

Potassium

K

DK

Decay

The KDK (^{40}K decay) experiment: dark matter, geochronology, and a rare decay of ^{40}K

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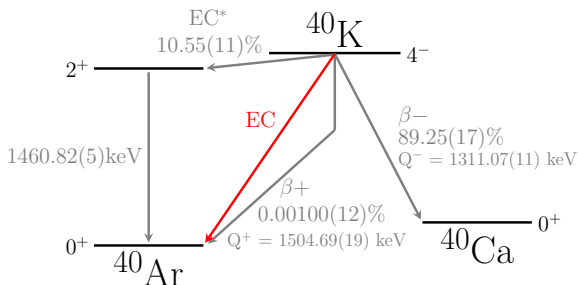
Results: PRL 131 052503 2023, PRC 108 014327 2023

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

⁴⁰K. Engineering support has been contributed by Miles Constable and Fabrice Rétière of TRIUMF, as well as by Koby Dering through the NSERC/Queen's MRS. Funding in Canada has been provided by NSERC through SAPIN and SAP RTI grants, as well as by the Faculty of Arts and Science of Queen's University, and by the McDonald Institute. This work has been partially supported by U.S. DOE. ORNL is managed by UT-Battelle, LLC, under Contract No. DE-AC05-00OR22725 for the U.S. Department of Energy. Thermal deposition was conducted at the Center for Nanophase Materials Sciences, which is a DOE Office of Science User Facility. J. C., L. E. M., and P. R. R. acknowledge support from NSF Grant No. 2102788. U.S. support has also been supplied by the Joint Institute for Nuclear Physics and Applications, and by NSF Grant No. EAR-2102788. This material is based upon work supported by the U.S. Department of Homeland Security.

Decays of ^{40}K [1]

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



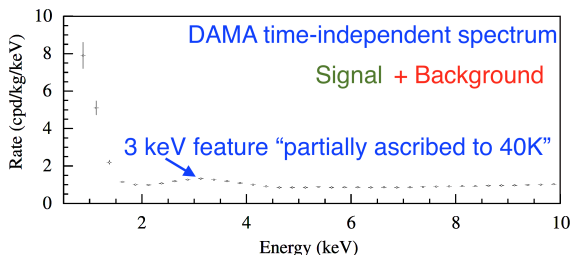
- ▶ Electron capture (EC): $^{40}_{19}\text{K} + e^- \rightarrow ^{40}_{18}\text{Ar} + \nu_e$
 - ▶ ~ 3 keV X-rays, Auger electrons from K-shell electron capture
 - ▶ Also 1.4 MeV γ (or conversion electron) if EC^* to excited state
- ▶ **Direct-to-ground-state EC0 has never been observed**
- ▶ **Nuclear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

The mystery of dark matter

- ▶ Observations of universe at various scales (galaxies, clusters, CMB...) and with various techniques indicate that **most of matter in universe only appears through gravitational interactions**
- ▶ Big Bang Nucleosynthesis: dark matter mainly non-baryonic
- ▶ Possible solutions:
 - ▶ Astrophysical objects like black holes? Constrained by microlensing etc.
 - ▶ Known subatomic particles like neutrinos? Constrained by structure formation
 - ▶ Misunderstanding of gravity? MOND?
 - ▶ New subatomic particles?
 - ▶ ?
- ▶ **Explanation could also be something completely unexpected, and will likely lead to change in paradigm**

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

- ▶ ~ 3 keV from $\text{EC0}/\text{EC}^*$ 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) [3, 4]**



More EC0 background $\Rightarrow$ less signal (Pradler et al PLB 720 2013)

(also requires assumptions on tagging efficiency and other BGs)

^{40}K and geochronology

- ▶ ^{40}K ubiquitous, half-life of ~ 1.25 Ga $\Rightarrow$ used for radioactive dating
- ▶ Decay to ^{40}Ar forms basis of **K-Ar dating** [5]: measure ratio of ^{40}Ar to ^{40}K (2 mass spec. measurements); need λ_{Ar} and λ_{tot}
- ▶ Generally supplanted by **Ar-Ar dating** [6]: measure ratio of neutron-activated ^{39}Ar to ^{40}Ar (1 mass spec. measurement), compare to reference sample of known age; only need λ_{tot}
- ▶ Suitable for timescales from **historical** (ka, eg Vesuvius [7]) to **age of Earth** (Ga, eg Acapulco meteorite [8])
- ▶ Applications: archaeology, volcanos, impact craters, meteorites, planetary science etc.
- ▶ Current analytical precision: **0.5% for K-Ar** [9] and **0.1% for Ar-Ar** [10]

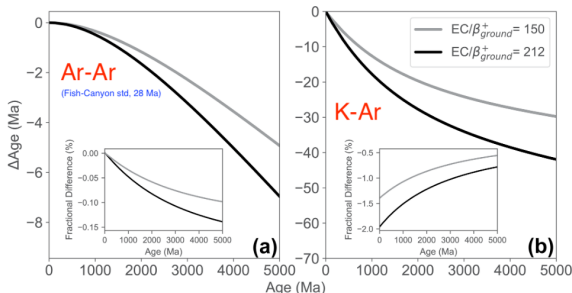
Impact of ^{40}K EC0 on geochronology

- Longstanding calls to verify existence and intensity of EC0 [11, 12]:

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.

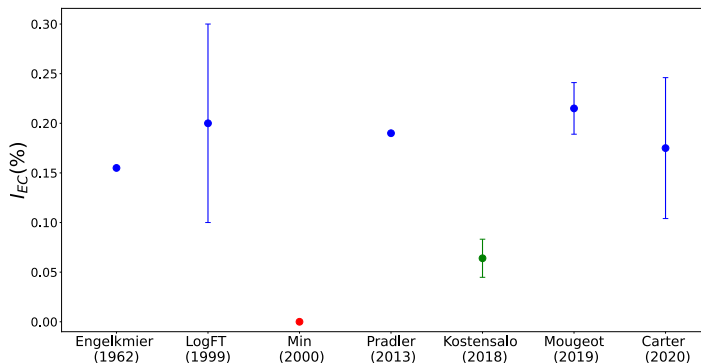
Outstanding problems remaining to be addressed in evaluating the ^{40}K decay constants include: (i) improving disintegration counting experiments to provide better data for β and γ activities and (ii) verifying the existence and magnitude of the hypothetical γ -less electron capture decay directly to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

- K-Ar and Ar-Ar dating [13]: as analytical precision improves (resp 0.5% and 0.1%), EC0 uncertainty noticeable:



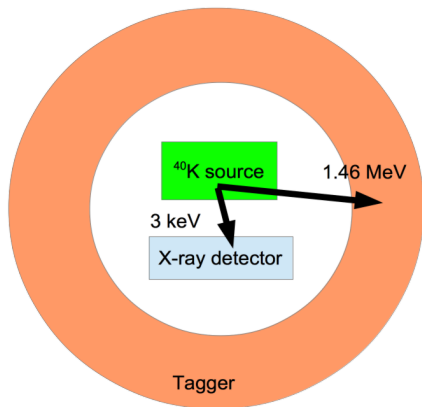
Neglecting EC0 overestimates ages

Theory predictions, assumptions, for EC0 branching ratio



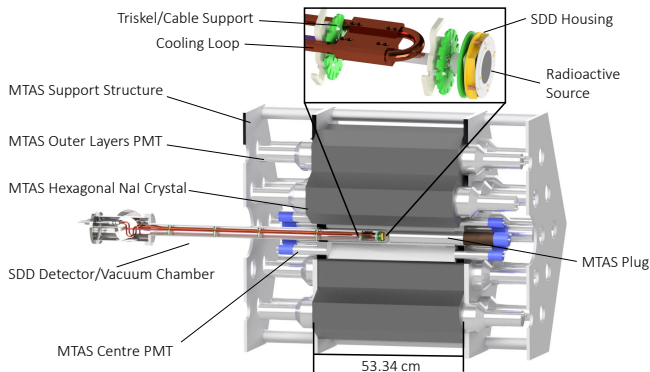
EC0 expected to be roughly $EC^*/50$, ie branching ratio of 0.2%

Measuring EC0: KDK [19, 20]



- ▶ 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 γ s
- ▶ **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***

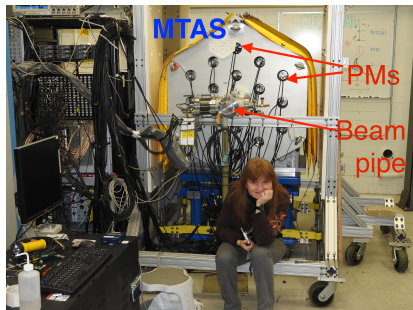
Modular Total Absorption Spectrometer (MTAS) tagger [21] and insert



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

Setup at ORNL

MTAS

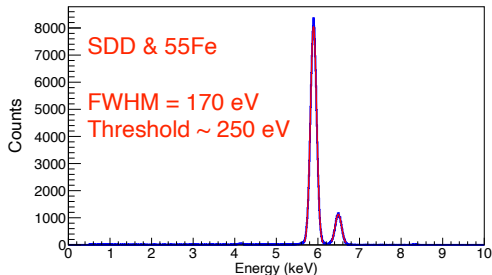
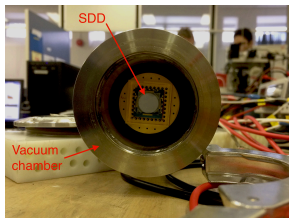
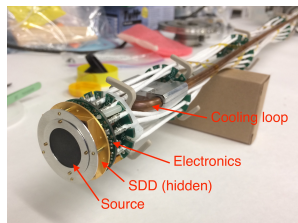
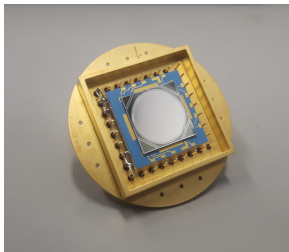


Vacuum insert with X-ray detector

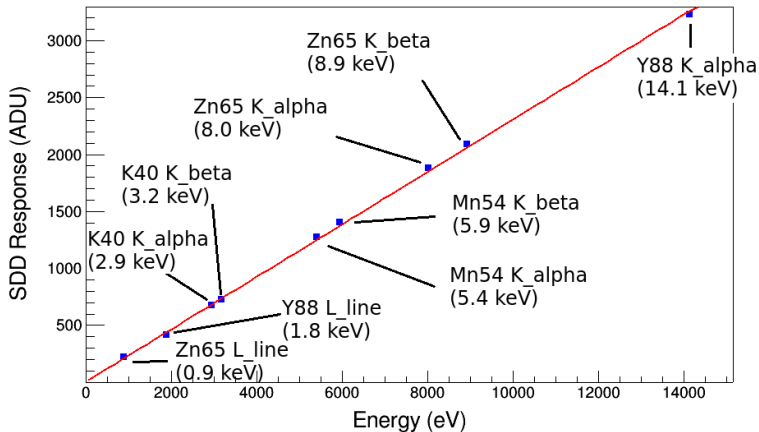


X-ray detector

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



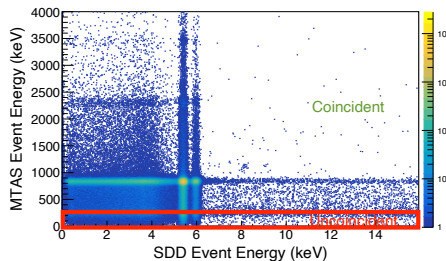
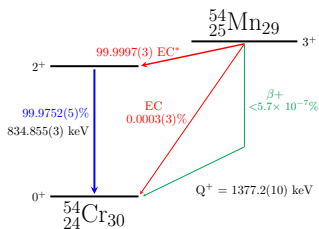
SDD: all energy calibrations



Calibrating tagging efficiency with ^{54}Mn

Overwhelmingly decays by EC*

Data: ≈ 2 days, $\gtrsim 10^6$ events



- ▶ $E_X = 5.5$ keV (also 4–6 keV Augers), $E_\gamma = 835$ keV
- ▶ Standard-geometry source

Something in MTAS: coincident
Nothing in MTAS: uncoincident

Combine with ratio of $^{40}\text{K}/^{54}\text{Mn}$ Geant4 sims

$\Rightarrow$ ^{40}K tagging efficiency = $0.9789(6)$ (1 μs coinc window)

Determining tagging efficiency for ^{40}K γ s [20]

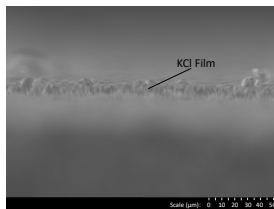
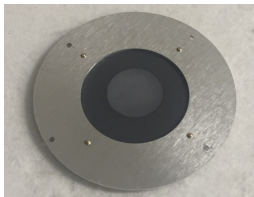
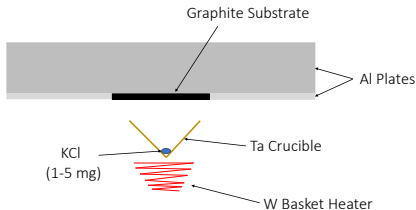
- ▶ Many additional ingredients for ^{54}Mn 835 keV efficiency: **source-BG pileup**, **source-source pileup**, **coincidence window**, **conversion electrons**, **deadtime**... → likelihood function
- ▶ Scale up to ^{40}K 1.4 MeV efficiency with GEANT 4 Monte-Carlos
 - ▶ Simulate **ratio** of efficiencies at 835 keV and 1.4 MeV
 - ▶ Ratio is insensitive to details of geometry, changes of threshold, choice of physics list
 - ▶ Results

Coin Win (μs)	Energy & Live Time	Corrected Efficiency	
	^{54}Mn	^{40}K	^{65}Zn
1	0.9775 (1)	0.9789 (6)	0.9790 (6)
2	0.9778 (1)	0.9792 (6)	0.9793 (6)
4	0.9778 (1)	0.9792 (6)	0.9793 (6)

Numbers consistent across coinc. windows.

The source: KCl using 16% enriched $^{40}\text{K}/\text{K}$

- Thermally deposited to same geometry as other sources (cm diam disk)



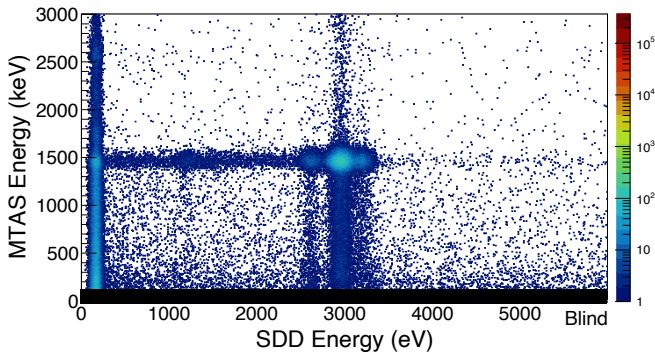
(test source)

- 5 μm thick, $\sim 9 \times 10^{17}$ atoms ^{40}K : activity equivalent to

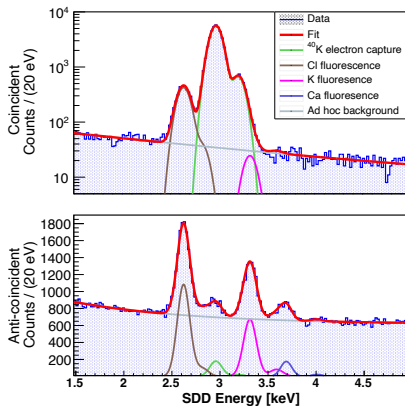


^{40}K run — BLINDED

- ▶ Using thermally deposited ^{enr}KCl source, activity $\sim$
- ▶ 33 days of usable data
- ▶ ^{40}K visible in MTAS and SDD



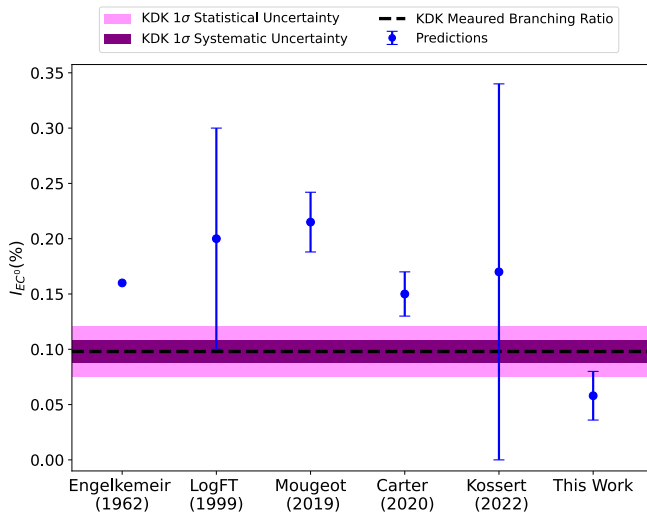
Results after unblinding: PRL 131 052503 2023, PRC 108 014327 2023



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

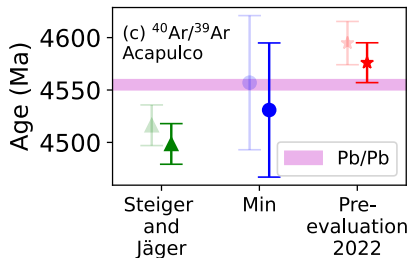
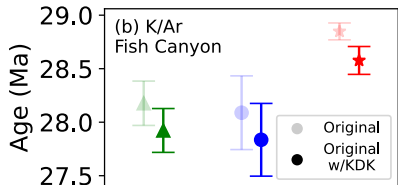
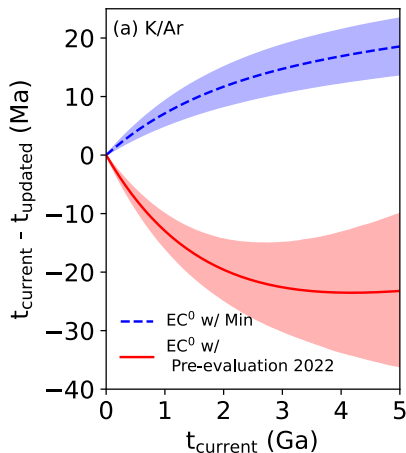
$$\text{Branching ratio: } I_{\text{EC}^0} = 0.098\%^{\text{stat}} \pm 0.023\%^{\text{sys}} \pm 0.010\%$$

Comparing to predictions



Discrepancy perhaps linked to 1960s measurements of β^+ [22, 23]

Implications for geochronology



Limiting factor now variability in other ^{40}K branches.

Conclusions and prospects for KDK

- ▶ Detector characterized, target tagging efficiency achieved $(97.89 \pm 0.06)\%$ — (NIM A 1012 (2021) 165593)
- ▶ **^{40}K unblinded, analyzed: first observation of EC0 accomplished** $I_{\text{EC}^0} = 0.098\% \pm 0.023\%_{\text{stat}} \pm 0.010\%_{\text{sys}}$ **PRL 131 052503 2023, PRC 108 014327 2023**
- ▶ Branching ratio of ^{40}K electron capture to ^{40}Ar ground state:
 - ▶ Reduces background constraints on DAMA claim of dark matter discovery, simplifies things for NaI experiments
 - ▶ Resolves longstanding question in geochronology
 - ▶ Informs nuclear structure
 - ▶ Suggests forbidden contributions to $0\nu\beta\beta$ are suppressed
- ▶ Also ^{65}Zn (Hariasz et al, Nuclear Data Sheets, 189, June 2023, 224–234) and ^{88}Y data
- ▶ Interested in measuring other rare decays