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

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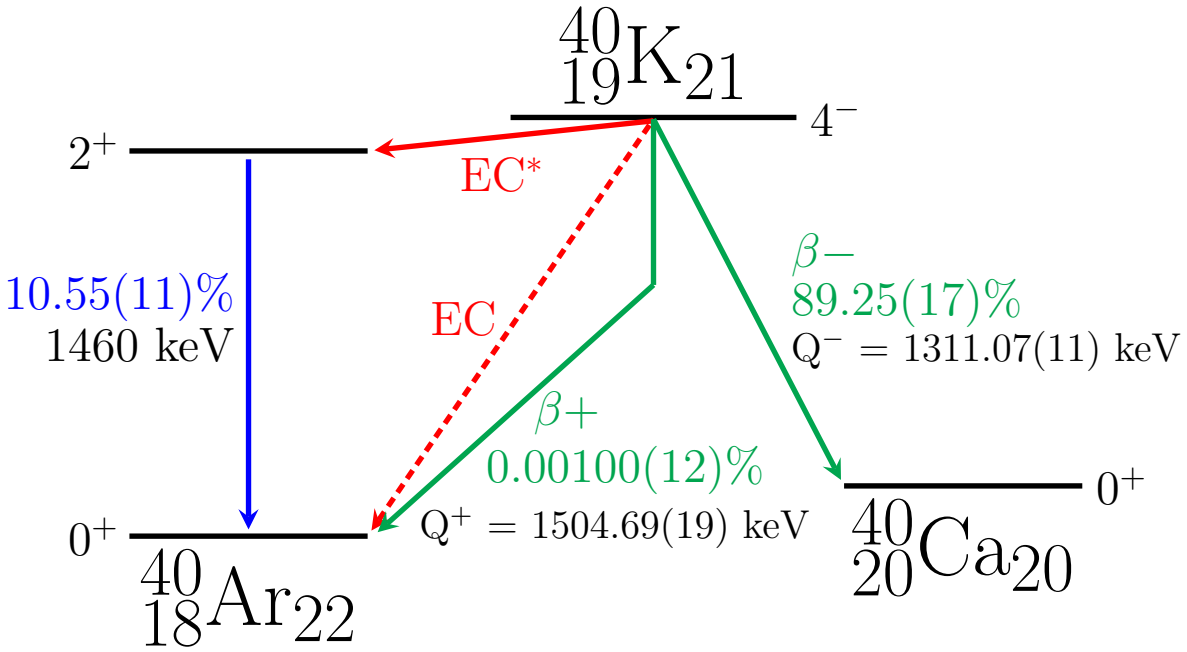
Decays of ^{40}K [1]

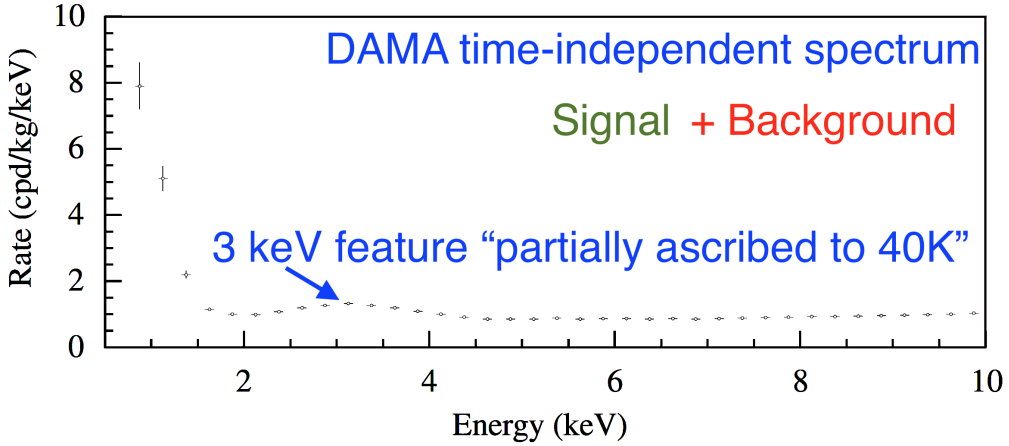
- ^{40}K: naturally occurring; 0.012% abundance; $T_{1/2} = 1.2 \times 10^9$ years



- Electron capture (EC):
  - $\sim$ 3 keV X-rays and Auger electrons from K-shell electron capture: $^{40}\mathrm{K} + e^- \rightarrow {}^{40}\mathrm{Ar} + \nu_e$.
  - Also 1.4 MeV γ (or conversion electron) if EC* to excited state
- Direct-to-ground-state EC has never been observed

Importance of ^{40}K EC decay

Rare-event searches Untaggable $\sim$ 3 keV BG in many rare-event expts. May constrain interpretations of DAMA dark matter claim [2] (Pradler et al 2013 [3])

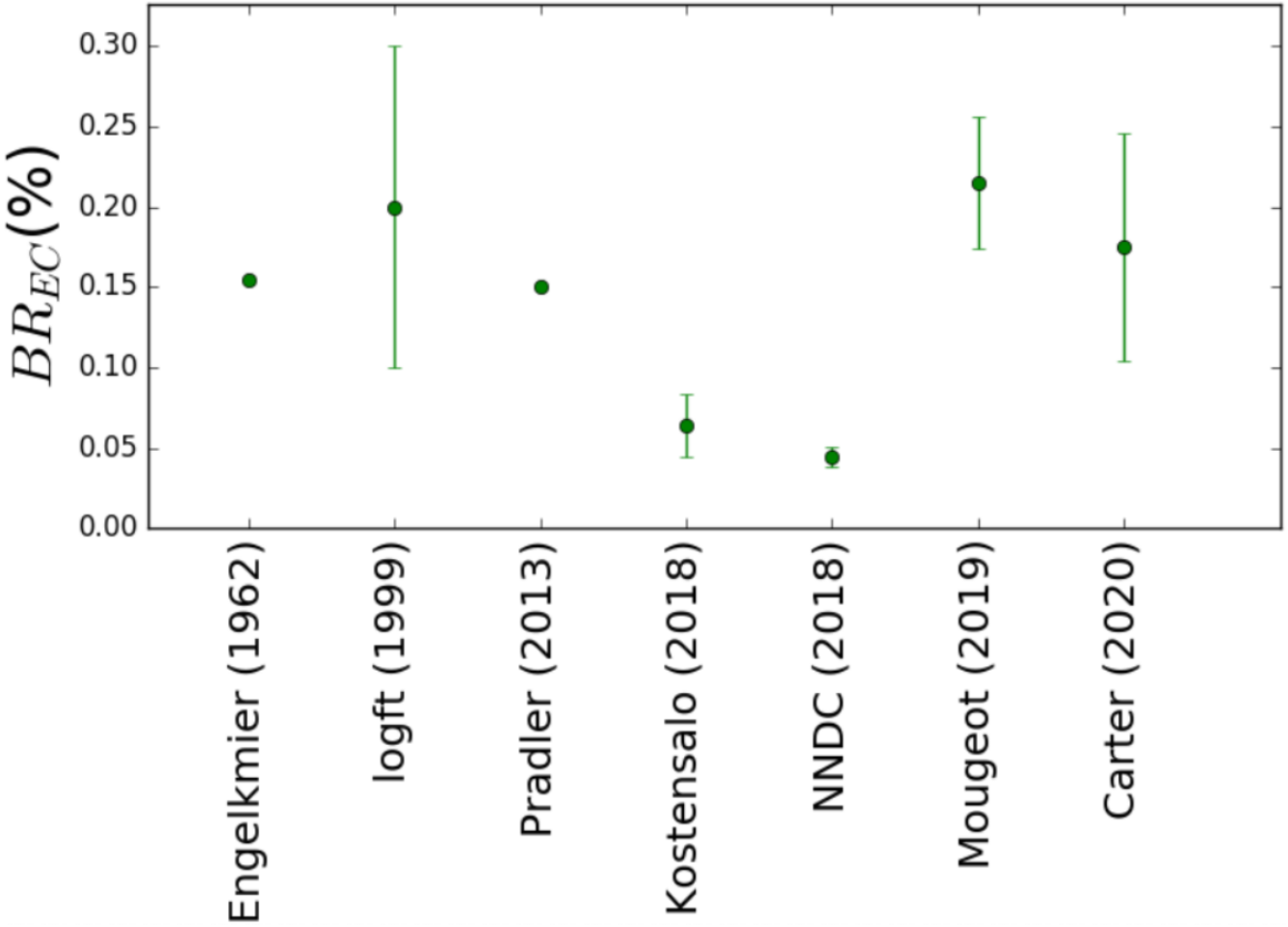


Geochronology Uncertainty limits precision of K/Ar dating [4]. Others in field dispute existence of branch [5]:

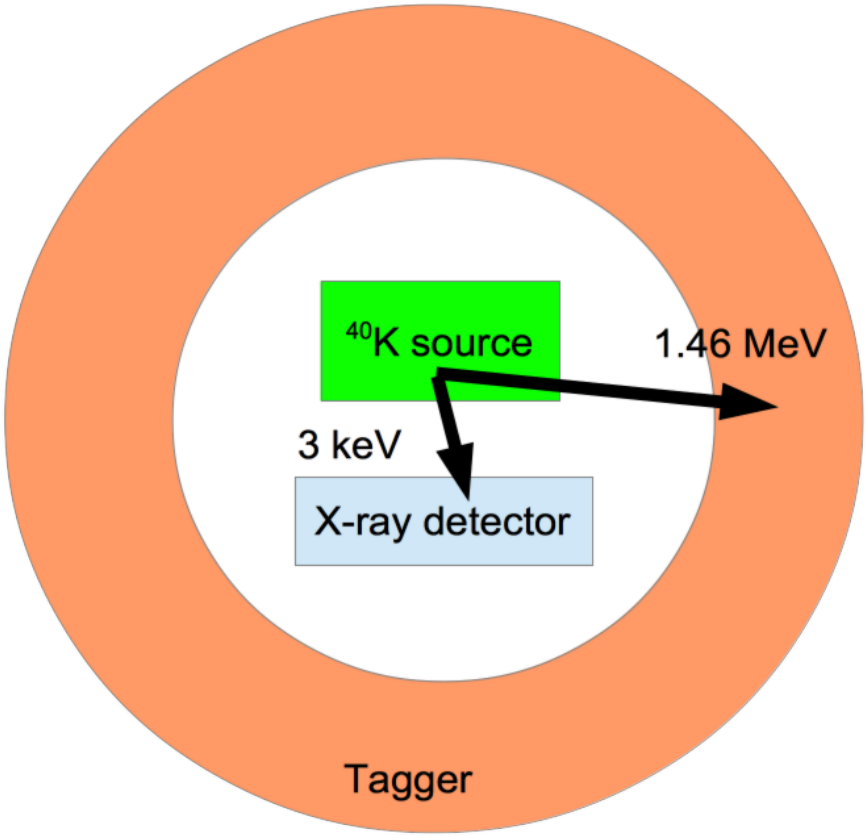
> by Endt and Van der Leun (1973, 1978), Endt (1990), and Audi et al. (1997), this decay mode is unverified and its existence is questionable.

Nuclear theory Rare example of third-forbidden unique transition

Theoretical predictions for the EC branching ratio



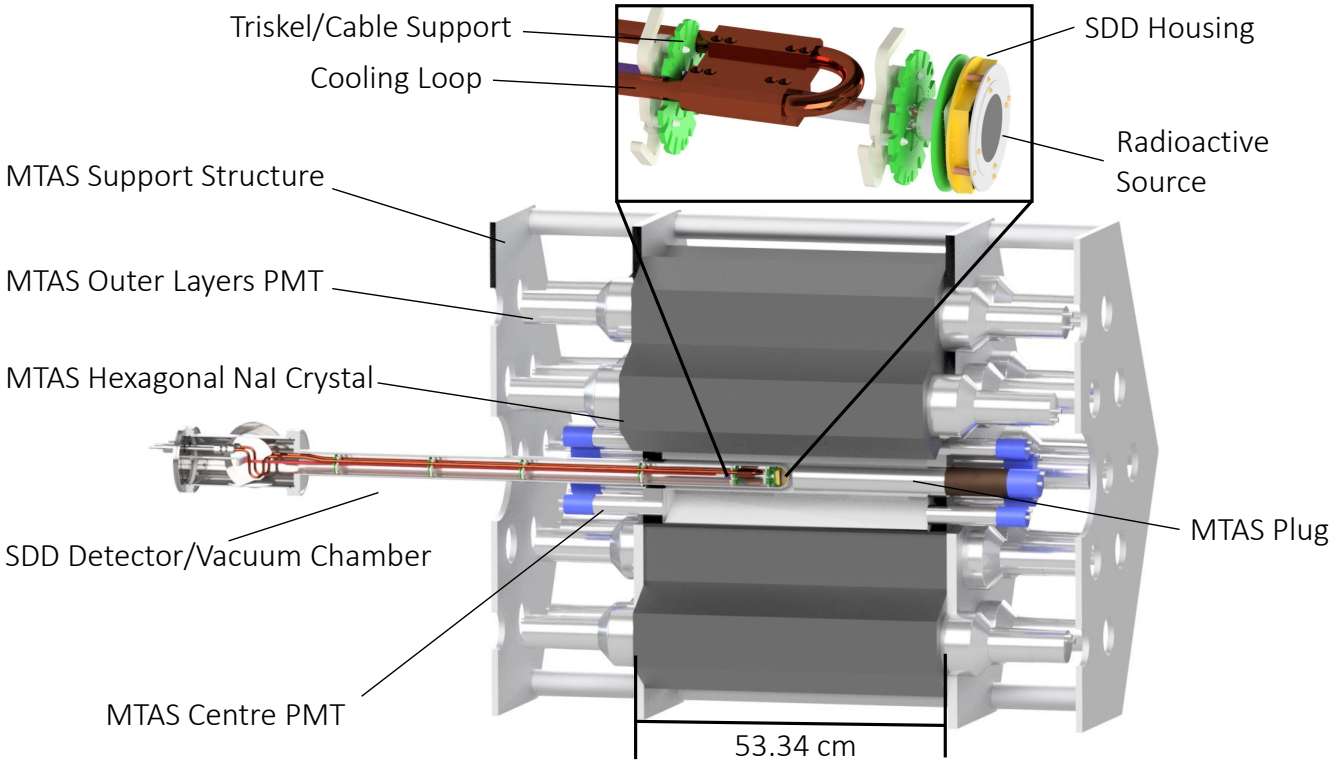
Measuring EC with KDK [6, 7]: X-ray detector and tagger



- EC/EC* trigger on 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 [8]

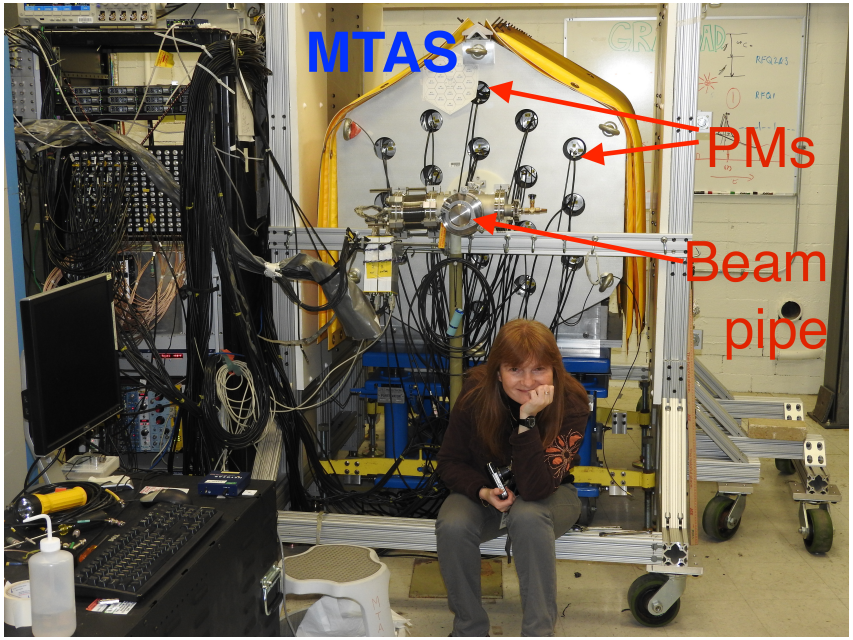
MTAS and insert



- $\sim$ 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

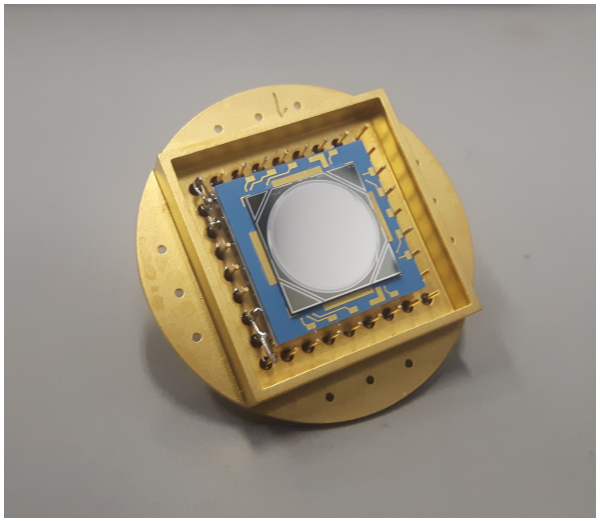


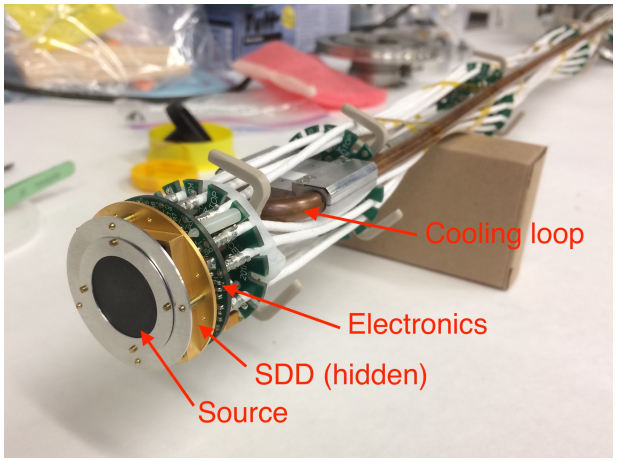
Vacuum insert with X-ray detector slides into beam pipe

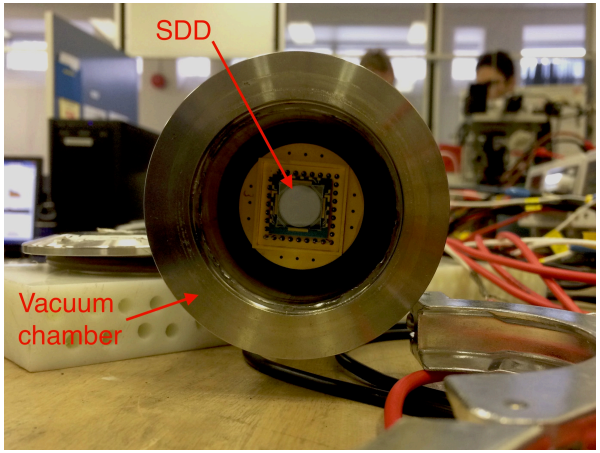
Material minimized around source to avoid γ scattering

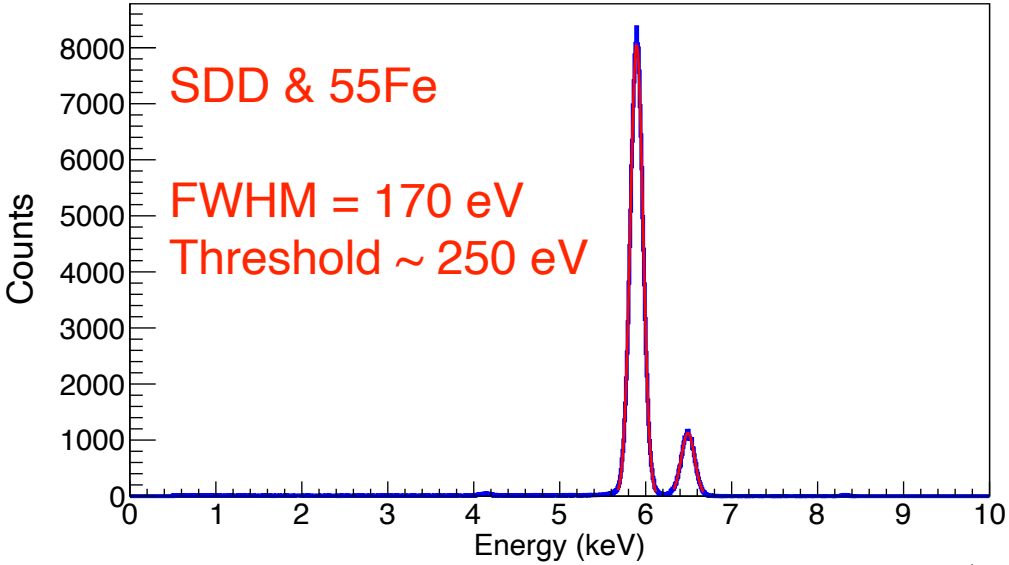
X-ray detector

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

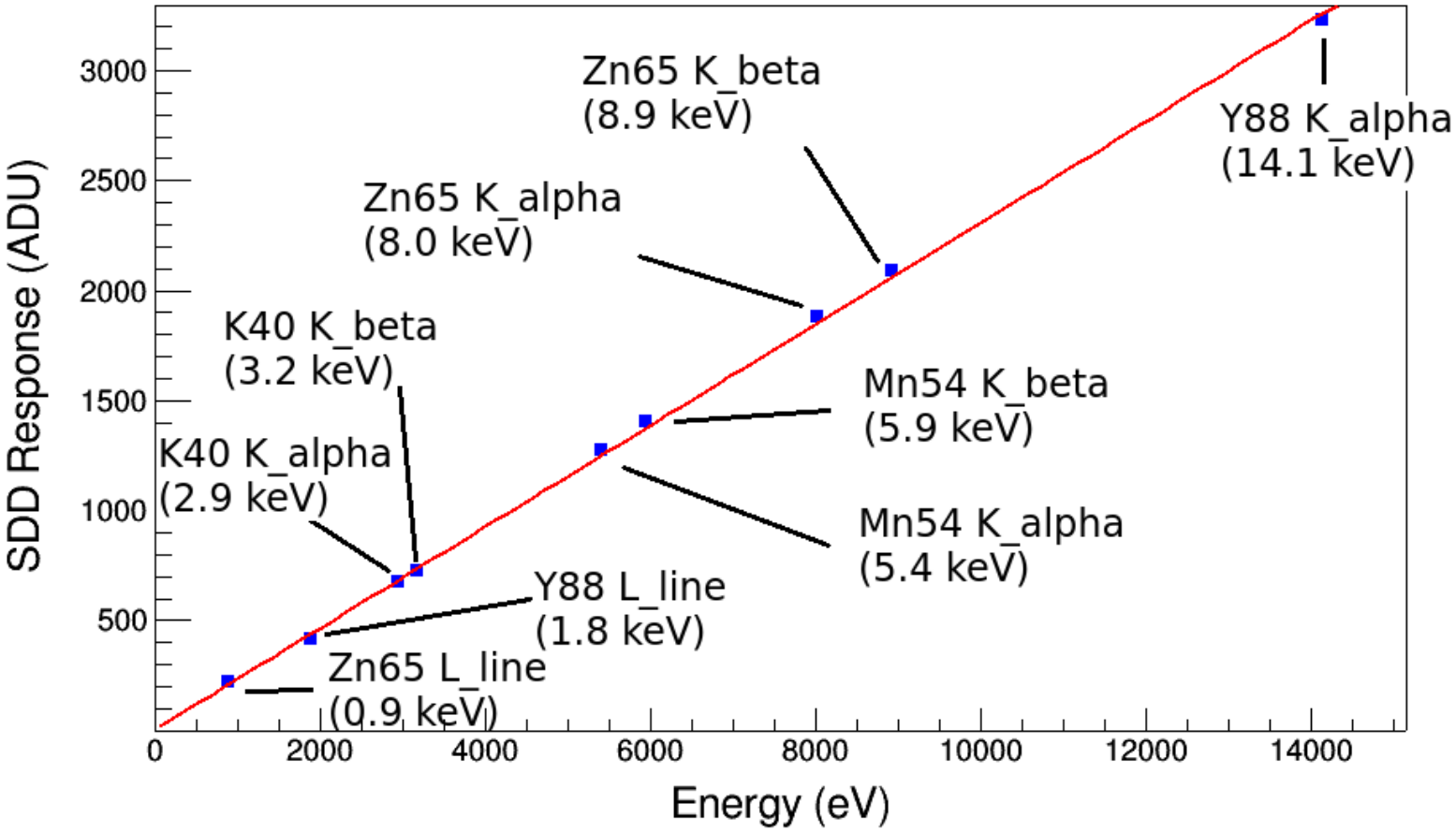






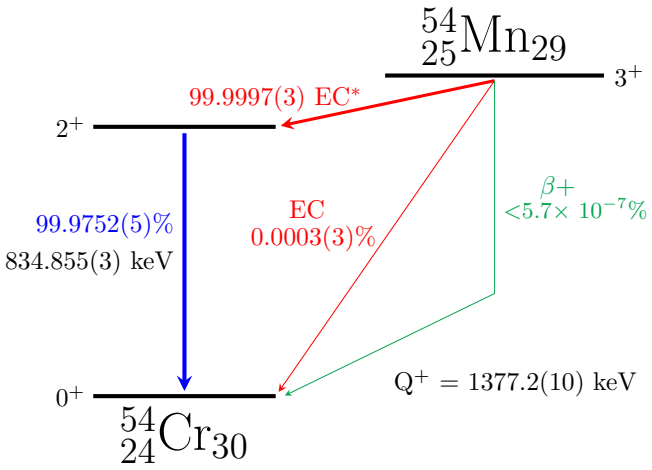


SDD: all energy calibrations



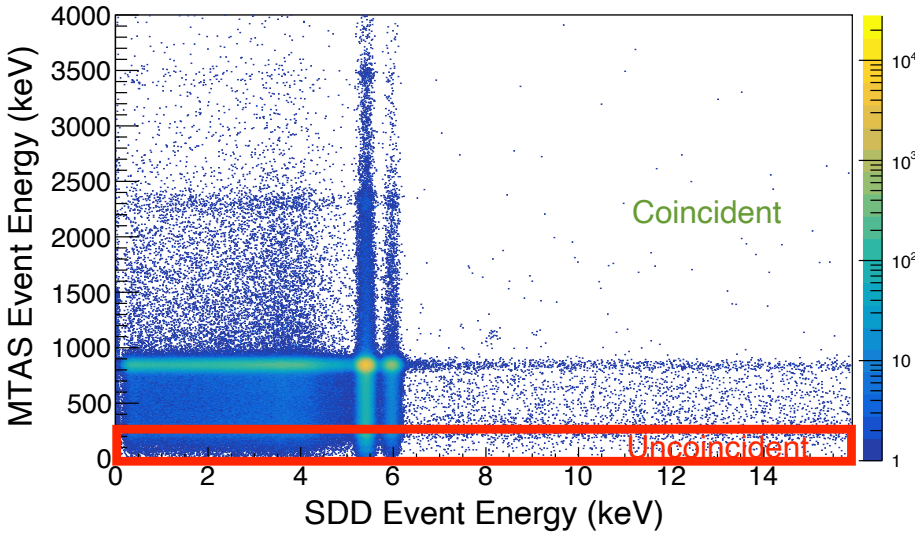
Calibrating tagging efficiency with ^{54}Mn

Overwhelmingly decays by EC*



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

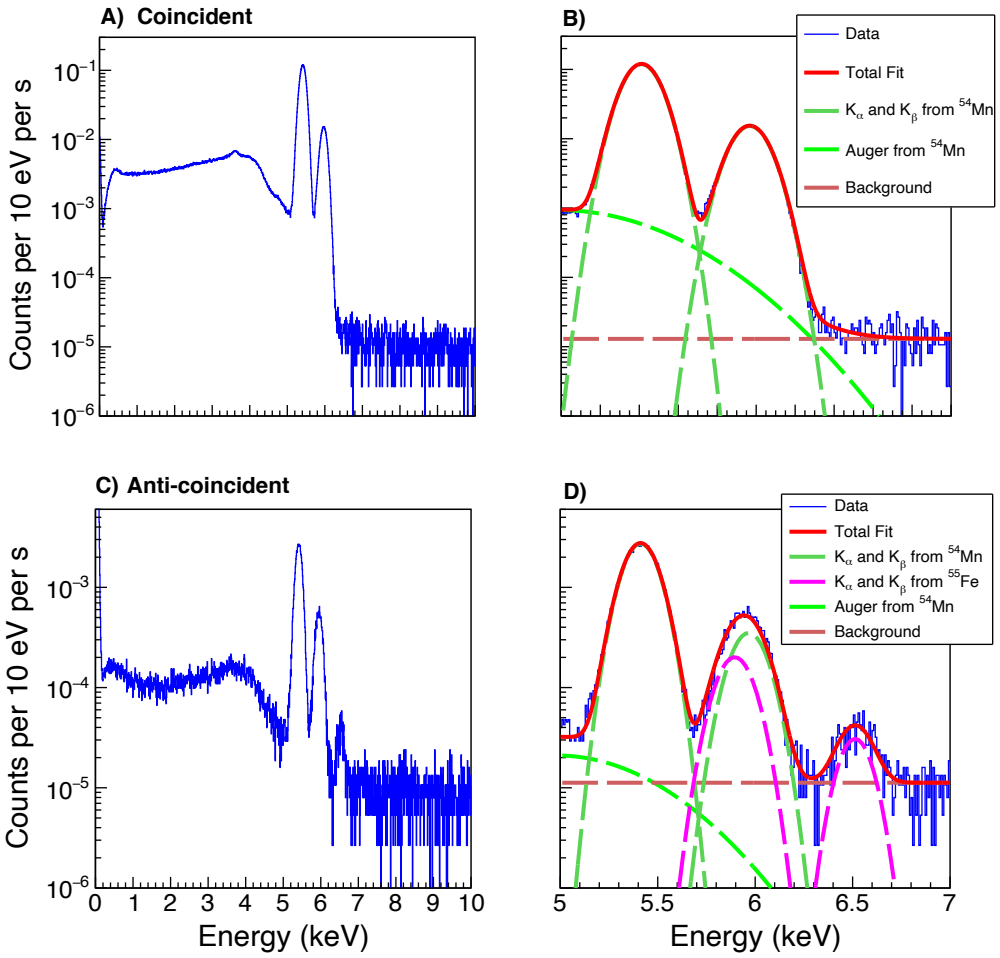
Data: ≈ 2 days, $\gtrsim 10^6$ events



(spurious coinc. with ^{40}K BG visible)

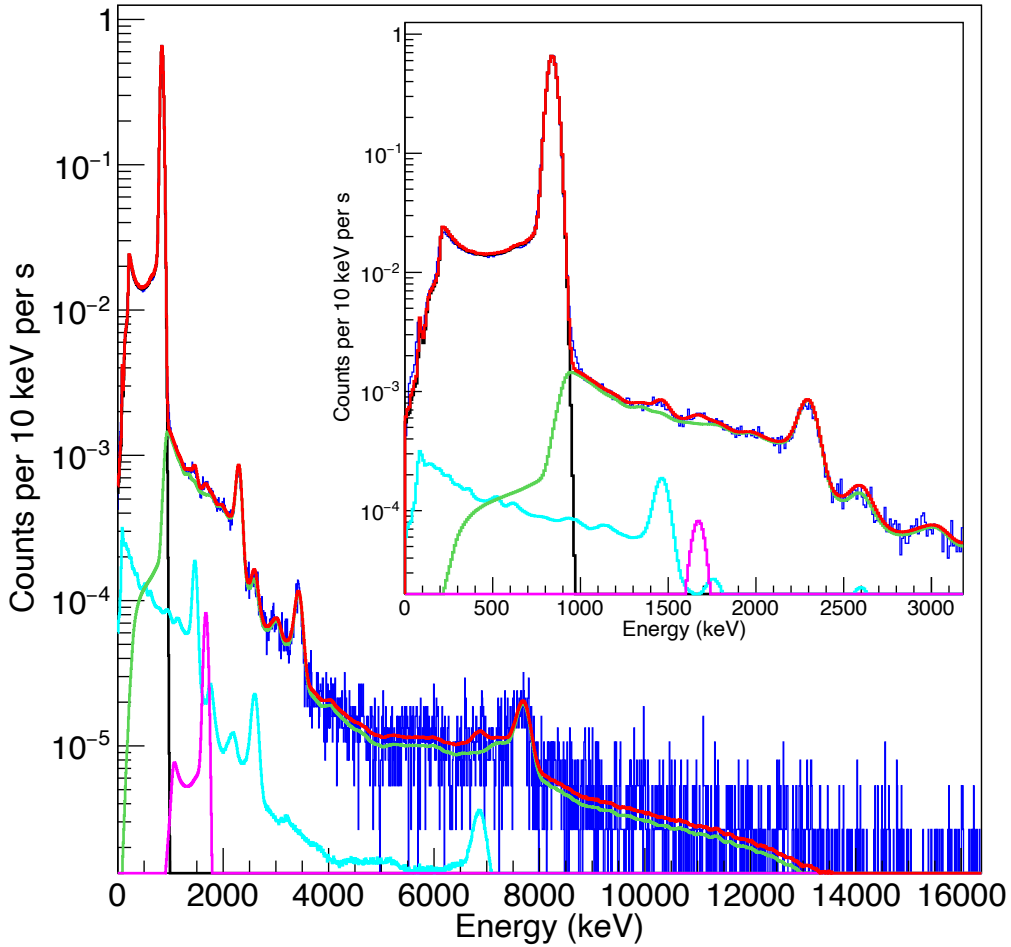
^{54}Mn tagging efficiency calibration and background

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 — Green: source-BG coincidence — Magenta: source-source coincidence — Red: total sim

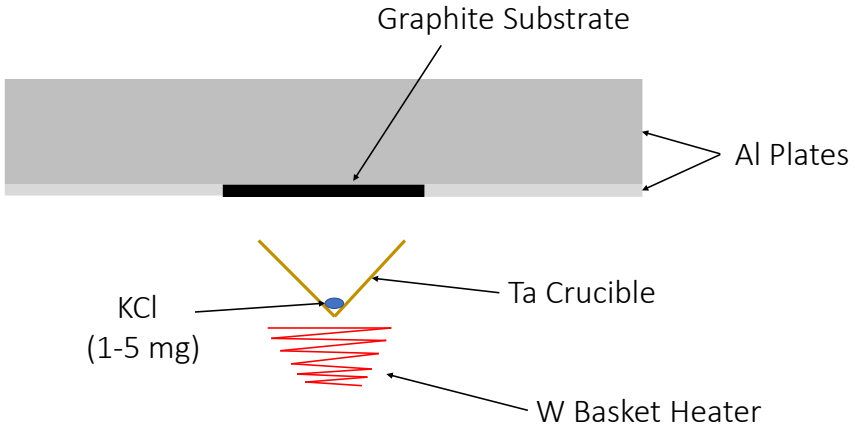
Determining tagging efficiency for ^{40}K γs

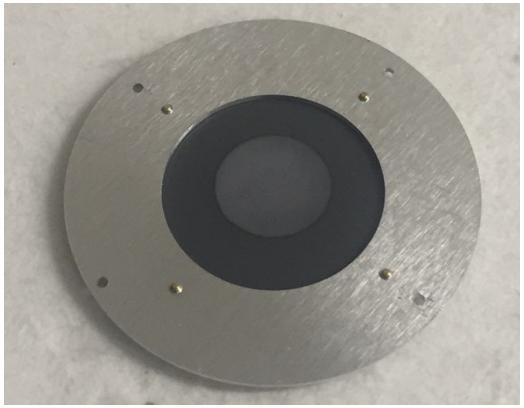
- Many additional ingredients for ^{54}Mn 835 keV efficiency: source-BG pileup, source-source pileup, coincidence window, conversion electrons, deadtime... $\rightarrow$ likelihood function
- Scale up to ^{40}K 1.4 MeV efficiency with GEANT 4 Monte-Carlos
  - Simulate **ratio** of efficiencies at 835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

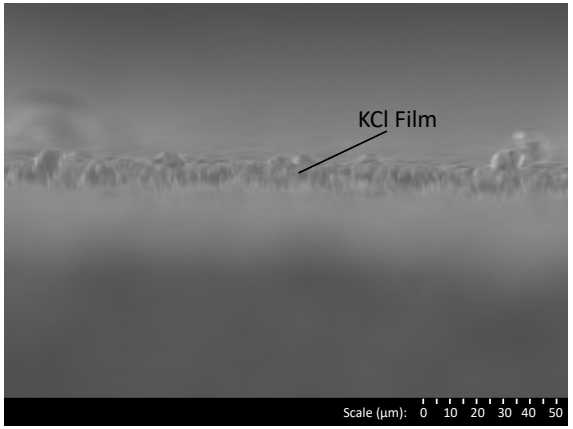
Coin Win (μs)	Energy & Live Time Corrected Efficiency		
	^{54}Mn	^{40}K	^{65}Zn
1	0.9775 (1)	0.9789 (6)	0.9790 (6)
2	0.9778 (1)	0.9792 (6)	0.9793 (6)
4	0.9778 (1)	0.9792 (6)	0.9793 (6)

The ^{40}K source

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





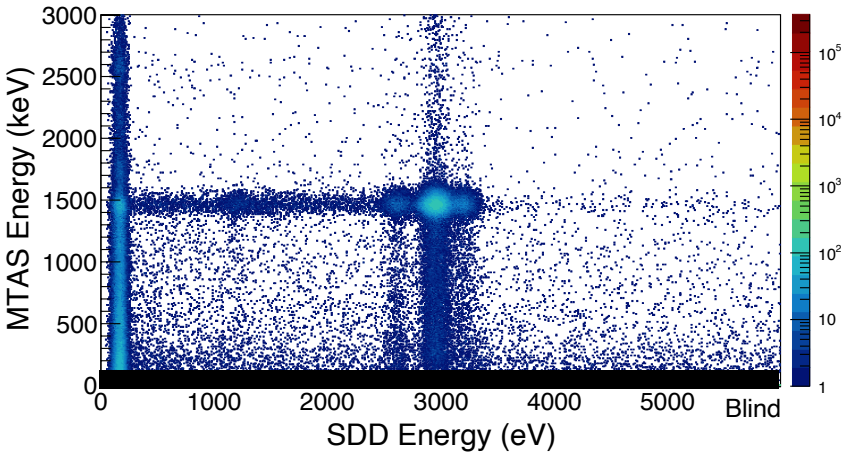


(test source)

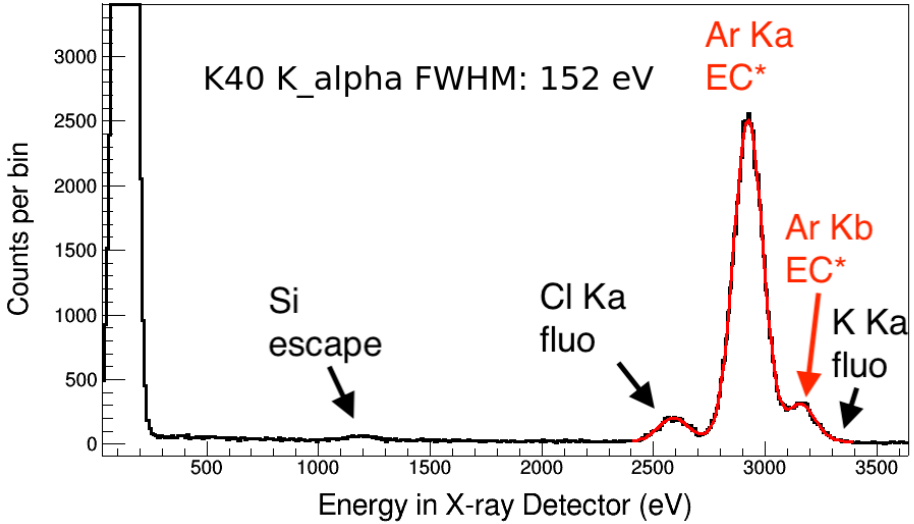
- 5 μm thick, $\sim 9 \times 10^{17}$ atoms ^{40}K: activity equivalent to

^{40}K run: Dec 2017 – Feb 2018 — BLINDED

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

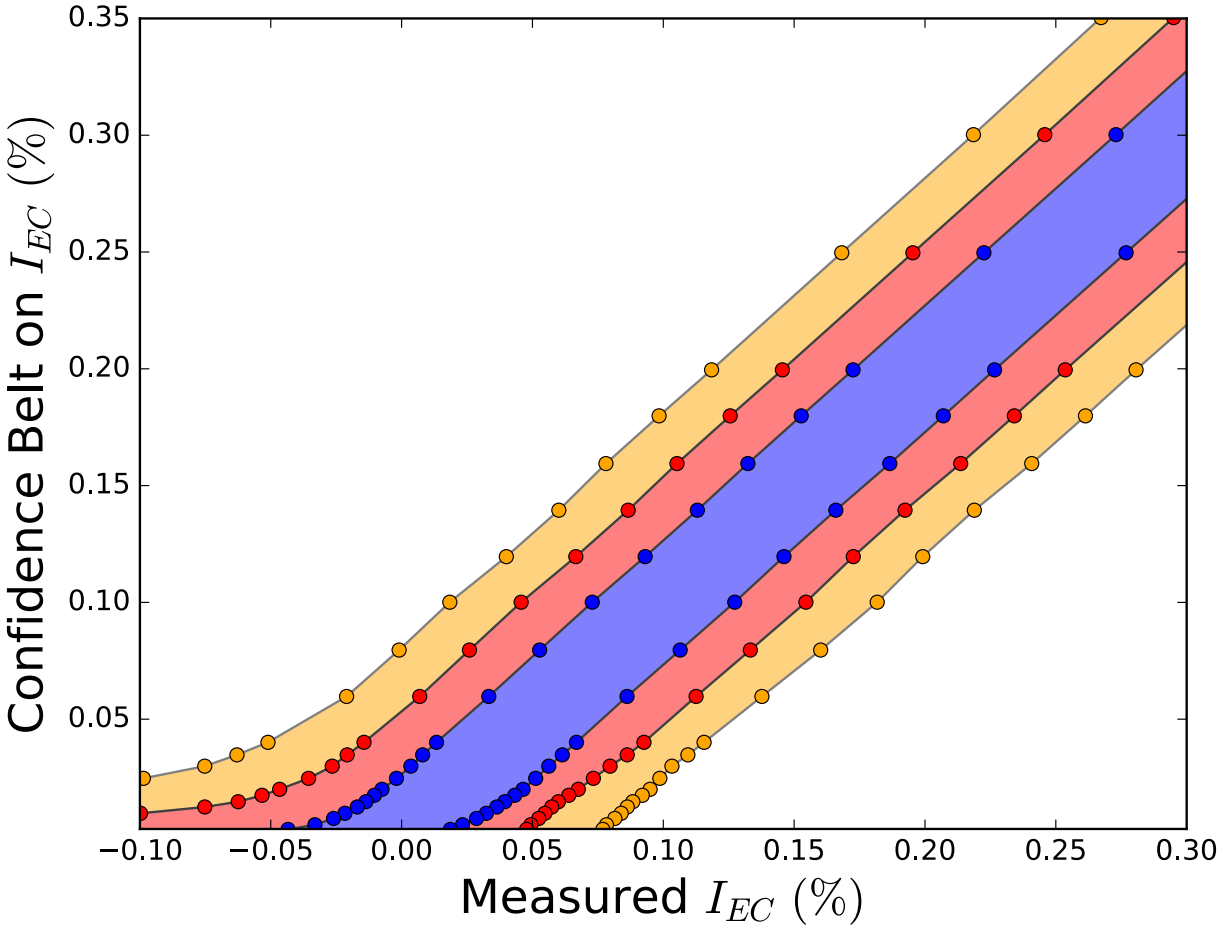


Coincident X-ray spectrum



- $K_{\alpha,\beta}$ from EC* to Ar visible
- Ongoing work to understand
  - Source fluorescence (Cl 2.6 keV, K 3.3 keV)
  - Other coincident, uncoincident BGs

Feldman and Cousins [9] expected sensitivity

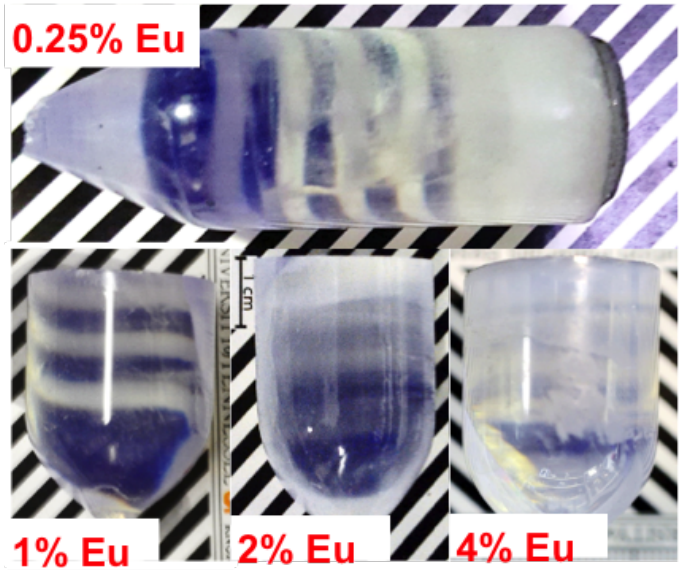


(68, 95, 99% CI)

Likelihood ratio test: EC BR of 0.2% could be observed at $> 5\sigma$

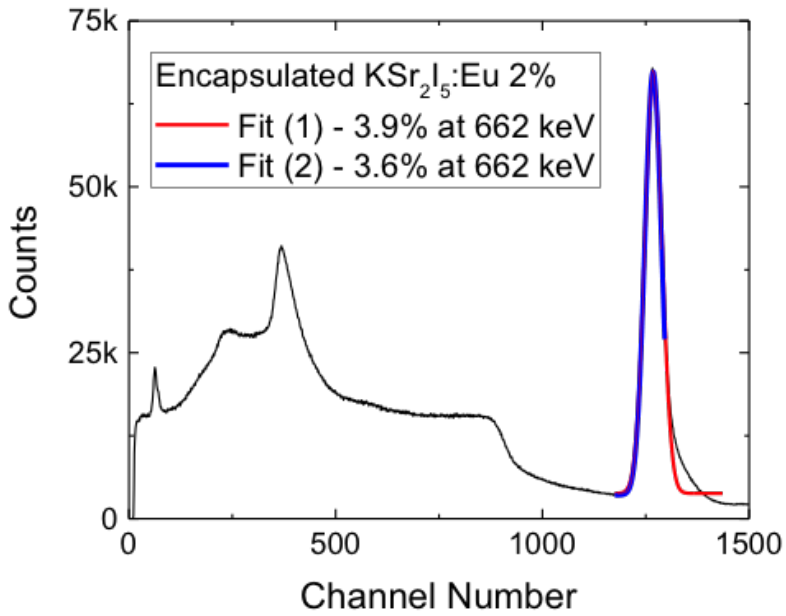
Complementary approach: KSr_2I_5:Eu scintillator (KSI)[c]

- Novel scintillator [10], high light yield $\approx$ 100 photons/keV, $\lambda \approx 450$ nm
- Density 4.4 g/cm^3, total ^{40}K activity 6.6 Hz/cm^3
- Available in several cm^3
- 1" diameter crystals:



- Hygroscopic $\rightarrow$ encapsulate

- Excellent energy resolution (^{137}Cs):



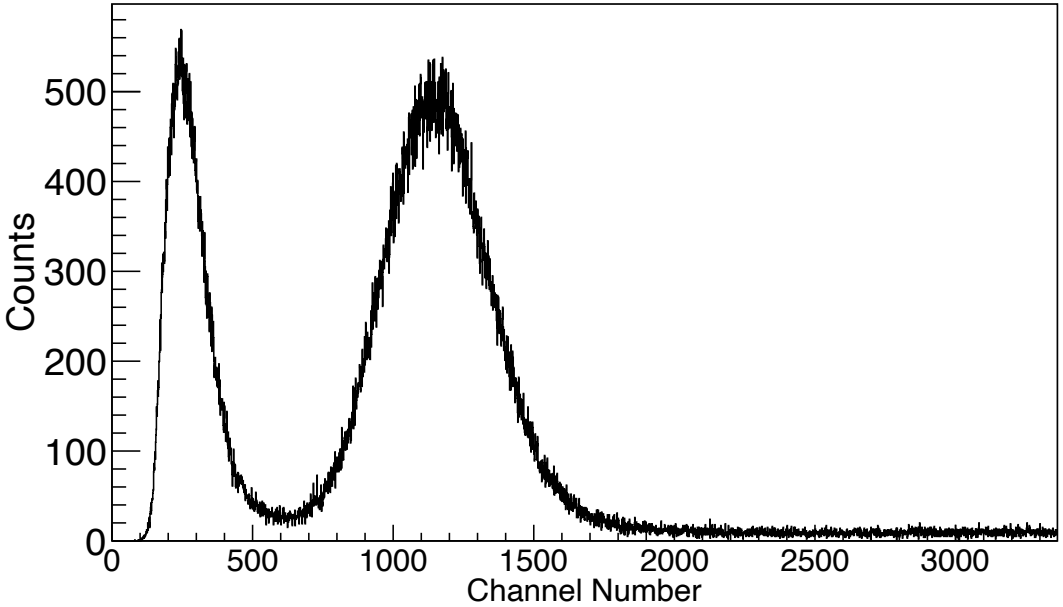
[c] C. Goetz, E. Lukosi, C. Melcher, L. Stand — U. Tennessee

KSI in MTAS (preliminary)

Setup inserted into MTAS

- 4 g KSI
  - $7 \times 7 \times 20$ mm^3
  - Total ^{40}K activity ~ 6 Hz
- 2 PMs

Scintillator spectrum of events coincident with MTAS



- 3 keV X-rays and Auger electrons visible
- Analysis ongoing

Conclusions and prospects for KDK

- Measuring branching ratio of ^{40}K e^- capture to ^{40}Ar ground state will:
  - provide better understanding of backgrounds in dark matter searches, and in DAMA claim for discovery
  - improve precision of K/Ar dating for geochronology
  - inform nuclear structure and beta decay models
- Detector fully characterized: $(97.89 \pm 0.06)\%$ tagging efficiency will allow target sensitivity (arXiv:2012.15232 submitted to NIM)
- ^{40}K data in hand, unblinding expected by summer (also have ^{65}Zn and ^{88}Y data)
- Complementary analysis of KSr_2I_5 data advancing in parallel

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