



Direct measurement of the ^{39}Ar half-life from 3.4 years of data with the DEAP-3600 detector

DEAP Collaboration*

Received: 22 January 2025 / Accepted: 7 May 2025
© The Author(s) 2025

Abstract The half-life of ^{39}Ar is measured using the DEAP-3600 detector located 2 km underground at SNOLAB. Between 2016 and 2020, DEAP-3600 used a target mass of (3269 ± 24) kg of liquid argon distilled from the atmosphere in a direct-detection dark matter search. Such an argon mass also enables direct measurements of argon isotope properties. The decay of ^{39}Ar in DEAP-3600 is the dominant source of triggers by two orders of magnitude, ensuring high statistics and making DEAP-3600 well-suited for measuring this isotope's half-life. Use of the pulse-shape discrimination technique in DEAP-3600 allows powerful discrimination between nuclear recoils and electron recoils, resulting in the selection of a clean sample of ^{39}Ar decays. Observing over a period of 3.4 years, the ^{39}Ar half-life is measured to be $(302 \pm 8_{\text{stat}} \pm 6_{\text{sys}})$ years. This new direct measurement suggests that the half-life of ^{39}Ar is significantly longer than the accepted value, with potential implications for measurements using this isotope's half-life as input.

1 Introduction

Argon is the third-most abundant gas in Earth's atmosphere, comprising about 0.93% of the atmosphere by volume. The majority of this argon exists in the form of the stable isotopes ^{36}Ar , ^{38}Ar , and ^{40}Ar with abundances of 0.0033, 0.0006, and 0.9960, respectively [1]. Interactions between cosmic ray-induced neutrons and this argon result in three long-lived radioisotopes, ^{39}Ar , ^{37}Ar , and ^{42}Ar , with the dominant long-lived isotope being ^{39}Ar [2, 3]. The abundance of ^{39}Ar was previously inferred to be 8.2×10^{-16} [2, 4, 5] using the measured specific activity and half-life. This isotope β -decays to ^{39}K with a Q-value of (565 ± 5) keV [6]. The most recent measurement for the specific activity of ^{39}Ar was performed by the DEAP-3600 collaboration with a value of $(0.964 \pm 0.001_{\text{stat}} \pm 0.024_{\text{sys}})$ Bq/kg_{atmAr} [7]. Understanding the half-life of ^{39}Ar is important in areas such as radioiso-

tope dating, radiochemistry, radiometry, geochronology, and nuclear physics measurements [8–10].

Several measurements of the half-life of ^{39}Ar exist, with the first estimate of 4 min made in 1937 [11, 12]. This estimate was contradicted by Brosi et al. in 1950 who, while investigating the β -spectrum for this isotope, estimated a lower limit of the half-life of greater than 15 years [6]. In 1952 they presented a half-life and mass measurement of ^{39}Ar in Zeldes et al. [13] using argon produced from four samples of potassium chloride which had been bombarded in a nuclear reactor for about one year: the half-life was calculated for three of the samples independently by comparing isotopic ratios from mass spectrometry measurements to the fourth sample whose decay rate was measured in a magnetic lens beta-ray spectrometer. Their results ranged from 240 to 290 years and an average value was reported as (265 ± 30) years.

The most widely referenced value for the half-life of ^{39}Ar is $(269 \pm 3_{\text{stat}} \pm 8_{\text{sys}})$ years; this value was estimated by Stoenner et al. in 1965 [14] from the isotopic ratio of ^{39}Ar to ^{37}Ar and the measured disintegration rates in 10 samples. Their reported half-life measurement is the average from the 10 samples with the individual measured values ranging from 253 to 288 years. An earlier publication by Stoenner et al. in 1960 [15] gave an ^{39}Ar half-life of 325 years but did not provide an uncertainty. For the purpose of comparison, uncertainties on their measured rates of $\sim 5\%$ were propagated to their half-life measurement giving an estimated half-life with statistical uncertainty of (325 ± 16) years.

A method to measure the half-life of ^{39}Ar through mass spectrometry by recording the ^{39}Ar to ^{38}Ar isotopic ratios in a double-spike over a period of 31.8 years was published by Baksi et al. in 1996 [16]. Their measurement of the ^{39}Ar half-life is reported as (276 ± 3) years. While they recognized the “use of measurements made at different laboratories using different instrumentation” without taking this into account as a source of uncertainty, and given the spread of their three data points, it is possible that the systematic uncertainty they reported may be an underestimate. The Nuclear Data Sheets (NDS) from 2018, produced by the National Nuclear Data

* e-mail: deap-papers@snolab.ca

Table 1 A comparison of existing ^{39}Ar half-life measurements with this result

Measurement	Half-life [years]	Method
Zeldes et al. (1952)	265 ± 30	Isotopic ratios of argon samples using mass spectrometry
Stoenner et al. (1960)	$325 \pm 16_{\text{stat}}^{\text{a}}$	Activity ratios of ^{39}Ar to ^{37}Ar
Stoenner et al. (1965)	$269 \pm 3_{\text{stat}} \pm 8_{\text{sys}}$	Activity ratios of ^{39}Ar to ^{37}Ar
Baksi et al. (1996)	$276 \pm 3_{\text{sys}}$	Isotopic ratios of ^{39}Ar to ^{38}Ar in a double-spike using mass spectrometry
NDS (2018)	$268 \pm 8_{\text{sys}}$	Re-evaluation of the Stoenner et al. (1965) result with an updated ^{37}Ar half-life
DEAP-3600 (2025)	$302 \pm 8_{\text{stat}} \pm 6_{\text{sys}}$	Direct observation of the decay curve

^aEstimated from uncertainty on the measured count rates

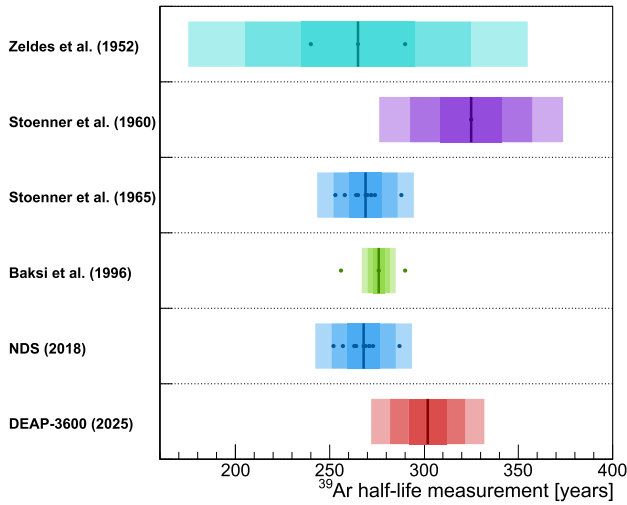


Fig. 1 A comparison of existing ^{39}Ar half-life measurements with this work. The points shown for Zeldes et al. (1952) [13], Stoenner et al. (1960) [15], Stoenner et al. (1965) [14], Baksi et al. (1996) [16], and NDS (2018) [17] denote the individual measurements which were reported. The vertical line represents either the average value or the single reported value. The shaded boxes indicate the 1σ , 2σ , and 3σ error bands with Stoenner et al. (1960) showing the statistical error, Baksi et al. (1996) and NDS (2018) showing the systematic error, and the others showing the combination of their statistical and systematic uncertainties

Center at Brookhaven National Laboratory, re-evaluated the Stoenner et al. 1965 result using an updated ^{37}Ar half-life and give the ^{39}Ar half-life as (268 ± 8) years [17].

To date there have been no direct measurements of the ^{39}Ar half-life by continuously observing its decay curve. The DEAP-3600 detector can directly observe the decay of ^{39}Ar , which is the dominant source of triggers in the detector. This paper presents a measurement of the ^{39}Ar half-life by observing changes in the event rate due to the decay of this isotope. Existing measurements are compiled along with this result and presented in Table 1 and Fig. 1.

The DEAP-3600 detector is described in Sect. 2. Section 3 provides a description of the dataset along with the event selection procedure and detector livetime calculation. The model used to fit the data and measure the ^{39}Ar half-life

is derived in Sect. 4, and the parameters of this model are described in Sect. 5. Systematic uncertainties are described in Sect. 6, and the result is given with concluding statements in Sect. 7.

2 The DEAP-3600 detector

The DEAP-3600 detector is located 2 km underground at SNOLAB in Sudbury, Canada, and was designed to observe scintillation light produced when energy is deposited in the target material of (3269 ± 24) kg of ultra-pure liquid argon (LAr) [7]. A detailed description of the detector can be found in Ref. [18].

The DEAP-3600 detector consists of a spherical acrylic vessel (AV) with a radius of 85 cm which contains the LAr. Surrounding the AV are 255 inward-facing Hamamatsu R5912 Photomultiplier Tubes (PMTs) which observe and record scintillation light from the LAr. During data taking the AV was partially filled with the LAr level approximately 55 cm above the equator. This LAr remained hermetically sealed within the AV for the duration of data taking. A $3 \mu\text{m}$ thick layer of tetraphenyl butadiene (TPB) coats the inner surface of AV and is present to shift the ultraviolet scintillation light at 128 nm into the visible light spectrum at 420 nm [19]. Attached to the top of the AV is a cylindrical acrylic neck. This neck surrounds a liquid nitrogen filled cooling coil which condenses gaseous argon (GAr) in the upper portion of the AV. The AV is situated within a spherical stainless steel shell which is continuously flushed with radon-scrubbed nitrogen gas. The steel shell is submerged in a cylindrical tank containing ultra-pure water. This tank, along with 48 additional PMTs on the outer surface of the steel shell, acts as a muon veto system by detecting Cherenkov radiation produced by muons passing through the water. A schematic of the detector is shown in Fig. 2.

Within the data acquisition system (DAQ) each PMT is connected to a single channel on a custom-built signal conditioning board (SCB) which decouples each PMT's high voltage and shapes the signals. Outputs from the SCBs are transmitted to high-gain (CAEN V1720) and low-gain (CAEN

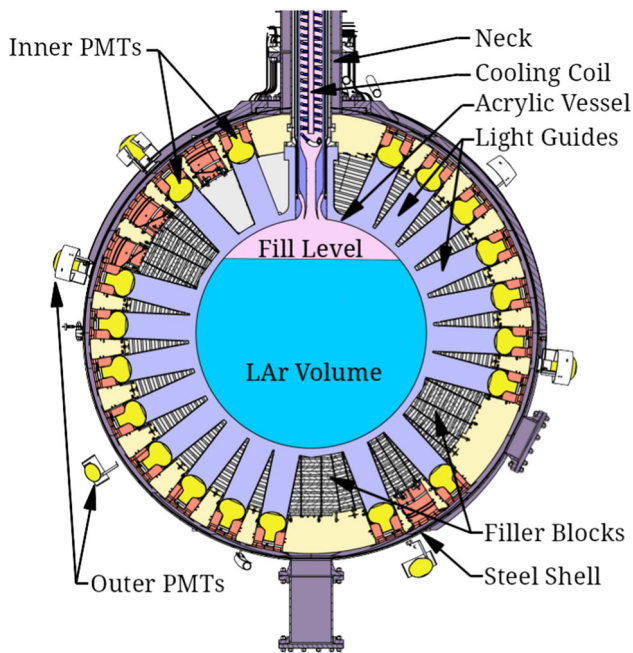


Fig. 2 A cross-section of the DEAP-3600 detector components which are located within the cylindrical water tank

V1740) digitizers which convert continuous analogue signals into discrete digital signals using analogue-to-digital converters. The summed output from each SCB is also transmitted to a digitizer and trigger module (DTM) which makes triggering decisions based on two rolling charge integrals: a narrow integral Q_n over a 177 ns window and a wide integral Q_w over a 3.1 μs window. The promptness of the signal is computed from the Q_n/Q_w ratio. Five trigger regions are defined based on these three variables and a prescaling factor of 100 is applied to events in the energy range of $Q_w \approx (50 \text{ to } 565) \text{ keV}_{\text{ee}}$, in the low Q_n/Q_w region. This prescaling mainly affects ^{39}Ar decays and reduces the statistics by storing PMT waveforms for only 1 out of every 100 triggers. Roughly 2.7×10^6 ^{39}Ar decays remain from a 24-h period after this prescaling. The timestamp for every trigger is recorded, including those which are prescaled.

Each digitizer channel records PMT waveforms for 16 μs , including a pre-trigger window of 2.4 μs . Each PMT's observed charge is integrated over a window of $[-28, 10000]$ ns relative to the event time. The PMTs are calibrated on a daily basis [20] and a PMT charge response model is used to calculate the number of photoelectrons (PEs) detected in each identified pulse which provides the energy estimator for data. The DAQ is operated using MIDAS [21], and the data are analyzed with the RAT software framework [22] which is based on GEANT4 [23] and ROOT [24].

The pulse-shape discrimination (PSD) parameter F_{prompt} [25] is defined for each event as the ratio of prompt to total

charge,

$$F_{\text{prompt}} = \frac{\sum_{t=-28 \text{ ns}}^{t=150 \text{ ns}} Q(t)}{\sum_{t=-28 \text{ ns}}^{t=10 \mu\text{s}} Q(t)} \quad (1)$$

where $Q(t)$ is the pulse charge in PE and t is the pulse time relative to the trigger time. F_{prompt} is sensitive to the ratio of singlet to triplet excimer states in LAr, with lifetimes of 6 ns [26] and approximately 1.5 μs [27], respectively. This ratio is significantly different for electron recoils and nuclear recoils. This technique provides powerful discrimination between events in the nuclear recoil band (NRB) centered at $F_{\text{prompt}} \approx 0.70$ and the electron recoil band (ERB) centered at $F_{\text{prompt}} \approx 0.25$. Figure 3 shows F_{prompt} over a wide PE range.

Another parameter of interest for this analysis, F_{maxPE} , gives the fraction of the total PEs seen by the PMT which observed the most PEs in an event. A high value for this parameter indicates that the majority of the signal from an event was observed by a single PMT. This would be the case when Cherenkov radiation is produced in a light guide, for example.

3 Dataset

The dataset for this analysis is divided into discrete runs which were taken over a period of 3.4 years. Individual run-times T_{run} vary in the range of $[\mathcal{O}(1 \text{ minute}), \sim 2 \text{ days}]$ but a typical run is roughly 22 h long. A requirement that $T_{\text{run}} \geq 4.85 \text{ h}$ is made to ensure sufficient statistics for the light yield corrections described in Sect. 3.1. Runs selected for analysis meet several criteria including the stability of the LAr cooling system, the charge distribution of the PMTs, and the efficiency of the trigger.

A subset of the full energy spectrum between 700 and 1200 PE (approximately 115 keV to 195 keV) is selected for analysis. The region of interest (ROI) is highlighted in Fig. 3. The lower limit at 700 PE is selected to be well above the prescaling boundary at around 500 PE. The upper limit at 1200 PE is selected to reject any systematic effects resulting from saturation of the PMTs. These effects can be seen in Fig. 4. The limit of $F_{\text{prompt}} \leq 0.41$ is made to reject events outside of the ERB.

Within the ROI the PE spectrum is comprised of single ^{39}Ar events, double and triple ^{39}Ar pile-up events (uncorrelated coincidences in which multiple signals from ^{39}Ar decays occur within the same trigger window), and events which contain the pile-up of ^{39}Ar with Cherenkov radiation. A final contribution comes from the low-energy tails of γ -rays resulting from the decay of daughter products of long-lived radioisotopes in the detector components. This γ -ray

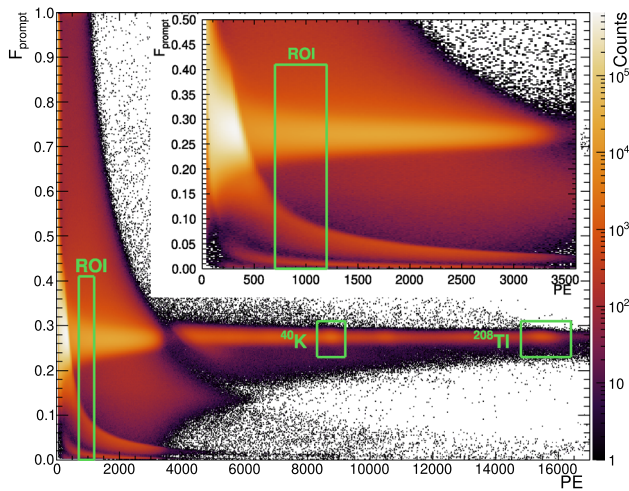


Fig. 3 Histogram of F_{prompt} versus the number of observed PE. The ROI is highlighted in the left-most box for ~ 20 days of data. All the events in the ROI are within the prescaled region. The regions labeled ^{40}K and ^{208}Tl highlight the γ -peak positions of those isotopes. The events within the ROI at $F_{\text{prompt}} < 0.15$ are due to pile-up and are accounted for in the analysis

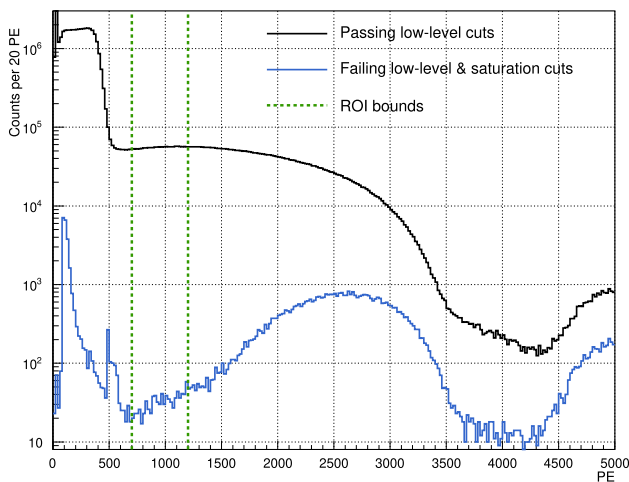


Fig. 4 The PE spectrum of events with $F_{\text{prompt}} \leq 0.41$, showing separately the subset of events failing low-level cuts or where PMT saturation effects are present. The prescaling region, seen as a sharp drop at around 500 PE and a rise at around 4500 PE, and the events where PMT saturation begins to increase at around 1400 PE can be seen. These two boundaries inform the ROI selection with range 700–1200 PE

component, however, is relatively featureless in the ROI and is considered to be a constant background.

A data-cleaning cut is applied to data which rejects events occurring within $\delta t_{\text{cut}} = 70 \mu\text{s}$ of an earlier event, where late light from the earlier event may leak into the trigger window. The number of events removed with this cut is N_{DCcut} , with $\delta t_k \leq 70 \mu\text{s}$ removed for each event k . Further low-level cuts are made to reject any trigger sources other than LAr scintillation such as internal calibration and muon veto triggers, removing δt_{cut} for each of the total N_{LLcut} events. The

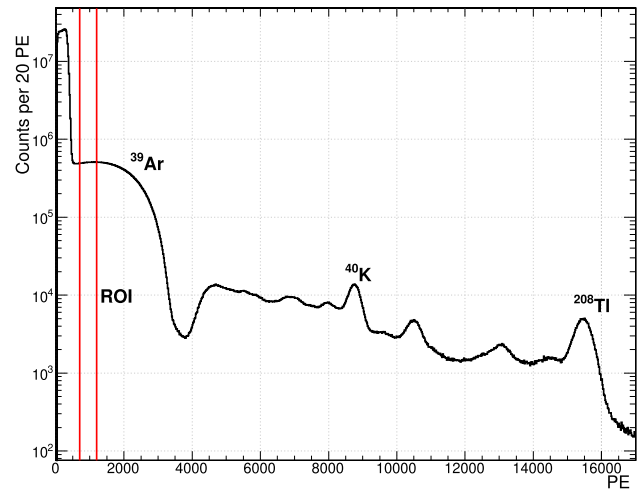


Fig. 5 The PE spectrum of events with $F_{\text{prompt}} \leq 0.41$. The three light yield calibration sources are highlighted. The lower and upper prescaling bounds, at ~ 500 PE and ~ 4000 PE respectively, are clearly seen. This spectrum represents ~ 20 days worth of data

number of remaining physics triggers N_{phys} each introduce additional deadtime of δt_{cut} . The livetime T_{live} for a given run is calculated as follows:

$$T_{\text{live}} = T_{\text{run}} - \sum_{k=1}^{N_{\text{DCcut}}} \delta t_k - N_{\text{LLcut}} \cdot \delta t_{\text{cut}} - N_{\text{phys}} \cdot \delta t_{\text{cut}}. \quad (2)$$

A final requirement for the remaining N_{phys} events is that F_{maxPE} is less than 0.4. A parameter in data which is a count of the sub-events within a trigger window is used to identify pile-up events; no cut is applied on this parameter for the nominal fit to data, however a cut is applied when evaluating the double and triple ^{39}Ar pile-up event selection efficiencies described in Sect. 5.2.

3.1 Correction for light yield variations

The light yield, a ratio of the number of PEs which are observed by the PMTs to the amount of energy deposited in the LAr, is measured in the ERB from three calibration sources. The γ -peaks of ^{40}K (at 1460 keV, or ~ 8750 PE) and ^{208}Tl (at 2615 keV, or $\sim 15,500$ PE) are fit with Gaussian distributions and the mean PE value of each peak is divided by their respective peak energies. The third source is measured by fitting the ^{39}Ar spectrum with the convolution of the β -spectrum model described in Ref. [28] and a detector response model which includes a light yield parameter. Each of these sources are shown for data in Fig. 5. Figure 6 shows the run-by-run light yield measurements where the variations over the length of the dataset can be seen.

These variations in the light yield affect the fraction of events within the ROI across the dataset by stretching or

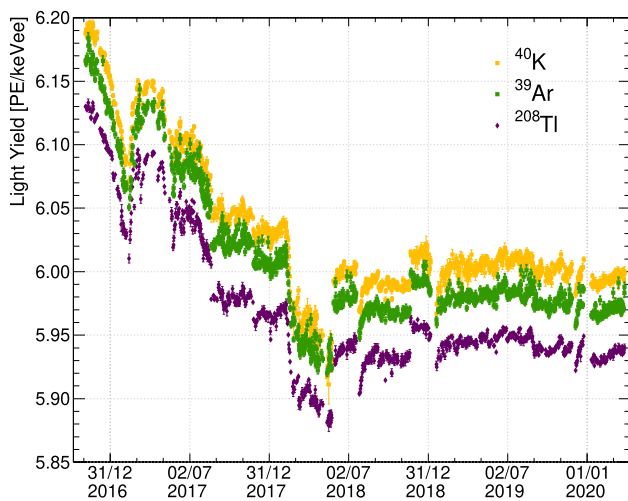


Fig. 6 The light yield as measured from three calibration sources for all runs in the dataset. Variations over time can be seen, though the general trends are similar for each source. The error bars shown are the statistical uncertainties from the fits to each source

compressing the PE spectrum. To correct for these variations, the fractional change in the average light yield ratio is calculated for each run j as the average light yield ratio Y_j for that run to that of the first run Y_0 . Both Y_j and Y_0 are the arithmetic means of the three different calibration sources for their respective runs. The PE value of each event in a run is then corrected by a factor of Y_j/Y_0 .

4 Model of ^{39}Ar trigger rates

The model used to fit the ^{39}Ar trigger rate includes components which account for single ^{39}Ar events and pile-up events. A trigger may consist of a single ^{39}Ar event, multiple ^{39}Ar pile-up events, or ^{39}Ar -Cherenkov pile-up events. The trigger rate in the ROI is given by

$$R(t) = \sum_{i=1}^4 R_i(t) \eta_i f_i \epsilon_i, \tag{3}$$

where $R(t)$ is the total trigger rate at time t , R_i are the rates for the various event types with $i = 1$ for single ^{39}Ar , $i = 2$ and 3 for double and triple ^{39}Ar pile-up respectively, and $i = 4$ for ^{39}Ar -Cherenkov pile-up. The f_i terms are the fraction of each spectrum that falls within the ROI, the ϵ_i terms are the event selection efficiencies. The $\eta_i = 1/N$ terms account for the number of uncorrelated events N observed in each trigger with $\eta_1 = 1$ for single ^{39}Ar decays, $\eta_2 = 1/2$ for double ^{39}Ar pile-up, $\eta_3 = 1/3$ for triple ^{39}Ar pile-up, and $\eta_4 = 1/2$ for ^{39}Ar -Cherenkov pile-up.

Including a constant ERB γ background trigger rate R_{bg} (see Sect. 5.3), Eq. 3 becomes

$$R(t) = R_1(t) f_1 \epsilon_1 + \frac{1}{2} R_2(t) f_2 \epsilon_2 + \frac{1}{3} R_3(t) f_3 \epsilon_3 + \frac{1}{2} R_4(t) f_4 \epsilon_4 + R_{\text{bg}}. \tag{4}$$

The rate of single ^{39}Ar decays in a time interval $\delta t = 10 \mu\text{s}$ is given by the product of the decay rate with the probability $P(0)$ that there is no other decay in that interval as determined from Poisson statistics. This probability is given by

$$P(0) = e^{-R_{39\text{Ar}}(t)\delta t}, \tag{5}$$

where $R_{39\text{Ar}}(t)$ is the ^{39}Ar trigger rate. The trigger rate for single ^{39}Ar decays is then

$$R_1(t) = R_{39\text{Ar}}(t) P(0) = R_{39\text{Ar}}(t) e^{-R_{39\text{Ar}}(t)\delta t}. \tag{6}$$

The rates for double and triple ^{39}Ar pile-up triggers can similarly be determined from Poisson statistics, where the probability $P(1)$ for one other decay in the interval given by

$$P(1) = R_{39\text{Ar}}(t) e^{-R_{39\text{Ar}}(t)\delta t} \delta t \tag{7}$$

and the probability $P(2)$ for two other decays in the interval given by

$$P(2) = \frac{1}{2} R_{39\text{Ar}}^2(t) e^{-R_{39\text{Ar}}(t)\delta t} \delta t^2. \tag{8}$$

The trigger rates are then given by

$$R_2(t) = R_{39\text{Ar}}(t) P(1) = R_{39\text{Ar}}^2(t) e^{-R_{39\text{Ar}}(t)\delta t} \delta t, \tag{9}$$

and

$$R_3(t) = R_{39\text{Ar}}(t) P(2) = \frac{1}{2} R_{39\text{Ar}}^3(t) e^{-R_{39\text{Ar}}(t)\delta t} \delta t^2. \tag{10}$$

Pile-up of ^{39}Ar with Cherenkov radiation is given by

$$R_4(t) = R_1(t) R_{\text{Chv}}(t) e^{-R_{\text{Chv}}(t)\delta t} \delta t, \tag{11}$$

where $R_{\text{Chv}}(t) = R_{\text{Chv}}$ is the rate of Cherenkov triggers, observed to be constant across the dataset.

The ^{39}Ar trigger rate can be expanded to

$$R_{39\text{Ar}}(t) = R_{39\text{Ar}} e^{-t/\tau_{39\text{Ar}}}, \tag{12}$$

where $R_{39\text{Ar}}$ is taken at the start of the dataset, and $\tau_{39\text{Ar}}$ is the mean lifetime of ^{39}Ar . These are the two parameters that are free-floating in the fits.

The total trigger rate in Eq. 4 then becomes

$$R(t) = e^{-R_{39\text{Ar}}(t)\delta t} \left[R_{39\text{Ar}}(t) f_1 \epsilon_1 + \frac{1}{2} R_{39\text{Ar}}^2(t) \delta t f_2 \epsilon_2 + \frac{1}{6} R_{39\text{Ar}}^3(t) \delta t^2 f_3 \epsilon_3 + \frac{1}{2} R_{39\text{Ar}}(t) R_{\text{Chv}} e^{-R_{\text{Chv}}\delta t} \delta t f_4 \epsilon_4 \right] + R_{\text{bg}}. \quad (13)$$

The mean lifetime measured with this model can then be converted into a half-life: $T_{1/2} = \ln(2)\tau_{39\text{Ar}}$. The parameters in Eq. 13 are further described in Sect. 5 and summarized in Table 2.

5 Fit model parameters

This section provides details of the parameters of the fit model described in Sect. 4, including how each parameter value is determined. Two sets of Monte Carlo (MC) simulations were performed to estimate these parameters. The first set of toy MC takes the analytical β -spectrum of ^{39}Ar given in Ref. [28] and convolves it with a detector response model to estimate detector effects. This model uses a Gaussian response with mean μ given by

$$\mu = \langle N_{DN} \rangle + Y \cdot E, \quad (14)$$

where $\langle N_{DN} \rangle$ is the average number of PE produced by dark noise and stray photons in the trigger window, Y is the light yield of the detector, and E is the energy of an event. The average value of the dark noise has been measured to be (1.1 ± 0.2) PE [29]. A toy MC simulation uses this model to estimate the fraction of different pile-up ^{39}Ar events, f_2 and f_3 , which fall within the ROI by randomly selecting events and adding their PE values to generate pile-up spectra. These pile-up spectra are also used to estimate the values of ϵ_2 and ϵ_3 . The pile-up spectrum of ^{39}Ar with low-energy Cherenkov radiation (described in Sect. 5.1) is generated using a similar toy MC to estimate the values of f_4 and ϵ_4 .

The second set of MC simulations used RAT to estimate detector effects. Simulations of γ -rays emitted by ^{40}K and ^{208}Tl in the PMT glass were performed at various trigger thresholds. The efficiency of the cuts included in the analysis is calculated from these simulated samples. Additionally, RAT was used to verify the fit model parameters evaluated from the toy MC simulations.

5.1 Rate of Cherenkov radiation

Cherenkov radiation is generated in acrylic and PMT glass by electrons with kinetic energies above thresholds of 175 keV and 126 keV, respectively. MC simulations were performed

with RAT to obtain the full Cherenkov energy spectrum from ^{40}K and ^{208}Tl decays in the PMTs with the detector threshold set to values of 0, 1, and 3 PE. The Cherenkov spectrum is also measured from data using a trigger threshold of 3 PE. The simulated spectra match data well. The Cherenkov spectrum from all other data taken at the nominal detector threshold is normalized to the spectrum obtained from the low-threshold run. Weekly averages for the Cherenkov rates are stable across the dataset, as expected, and small variations observed are included as a systematic uncertainty. The trigger rate due to Cherenkov radiation is determined to be $R_{\text{Chv}} = (538 \pm 4)$ Hz.

5.2 Event selection efficiencies

The efficiency of the F_{prompt} and F_{maxPE} cuts used to select events was investigated across all runs in the dataset. The efficiencies are calculated as the ratio of triggers passing a cut to the total number of triggers before that cut within the PE range of the ROI. The product of efficiencies for all the cuts is determined on a run-by-run basis.

The efficiency for the selection of single ^{39}Ar decay triggers is 100% in both the MC samples and data. The efficiency for selecting double ^{39}Ar pile-up triggers in MC is roughly 91%. In data selected with the additional requirement that exactly two sub-events are detected, this efficiency is roughly 85%; applying the same additional cut to MC results in the same value. The efficiency in data is corrected to account for the effect of this additional cut by adding the difference between the value determined in MC and the average pre-correction efficiency in data to the efficiency in data for each run. The corrected mean efficiency for selecting double ^{39}Ar pile-up triggers in data is then (0.9099 ± 0.0033) . For triple ^{39}Ar pile-up trigger efficiencies, in a similar method but selecting events with exactly 3 sub-events, the difference between data and MC is taken into account and the corrected mean efficiency is (0.860 ± 0.039) . The efficiency for selecting ^{39}Ar -Cherenkov pile-up is evaluated using MC to be 100%, consistent with the amount of Cherenkov light being small compared to scintillation from the single ^{39}Ar decay in that event.

5.3 ERB γ background rate

The PE spectrum for electron recoils in DEAP-3600 is described in detail in Ref. [30]. The trigger count for these backgrounds in the ROI is determined by subtracting the MC ^{39}Ar spectrum from the total MC ERB sum. The difference is then normalized to the livetime of the dataset and the rate is determined to be $R_{\text{bg}} = (1.65 \pm 0.31)$ Hz.

Table 2 List of parameters used in the model of ^{39}Ar trigger rates (Sects. 4, 5) along with their uncertainties. The uncertainties due to the event selection efficiencies for each event type are given as a combined

value. The uncertainties are estimated with respect to the measured mean lifetime and converted to half-life values. The character ‘-’ indicates an uncertainty of less than 0.01 years which is considered negligibly small

Parameter	Symbol	Value	Constraints	Absolute uncertainty on $T_{1/2}$ [years]
^{39}Ar trigger rate at dataset start	$R_{^{39}\text{Ar}}$		Free-floating	
^{39}Ar lifetime	$\tau_{^{39}\text{Ar}}$		Free-floating	
Cherenkov trigger rate	R_{Chv}	(538 ± 4) Hz	Fixed	–
ERB background rate	R_{bg}	(1.65 ± 0.31) Hz	Fixed	0.15
Livetime	T_{live}	1.80 years	Fixed	–
Bin width for trigger rate averages		7 days	Fixed	1.0
Fraction of single ^{39}Ar spectrum in the ROI	f_1	0.21 ± 0.05	Fixed	0.21
Cut efficiency for single ^{39}Ar	ϵ_1	1	Fixed	–
Fraction of double ^{39}Ar spectrum in the ROI	f_2	0.20 ± 0.05	Fixed	1.1
Cut efficiency for double ^{39}Ar	ϵ_2	0.9099 ± 0.0033	Fixed	1.8
Fraction of triple ^{39}Ar spectrum in the ROI	f_3	0.19 ± 0.05	Fixed	0.01
Cut efficiency for triple ^{39}Ar	ϵ_3	0.860 ± 0.039	Fixed	0.19
Fraction of ^{39}Ar -Cherenkov pile-up spectrum in the ROI	f_4	0.21 ± 0.05	Fixed	0.04
Cut efficiency for ^{39}Ar -Cherenkov pile-up	ϵ_4	1	Fixed	–
Light yield corrections (constant)		Run-dependent	N/A	2.3
Light yield corrections (differential)		Run-dependent	N/A	5.1
Correlated triggers		Run-dependent	N/A	2.1

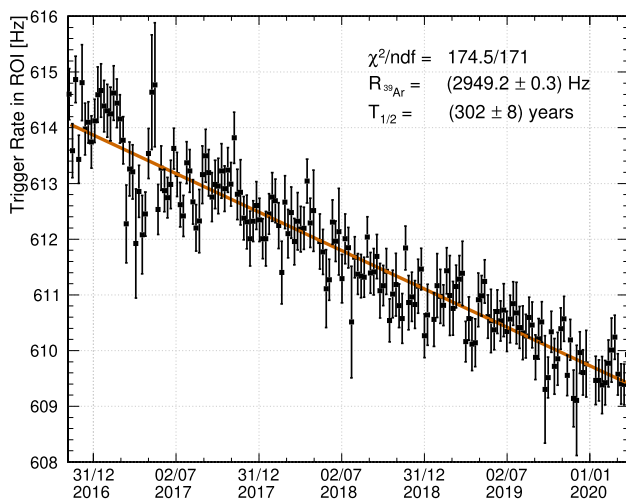


Fig. 7 The trigger rate fit for the full dataset. Each point here represents the rates averaged over a 1 week period. The best-fit values of $R_{^{39}\text{Ar}}$ and $T_{1/2}$ are shown with statistical uncertainties only

5.4 Results

The trigger rate across the dataset is fit with the model in Eq. 13 and shown in Fig. 7. The measured trigger rate at the start of the dataset of $R_{^{39}\text{Ar}} = (2949.2 \pm 0.3_{\text{stat}})$ Hz, comprised of mainly single ^{39}Ar decays, but also double ^{39}Ar pile-up, triple ^{39}Ar pile-up, and ^{39}Ar -Cherenkov pile-up, is

consistent with the ^{39}Ar decay rate measured in Ref. [7] given the systematic uncertainty on the f_1 parameter in this half-life measurement analysis.

The fit is repeated for fixed values of $T_{1/2}$ between 140 and 415 years. Figure 8 shows the reduced χ^2 values from these fits.

6 Systematic uncertainties

This section describes the individual contributions to the systematic uncertainty on the ^{39}Ar half-life. These uncertainties are summarized in Table 2. The total systematic uncertainty is calculated by adding uncertainties from each contribution in quadrature which results in a systematic uncertainty on $T_{1/2}$ of ± 6 years.

6.1 Light yield corrections

In order to assess the uncertainty on the half-life due to uncertainties in the light yield correction two components are considered: a constant offset component describes the effect of an absolute change in the light yield scale; a differential drift over time component describes the effect of continuous changes in the light yield scale across the dataset. To estimate these two components the uncertainty on the average light yield ratio, measured as the RMS of the distribution

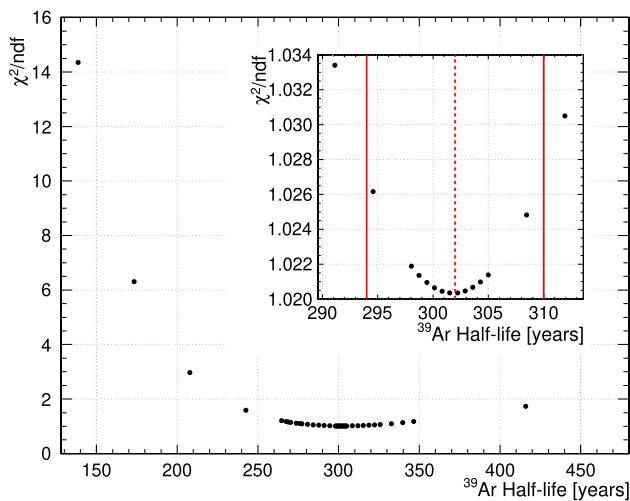


Fig. 8 The χ^2 to degrees of freedom (ndf = 171) ratio obtained by fixing $T_{1/2}$ in the fit to data. The insert plot shows the region around the minimum with the nominal $T_{1/2}$ (dashed line) $\pm 1\sigma$ (solid lines) region shown

of uncertainties on Y_j to be $\Delta Y = 0.00076$, is considered in three ways. For the constant offset component a value of ΔY is added to the average light yield ratio for each run in the dataset such that the correction described in Sect. 3.1 becomes $Y_j/Y_0 + \Delta Y$, and the fit to data is performed again. This results in a constant offset uncertainty of 2.3 years. The differential component is considered by correcting the average light yield ratio across the dataset as with the constant offset case where ΔY is replaced with a linearly decreasing value in the range $[\Delta Y, 0]$ and separately by replacing ΔY with a linearly increasing value in the range $[0, \Delta Y]$. For both cases the fit is re-done: this results in a differential drift over time uncertainty of 5.1 years.

As a cross-check on this method, the effect of each of the three calibration sources was considered relative to the average light yield. With each calibration source considered individually, the difference in the fraction of the ^{39}Ar spectrum falling within the ROI relative to the spectrum fraction from the average light yield ratio is measured. This is done for each run in the dataset. This cross-check provides consistent results to the method above. The light yield corrections are the dominant source of systematic uncertainty on this half-life measurement.

6.2 Energy resolution

Uncertainty due to the detector energy resolution is estimated by first fitting the ^{208}Tl γ -ray peak for each run in the dataset and generating a distribution of the peak widths. The variation in this distribution is then taken as an additional input to the toy MC used to estimate the fraction f_i of each event type's spectrum within the ROI (described in Sect. 5). The

energy resolution is both increased and decreased by this variation, new fractions are measured for each case, and the fit to data is re-evaluated using the new fractions. Changing the detector resolution in this way has a negligibly small effect on the ^{39}Ar half-life.

6.3 ER background variation

As a cross-check method for the determination of R_{bg} , contributions from the ^{232}Th and ^{238}U decay chains are examined. ^{208}Tl rates, representative of the ^{232}Th chain, are scaled based on the ratio of events in the peak to the low-energy tail events in the ROI. Similarly, ^{226}Ra rates are examined to account for the ^{232}U chain. The updated background rates are then added to the fit model and the fit performed again. The maximum observed difference in the ^{39}Ar half-life from the nominal value is 0.15 years.

6.4 Bin width for trigger rate averages

To determine if there are any effects due to averaging the trigger rates over 7 day periods, the rates were separately averaged over 3, 5, 10, 14, 21, and 30 day periods and the fit performed again. The maximum observed difference corresponds to a change in the measured half-life of 1.0 years.

6.5 Event type fractions in the ROI

For each event type the fraction of events in the ROI are varied such that $f'_i = f_i \pm 0.05$. The uncertainty of ± 0.05 is a conservative choice which considers uncertainty in the shape of the ^{39}Ar spectrum and differences between theoretical models. One event type's fraction is varied at a time and the fit is performed again using each adjusted f'_i value in Eq. 13. The differences between the nominal value and that from each new fit are taken as the systematic uncertainties and are listed in Table 2.

6.6 Event selection efficiencies

The run-by-run event selection efficiencies for each event type show small variations over the dataset. These variations are considered to estimate their effects on the ^{39}Ar lifetime by adding them to the efficiencies in three ways and performing the fit again: (1) the variation is kept constant; (2) the variation increases from a value of 0 at the start of the dataset to the maximum value at the end; (3) the variation decreases from the maximum value at the start of the dataset to 0 at the end. For each event type the largest change in the measured ^{39}Ar half-life is observed for the third case. As a conservative approach these values are taken as the systematic uncertainties listed in Table 2.

6.7 Correlated triggers

A small fraction of events in DEAP-3600 are correlated with an earlier event on a time-scale that is greater than the data-cleaning cut. Light from these earlier events can leak into the trigger window of a subsequent event which affects the observed number of PE. The data-cleaning cut which rejects events occurring within $\delta t_{\text{cut}} = 70 \mu\text{s}$ of an earlier event does not remove all correlated triggers, though a cut of greater than $70 \mu\text{s}$ would reduce the available statistics.

The effect of the correlated triggers is estimated on a run-by-run basis by fitting an exponential curve to the distribution of the time between triggers. The ratio of the data to the fit for each run's distribution is evaluated at a time of $70 \mu\text{s}$. A linear fit to these values across the dataset is used to estimate the maximum expected effect on the change in trigger rate over time of 0.03 Hz. This corresponds to a 0.7% change in the measured half-life, equal to 2.1 years.

7 Conclusion

A direct measurement of the half-life of ^{39}Ar has been performed using data collected by the DEAP-3600 detector over a period of 3.4 years. The statistical and systematic uncertainties are on the same order. The systematic uncertainty is dominated by effects from the light yield corrections. This measurement gives a value of the ^{39}Ar half-life of

$$T_{1/2} = (302 \pm 8_{\text{stat}} \pm 6_{\text{sys}}) \text{ years.}$$

This new measurement is in tension with the half-life evaluated by NDS, with a p -value of 0.008 for the two measurements to have the same central value.

When considered with the specific activity measured in Ref. [7] this half-life measurement corresponds to a decay constant of $\lambda = (7.4 \pm 0.4) \times 10^{-11} \text{ s}^{-1}$. The relative abundance of ^{39}Ar in atmospheric argon is determined to be $(8.6 \pm 0.4) \times 10^{-16}$. In addition to impacting measurements sensitive to this isotope's half-life, such as studies of meteorites, this result is relevant for future experiments using atmospheric argon.

Acknowledgements We thank the Natural Sciences and Engineering Research Council of Canada (NSERC), the Canada Foundation for Innovation (CFI), the Ontario Ministry of Research and Innovation (MRI), and Alberta Advanced Education and Technology (ASRIP), the University of Alberta, Carleton University, Queen's University, the Canada First Research Excellence Fund through the Arthur B. McDonald Canadian Astroparticle Physics Research Institute, Consejo Nacional de Ciencia y Tecnología Project No. CONACYT CB-2017-2018/A1-S-8960, DGAPA UNAM Grants No. PAPIIT IN108020 and IN105923, and Fundación Marcos Moshinsky, the European Research Council Project (ERC StG 279980), the UK Science and Technology Facilities Council (STFC) (ST/K002570/1 and

ST/R002908/1), the Leverhulme Trust (ECF-20130496), the Russian Science Foundation (Grant No. 21-72-10065), the Spanish Ministry of Science and Innovation (PID2022-138357NB-C2) and the Community of Madrid (2018-T2/TIC-10494), the International Research Agenda Programme AstroCeNT (MAB/2018/7) funded by the Foundation for Polish Science (FNP) from the European Regional Development Fund, and the Polish National Science Centre (2022/47/B/ST2/02015). Studentship support from the Rutherford Appleton Laboratory Particle Physics Division, STFC and SEPNet PhD is acknowledged. We thank SNOLAB and its staff for support through underground space, logistical, and technical services. SNOLAB operations are supported by the CFI and Province of Ontario MRI, with underground access provided by Vale at the Creighton mine site. We thank Vale for their continuing support, including the work of shipping the acrylic vessel underground. We gratefully acknowledge the support of the Digital Research Alliance of Canada, Calcul Québec, the Centre for Advanced Computing at Queen's University, and the Computational Centre for Particle and Astrophysics (C2PAP) at the Leibniz Supercomputer Centre (LRZ) for providing the computing resources required to undertake this work.

Data Availability Statement Data cannot be made available for reasons disclosed in the data availability statement. [Authors' comment: The data used in this paper requires approximately 150 TB of disk space and its interpretation requires an extensive understanding of the detector. Therefore, making the data publicly available is impractical. Access to the data may be granted on request to the DEAP collaboration (email: deap-papers@snolab.ca).]

Code Availability Statement Code/software cannot be made available for reasons disclosed in the code availability statement. [Authors' comment: The software used in this paper is a large specialized set of codes for particular computing environments. Therefore, making the software publicly available is impractical. Access to the code may be granted on request to the DEAP collaboration.]

Open Access This article is licensed under a Creative Commons Attribution 4.0 International License, which permits use, sharing, adaptation, distribution and reproduction in any medium or format, as long as you give appropriate credit to the original author(s) and the source, provide a link to the Creative Commons licence, and indicate if changes were made. The images or other third party material in this article are included in the article's Creative Commons licence, unless indicated otherwise in a credit line to the material. If material is not included in the article's Creative Commons licence and your intended use is not permitted by statutory regulation or exceeds the permitted use, you will need to obtain permission directly from the copyright holder. To view a copy of this licence, visit <http://creativecommons.org/licenses/by/4.0/>.


Funded by SCOAP³.

References

1. J. Böhlke, PAC **86**(9), 1421 (2014). <https://doi.org/10.1515/pac-2013-0918>
2. P. Benetti et al. (WARP Collaboration), NIM-A **574**(1), 83 (2007). <https://doi.org/10.1016/j.nima.2007.01.106>
3. J. Calvo et al. (ArDM Collaboration), JCAP **2018**(12), 011 (2018). <https://doi.org/10.1088/1475-7516/2018/12/011>
4. R. Saldanha et al., PRC (2019). <https://doi.org/10.1103/physrevc.100.024608>
5. H. Loosli, H. Oeschger, EPSL **5**, 191 (1968). [https://doi.org/10.1016/S0012-821X\(68\)80039-1](https://doi.org/10.1016/S0012-821X(68)80039-1)
6. A.R. Brosi, H. Zeldes, B.H. Ketelle, Phys. Rev. **79**, 902 (1950). <https://doi.org/10.1103/PhysRev.79.902>

7. P. Adhikari et al. (DEAP Collaboration), EPJ C **83**(642) (2023). <https://doi.org/10.1140/epjc/s10052-023-11678-6>
8. A.K. Baksi, Earth Syst. Sci. (2022). <https://doi.org/10.1007/s12040-022-01855-8>
9. C. Yu, R.C. Zhong, Y.L. Xie, W.B. Li, Minerals (2019). <https://doi.org/10.3390/min9100622>
10. F. Ritterbusch et al., PNAS **119**(40), e2200835119 (2022). <https://doi.org/10.1073/pnas.2200835119>
11. M.L. Pool, J.M. Cork, R.L. Thornton, Phys. Rev. **52**, 239 (1937). <https://doi.org/10.1103/PhysRev.52.239>
12. G.T. Seaborg, I. Perlman, RMP **20**, 585 (1948). <https://doi.org/10.1103/RevModPhys.20.585>
13. H. Zeldes et al., Phys. Rev. **86**, 811 (1952). <https://doi.org/10.1103/PhysRev.86.811>
14. R.W. Stoenner, O.A. Schaeffer, S. Katcoff, Science **148**(3675), 1325 (1965). <https://doi.org/10.1126/science.148.3675.1325>
15. R.W. Stoenner, O.A. Schaeffer, R. Davis Jr., JGR **65**(8), 2521 (1960). <https://doi.org/10.1029/JZ065i010p03025>
16. A.K. Baksi, D.A. Archibald, E. Farrar, Can. J. Phys. **74**(5–6), 263 (1996). <https://doi.org/10.1139/p96-041>
17. J. Chen, Nucl. Data Sheets (2018). <https://doi.org/10.1016/j.nds.2018.03.001>
18. P.-A. Amaudruz et al. (DEAP Collaboration), Astropart. Phys. **108**, 1 (2019). <https://doi.org/10.1016/j.astropartphys.2018.09.006>
19. R. Francini et al., JINST **8**(09), C09010 (2013). <https://doi.org/10.1088/1748-0221/8/09/C09010>
20. P.-A. Amaudruz et al. (DEAP Collaboration), NIM-A **922**, 373 (2019). <https://doi.org/10.1016/j.nima.2018.12.058>
21. Thomas Lindner for the DEAP-3600 collaboration, J. Phys. Conf. Ser. **664**(8), 082026 (2015). <https://doi.org/10.1088/1742-6596/664/8/082026>
22. S. Seibert et al., RAT (is an Analysis Tool) User's Guide (2014). <https://rat.readthedocs.io/en/latest/>
23. S. Agostinelli et al., NIM-A **506**(3), 250 (2003). [https://doi.org/10.1016/S0168-9002\(03\)01368-8](https://doi.org/10.1016/S0168-9002(03)01368-8)
24. R. Brun, F. Rademakers, NIM-A **389**(1), 81 (1997). [https://doi.org/10.1016/S0168-9002\(97\)00048-X](https://doi.org/10.1016/S0168-9002(97)00048-X)
25. P. Adhikari et al. (DEAP Collaboration), EPJ C **81**(823) (2021). <https://doi.org/10.1140/epjc/s10052-021-09514-w>
26. T. Heindl et al., EPL **91**(6), 62002 (2010). <https://doi.org/10.1209/0295-5075/91/62002>
27. P. Adhikari et al. (DEAP Collaboration), EPJ C **80**(303) (2020). <https://doi.org/10.1140/epjc/s10052-020-7789-x>
28. J. Kostensalo, J. Suhonen, K. Zuber, J. Phys. G Nucl. Part. Phys. **45**(2), 025202 (2018). <https://doi.org/10.1088/1361-6471/aa958e>
29. R. Ajaj et al. (DEAP Collaboration), PRD **100**, 022004 (2019). <https://doi.org/10.1103/PhysRevD.100.022004>
30. R. Ajaj et al. (DEAP Collaboration), PRD **100**(7) (2019). <https://doi.org/10.1103/physrevd.100.072009>

DEAP Collaboration

P. Adhikari⁶, R. Ajaj^{6,23}, M. Alpízar-Venegas¹³, P.-A. Amaudruz²¹, J. Anstey^{6,23}, D. J. Auty¹, M. Batygov¹¹, B. Beltran¹, M. A. Bigentini^{6,23}, C. E. Bina^{1,23}, W. M. Bonivento⁹, M. G. Boulay⁶, J. F. Bueno¹, M. Cadeddu⁹, B. Cai^{6,23}, M. Cárdenas-Montes⁷, S. Cavuoti^{24,10}, Y. Chen¹, S. Choudhary², B. T. Cleveland^{20,11}, R. Crampton^{6,23}, S. Daugherty^{20,11,6}, P. DelGobbo^{6,23}, P. Di Stefano¹⁸, G. Dolganov^{15,16}, L. Doria¹⁷, F. A. Duncan^{20,*}, M. Dunford^{6,23} , E. Ellingwood¹⁸, A. Erlandson^{6,4}, S. S. Farahani¹, N. Fatemighomi^{20,19}, G. Fiorillo^{8,10}, R. J. Ford^{20,11}, D. Gahan^{3,9}, D. Gallacher⁶, A. Garai¹⁸, P. García Abia⁷, S. Garg⁶, P. Giampa^{18,21}, A. Giménez-Alcázar⁷, D. Goeldi^{6,23}, V. V. Golovko^{4,18}, P. Gorel^{20,11}, K. Graham⁶, A. Grobov¹⁵, A. L. Hallin¹, M. Hamstra^{6,18}, S. Haskins^{6,23}, J. Hu¹, J. Hucker¹⁸, T. Hugues^{2,18}, A. Ilyasov^{15,16}, B. Jigmeddorj¹¹, C. J. Jillings^{20,11}, A. Joy^{1,23}, G. Kaur⁶, A. Kemp^{19,18}, M. Khoshraftar Yazdi¹, M. Kuźniak^{2,6,23}, F. La Zia¹⁹, M. Lai^{5,3,9}, S. Langrock^{11,23}, B. Lehnert¹², J. LePage-Bourbonnais^{6,23}, N. Levashko¹⁵, M. Lissia⁹, L. Luzzi⁷, I. Machulin^{15,16}, A. Maru^{6,23}, J. Mason^{6,23}, A. B. McDonald¹⁸, T. McElroy¹, J. B. McLaughlin^{19,21}, C. Mielnichuk¹, L. Mirasola^{3,9}, A. Moharana⁶, J. Monroe^{19,a}, A. Murray¹⁸, C. Ng¹, G. Oliviero^{6,23}, M. Olszewski², S. Pal^{1,23}, D. Papi¹, B. Park¹, M. Perry⁶, V. Pesudo⁷, T. R. Pollmann^{22,11,18,b}, F. Rad^{6,23}, C. Rethmeier⁶, F. Retière²¹, I. Rodríguez García⁷, L. Roszkowski^{2,14}, R. Santorelli⁷, F. G. Schuckman II¹⁸, S. Seth^{6,23}, V. Shalamova⁵, P. Skensved¹⁸, T. Smirnova⁵, K. Sobotkiewich⁶, T. Sonley^{20,6,23}, J. Sosiak^{6,23}, J. Soukup¹, R. Stainforth⁶, M. Stringer^{18,23}, J. Tang¹, R. Turcotte-Tardif^{6,23}, E. Vázquez-Jáuregui¹³, S. Viel^{6,23}, B. Vyas⁶, M. Walczak², J. Walding¹⁹, M. Ward¹⁸, S. Westerdale⁵, R. Wormington¹⁸, A. Zuñiga-Reyes¹³

¹ Department of Physics, University of Alberta, Edmonton, AB T6G 2R3, Canada

² AstroCeNT, Nicolaus Copernicus Astronomical Center, Polish Academy of Sciences, Rektorska 4, 00-614 Warsaw, Poland

³ Physics Department, Università degli Studi di Cagliari, Cagliari 09042, Italy

⁴ Canadian Nuclear Laboratories, Chalk River, ON K0J 1J0, Canada

⁵ Department of Physics and Astronomy, University of California, Riverside, CA 92521, USA

⁶ Department of Physics, Carleton University, Ottawa, ON K1S 5B6, Canada

⁷ Centro de Investigaciones Energéticas, Medioambientales y Tecnológicas, Madrid 28040, Spain

⁸ Physics Department, Università degli Studi “Federico II” di Napoli, Napoli 80126, Italy

⁹ INFN Cagliari, Cagliari 09042, Italy

¹⁰ INFN Napoli, Napoli 80126, Italy

¹¹ School of Natural Sciences, Laurentian University, Sudbury, ON P3E 2C6, Canada

¹² Nuclear Science Division, Lawrence Berkeley National Laboratory, Berkeley, CA 94720, USA

¹³ Instituto de Física, Universidad Nacional Autónoma de México, A. P. 20-364, Ciudad de Mexico 01000, Mexico

¹⁴ BP2, National Centre for Nuclear Research, ul. Pasteura 7, 02-093 Warsaw, Poland

¹⁵ National Research Centre Kurchatov Institute, Moscow 123182, Russia

¹⁶ National Research Nuclear University MEPhI, Moscow 115409, Russia

¹⁷ PRISMA⁺ Cluster of Excellence, Institut für Kernphysik, Johannes Gutenberg-Universität Mainz, 55128 Mainz, Germany

¹⁸ Department of Physics, Engineering Physics and Astronomy, Queen’s University, Kingston, ON K7L 3N6, Canada

¹⁹ Royal Holloway University London, Egham Hill, Egham, Surrey TW20 0EX, UK

²⁰ SNOLAB, Lively, ON P3Y 1M3, Canada

²¹ TRIUMF, Vancouver, BC V6T 2A3, Canada

²² Department of Physics, Technische Universität München, 80333 Munich, Germany

²³ Arthur B. McDonald Canadian Astroparticle Physics Research Institute, Queen’s University, Kingston, ON K7L 3N6, Canada

²⁴ Astronomical Observatory of Capodimonte, Salita Moiariello 16, I-80131 Napoli, Italy

^a Currently at University of Oxford, Oxford OX1 3PU, UK

^b Currently at University of Amsterdam, Science Park, 1098XG Amsterdam, Netherlands

* Deceased