Rare nuclear decays for standard and exotic physics

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A) ^{40}K and KDK

B) KDK+

C) RAMPS

D) Exotic decays

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A) KDK: completed

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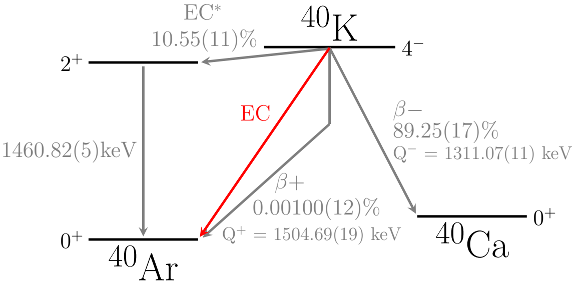
^{40}K results PRL 131 052503 2023, PRC 108 014327 2023

^{65}Zn results Nucl Data Sheets 189 224 2023

Details NIM A 1012 (2021) 165593, JPhys Conf Series 1342 2020

Decays of ^{40}K [1]

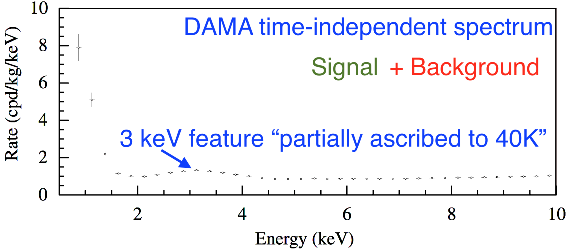
- ^{40}K: naturally occurring; 0.012% abundance; $T_{1/2} = 1.2 \times 10^9$ years



- Electron capture (EC): ${}^{40}_{19}\text{K} + e^- \rightarrow {}^{40}_{18}\text{Ar} + \nu_e$
  - ~ 3 keV X-rays, Auger electrons from K-shell electron capture
  - Also 1.4 MeV γ (or conversion electron) if EC* to excited state
- Direct-to-ground-state EC0 has never been observed
- Nuclear theory: would be only measured 3rd forbidden unique EC

^{40}K EC decay and direct dark matter searches

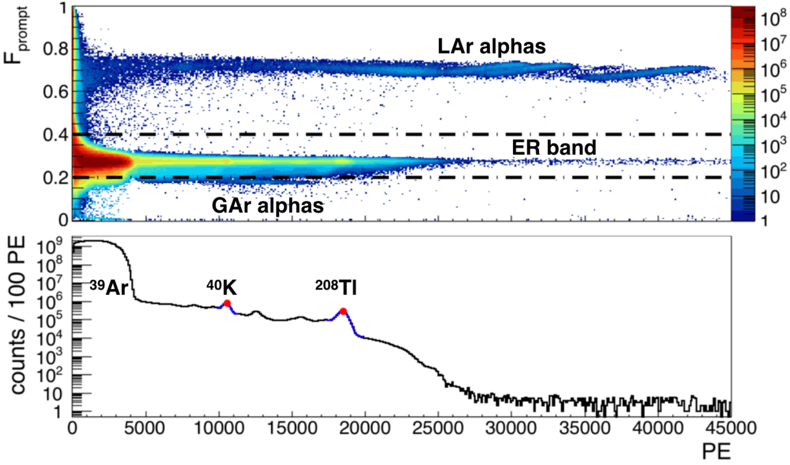
- ~ 3 keV from EC0/EC* is background in energy region expected for many dark matter models
- EC* can be tagged by 1.4 MeV γ, EC0 can not be tagged: irreducible background
- K contaminates many NaI experiments (ANAIS, ASTAROTH, COSINE, COSINUS, SABRE...): draconian measures to grow pure crystals, veto EC*
- In particular, EC0 may constrain longstanding (> 25 y) controversial dark matter claim by DAMA/LIBRA (13 ppb K) [2, 3]



More EC0 background ⇒ less signal (Pradler et al PLB 720 2013)

(also requires assumptions on tagging efficiency and other BGs)

DEAP and ^{40}K



https://arxiv.org/abs/1905.05811

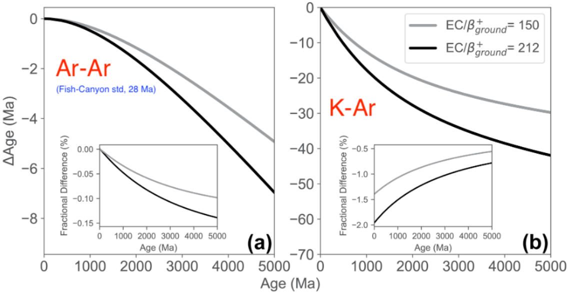
Impact of ^{40}K EC0 on geochronology

- Longstanding calls to verify existence and intensity of EC0 [4, 5]:

> by Endt and Van der Leun (1973, 1978), Endt (1990), and Audi et al. (1997), this decay mode is unverified and its existence is questionable.

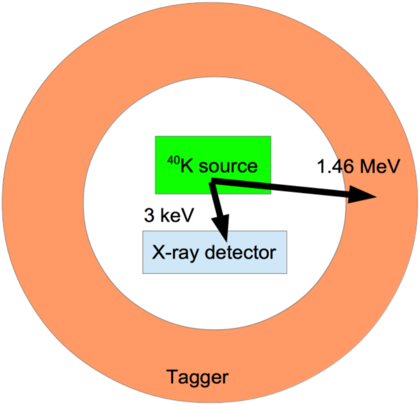
> Outstanding problems remaining to be addressed in evaluating the ^{40}K decay constants include: (i) improving disintegration counting experiments to provide better data for β and γ activities and (ii) verifying the existence and magnitude of the hypothetical γ-less electron capture decay directly to ^{40}Ar in the ground state. Concern about the level at which ^{40}K/K is

- K-Ar and Ar-Ar dating [6]: as analytical precision improves (resp 0.5% and 0.1%), EC0 uncertainty noticeable:



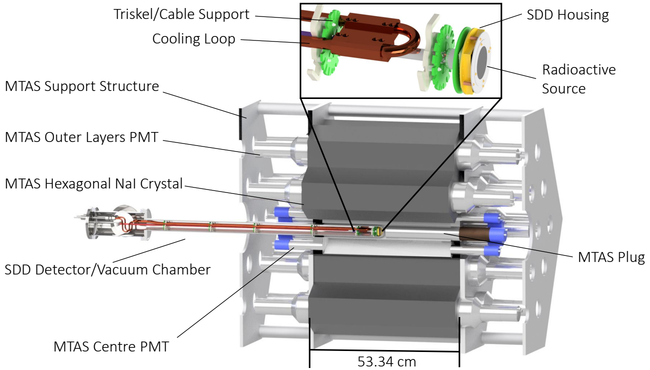
Neglecting EC0 overestimates ages

Measuring EC0: KDK [7, 8]



- Custom, thin, enriched **^{40}K source**, activity equivalent to 
- **Small inner detector** triggered by EC0/EC* X/Augers trigger;
  - $\sim$ keV threshold
  - Minimize scatter of γs
- **Surrounding 4π veto** to tag EC* 1.46 MeV γ
  - For signal-to-noise of 1, need 98% efficiency ...
  - ... which requires 22 cm of NaI (BIG!) to stop 1.46 MeV γ
- **Compare tagged to untagged triggers to determine ρ, ratio of EC0 to EC***

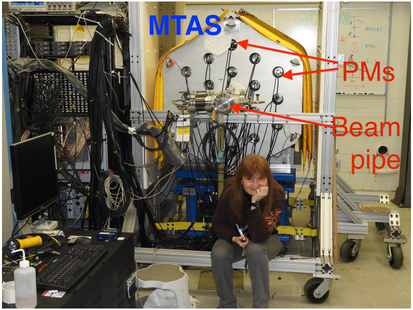
Modular Total Absorption Spectrometer (MTAS) tagger [9] and insert



- ~ 1 tonne of NaI at Oak Ridge (now at MSU)
- Surface site, BG rate ~ 2.6 kHz (!).

Setup at ORNL

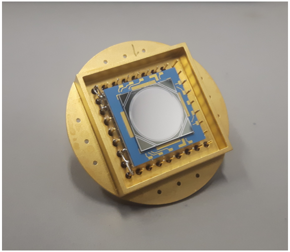
MTAS

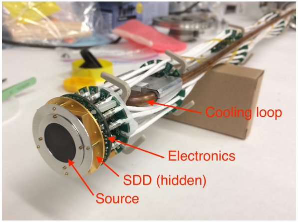


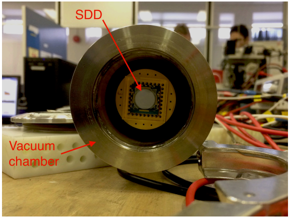
Vacuum insert with X-ray detector

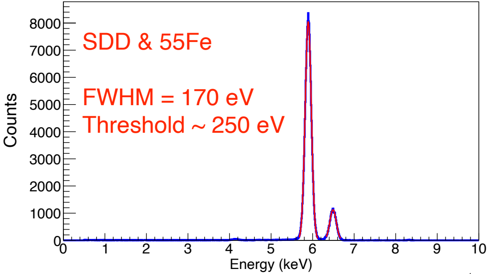
X-ray detector

- Custom silicon drift detector (SDD) from HLL Munich
- Surface area 1 cm^2
- Electronics from TRIUMF (Constable, Rétière)

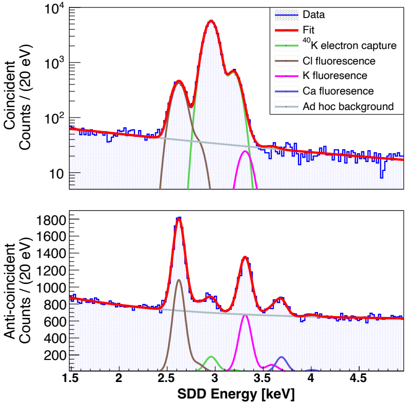








Results after unblinding: PRL 131 052503 2023, PRC 108 014327 2023



$I_{EC^0}/I_{EC*} = 0.0095 \overset{stat}{\pm} 0.0022 \overset{sys}{\pm} 0.0010$ (H0 rejected at 4σ)

Branching ratio: $I_{EC^0} = 0.098\% \overset{stat}{\pm} 0.023\% \overset{sys}{\pm} 0.010\%$

Some implications of KDK [10]

Dark matter BR0 smaller than expected, so relaxes ^{40}K BG constraints on DAMA claim

$0\nu\beta\beta$ Implies contributions of forbidden transitions to nuclear matrix elements are suppressed, in turn suggesting eg $T_{1/2}$ could be a factor 7 longer than expected for ^{48}Ca

Geochronology Retires uncertainty on existence of EC0 from measurements

B) KDK+: getting started

Queen's	Arsenne, Di Stefano, Lemaire, Swidinsky
SNOLAB	Stukel
SFU	Hariasz
CNL	Erlandson
ORNL	Rasco, Rykaczewski

Motivation for KDK+

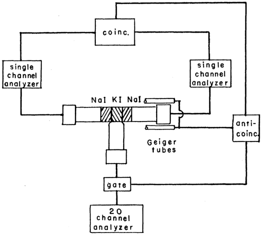
Inconsistency

1. KDK expt 2023 [11]: $BR0/BR* = 0.0095 \pm 0.0022 \pm 0.0010$
2. Engelkemeir expt 1962 [12]: $BR+/BR- = (1.12 \pm 0.14) \times 10^{-5}$
3. Mougeot theory 2018 [13]: $BR0/BR+ = 215.0 \pm 3.1$

Assuming 1. is correct, and taking Kossert 2022's evaluation [14] for $\lambda-$ and $\lambda*$, we find inconsistent values for $\lambda+$:

- 1+2) $\lambda+ = (5.5 \pm 0.7) \times 10^{-6}$ /Ga
- 1+3) $\lambda+ = (2.5 \pm 0.6) \times 10^{-6}$ /Ga

Previous ^{40}K β^+ work



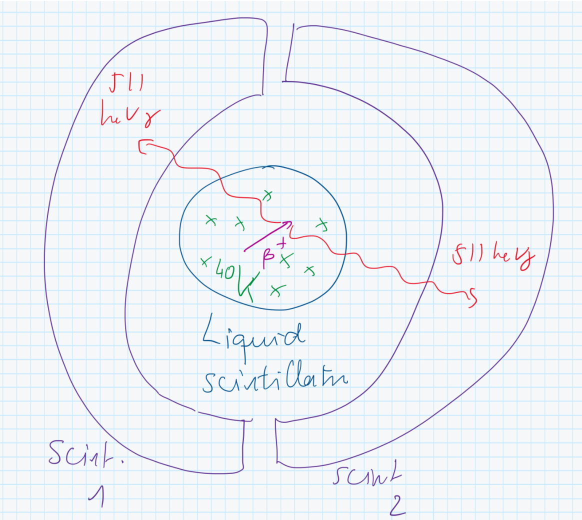
Tilley 1959 [15] First to use triple coinc for ^{40}K β^+. Main detector KI. Find $P+/P- < (1.3 \pm 0.7) \times 10^{-5}$.

Engelkemeir 1962 [12] Triple coin with liquid scint. Find $P+/P- = (1.12 \pm 0.14) \times 10^{-5}$. Considered most credible by X. Mougeot as attention paid to pair creation from EC*.

Leutz 1965 [16] Study of β^-, EC* and β^+. Triple coin with plastic scintillator. Find $P+/P- = (1.5 \pm 0.5) \times 10^{-5}$. Presents Tilley's result as value instead of limit.

General concept to measure ^{40}K β^+ to within 10%

- ^{40}K source and β^+ detector, likely combined ($K_+ \leq Q_+ - 2m_e \approx 480$ keV)
- Segmented 511 keV γ detector



Miscellaneous

Potential backgrounds

- ^{40}K BG from environment: use SNOLAB-type techniques and environment?
- Random coincs with external BG: use short window (100 ns), use SNOLAB-type techniques and environment?
- Random coincs with source: use short window (100 ns)
- External pair creation from EC* (1.46 MeV γ interacts in field of other nucleus, creating $e+, e-$ pair): theory, sims, ^{42}K
- Internal pair creation from EC* (1.46 MeV γ interacts in field of emitting nucleus, creating $e+, e-$ pair; order of magnitude is 1 per 10^5 γ): theory, sims, ^{42}K

Calibrations

- Tagged ^{22}Na for overall efficiency
- ^{42}K for 1.46 MeV pair creation

^{40}K in liquid scintillator

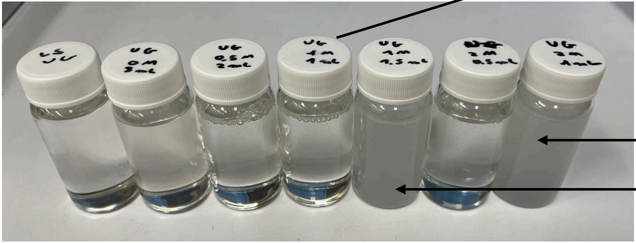
- Engelkemeier used K enriched to 30% ^{40}K in potassium octoate salt (a food additive, eg `https://www.biosynth.com/p/FP158289/764-71-6-potassium-octoate`)
- Solubility of KCl in water is $\sim$ 30 g/100 mL @Troom (wikipedia)
- Activity of natKCl is $r = 16.35$ Bq/g. β^+ activity is roughly $r^+ = BR^+ \, r = 0.16$ mBq/g. To get $N^+ = 1000$ β^+ decays in $T = 1$ month, need $m = 2.35$ g of natKCl.
- If enriched to 3% ^{40}K/K, with 0.3 g KCl will get $N^+ = 1000$ β^+ decays in $T = 1$ day
- Kossert 2004 [17] used KNO3 and KCl in water mixed into Hionic Fluor, Ultima Gold LLT and Ultima Gold AB. For BG, used NaNO3 and NaCl. Used 20 ml low-K borosilicate vials.

KCl loading in Liquid Scintillator: Ultima Gold, PerkinElmer

Table 3. Sample capacity of selected cocktails for various ionic strength buffers (sample capacities are for 10 mL cocktail at 20 °C).

Ionic Strength	Ultima Gold XR	Hionic-Fluor	Pico-Fluor Plus	Ultima Gold	Ultima Gold MV	Opti-Fl
0.5 M NaCl	9.0 mL	1.4 mL	3.0 mL	1.5 mL	1.25 mL	1.1 mL
0.75 M NaCl	6.5 mL	2.25 mL	2.75 mL	0.75 mL	0.75 mL	0.75 m
1.0 M NaCl	5.5 mL	8.5 mL	2.3 mL	0.5 mL	0.5 mL	0.5 mL

Source: PerkinElmer



Too much aqueous solution or KCl: cocktail separates in 2 phases and becomes cloudy when shaked

KCl loading in Liquid Scintillator: Ultima Gold, PerkinElmer

❌

❌

✅

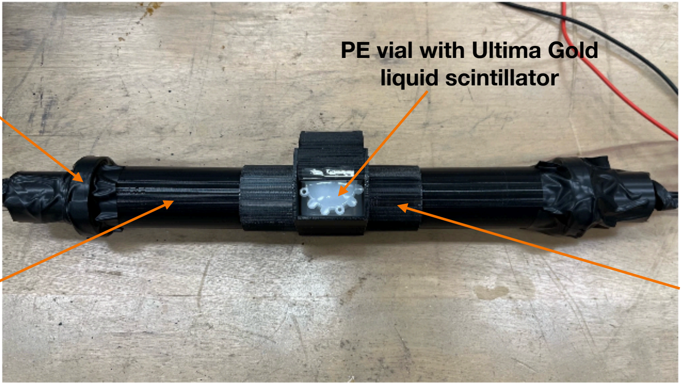
KCl loading in Liquid Scintillator: Ultima Gold, PerkinElmer

Results:

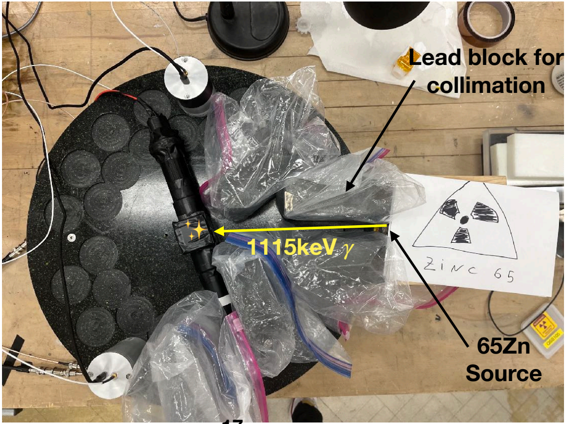
Cocktail in 20mL glass vial	Ultima Gold	Ultima Gold LLT
Quantity of dissolved K mmol	1	3
Mass of dissolved K mg	39	117
For natural potassium abundance		
Mass of 40K µg	4,6	13,8
Atoms of 40K	7E+16	2,1E+17
Activity of the source Bq	1,2	3,6
ß+ emitted in a month	32	96
For 3% enrichment		
Mass of 3% enriched 40K µg	1170	3510
Atoms of 40K	1,8E+19	5,4E+19
Activity of the source Bq	317	951
ß+ emitted in a month	8,3E+03	2,49E+04

Energy calibration of the liquid scintillator

Compton coincidence experiment - setup

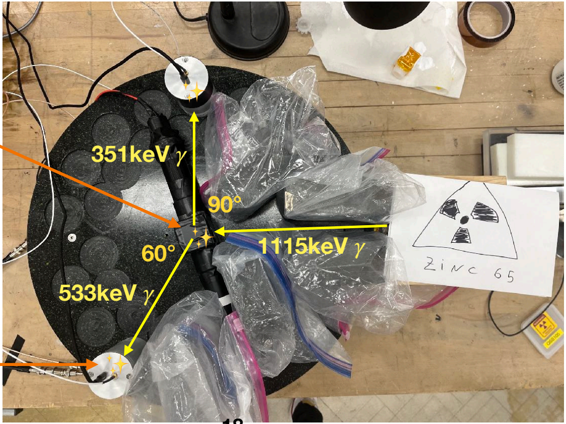


Energy calibration of the liquid scintillator



Energy calibration of the liquid scintillator

Incident gamma scatters and deposits energy in the liquid scintillator



Scattered gamma detected on NaI crystal

Energy calibration of the liquid scintillator

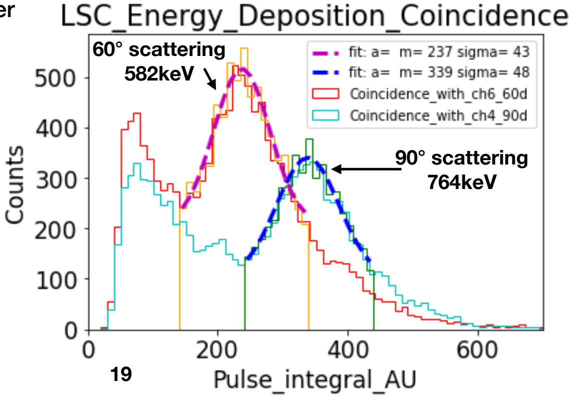
60° - 90°, UltimaGold, 2 PMT Hamamatsu R6095
65Zn Source - 240ns Coincidence Window
400lsb LSC - 200lsb NaI - 1050V high voltage 15h

Kinetic energy of the electron after scattering with incident γ E_o:

$$T_e = E_0 - E = E_0 - \frac{E_0}{1 + \alpha(1 - \cos\theta)}$$

$$\alpha = \frac{E_0}{m_e\, c^2}$$

- ✓ Compare light yield of different cocktail
- ✓ Compare light collection of different setup
- ✓ Energy calibration of beta detector

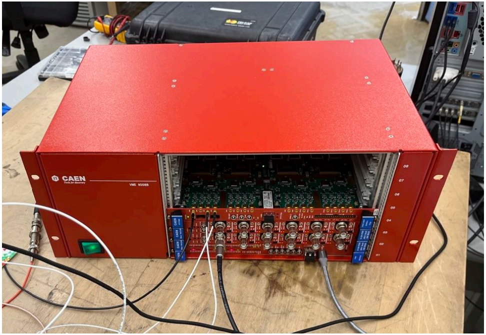


Energy calibration of the liquid scintillator

Data acquisition

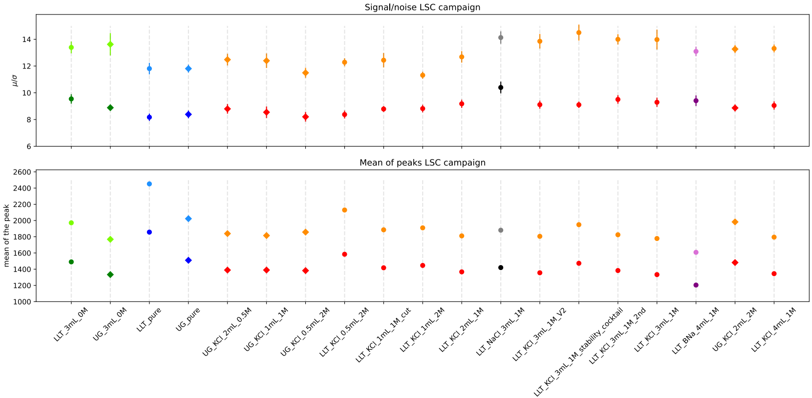
CAEN Digitizer V1730

- 16 channels
- CoMPASS software
- Spectra and Coincidence in live
- Data written on CSV, binary or root files. Analysis carried out offline

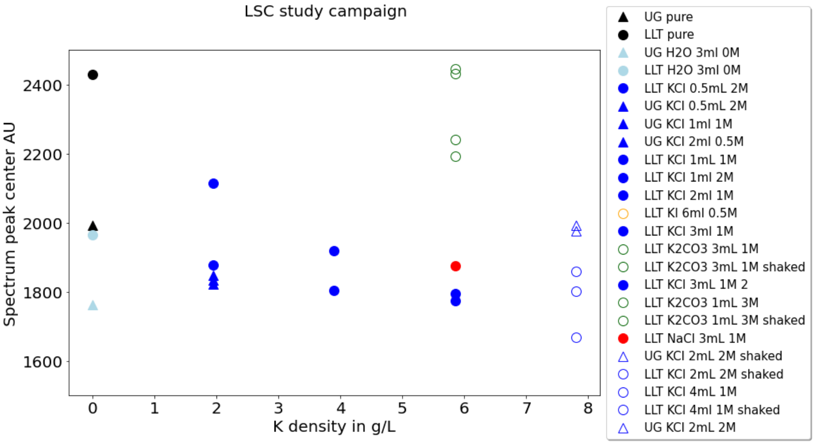


With the help of Emma and Nick to set up the computer and the configuration

Light yield summary



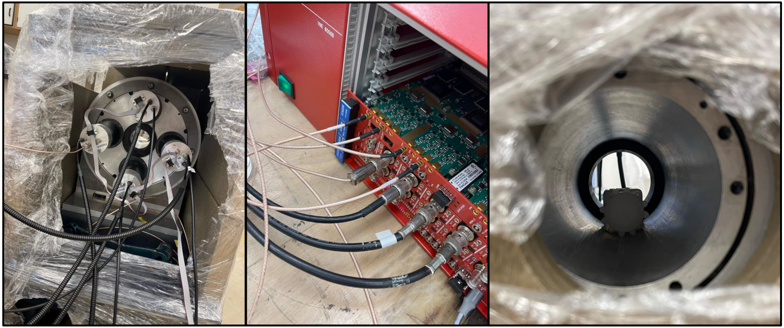
Loading and light yield results



- Preferred cocktail selected
- Multi-week stability check underway

Tagging the annihilation 511 keV γs with NaI annulus

Annulus Setup



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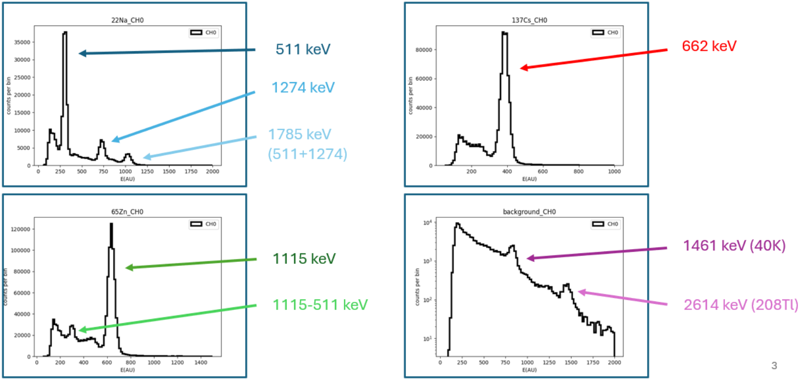
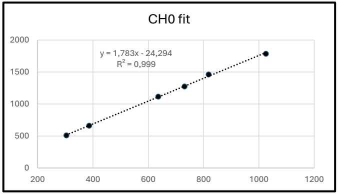
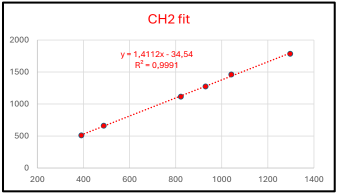
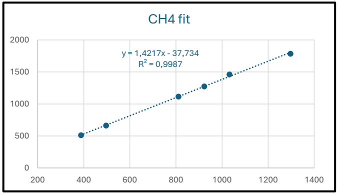
Calibrating the NaI annulus

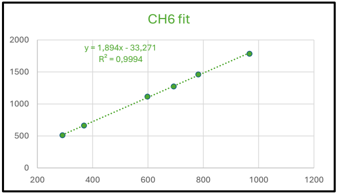


Linear regression



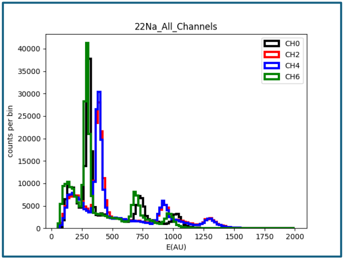




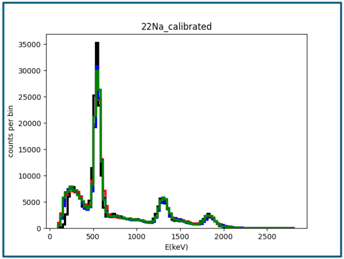


Energy calibration

Before

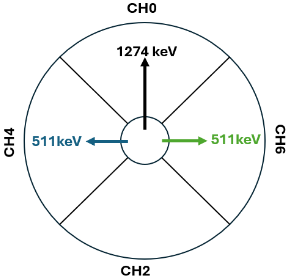


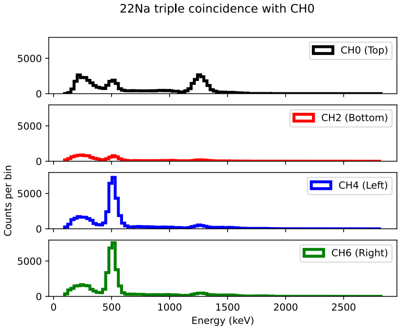
After



^{22}Na triple coincidences in NaI annulus I

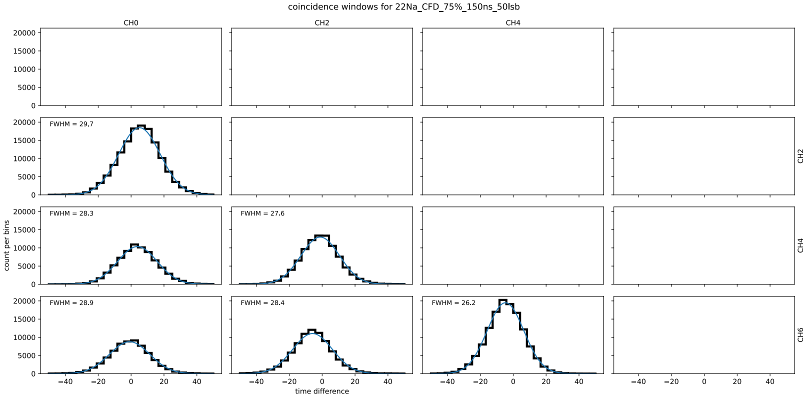
Coincidence: C0>0 AND C2>0 AND C4>0





511 keV annihilation lines and 1.26 MeV excitation line clearly visible

^{22}Na triple coincidences in NaI annulus II



Time difference FWHM = 30 ns with CFD

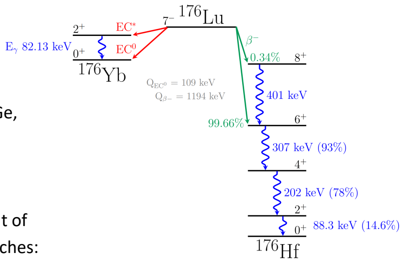
KDK+ status

- Liquid scintillator and loading selected
- Stability of cocktail being studied
- Rescue 511 keV tagger being characterized
- Pathfinder experiment planned 2024
- Depending on backgrounds, may be necessary to go to a low-radioactivity environment

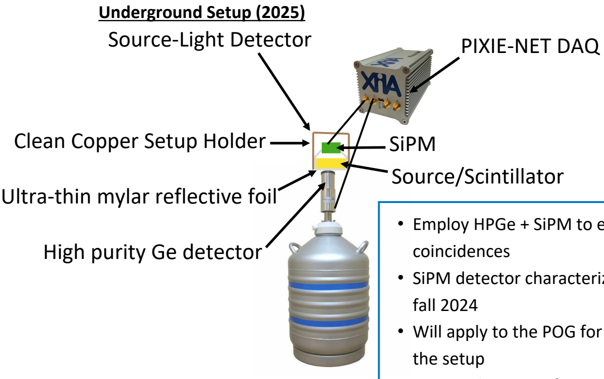
C) RAMPS project (M. Stukel, SNOLAB)

RAMPS (RadioActive isotope Measurement Program at SNOLAB)

- **GOAL:** Perform novel, precision or standardization measurements of long-lived isotopes, that have relevance for a variety of fields of physics.
- **Method:** Use (or enhance) existing SNOLAB infrastructure to perform these measurements (HPGe, HPGe+SiPM, CUTE etc..).
- **Target Isotopes:** Lu-176, Si-32, V-50, Zr-96, Cd-113, elements of the U and Th decay chains + more
- **Pilot Project:** Aims to perform the first measurement of the electron capture channel of Lu-176. Two approaches:
  - HPGe + SiPM coincidence setup
  - Cryogenic calorimeter (potentially at CUTE). See reference here
- **Want to know more:** matthew.stukel@snolab.ca



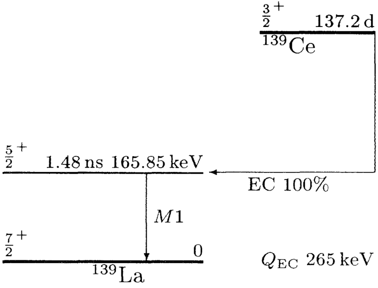
RAMPing up: LBL Extended Capabilities, HPGe + SiPM



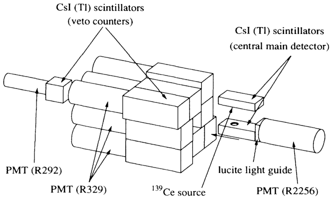
- Employ HPGe + SiPM to exploit detector coincidences
- SiPM detector characterization to be performed in fall 2024
- Will apply to the POG for funds for DAQ and rest of the setup
- Expected testing of complete setup in 2025

D) Searches for exotic particles in nuclear decays

- Putative axion-like particle (ALP) may be emitted in place of γ in nuclear transitions.
- ALP escapes detector
- Ex: EC* decay of ^{139}Ce (PRL 71 4120 1993)



- Trigger on X-rays/Augers
- Missing $\gamma \Rightarrow$ (axion + ground state) BR



- Need to know tagging efficiency, also EC0 if possible (see arXiv:2405.15591)
- Typical BR $< 10^{-7}$
- Other isotopes and decay schemes can be considered

Conclusion

- ^{40}K: KDK successfully observed EC0, KDK+: underway to check β^+
- Rare nuclear decays of interest to many fields including nuclear theory, geochronology, searches for $0\nu\beta\beta$, dark matter and axions
- SNOLAB know-how and possibly infrastructure may be beneficial to such searches
- RAMPS is an example