Potassium
K
DK
Decay

The KDK (^{40}K decay) experiment: Measuring a rare decay of ^{40}K

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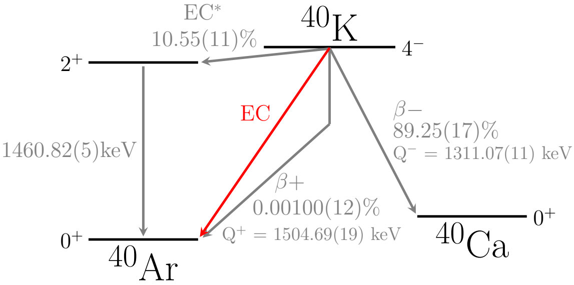
Decays of ^{40}K [1]

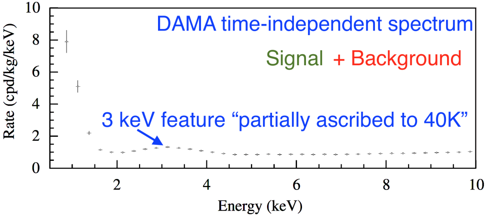
- ^{40}K: naturally occurring; 0.012% abundance; $T_{1/2} = 1.2 \times 10^9$ years



- Electron capture (EC): ${}^{40}_{19}\mathrm{K} + e^- \rightarrow {}^{40}_{18}\mathrm{Ar} + \nu_e$
  - ~ 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 EC has never been observed
- Nuclear theory: would be only measured 3rd forbidden unique EC

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

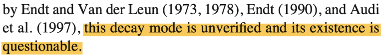
- ~ 3 keV from EC/EC* is a BG in energy region expected for many dark matter models
- EC* can be tagged by 1.4 MeV γ, EC can not be tagged: irreducible BG
- K contaminates many NaI experiments (ANAIS, ASTAROTH, COSINE, COSINUS, SABRE...): draconian measures taken to grow pure crystals, veto EC*
- In particular, EC may constrain interpretations of DAMA dark matter claim [2] (Pradler et al 2013 [3])



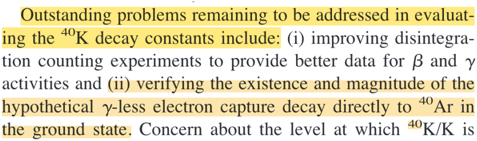
(also requires assumptions on tagging efficiency and other BGs)

^{40}K EC and geochronology

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

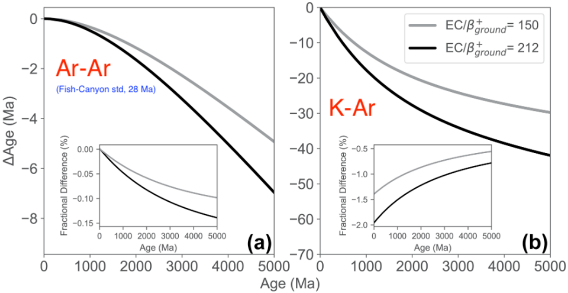


by Endt and Van der Leun (1973, 1978), Endt (1990), and Audi et al. (1997), this decay mode is unverified and its existence is questionable.



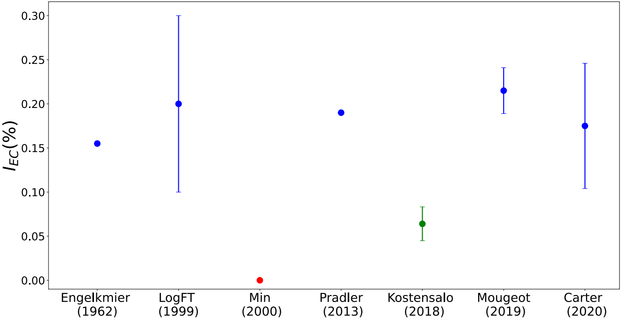
Outstanding problems remaining to be addressed in evaluating the ^{40}K decay constants include: (i) improving disintegration counting experiments to provide better data for β and γ activities and (ii) verifying the existence and magnitude of the hypothetical γ-less electron capture decay directly to ^{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%), EC uncertainty noticeable:

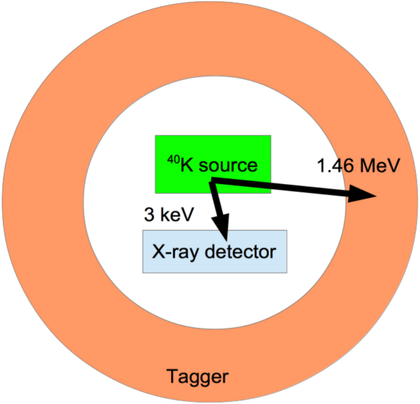


Neglecting EC tends to overestimate ages

Theory predictions, assumptions, for EC branching ratio



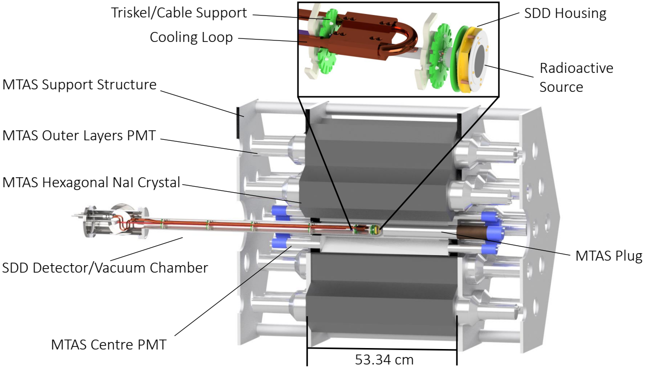
Measuring EC with KDK [7, 8]: X-ray detector and tagger



- EC/EC* trigger small inner detector
  - $\sim$ keV threshold for X-rays/Augers
  - Transparent to $E \gtrsim 10$ keV to reduce scattering, background
- Surround with 4π veto to tag EC* 1.46 MeV γ
  - For signal-to-noise of 1, need 98% efficiency
  - 98% absorption efficiency of 1.46 MeV γ requires 22 cm of NaI (or 77 cm of LAB, or 59 cm of LAr)
- Compare tagged to untagged triggers to determine ρ, ratio of EC to EC*.

Modular Total Absorption Spectrometer (MTAS) tagger [9]

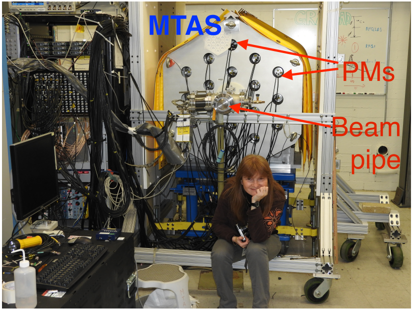
MTAS and insert



- $\sim$ 1 tonne of NaI at Oak Ridge (now at Argonne)
- Surface site, BG rate $\sim$ 2.8 kHz.

MTAS and X-ray detector at ORNL

MTAS

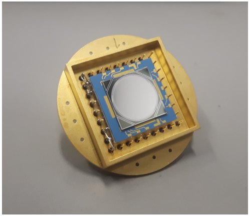


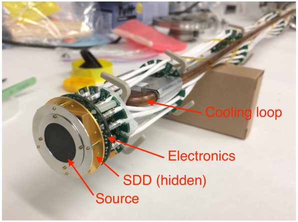
Vacuum insert with X-ray detector slides into beam pipe

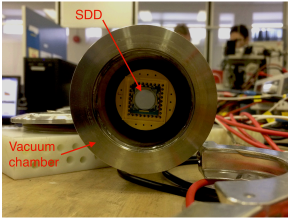
Material minimized around source to avoid γ scattering

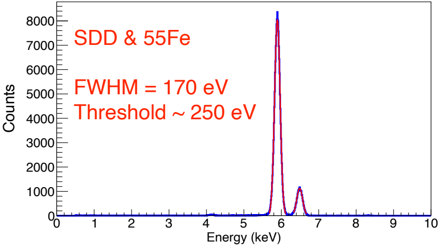
X-ray detector

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

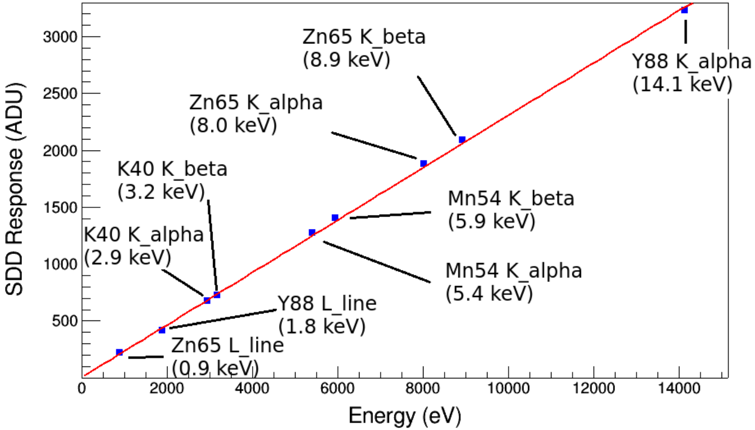






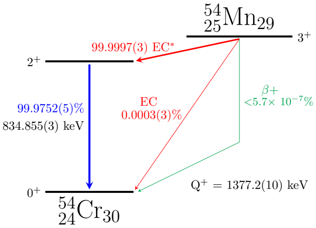


SDD: all energy calibrations



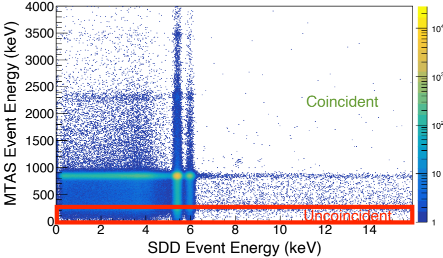
Calibrating tagging efficiency with ^{54}Mn

Overwhelmingly decays by EC*



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

Data: ≈ 2 days, $\gtrsim 10^6$ events



Something in MTAS: coincident

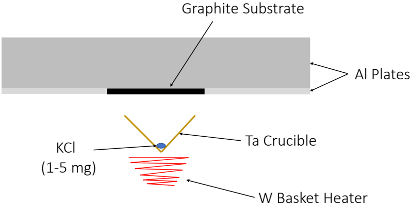
Nothing in MTAS: uncoincident

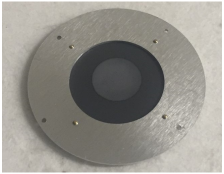
Combine with ratio of ^{40}K/^{54}Mn Geant4 sims

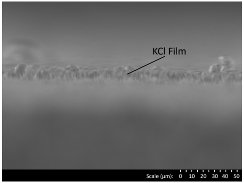
⇒ ^{40}K tagging efficiency = 0.9789(6) (1 μs coinc window)

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

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





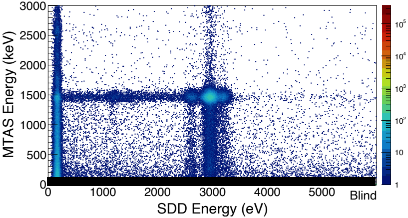


(test source)

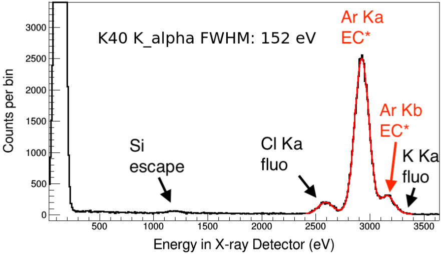
- 5 μm thick, $\sim 9 \times 10^{17}$ atoms ^{40}K: activity $\sim$ 

3-month ^{40}K run — BLINDED

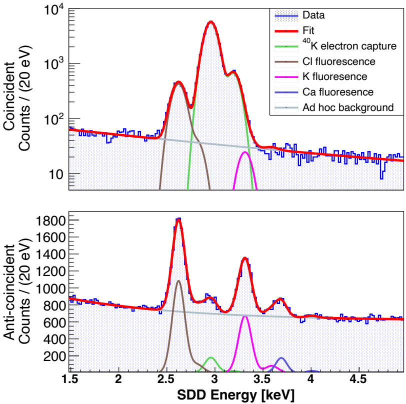
- Using thermally deposited ^{enr}KCl source
- 33 days of usable data
- **^{40}K visible in MTAS and SDD**

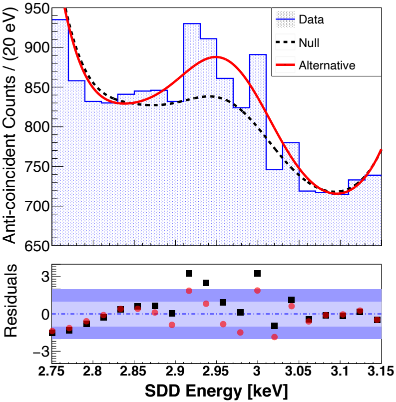


Coincident X-ray spectrum



Results of blind analysis: arXiv:2211.10319, arXiv:2211.10343

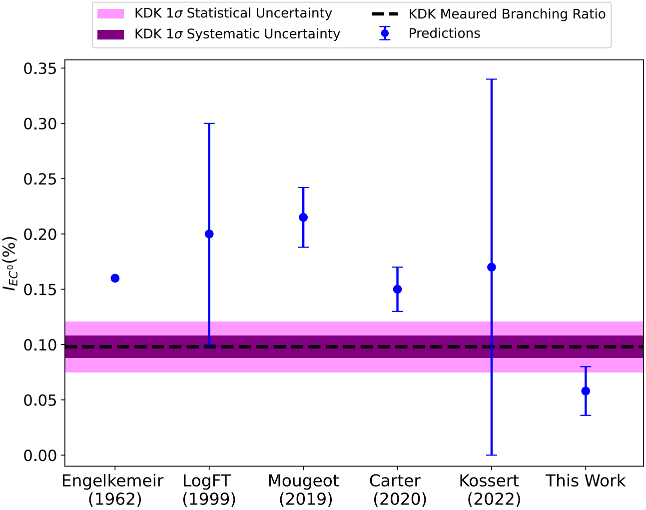




$I_{EC^0}/I_{EC^*} = 0.0095 \overset{\text{stat}}{\pm} 0.0022 \overset{\text{sys}}{\pm} 0.0010$ (H0 rejected at 4σ)

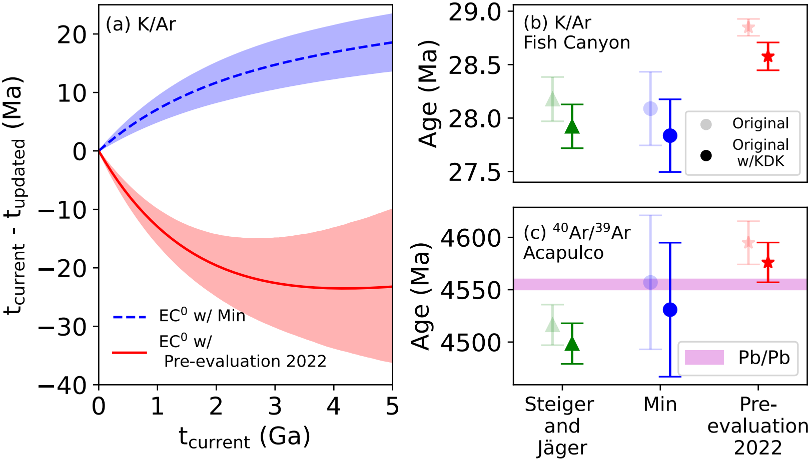
Branching ratio: $I_{EC^0} = 0.098\% \overset{\text{stat}}{\pm} 0.023\% \overset{\text{sys}}{\pm} 0.010\%$

Comparing to predictions



Discrepancy probably caused by 1960s measurements of β^+

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 arXiv:2211.10319, arXiv:2211.10343**
- 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 have ^{65}Zn and ^{88}Y data

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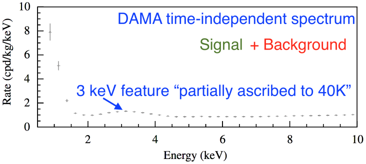
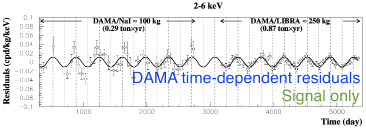
Dark matter, DAMA/LIBRA, and ^{40}K [3, 2]

- DAMA: $\sim$ 250 kg low-background NaI experiment
- Since 1997, DAMA claims detection based on annual modulation caused by rotation of Earth around Sun, through particle halo of galaxy:

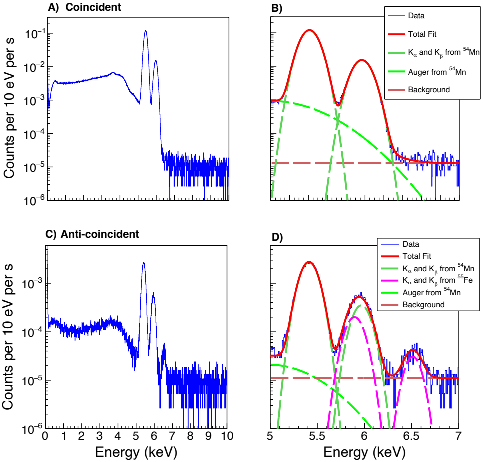




- $$\frac{\overbrace{\text{modulation amplitude}}^{\text{signal}}}{\underbrace{\text{time-independent amplitude}}_{\text{signal} + \text{background}}} \approx \frac{1}{100}$$
- DAMA controversial:
  - tension with other experimental results
  - disagreement on background model, eg [10]
- Consensus that 3 keV X-rays/Augers from ^{40}K contribute to low-energy DAMA spectrum
- Contribution may be of the order of the amplitude of modulation
- Pradler et al, PLB 2013 [3]: precise understanding of ^{40}K necessary to constrain modulation fraction of signal, and dark matter interpretation

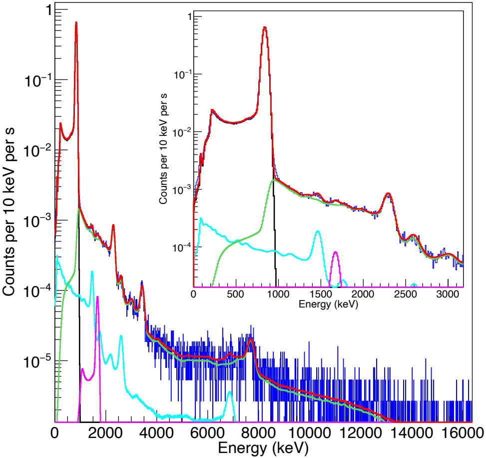
^{54}Mn tagging efficiency calibration and background

Compare number of uncoincident to coincident ^{54}Mn X-rays to obtain efficiency



Good resolution reveals ^{55}Fe (eg Mn X-rays) contamination in ^{54}Mn (Cr X-rays) source that must be accounted for in efficiency calculation.

MTAS ^{54}Mn spectrum (SDD trig, 4 μs CW): data and sims



Blue: data — Black: pure source sim — Cyan: BG data (measured) — Green: source-BG coincidence

Magenta: source-source coincidence — Red: total sim

Confirms BG coincidence rate

Determining tagging efficiency for ^{40}K γs [8]

- 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.

Systematic errors on ρ

All syst errors are smaller than statistical (0.0022).

Source	Systematic Error
Fit range	9×10^{-4}
MTAS γ-ray-tagging efficiency	5×10^{-4}
Binning	1×10^{-4}
SDD γ-ray-tagging efficiency	4×10^{-5}
K-shell capture probabilities	8×10^{-6}
Expected MTAS background counts	3×10^{-6}

Count summary

Component	Visible counts
Total Ar ($\Sigma^* + \Sigma$)	4.78×10^4
Coincident Ar (Σ^*)	4.63×10^4
Anti-coincident Ar (Σ)	1.50×10^3
EC^0 decay (σ)	5.00×10^2

Consequences for $0\nu\beta\beta$ (Sec IIIB arXiv:2211.10343)

"Using this Hamiltonian the half-lives of the three decay branches, β^-, EC*, and EC^0, could be calculated. The corresponding decay amplitudes are proportional to the weak axial-vector coupling g_A, the value of which is known to be quenched for a wide range of nuclear masses [**?**]. Here the effective value of it can be determined by comparison of the computed and experimental half-lives, giving for the first-forbidden unique transition EC* the value $g_\mathrm{A}^\mathrm{eff} = 0.34$ and for the two third-forbidden unique transitions a value $g_\mathrm{A}^\mathrm{eff} = 0.43$ for β^- branch and $g_\mathrm{A}^\mathrm{eff} = 0.53$ for the EC^0 branch. These values of $g_\mathrm{A}^\mathrm{eff}$ are very well in line with the values $g_\mathrm{A}^\mathrm{eff} = 0.43 - 0.66$ obtained in the mass range $A = 74 - 126$ for the $2^- \leftrightarrow 0^+$ first-forbidden unique β and EC transitions in the framework of the proton-neutron quasiparticle random-phase approximation [**?**]. These results suggest that the forbidden contributions to the nuclear matrix elements of the decay are very much suppressed and the resulting half-lives are much longer that expected based on the bare value $g_\mathrm{A}^\mathrm{bare} = 1.27$ of the axial-vector coupling. Using values in [**?**], we expect the quenching of this axial-vector coupling strength to **increase the neutrinoless double-beta decay half-life of ^{48}Ca by a factor of 7^{+3}_{-2}.**"