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

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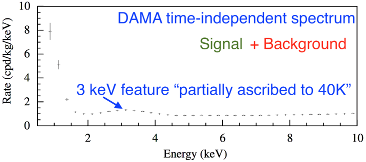
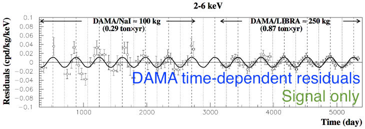
# Dark matter, DAMA/LIBRA, and $^{40}$K [2, 3]

- 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:

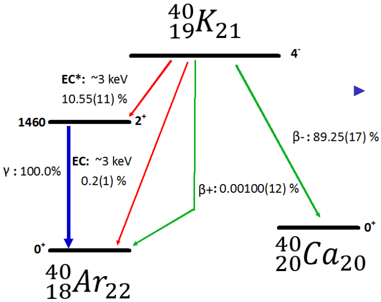



- $$\frac{\overbrace{\text{modulation amplitude}}^{\text{signal}}}{\underbrace{\text{time-independent amplitude}}_{\text{signal}+\text{background}}} \approx \frac{1}{100}$$
- DAMA controversial:
  - tension with other experimental results
  - disagreement on background model, eg [1]
- Consensus that 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 [2]: precise understanding of $^{40}$K necessary to constrain modulation fraction of signal, and dark matter interpretation
- $^{40}$K also a background in other rare-event searches

# Decays of $^{40}$K [6]

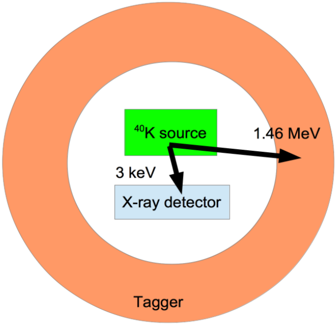
- $^{40}$K: naturally occurring; 0.012% abundance
- $T_{1/2} = 1.2 \times 10^{9}$ years; main decay is $\beta^{-}$ with branching ratio of 90%:




- Also electron capture (EC):
  - 3 keV X-rays and Auger electrons from K-shell electron capture: $^{40}\text{K} + e^{-} \to {}^{40}\text{Ar} + \nu_e$.
  - Main contribution: EC* to excited state of $^{40}$Ar, which decays in ps, emitting a 1.46 MeV $\gamma$. Branching ratio (BR*) is 10%. Can be tagged by 1.46 MeV $\gamma$.
  - Also contribution that can not be tagged, from direct EC to ground state. BR predicted from $\beta^{+}$ decay [4] of $^{40}$K to $^{40}$Ar as $0.2 \pm 0.1\%$ (theory dependent)[a], 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.

[a]Update: $0.045 \pm 0.006\%$ [5]

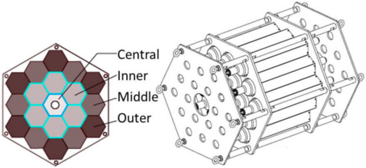
# Measuring EC with KDK [7]: X-ray detector and tagger




- 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 $4\pi$ veto to tag 1.46 MeV $\gamma$ with high efficiency (bonus if threshold low enough to measure 511 keV $\gamma$ 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 $\gamma$ 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 [8]

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




- Total BG rate $\leq$ 1.46 MeV $\approx$ 2.8 kHz (probability one of these events arrives in random 1 $\mu$s window is $2.8 \times 10^{-3}$)

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

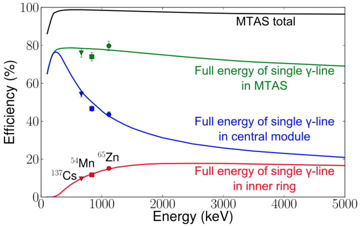
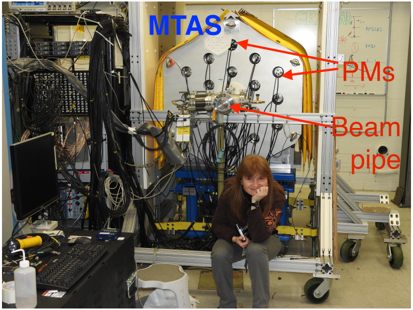



FIG. 3. The efficiencies of MTAS to detect single $\gamma$-ray transition are compared to GEANT4 simulations.

- 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

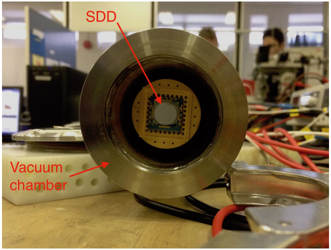


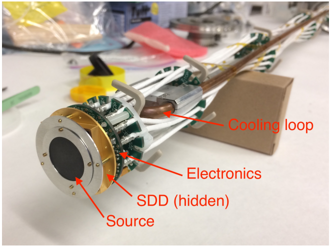

## Vacuum insert with X-ray detector slides into beam pipe

Material minimized around source to avoid $\gamma$ scattering

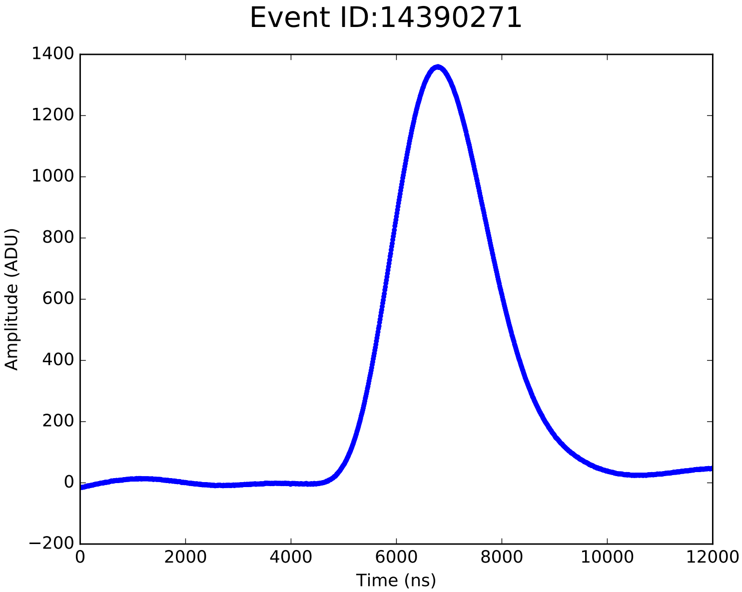
# X-ray detector

- Requirements include $\lesssim 1$ keV threshold and 1 cm$^2$ surface area, placed $\approx 1$ mm from sources of standard geometry.
- Have switched from commercial large-area avalanche photodiode (APD) to custom silicon drift detector (SDD) provided by HLL Munich.
- Resolution FWHM @ 6 keV improves from 1 keV to 170 eV.



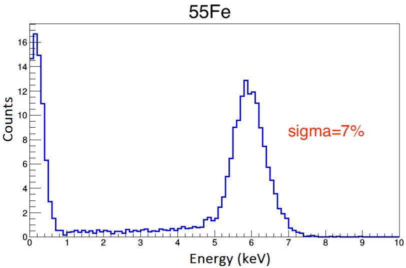



# 6 keV SDD pulse (1 $\mu$s shaping)

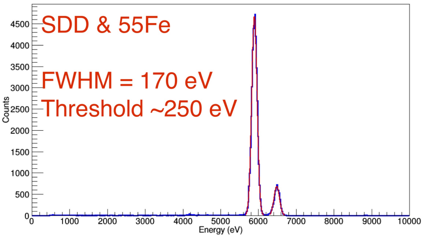


# APD vs SDD: $^{55}$Fe calibration

## APD

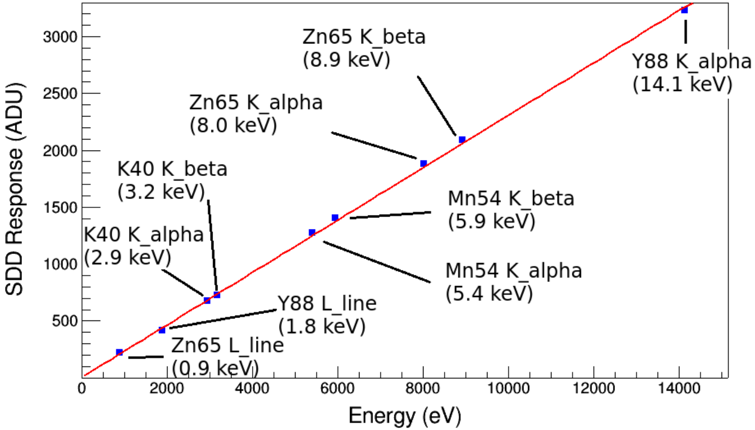



## SDD



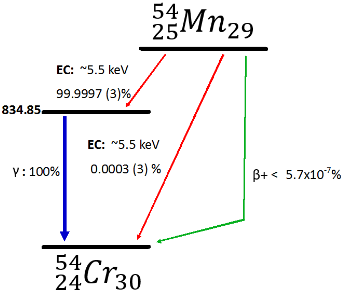

Resolution improved by factor 5, can now resolve $K_\alpha$ and $K_\beta$.

# All energy calibrations



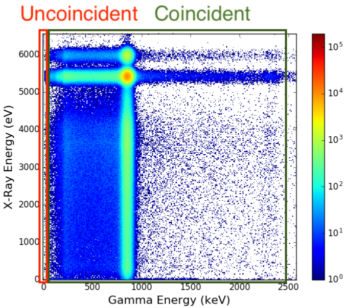
# Calibrating tagging efficiency with $^{54}$Mn

Overwhelmingly decays by EC*



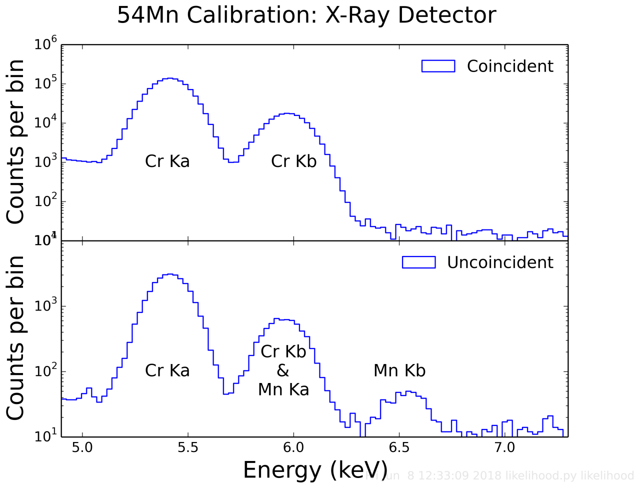

$E_X = 5.5$ keV (also 4–6 keV Augers), $E_\gamma = 835$ keV
Standard geometry source

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




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

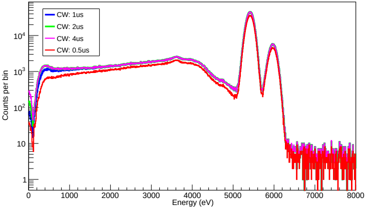
# $^{54}$Mn efficiency calibration and background




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

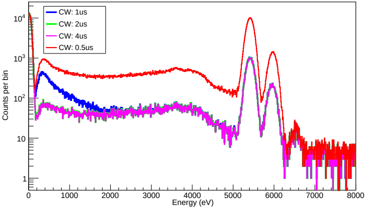
# $^{54}$Mn: effect of coincidence window on SDD spectra

## Coincident with MTAS



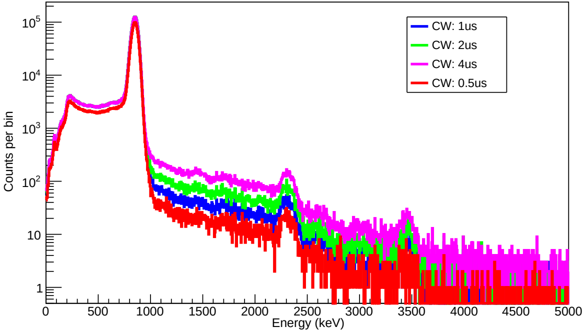

- Longer coincidence $\longleftrightarrow$ more $^{54}$Mn events

## Uncoincident




- Longer coincidence $\longleftrightarrow$ fewer $^{54}$Mn events
- $^{55}$Fe relatively unaffected

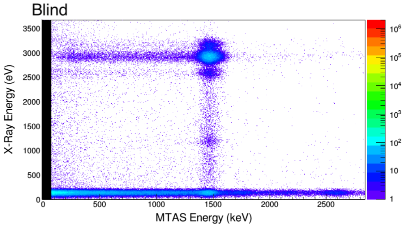
# $^{54}$Mn: effect of coincidence window on MTAS spectrum

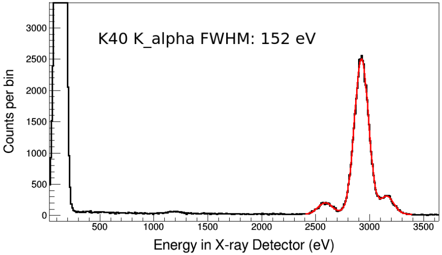



Above 835 keV see effect of spurious coincidences with 1.4 MeV $^{40}$K $\gamma$s and 2.6 MeV $^{208}$Tl (from $^{232}$Th) $\gamma$s BGs

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

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

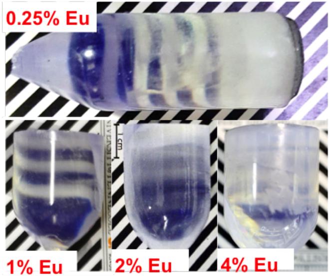



- $K_{\alpha,\beta}$ from EC* to Ar visible
- Ongoing work to understand
  - Cl fluorescence visible at 2.6 keV
  - Expected K fluorescence at 3.3 keV
  - Si escape line @ $2.9 - 1.7 = 1.2$ keV
  - Uncoincident BGs

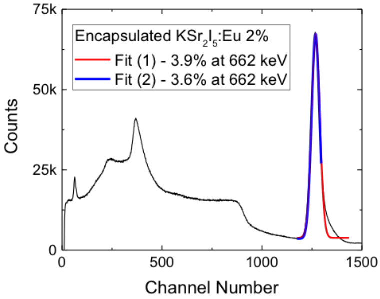
# Complementary approach: $KSr_2I_5$:Eu scintillator (KSI)[c]

- Novel scintillator [9], high light yield ≈ 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 → encapsulate


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



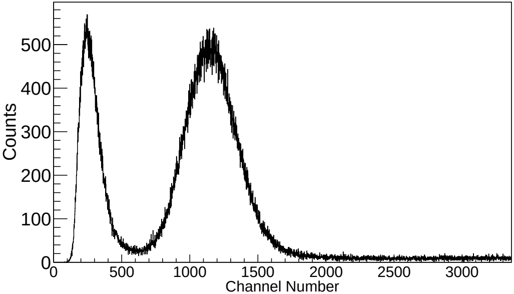

[c] C. Goetz, E. Lukosi, C. Melcher, L. Stand — U. Tennessee

# KSI in MTAS (preliminary)

Setup inserted into MTAS


- 4 g KSI
  - $7 \times 7 \times 20\ \text{mm}^3$
  - Total $^{40}$K activity $\sim 6$ 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 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
- Data, including $\gamma$-efficiency calibration, and $^{40}$K, in hand; coincidences visible
- Excellent performance of SDD X-ray detector
- Analysis progressing: $\gamma$-tagging efficiency, backgrounds, simulations, and $^{40}$K data
- Complementary analysis of $KSr_2I_5$ data advancing in parallel

# $^{40}$K contribution to DAMA

- 2–6 keVee energy range: DAMA observes time-independent component of $\sim 4$ events/d/kg, and modulation component of $\sim 0.05$ events/d/kg [10].
- DAMA reports 13 ppb contamination of $^{nat}$K based on 3 keV–1.4 MeV coincidence between detectors and on Monte-Carlo of unknown efficiency (Sec. 5.3 of [10], and Sec. 5.4 of [3]).
- Given natural abundance of $^{40}$K and half-life [**?**], and atomic mass, leads to a total rate of $^{40}$K decays in NaI of 23/d/kg.
- 2–6 keVee range: EC and EC* contribute $\sim 7\%$ of these decays as an Auger electron and $\sim 1\%$ as an X-ray [**?**]
- Since these radiations are all absorbed by DAMA, but EC* are tagged with an efficiency $\epsilon$, EC* contribute $\sim 1.8(1-\epsilon)$ events/d/kg to the 2-6 keVee range. Assuming a 90% tagging efficiency, EC* contributes $\sim 0.18$ events/d/kg.
- The contribution of EC is $\sim 0.03\frac{\zeta}{0.02}$ events/d/kg to the 2-6 keVee range, ie of the order of the modulation, ie $\sim 0.03$ events/d/kg for EC at the expected value of $\zeta$. The modulation-to-constant fraction of DAMA signal interpretation is therefore quite sensitive to EC contribution.
- There should also be a contribution from the $\beta^-$ decays of $^{40}$K that are abundant, but spread over 0–1.3 MeV.

# DAMA: effect of EC BG on signal [2]

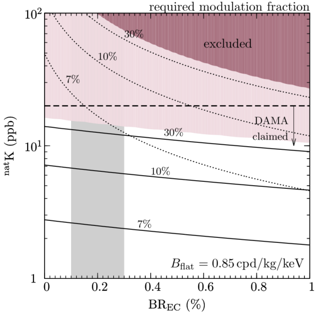



Figure 1: Solid: assuming some vetoed EC*. Dashed: no EC* at all. For fixed BR, as K concentration increases, one squeezes out signal DC, resulting in larger signal modulation fractions. For fixed K concentration, as BR increases , one squeezes the signal DC, and increases signal modulation fraction as well. Signal modulation must always be $\leq$ 100% (dark/light red area for dashed/solid ).

- In region of interest, DAMA observes a $\sim$ 1% modulation (AC — signal only) over a constant level (DC — signal and BG).
- Level of BG will squeeze level of DC signal
- This may push signal AC/DC to values $\geq$ 20% diffcult to reconcile with usual halo assumptions.
- Assuming 90% tagging of EC*, BG contribution of EC* relative to that of EC is $5 \times 0.2\%/\text{BR}$ [2].

# Effect of systematics: tagging efficiency

- Likelihood-based analysis, here on simulated data
- How is reconstruction of $\zeta \equiv 1/\eta$ (ratio of branching ratios for EC and EC*) affected by uncertainty on $\epsilon_\gamma$ (veto efficiency)?
- Very sensitive!

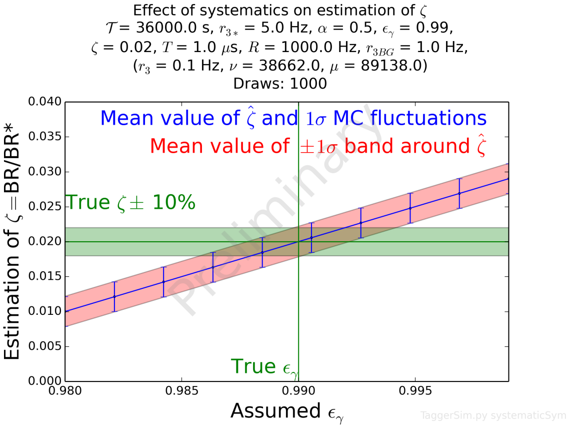



Figure 2: Simulations: how uncertainty on tagging efficiency affects reconstruction of $\zeta$ (ratio of branching ratios).

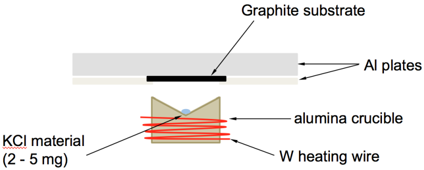
# Preparing $^{40}$K source (Y.Liu, ORNL)

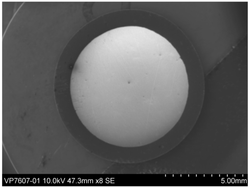
Equivalent $^{40}$K content

- 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 ($4 \times 10^3$ EC events/day)
  - Area 1 cm$^2$, thickness $< 10$ $\mu$m (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 $\mu$m)
- Expected efficiency 10%; started with natural K, then K enriched to 3% $^{40}$K

# $^{40}$K source upgrade: thermal deposition (Y. Liu, ORNL)

## Tests with $^{nat}$KCl




(SEM work K. G. Myhre, ORNL)

- Smooth KCl films obtained; thickness $11 \pm 1$ $\mu$m
- 30–50% efficiency demonstrated

## $^{40}$K sources

- 2 sources manufactured with 3% enriched $^{40}$K (1.5 mg and 3 mg)
- Tested early July in setup at ORNL; analysis underway: no more $^{125}$Sb contamination
- Also procuring 10% enriched $^{40}$K

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