a typical absorber signal in the top panel. All y axes are in arbitrary units.

measurement (red). These shaped pulses allow us to precisely determine the pulse amplitudes while minimizing bias from the trigger threshold and the amplitude dependence.

A. Triggering and efficiency

We employed a software trigger to detect pulses within the continuously recorded raw data stream. The short pulse was shaped with a peaking time comparable to the signal rise time t_r [62]. Each trigger was followed by dead times of 1.25 and 1 ms for Channel 0 and Channel 1, respectively. A much longer 125 ms dead time was applied after large pulses following α decays or SQUID flux jumps. This was necessary because the undershoot of the short pulse following such events would otherwise reduce the trigger efficiency for low-energy events. Because the DES detector provides nearly 100% quantum efficiency for 20 keV β signals, dead-time losses were the dominant source of inefficiency.

The triggering efficiency was estimated by injecting synthetic pulses into the recorded data and counting how many were detected by the same software-trigger algorithm. Pulse templates were generated by taking the median of normalized, triggered signals. The templates were sufficiently long (125 ms for Channel 0 and 75 ms for Channel 1) to capture the

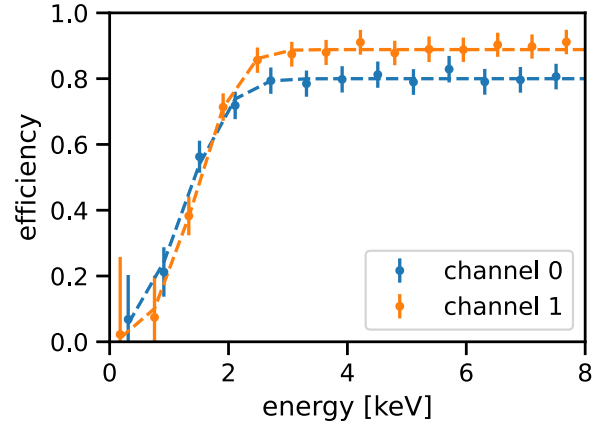


FIG. 5. Run 122 trigger efficiencies with best-fit sigmoid curves. Trigger dead time limited the asymptotic efficiency.

full decay. A subset of raw data was selected, and simulated pulses with random amplitudes and timestamps were added at a rate of 1 Hz. The resulting “salted” data were processed with the same trigger parameters as the original dataset. The efficiency was calculated as the fraction of injected signals successfully detected. Figure 5 shows the estimated efficiencies and their best-fit sigmoid curves. The centers of the best-fit sigmoid functions were 1.23 and 1.43 keV for Channel 0 and Channel 1, respectively. The efficiency saturated at 0.800 for Channel 0 and 0.888 for Channel 1 above 2 keV, limited by the trigger dead time.

B. Amplitude calculation

We used the fixed-point-amplitude method to extract pulse amplitudes. The method measured the long-pulse value at a fixed time interval t_a after the pulse began, minimizing bias in low-energy signals. In contrast, the conventional approach measures the maximum height of the trapezoid-shaped pulse, which tends to overestimate small-pulse amplitudes because noise adds a fixed width to the shaped waveform, a contribution that becomes proportionally larger for weaker signals.

To generate the long pulse, we subtracted the median pre-trigger baseline from each triggered waveform and applied a longer peaking time to suppress high-frequency noise. The shaping also included a pole-zero (PZ) correction for the decay time t_d and a flat-top interval comparable to t_r to capture the full pulse height. The flat-time and PZ parameters were tuned to flatten the long pulse near t_a , making the amplitude estimation robust against small jitters in determining the pulse start.

The fixed-point-amplitude method required a precise and unbiased determination of the pulse start. The simplest raw timestamp, when the trigger pulse crossed the threshold, varied with pulse amplitude and trigger level. The inset of Fig. 4 shows that the short pulse crosses the threshold after the raw pulse has already started. This delay was more pronounced for smaller pulses, whose short-pulse rise was slower, causing their amplitudes to be measured later than intended. To correct for this, we adopted the pulse-onset method of Ref. [63] as the timing reference: the pulse onset t_0 was defined as the

intersection of a linear fit to the rising edge of the long pulse with the mean pretrigger baseline (white dot-dashed lines). This approach improved timing accuracy beyond the digitization limit by using the entire rising edge of the long pulse. The pulse amplitude was extracted at t_a after t_0 , where t_a equaled the peaking time plus 80% of the flat-top duration. Figure 4 shows t_a (0.59 ms) located at the right edge of the flat-top region.

Baseline resolution was evaluated from noise traces processed identically to real pulses. The noise amplitudes were centered near zero: -0.100 (0.348) keV and -0.073 (0.387) keV for Channel 0 and Channel 1, respectively. The standard deviations of these distributions define the baseline resolutions, corresponding to FWHM values of 0.820 keV for Channel 0 and 0.911 keV for Channel 1. Beyond the baseline, the DES energy resolution increased approximately linearly with energy, primarily due to residual errors from the correction steps described in Sec. IV D.

C. Artifact removal

The data contained several types of artifacts, which were rejected based on their distinct pulse shapes. These artifacts included (i) direct hits from external radiation on the MMC sensor, (ii) SQUID flux jumps, and (iii) events occurring on the opposite side of the gradiometric MMC. Most of these artifacts exhibited rise and decay times shorter than 10 μ s, and their short pulse showed an abnormally large negative amplitude, as evident in the bottom panel of Fig. 4. The top panel of Fig. 6 compares these trigger minima with the amplitudes of the long pulse. For a given amplitude, artifacts exhibited much larger trigger minima than normal pulses originating from the absorber. Events lying below the blue dashed line were therefore rejected. This cut removed fewer than 3×10^{-6} of events at 4 keV, a negligible fraction compared with the statistical uncertainty. Artifacts with small amplitudes could still pass the cut and contribute marginally to the dataset, so data below 4 keV were excluded.

D. Sensitivity-drift corrections

The primary source of systematic error in our system was time-dependent variation in detector sensitivity. This variation arose because the detector temperature drifted over time, and the DES signal amplitude is inversely proportional to temperature: higher temperatures increase the heat capacity and reduce the signal size. To correct for this effect, we measured the correlation between the signal baseline, used as a proxy for the MMC sensor temperature, and the α -decay signal amplitudes. This correlation was then applied to correct the sensitivity drifts in all nearby events. Figure 7 summarizes the detailed steps of this procedure, referred to as the baseline correction. After the initial baseline correction, a smaller residual fluctuation remained. It was characterized using a rolling median of 200 ^{241}Am α decays at 5637.8 keV and applied to correct the sensitivity drift in nearby events. The correction sequence was repeated for each interval between SQUID flux jumps to account for subtle variations in detector conditions following each flux jump.

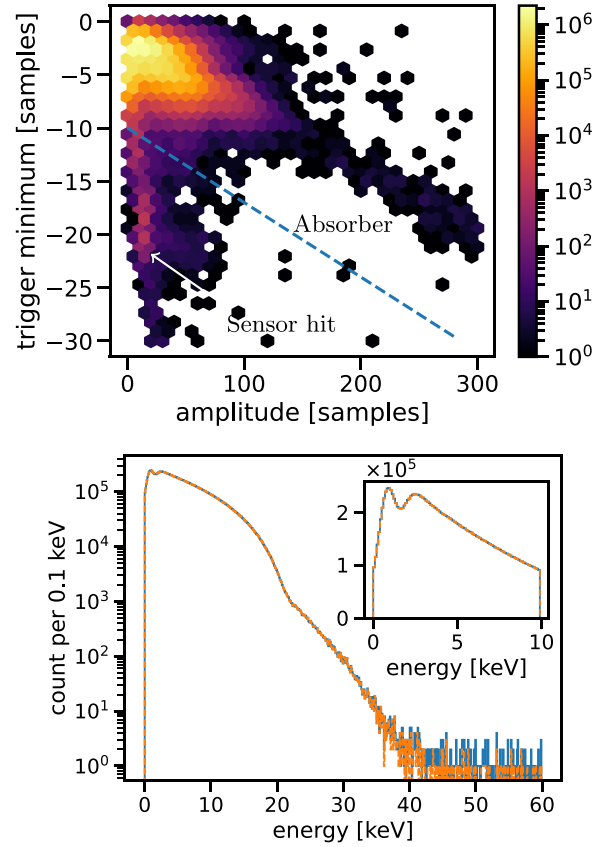


FIG. 6. (top) Histogram of the long-pulse amplitude (x axis) versus the trigger minimum (y axis) for low-energy events in Channel 1. Normal absorber events appear above the dashed line, whereas sensor-hit events lie below and are excluded from further analysis. (bottom) Energy spectra before (solid blue) and after (dashed orange) the cut are shown. The inset provides an expanded view of the spectrum below 10 keV on a linear scale.

E. Energy calibration

A major challenge in energy calibration for DES-based precision β spectrometry is Compton scattering from the calibration photons. While the DES absorbers are sufficiently thick to stop charged particles, they cannot fully absorb photons with energies comparable to the β spectrum. As a result, Compton scattering inevitably introduces additional counts and distorts the spectral shape. Although one can alternate external photon calibration sources on and off, ensuring calibration consistency and correcting sensitivity drifts during the off periods, when no monoenergetic reference lines are available, remains challenging. To address this issue, the energy calibration for Run 121 used monoenergetic actinide α decays from ^{238}Pu , ^{239}Pu , ^{240}Pu , ^{242}Pu , and ^{241}Am . As described in Sec. III B, these isotopes were part of the existing ^{241}Pu source in the absorber, and their decays did not produce signals within the ^{241}Pu β -decay region.

The amplitudes of these α decays were extracted from the peak centroids of the intrinsic detector response modeled with an exponentially modified Gaussian (EMG). Because energy deposited in the source crystal thermalizes slowly, a portion does not reach the gold absorber within the signal window,

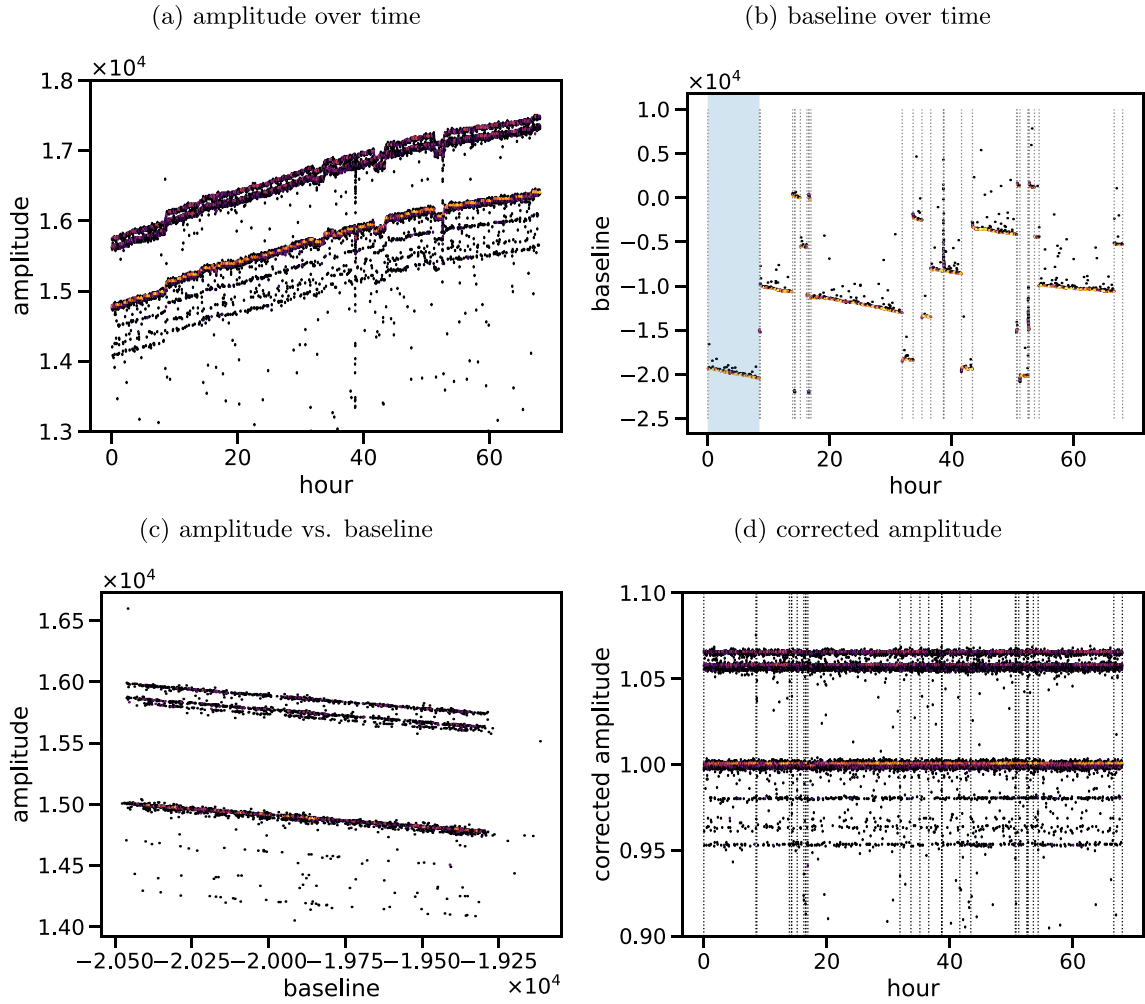


FIG. 7. Baseline-correction procedure. (a) α -decay amplitudes increase over time as the detector's sensitivity rises. (b) The pretrigger baseline decreases over time. SQUID flux jumps (vertical dotted lines) produce spontaneous baseline shifts. (c) An anticorrelation between the α -decay amplitude and the baseline in the first time interval [blue-shaded region in panel (b)] is measured and used to correct the sensitivity drift of all nearby events. (d) This correction is repeated for each time interval, yielding α amplitudes with reduced scatter over time.

causing the measured energies to fall below the true decay energy. To model this behavior consistently, a composite EMG function with one Gaussian width and two exponential decay constants was applied to all α peaks. Figure 8 shows the example of ^{241}Am and ^{238}Pu α -decay peaks accurately fitted with the composite-EMG detector response function. Low-energy β decays could also experience similar signal deformation. We estimate the maximum energy loss of 20 keV β particles to be 24 eV based on a comparison of the stopping powers of 20 keV β particles and 5 MeV α particles in a plutonium matrix, as reported in the NIST database [64].

We used a quadratic calibration function to describe the MMC response:

$$E = p_1(e - e_0) + p_2(e - e_0)^2. \quad (6)$$

Here, e denotes the measured amplitude and E the corresponding true energy in keV. The parameter p_1 denotes the gain, and p_2 characterizes the nonlinearity, primarily arising from the temperature-dependent susceptibility of MMC. The

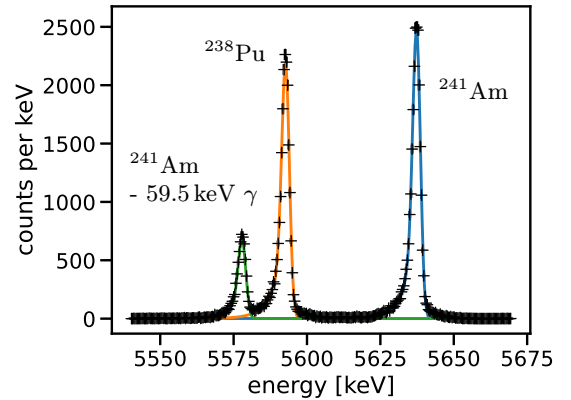


FIG. 8. ^{241}Am (5637.82 keV) and ^{238}Pu (5593.27 keV) peaks from Channel 1 with fitted EMG functions. ^{241}Am α decays also produce a 5578.28 keV peak when a 59.5 keV γ ray escapes the absorber without depositing its full energy.

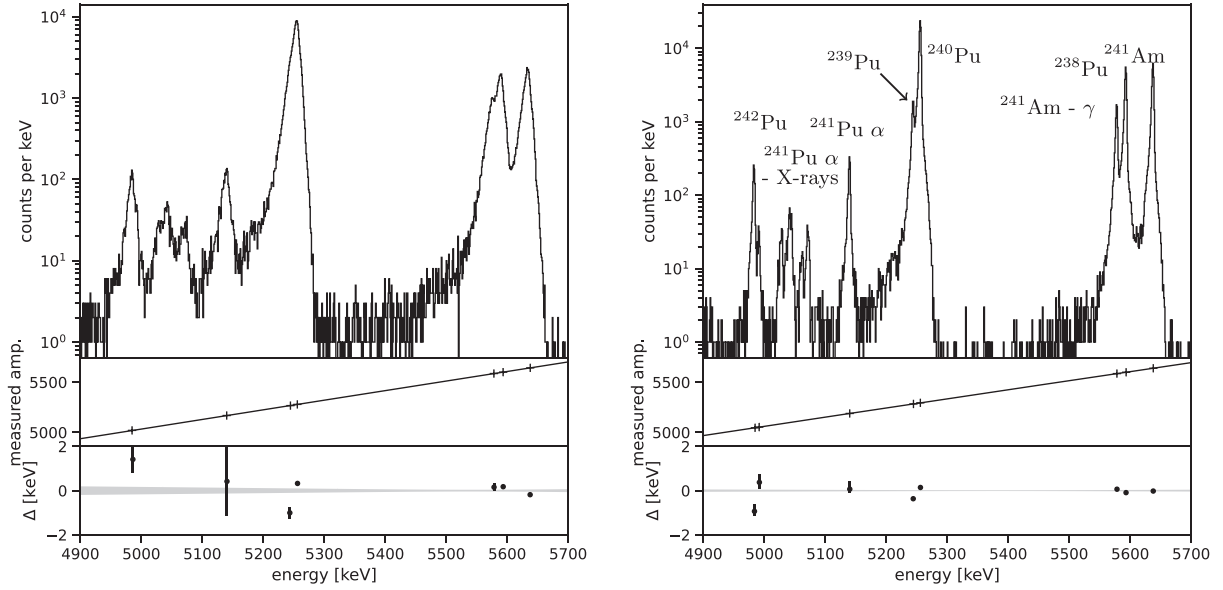


FIG. 9. (top) α -decay peaks in Channel 0 (left) and Channel 1 (right). (middle) Measured α -peak centroids with literature values. Solid lines show the best-fit detector responses. (bottom) Calibration residuals in keV with 1σ error bars. Gray bands represent calibration uncertainties. Discrepancies in ^{239}Pu and ^{240}Pu peak energies are likely due to errors in literature values, consistent with patterns observed in other independent MMC-based DES spectra (not shown).

term e_0 corresponds to the noise amplitude ($E = 0$) distribution defined in Sec. IV B and served as the low-energy calibration point. The values of p_1 and p_2 were obtained by comparing the measured α -peak centroids with literature energies. Equation (6), using the best-fit parameters, was applied to convert measured amplitudes to true energies. The detector responses remained highly linear. Nonlinearity contributed 0.022% (Channel 0) and 0.050% (Channel 1) at 22 keV, increasing to 5.0% and 11.4% at 5 MeV.

We note that this calibration had a limitation at the β energies of interest because most reference peaks lay at much higher energies of $O(5)$ MeV. Although MMCs exhibit excellent linearity, the lack of calibration points near the β region could introduce systematic uncertainties from higher-order nonlinearities beyond the quadratic term that could not be constrained by the α -decay peaks or the noise amplitudes alone. Because the HNL search is primarily sensitive to spectral-shape distortions, uncertainties in the absolute energy scale play only a minor role. Nevertheless, we rescaled the calibrated spectrum using the independently measured Q_β to ensure accurate comparison with theoretical beta-decay spectra and HNL models.

F. α -decay spectra

Figure 9 presents the final α spectra from Run 122. Channel 0 and Channel 1 contain 2.2×10^5 and 1.7×10^5 α decays, representing an unprecedented statistical sample. The peaks correspond to α decays of ^{242}Pu , ^{241}Pu , ^{240}Pu , ^{239}Pu , ^{241}Am with 59.54 keV γ -ray escape, ^{238}Pu , and ^{241}Am . The middle panels compare the measured peak amplitudes with literature energies. The calibration curves between these values are nearly linear. The lower panels display the calibration residuals. The error bars represent combined uncertainties from centroid determination and literature energies. The gray

bands indicate detector calibration uncertainties. All peaks align within 2 keV for Channel 0 and 1 keV for Channel 1. The FWHM values of the α peaks are 10.8 keV (Channel 0) and 2.9 keV (Channel 1). Channel 0 did not clearly resolve peak doublets such as ^{239}Pu and ^{240}Pu because of its inferior energy resolution. This broader resolution is attributable to slower signal rise times, more frequent SQUID flux jumps, every few minutes instead of hours, and less precise baseline-dependent sensitivity corrections. These combined effects lead to a larger calibration uncertainty for Channel 0.

Figure 10 displays the total energy spectrum from Run 122 for both channels. At low energies, most events originated from ^{241}Pu β decays, and accidental coincidences produce a broad hump above 20 keV. The flat background from 40 to 518.6 keV arose mainly from ^{237}U β decays. The peaks around 5 MeV correspond to α decays, as discussed in Fig. 9.

V. ^{241}Pu Q_β MEASUREMENT

The Q_β value of ^{241}Pu was determined in an independent experimental run, Run 151, using an external ^{133}Ba calibration source. Positioned outside the cryostat, the source irradiated the detector with 30.97313 (46) keV and 30.62540 (45) keV ^{133}Cs $K_{\alpha 1}$ and $K_{\alpha 2}$ x-rays through thin aluminum windows [65]. Below the ^{241}Pu Q_β , the same source's 80.9979 (11) keV γ ray produced escape peaks at 12.191 and 14.005 keV, corresponding to the escape of 68.8069 (22) keV and 66.9930 (23) keV Au $K_{\alpha 1}$ and $K_{\alpha 2}$ fluorescence x-rays from the absorber. Interpolation between these peaks provided a precise determination of Q_β . To isolate the intrinsic β spectrum, measurements were performed both with and without the γ -ray source under identical conditions in the same run, enabling a direct comparison and a Q_β determination free from γ -induced effects.

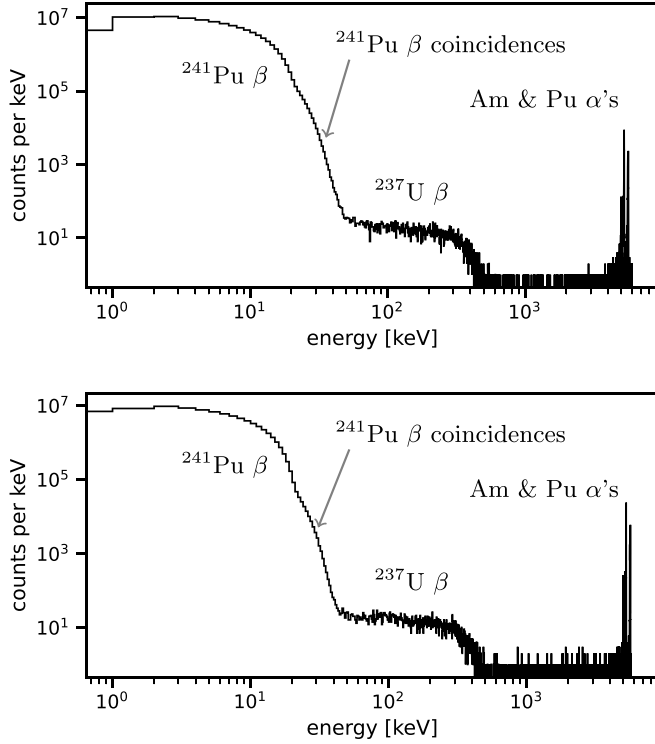


FIG. 10. Total-energy spectra from Run 122 for Channel 0 (top) and Channel 1 (bottom).

The measured data were processed using the same methodology as Run 122, with optimizations for the energy resolution near Q_β . The sensitivity drift was corrected using the internal α decays. We calibrated the detector by fitting Eq. (6) to the source-on data without the e_0 constraint, using a local rather than global calibration to suppress systematic uncertainty from the nonlinearity of the analog-to-digital converter (ADC) [66]. The resulting calibration was then applied to the source-off data. The top panel of Fig. 11 shows the energy spectra from Run 151, and the bottom panel confirms the accuracy of the quadratic fit via the residuals. The calibration uncertainty at 22 keV was 12 eV.

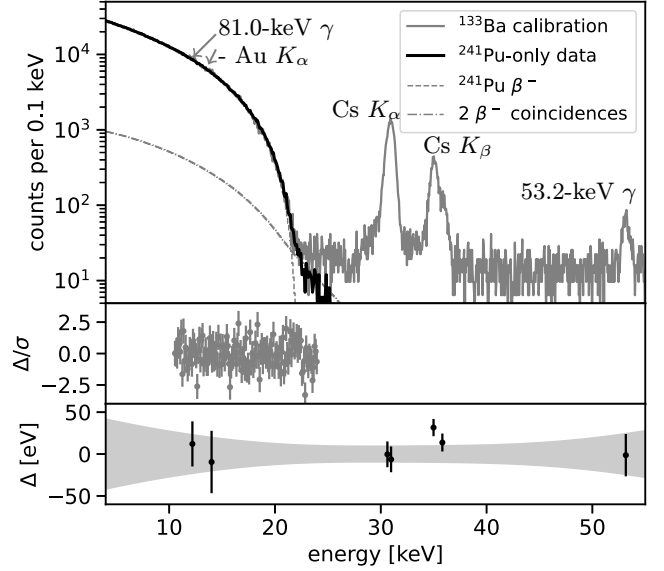


FIG. 11. (top) Run 151 spectra with (gray) and without (black) the external ^{133}Ba source. The source-on spectrum includes x-ray and γ -ray peaks. The source-off spectrum is fitted with ^{241}Pu β -decay model (dashed gray) and its double-coincidence model (dot-dashed gray). (middle) Residuals of the source-off spectrum. (bottom) Calibration residuals and uncertainty.

For the Q_β analysis, the source-off data were fitted with Eq. (1) over 10.5–24.5 keV. The fit included a background model for accidental coincidences of two ^{241}Pu β decays, as detailed in Sec. VIA. The energy resolution, $\sigma_{151} = 0.268$ (24) keV, was estimated by analyzing the 12.191 keV $K_{\alpha 1}$ escape peak and the 53.1622 (6) keV γ peak. The Lorentzian broadening of the $K_{\alpha 1}$ peak was 24 eV and therefore negligible. The estimated σ_{151} was incorporated into the fit as a Gaussian constraint. The best-fit result, obtained by minimizing the extended binned negative log-likelihood (NLL) and shown in Fig. 11, yielded

$$Q_\beta = 22.273(33) \text{ keV}. \quad (7)$$

TABLE III. ^{241}Pu Q_β uncertainty budget.

Source	δQ_β (eV)	$\delta Q_\beta / Q_\beta$ (%)	Comment
Statistical	15	0.067	Uncertainty from the fitting process.
Energy calibration	8	0.036	From the calibration uncertainty band in the bottom panel of Fig. 11.
Energy resolution	3	0.013	From the 24 eV uncertainty of the 12.191 keV $K_{\alpha 1}$ escape and 53.162 keV γ peaks; indirectly included in the total uncertainty through the statistical term.
Atomic overlap correction factor B''	12	0.054	Derived from the 5% theoretical uncertainty of B'' .
Background	25	0.112	Change in coincidence background when extending the fit range to 10–27 keV.
β coincidence model	5	0.022	Difference relative to a model using $Q_\beta = 21.6$ keV instead of 22.273 keV.
Total	33	0.150	Combined in quadrature.

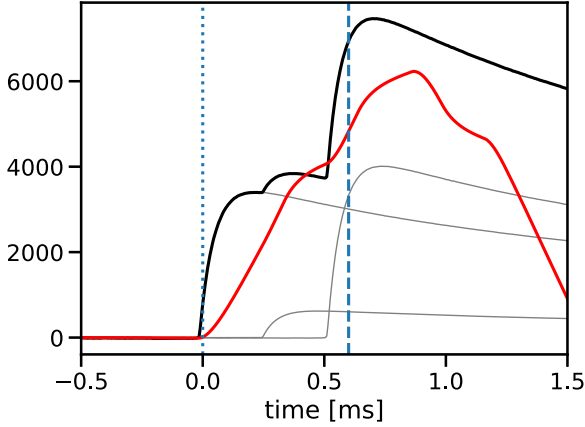


FIG. 12. Accidental-coincidence modeling. Coincidence waveform (black) is the sum of three constituent pulses (gray) with random onset times and amplitudes. This waveform was processed identically to the Run 122 data (see Fig. 4), yielding long pulse (red). Pulse-onset time t_0 (dotted) is measured from the first constituent pulse, and the amplitude is extracted at t_a after t_0 (dashed).

This value differs from the accepted 20.78 (17) keV and remains higher than the value reported by Loidl *et al.* [40]. Table III summarizes the uncertainty budget for this measurement. Uncertainties were evaluated by repeating the analysis with slightly varied input parameters; for example, Q_β shifted by 12 eV when the atomic-overlap correction factor $B'' = \frac{\partial^2}{\partial Z^2} B(G)$ was changed by 5%. The total variance was calculated as the quadratic sum of the individual contributions. Without the overlap correction, directly comparable to Loidl *et al.*, the result was $Q_\beta = 22.04$ keV.

VI. ^{241}Pu β DECAY SPECTRUM SHAPE AND HNL SEARCH

We used the Run 122 low-energy spectra to measure the ^{241}Pu β decay spectral shape and to search for HNLs. The spectra were calibrated using the Q_β value determined in Run

151, and they were compared with theoretical models and the previous measurements of Loidl *et al.* [40]. Finally, we constrained the possible admixture of HNLs by comparing the measured spectra with a series of HNL hypotheses.

A. Spectrum model

The spectrum model R_{active} represents the low-energy population as the sum of single-decay events, R_β , and background contributions, R_{bg} :

$$R_{\text{active}}(E) = n_1 N(E, Q_\beta) + R_{\text{bg}}(E, n_2, n_3, n_{^{237}\text{U}}). \quad (8)$$

$N(E, Q_\beta)$ follows Eq. (1), but its amplitude n_1 and endpoint energy Q_β are free parameters, while m_ν is fixed to the accepted neutrino masses. R_{bg} accounts for the accidental coincidences of two or three ^{241}Pu β decays of amplitude n_2 and n_3 and a nearly flat component from ^{237}U β decays [42]. Finally, $R_{\text{active}}(E)$ is convolved with a Gaussian response function [67] with a standard deviation σ to account for detector energy resolution.

B. Accidental coincidences

The dominant low-energy background arose from the accidental coincidences in the Run 122 spectra. At the ≈ 90 cts/s trigger rate and with the processing windows of 1.25 and 1 ms, the total coincidence probabilities are 15.2% and 10.3% for Channel 0 and Channel 1, respectively. Developing analysis cuts for these events was challenging because the cut efficiency significantly decreased at low energies, where the signal-to-noise ratio was reduced.

Instead, we constructed coincidence spectra by reproducing coincidence waveforms using a statistical model and pulse templates. We generated ten million simulated coincidence waveforms, each composed of two or more constituent pulses. The amplitudes of the constituent pulses were randomly sampled from the best-estimate theoretical β -decay model, and their timestamps were assigned randomly. The resulting coincidence waveforms were processed in the same manner as the Run 122 data, and the corresponding amplitude distribution

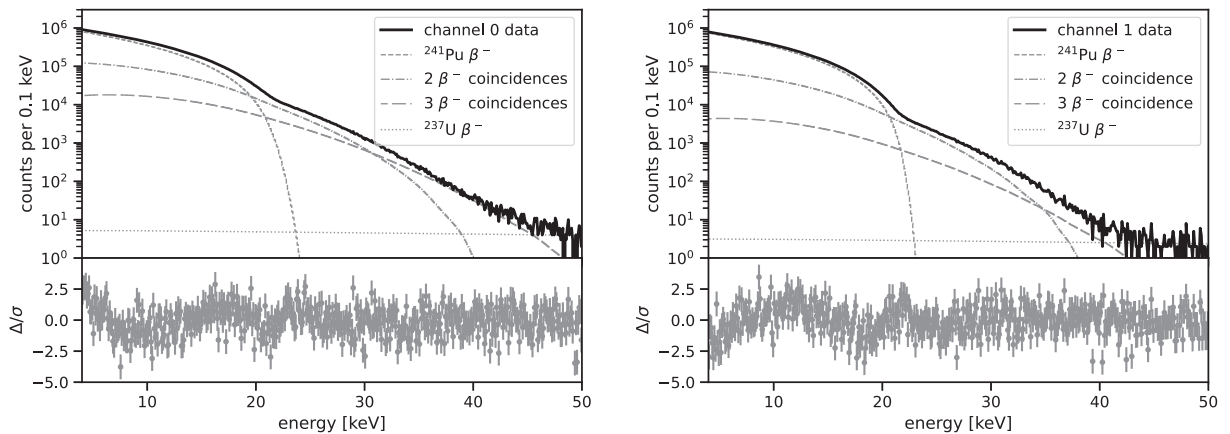


FIG. 13. Fits to the measured data from Channel 0 (left) and Channel 1 (right). Each fit includes contributions from ^{241}Pu β decays, accidental coincidences, and ^{237}U β decays. Bottom panels show the fit residuals, where positive values indicate that the observed data exceed the model prediction.

TABLE IV. Run-122 low-energy data fit results.

Fit parameter	Channel 0	Channel 1
σ [keV]	0.736 (14)	0.531 (15)
Single β	$85.51 (9) \times 10^6$	$80.38 (7) \times 10^6$
Two β coinc.	$15.81 (12) \times 10^6$	$8.61 (9) \times 10^6$
Three β coinc.	$2.95 (4) \times 10^6$	$0.65 (3) \times 10^6$
Total ^{241}Pu β	$104.27 (15) \times 10^6$	$89.64 (12) \times 10^6$
^{237}U β decays	$2.67 (2) \times 10^3$	$1.60 (13) \times 10^3$

defined the accidental-coincidence model used in R_{bg} . An example coincidence waveform and its corresponding trapezoidal shaping are shown in Fig. 12.

C. Low-energy calibration

The low-energy Run 122 spectra were rescaled so that their Q_β values matched those from Run 151. Fitting Eq. (8) to the Run 122 spectra before rescaling yielded Q_β values of 22.050 and 21.645 keV for Channel 0 and Channel 1, respectively. The deviations from the Run 151 result, attributed to higher-order nonlinearities, were modest at 1.0%–2.8%, indicating that Eq. (6) remained a good description of the response. Several features of the data enable such linear rescaling. The fitted Q_β values were derived from the full spectral shape and carried small statistical uncertainties of 4 and 5 eV, providing precise calibration points. The detector response was highly linear over the fitted range, since the quadratic calibration canceled most of the residual nonlinearity. Finally, the calibration simultaneously accounted for the zero-energy offset by incorporating the measured noise amplitude.

D. ^{241}Pu β decay spectrum shape

We measured the ^{241}Pu β decay spectral shape and performed HNL searches by fitting Eq. (8) to the rescaled Run 122 spectra over the 4–50 keV range. The fits are shown in Fig. 13, and the corresponding best-fit parameters are

summarized in Table IV. Above 6.5 keV (Channel 0) and 8.5 keV (Channel 1), the spectra were statistically consistent (p value > 0.05) with $R_{\text{active}}(E)$, and most residuals in the lower panels lay within 3σ . The fit quality degraded at lower energies, as indicated by the increasing residuals. Because the residuals from Channels 0 and 1 were uncorrelated, we attributed these discrepancies to systematic effects, such as ADC nonlinearity and temperature-dependent signal-shape variations [68], rather than to an energy-dependent shape factor or the presence of HNLs. The best-fit σ exceeded the baseline resolution, likely due to uncertainties in the sensitivity-drift correction across datasets.

Figure 14 shows the background-subtracted ^{241}Pu β spectra for clearer visualization, with theoretical allowed-decay spectra overlaid for comparison. The lower panels display the same data as the Kurie plots. The Kurie factors include all atomic corrections, following Eq. (3), so the allowed decays appear linear. The measured spectra again agree closely with the allowed-decay model, showing no significant evidence of an energy-dependent shape factor.

Finally, Figure 15 compares the Channel 0 spectrum with that of Loidl *et al.* (LNHB) [40]. For direct comparison, the LNHB spectrum is linearly scaled with a constant-background component, and the MAGNETO- ν spectrum is rescaled to match the Q_β value. The two spectra show good agreement ($\chi^2/\text{n.d.f} = 1.2$).

E. ADC nonlinearity

The residuals in Fig. 13 are small (on the order of 0.1%), yet they can still affect the HNL-search sensitivity. A plausible source of these residuals is the nonlinearity and nonuniformity of the ADCs used in the experiment. This effect is well documented in cryogenic-microcalorimeter studies, with multiple prior cases reported [63,66,69,70]. Uneven ADC binning can distort spectra, particularly when signals occupy only a small fraction of the full input range due to a wide dynamic range. For instance, a 5-keV signal spanned $\approx 0.03\%$ of the full input voltage range of the Run 122 setup.

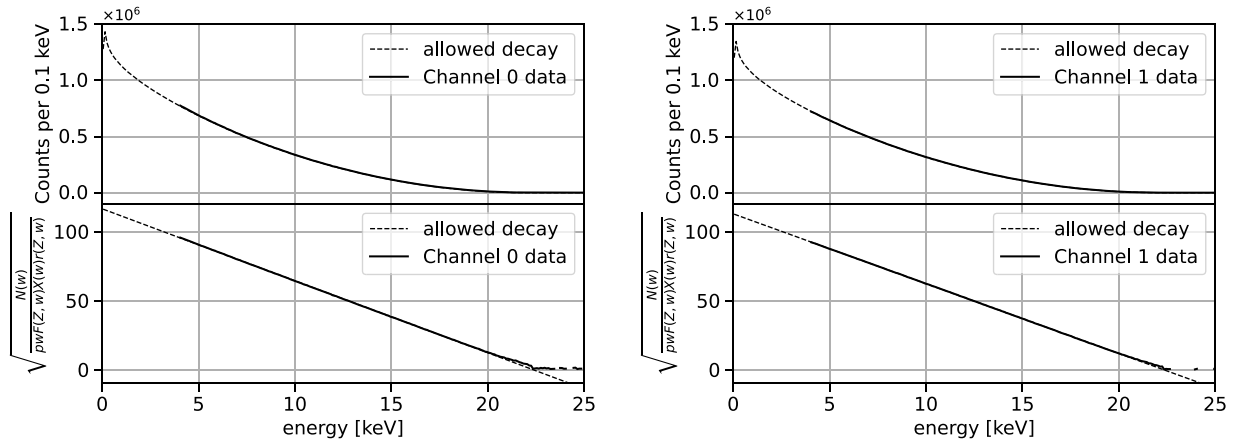


FIG. 14. Background-subtracted ^{241}Pu β decay spectra for Channel 0 (left) and Channel 1 (right). Top panels show the β differential rate on a linear scale, and bottom panels present the corresponding Kurie plots, in which the allowed decay model appears linear. Spectra from both channels agree closely with the allowed decay model when atomic corrections are included.

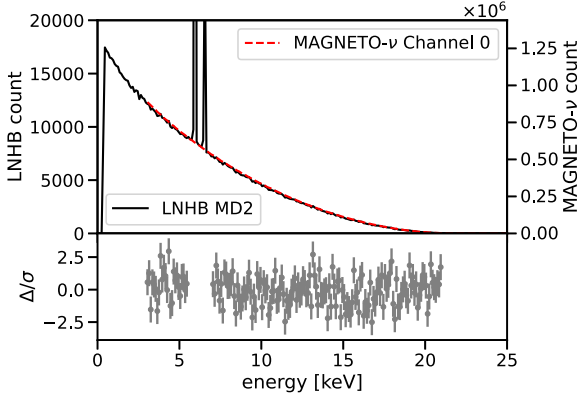


FIG. 15. Comparison of ^{241}Pu β spectra from Loidl *et al.* [40] (LNHB, black) and from MAGNETO- ν Channel 0 (red). The Loidl spectrum includes ^{55}Mn x-ray calibration peaks. The Channel 0 spectrum is plotted on a separate y axis (right) for direct visual comparison. Bottom panel shows the fit residuals.

Figure 16 reveals a potential correlation between the observed residuals and the signal baseline. It shows the residuals of Channel 0 data across energy and baseline. In particular, data near ADC channel $-15\,000$ counts (black arrow) exhibit a distinct residual pattern compared with the rest of the distribution, indicating stronger ADC nonlinearity in this range. Because most events fell near this baseline, these residuals dominated the overall pattern. The high statistical precision of the data further accentuated these residuals. Future work will focus on characterizing and correcting ADC nonlinearity [71] and refining the data-acquisition scheme to mitigate its impact. The PXIe-6356 digitizer, used for the remaining MAGNETO- ν data, is reported to exhibit a more linear response [70].

F. HNL search

To search for HNLs, we compared the test statistic of each HNL hypothesis with that of the null hypothesis ($|U_{e4}|^2 = 0$). Our signal model incorporates the effects of ADC

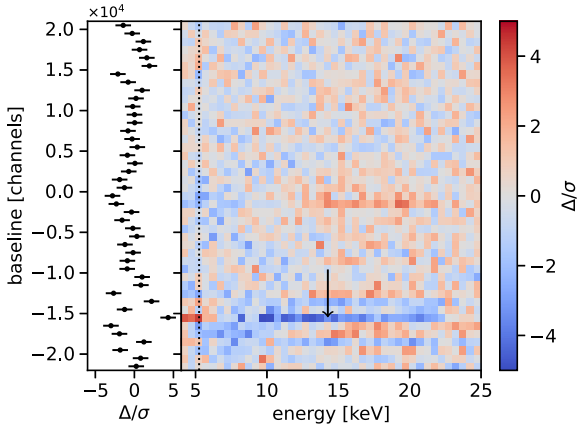


FIG. 16. Residuals of Channel 0 data as a function of energy and baseline. Left panel shows the variation of residuals at different baselines for 5.25 keV (vertical dotted line in the main panel).

nonlinearity, which can distort the spectral shape but preserves the total event count. A quadratic function with three free parameters provides the simplest such representation:

$$\lambda_{\text{ANL}} = j(E - h)^2 + k, \quad (9)$$

where h , j , and k are free fit parameters. These nuisance parameters improve the model fit but reduce the overall HNL-search sensitivity. The signal model is defined as the normalized product of R_β [Eq. (4)] and λ_{ANL} :

$$\tilde{R}_\beta(E, m_4^2, |U_{e4}|^2) = \text{Norm}(R_\beta \lambda_{\text{ANL}}). \quad (10)$$

The sum of $\tilde{R}_\beta(E, m_4^2, |U_{e4}|^2)$ and R_{bg} forms the total expected spectral model:

$$R_{\text{HNL}}(E, m_4^2, |U_{e4}|^2) = n_1 \tilde{R}_\beta(E, m_4^2, |U_{e4}|^2) + R_{\text{bg}}(E, n_2, n_3, n_{^{237}\text{U}}). \quad (11)$$

To keep the λ_{ANL} model simple and computationally efficient, we approximate that λ_{ANL} does not apply to R_{bg} , which is a subdominant component at low energies. Finally, R_{HNL} is convolved with a Gaussian detector-response function of width σ .

The likelihood minimizer compared Eq. (11) to the low-energy Run 122 spectra as discussed in Sec. VID and searched for the lowest NLL by varying all nuisance parameters except m_4 and $|U_{e4}|^2$. For each HNL scenario defined on a two-dimensional (2D) grid spanning (0.5, 19.5) keV for m_4 and $(10^{-4}, 0.1)$ for $|U_{e4}|^2$, the fitting process was repeated, and NLL was collected. The test statistic $\Delta\mathcal{L}$ was defined as the difference between the NLL of a given HNL scenario and that of the null hypothesis, $|U_{e4}|^2 = 0$.

The top plot of Fig. 17 shows the $\Delta\mathcal{L}$ values summed from both channels. According to Wilks' theorem, the $\Delta\mathcal{L}$ distribution is expected to follow one-half of a chi-squared distribution with two degrees of freedom, corresponding to the independent choices of m_4^2 and $|U_{e4}|^2$. For this distribution, the 95% confidence level corresponds to $\Delta\mathcal{L} = 2.996$. Consequently, parameter space exceeding this threshold, above the black contour line, was excluded at the 95% confidence level. The lowest exclusion limit achieved in our analysis was $|U_{e4}|^2 = 1.31 \times 10^{-3}$ at $m_4 = 11.5$ keV. The best fit point of R_{HNL} occurred at $m_4 = 15$ keV and $|U_{e4}|^2 = 2.7 \times 10^{-3}$. Because its significance (1.41) falls below the 95% threshold, only exclusion limits are presented.

To estimate the Phase I sensitivity of MAGNETO- ν , we recalculated $\Delta\mathcal{L}$ using toy Monte Carlo datasets generated from the β -decay model. Averaging the $\Delta\mathcal{L}$ values from 30 toy datasets reduced statistical fluctuations, and the resulting mean and standard deviation appear as the green line and band in Fig. 17. The figure also demonstrates that improved characterization of ADC nonlinearity substantially increases sensitivity (dash-dotted line). Increasing the dataset to one billion decays is projected to enhance the sensitivity further (dotted line), exceeding the limit set by Holzschuh *et al.* around 12.5 keV.

VII. CONCLUSION

We presented the MAGNETO- ν experiment, which searched for heavy neutral leptons (HNLs) in the $O(10)$ keV

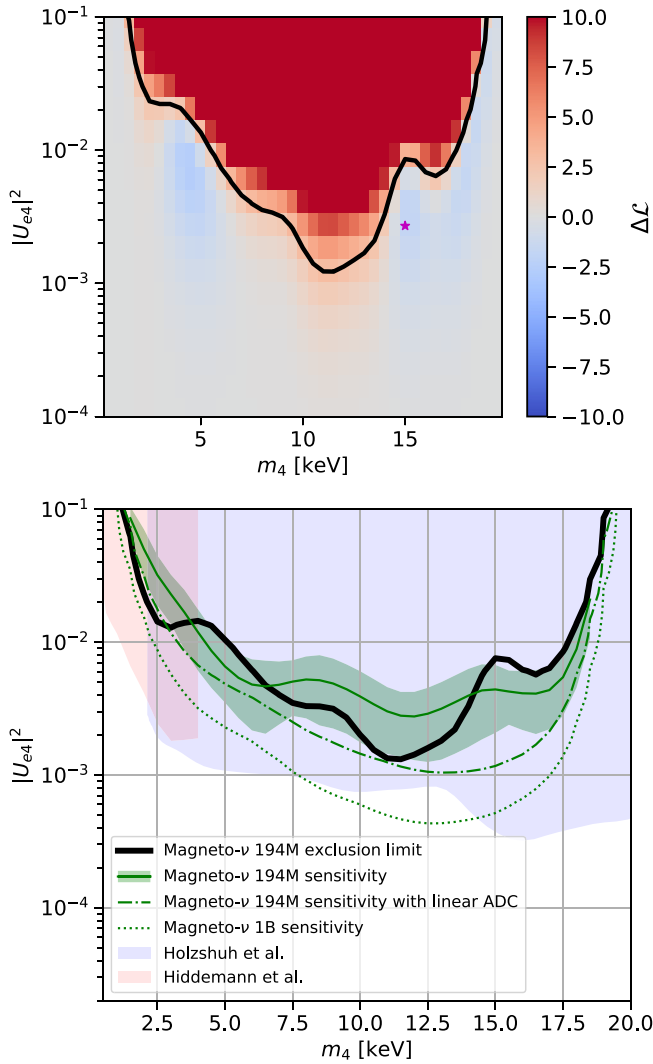


FIG. 17. (top) Test statistic $\Delta\mathcal{L}$ from Run 122 as a function of HNL mass m_4 and admixture $|U_{e4}|^2$. Region above the solid black contour is excluded at the 95% confidence level. Magenta star marks the best-fit point. (bottom) Sensitivity (green line and band) and exclusion limit (solid black) derived from the initial 194 million decay events of the first MAGNETO- ν dataset. Blue and red shaded regions are excluded by ^{63}Ni [14] and tritium [15] β -decay measurements, respectively.

mass range using high-precision ^{241}Pu β spectra measured with an MMC-based DES spectrometer. The experiment collected the highest-statistics ^{241}Pu β spectrum to date, accompanied by a rich set of actinide α -decay data used for energy calibration and stability monitoring.

Using an external ^{133}Ba calibration source, we obtained ^{241}Pu $Q_\beta = 22.273$ (33) keV, which is essential for modeling the beta spectrum. This value is slightly higher than that reported by Loidl *et al.* and substantially higher than the accepted literature value of 20.78 (17) keV. The measured spectral shape agrees well with the theoretical allowed-decay model once atomic effects are included. Small residual deviations from the model at low energies are attributed to systematic effects.

From the initial sample of 194 million β -decay events, we established the most stringent HNL-mixing limit yet derived from the ^{241}Pu spectrum, comparable to the best existing constraints. This exclusion limit will be further improved if the aforementioned systematic effects are better characterized and controlled. We estimate that analysis of one billion events will reach a sensitivity of $|U_{e4}| \approx 4 \times 10^{-4}$ for an HNL mass around 13 keV, surpassing the existing limit set by Holzschuh *et al.*

ACKNOWLEDGMENTS

This work was performed under the auspices of the U.S. Department of Energy by Lawrence Livermore National Laboratory under Contract No. DE-AC52-07NA27344. This work was funded by the Laboratory Directed Research and Development program of Lawrence Livermore National Laboratory (20-LW-024 and 23-LW-043). This work was funded by the National Nuclear Security Administration of the Department of Energy, Office of Defense Nuclear Nonproliferation Research and Development (NA-22) and International Nuclear Safeguards (NA-241). This material is based upon work supported by the Consortium for Nuclear Forensics under the Department of Energy, National Nuclear Security Administration Award No. DE-NA0004142.

DATA AVAILABILITY

The data that support the findings of this article are not publicly available. The data are available from the authors upon reasonable request.

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