The KDK (^{40}K decay) project: Measuring a rare decay of ^{40}K with implications for dark-matter claims

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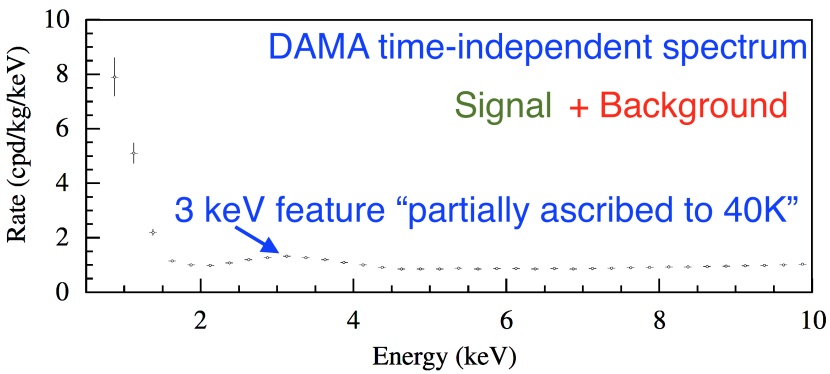
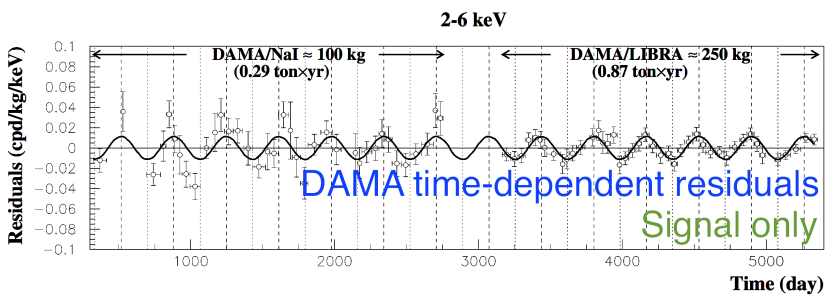
Dark matter, DAMA/LIBRA, and ^{40}K [2, 3]

- Exotic new dark particles may make up bulk of matter in universe.
- 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:

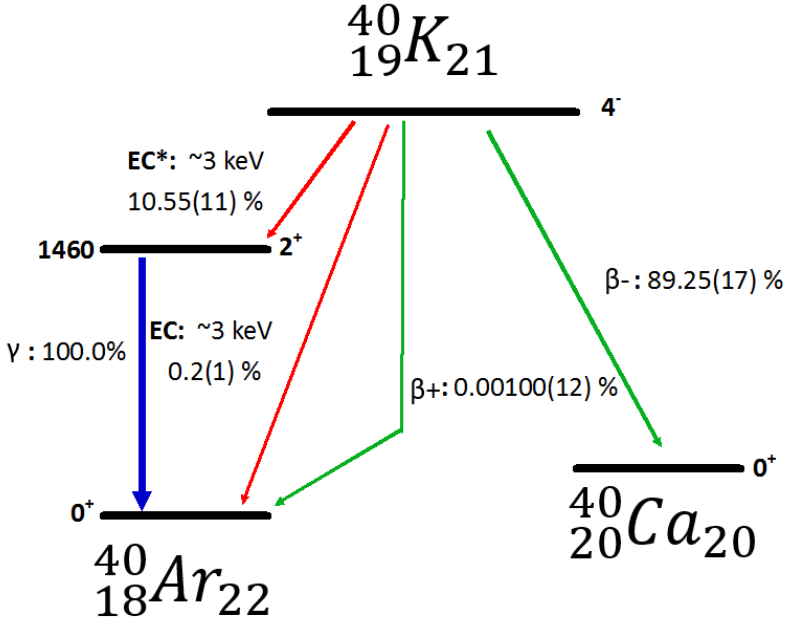




- $\dfrac{\overbrace{\text{modulation amplitude}}^{\text{signal}}}{\underbrace{\text{time-independent amplitude}}_{\text{signal + background}}} \approx \frac{1}{100}$
- DAMA controversial:
  - contradicted by numerous other experiments
  - no background model [1]
- Consensus that 3 keV X-rays/Augers from ^{40}K contribute to low-energy DAMA spectrum
- Contribution is of the order of the amplitude of modulation
- Precise understanding of ^{40}K is necessary to constrain modulation fraction of signal, and dark matter interpretation [2]
- ^{40}K is also a background in many other rare-event searches

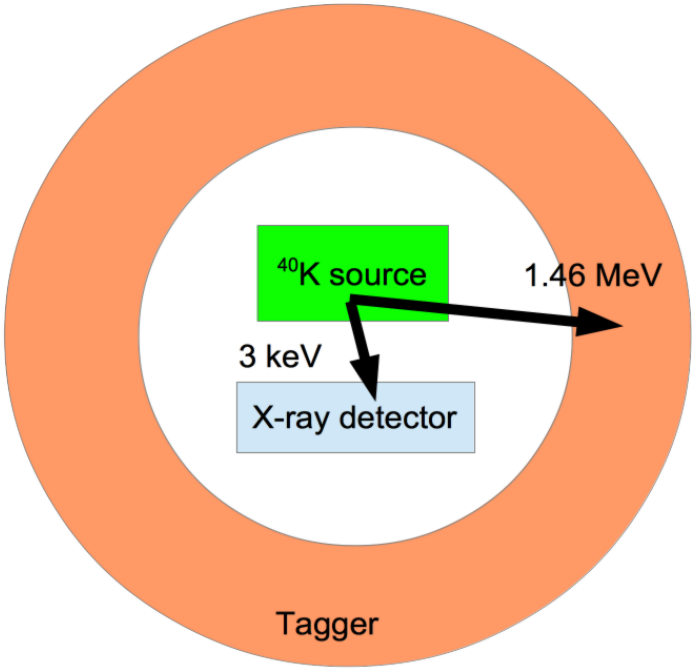
Decays of ^{40}K

- ^{40}K: naturally occurring; 0.012% abundance
- $T_{1/2} = 1.2 \times 10^9$ years; main decay is β^- with branching ratio of 90%:



- Also electron capture (EC):
  - 3 keV X-rays and Auger electrons from K-shell electron capture: $^{40}\mathrm{K} + e^- \rightarrow {}^{40}\mathrm{Ar} + \nu_e$.
  - Main contribution: EC* to excited state of ^{40}Ar, which then decays with $T_{1/2} = 1.6$ ps [4], emitting a 1.46 MeV γ. Branching ratio (BR*) is 10%. Can be tagged by 1.46 MeV γ.
  - Also contribution that can not be tagged, from direct EC to ground state. BR predicted from β^+ decay [5] of ^{40}K to ^{40}Ar as $0.2 \pm 0.1\%$ (theory dependent), and from total decay rate as $0.8 \pm 0.8\%$ (theory independent), but has never been measured [2]
  - EC to ground state would be the only known EC unique third-forbidden transition.

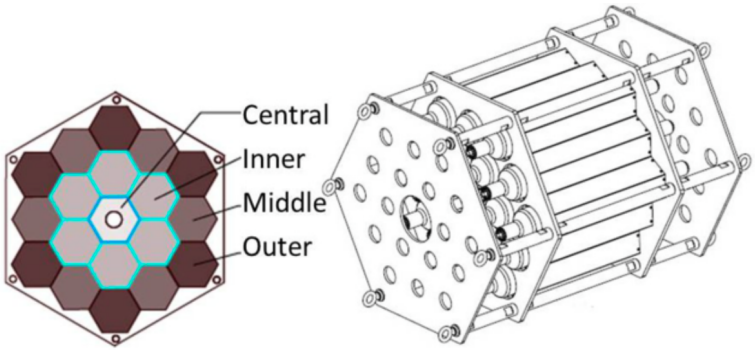
Measuring direct EC with KDK: X-ray detector and tagger



- Trigger on small inner detector
  - Low threshold ($\sim$ 1 keV) and high efficiency to detect 3 keV X-rays (and Augers?)
  - Transparent to $E \gtrsim 10$ keV to reduce scattering, background
- Surround with 4π veto to tag 1.46 MeV γ with high efficiency (bonus if threshold low enough to measure 511 keV γ as cross check of BR_{EC} estimation from $BR_{\beta+}$).
  - For a signal-to-noise of 1, need an efficiency of 98%
  - 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 ratio of EC to EC*.

Modular Total Absorption Spectrometer (MTAS) tagger [6]

- At Oak Ridge (ORNL), surface site
- Made up of 19 NaI(Tl) modules, ≈ 55 kg each, ~ 1 ton total
- Central tunnel (≈ 6.5 cm diam): source & X-ray detector go here



- Efficiency for tagging 1.46 MeV gammas from center is 98–99% (SNR: 1–2)

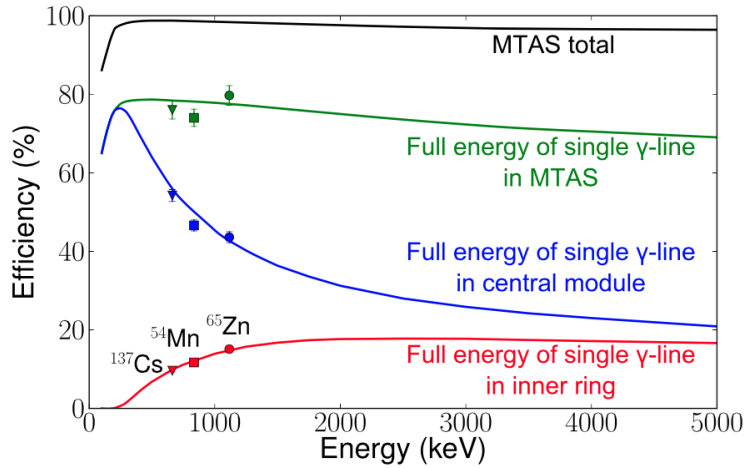
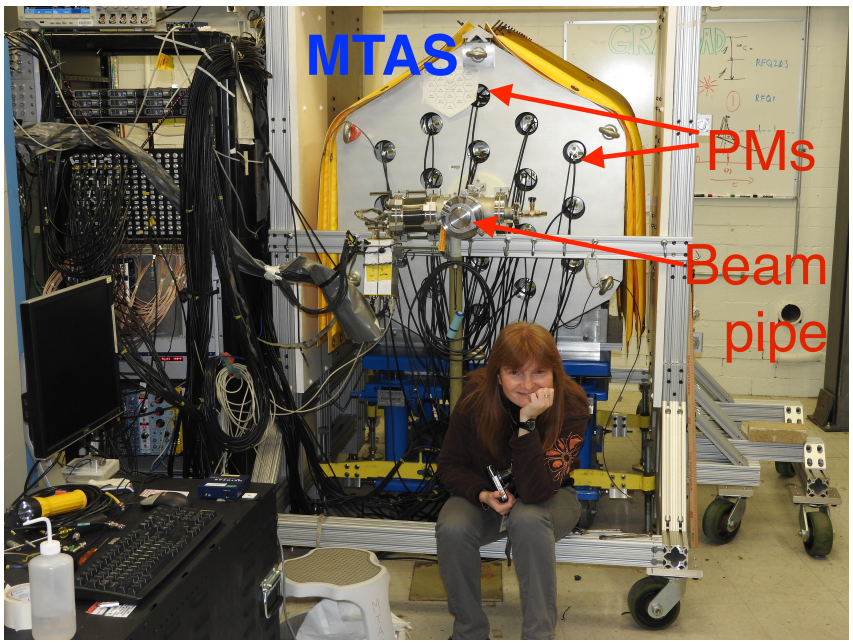


FIG. 3. The efficiencies of MTAS to detect single γ-ray transition are compared to GEANT4 simulations.

- BG rate ≤ 1.46 MeV ≈ 240 Hz per module (total ≈ 2.8 kHz $\Rightarrow$ probability one of these events arrives in random 1 μs window is 2.8×10^{-3})
- 0.1% error on efficiency leads to 10% error on branching ratio $\Rightarrow$ more calibrations needed to improve precision

MTAS and X-ray detector at ORNL

MTAS

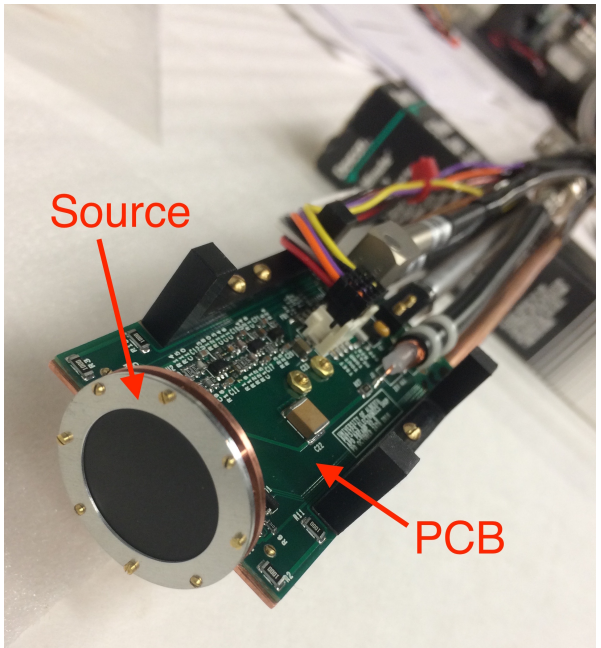


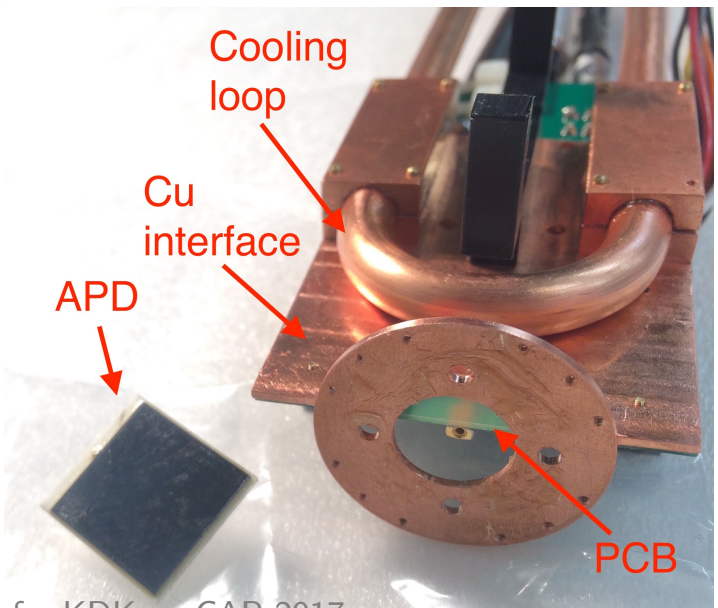
Vacuum insert with X-ray detector slides into beam pipe

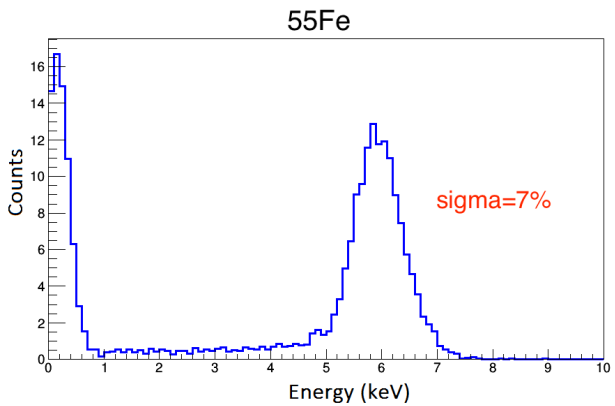
Material minimized around source to avoid γ scattering

X-ray detector (cf M. Stukel's talk M4-3)

- Large-area avalanche photodiode (APD) chosen for large area, low cost, rather than resolution ($\sigma \approx 7\%$ @ 6 keV)
- Device: RMD 1315, 1 cm^2
- ≈ 1 keV threshold when cooled to -25° C with water/glycol mix
- ≈ 1 mm to sources of standard geometry

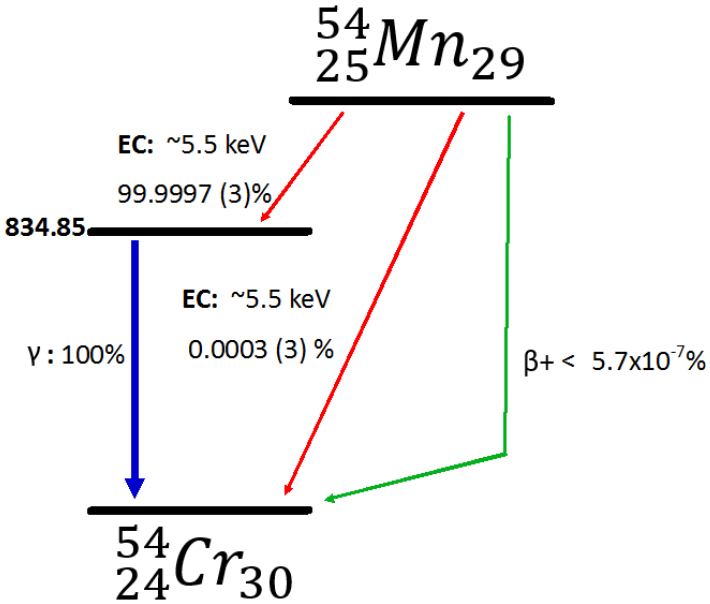






Calibrating tagging efficiency with ^{54}Mn (cf P. Squillari POS-38)

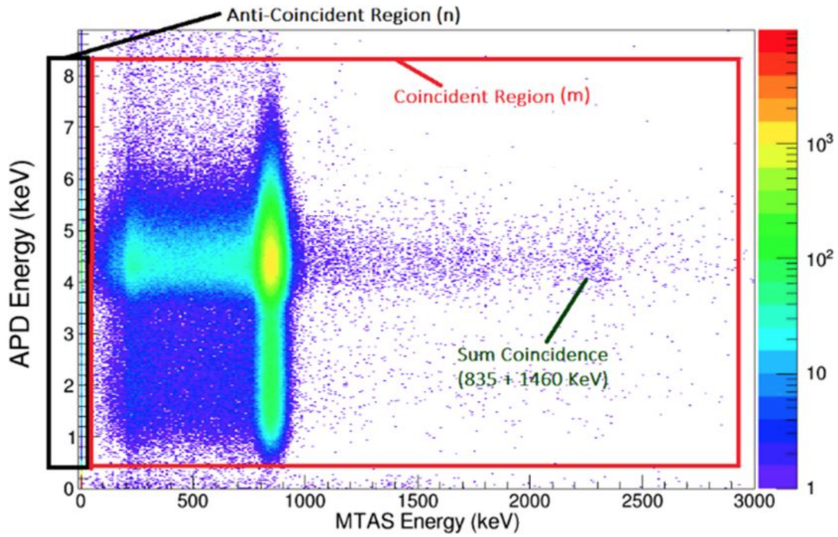
Overwhelmingly decays by EC*



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

Standard geometry source

Data: ≈ 1 week, $\gtrsim 10^6$ events



PRELIMINARY estimation indicates efficiency is $(98.89 \pm 0.01)\%$ (stat)

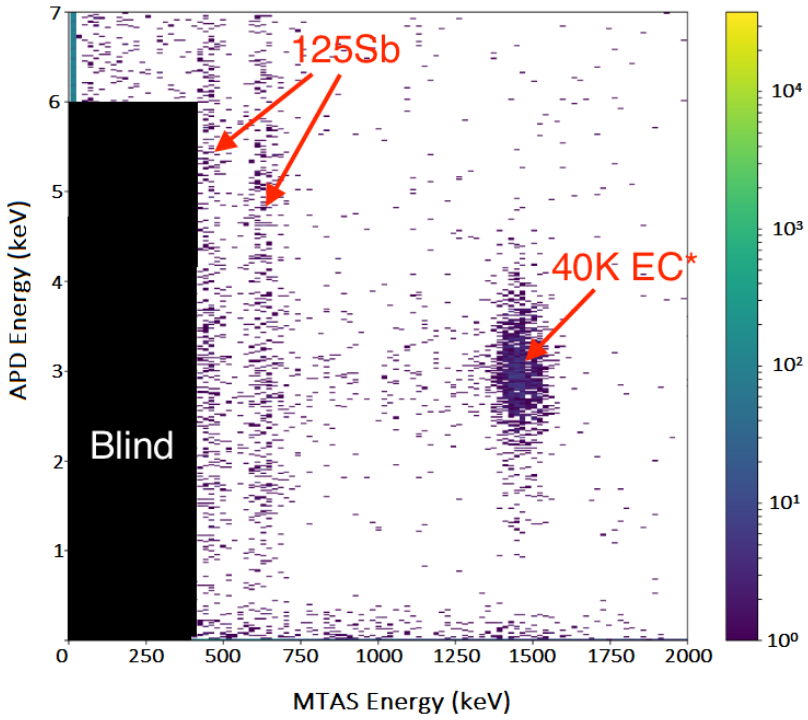
Also using ^{65}Zn ($EC/EC* \approx 1$, $E_X = 8$ keV, $E_\gamma = 1115$ keV), and Monte Carlos to extrapolate to $E_\gamma = 1.46$ MeV.

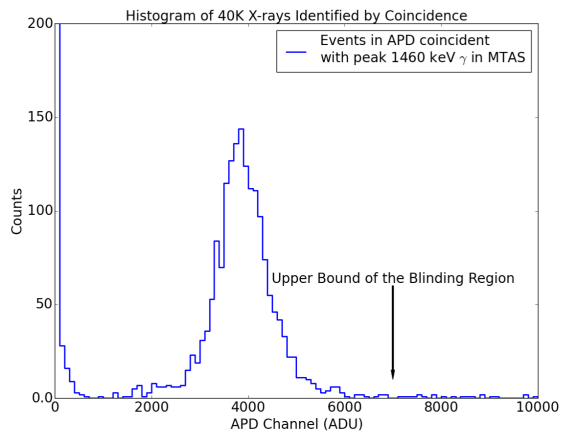
Preparing ^{40}K source (Y.Liu, ORNL)

Equivalent ^{40}K content

- Driver: $\sim 3 \times 10^4$ untagged 3 keV counts required to provide 10% stat error on ratio of EC/EC* branching ratios
- Source goals:
  - 10^{18} ^{40}K nuclei (4×10^3 EC events/day)
  - Area 1 cm^2, thickness < 10 μm (to reduced self-absorption and losses of efficiency)
- First approach: ion beam implantation
  1. Ion source: KCl $\rightarrow$ ^{39,40,41}K$^+$ @ 20–40 keV
  2. Magnetic mass separator $\rightarrow$ ^{40}K$^+$
  3. Implant into C foil (depth a few μm)
- Expected efficiency 10%; started with natural K, then K enriched to 3% ^{40}K

March 2017 ^{40}K run (EC region blinded) — PRELIM

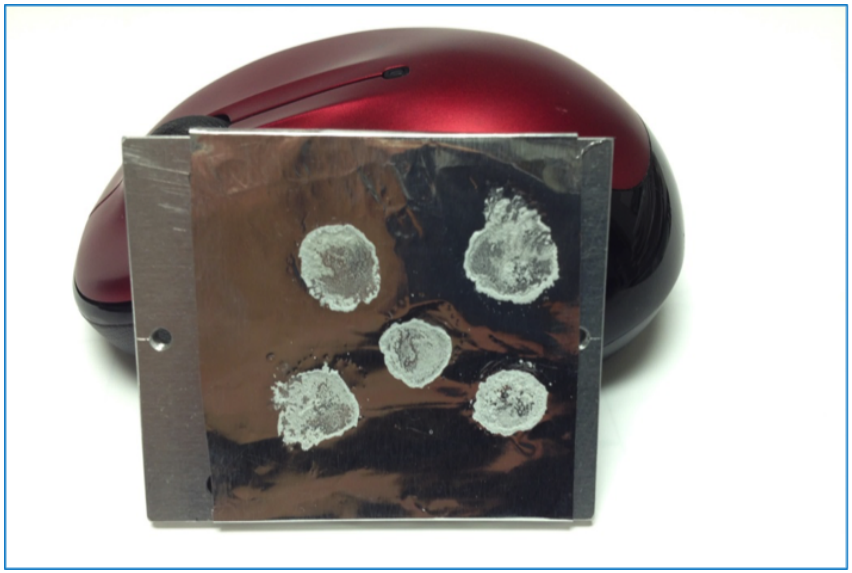




- **^{40}K visible in MTAS and APD! Technique is viable**
- Rate an order of magnitude lower than expected (only $\approx 10^{17}$ ^{40}K atoms)
  - Measured independently by MTAS, by APD, and by HPGe
  - Missing ^{40}K found in ion beam line by MTAS
  - Self-sputtered ^{40}K away?
- ^{125}Sb contamination in source, probably from ion-beam line
- Coincident events provide exact shape of signal spectrum to look for regardless of BGs

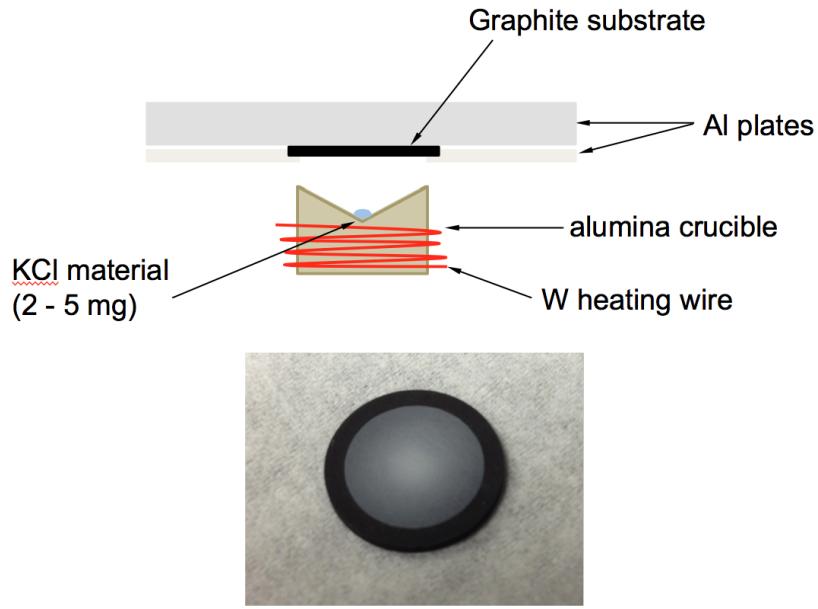
^{40}K source upgrade options: ^{nat}KCl tests (Y. Liu, ORNL)

Liquid solution evaporation



Thickness hard to control

Thermal deposition



- Smooth films obtained
- 30–50% efficiency demonstrated
- Optimization under way

Conclusions and prospects for KDK

- Measuring branching ratio of electron capture of ^{40}K to ground state of ^{40}Ar will:
  - provide better understanding of backgrounds in DAMA claim for discovery of dark matter, and in other dark matter searches
  - be first observation of EC unique third-forbidden decay
  - inform nuclear shell models
- γ-efficiency calibration data obtained
- **Ability to see ^{40}K coincidences between X-ray detector and γ-tagger has been demonstrated**
- Analysis progressing: γ-tagging efficiency, backgrounds, ^{40}K
- Other ongoing work:
  - stronger, cleaner, ^{40}K source
  - SDD X-ray detectors with 10$\times$ better resolution (MPP and HLL, Munich): insurance against possible β^- BG
  - KSr_2I_5 scintillator which combines source and X-ray detector (E. Lukosi, UTK)

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