

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

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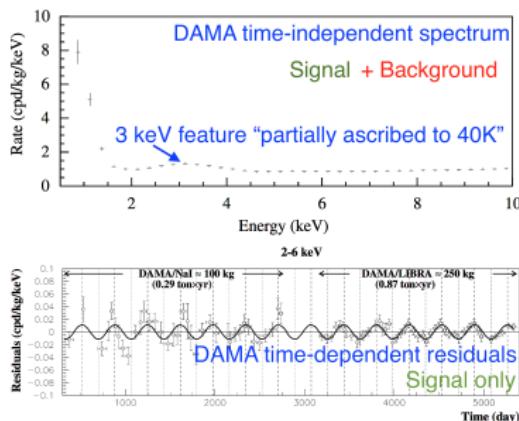
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# Dark matter, DAMA/LIBRA, and $^{40}\text{K}$ [2, 3]

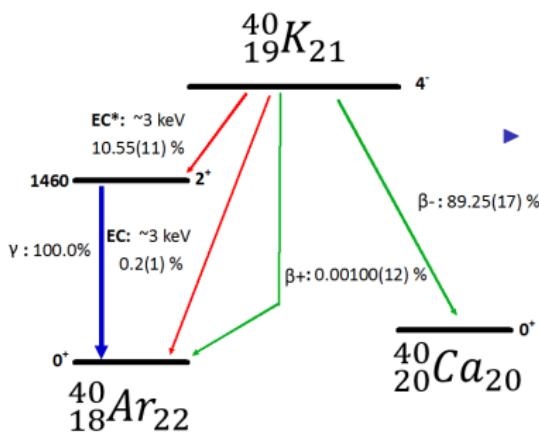
- ▶ Exotic new dark particles may make up bulk of matter in universe.
- ▶ DAMA:  $\sim 250$  kg low-background NaI experiment
- ▶ Since 1997, DAMA claims detection based on annual modulation caused by rotation of Earth around Sun, through particle halo of galaxy:



- signal**  
 $\overbrace{\text{modulation amplitude}}^{\text{time-independent amplitude}}$   $\approx \frac{1}{100}$   
**signal + background**
- ▶ DAMA controversial:
    - ▶ tension with other experimental results
    - ▶ disagreement on background model, eg [1]
  - ▶ Consensus that 3 keV X-rays/Augers from  $^{40}\text{K}$  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  $^{40}\text{K}$  necessary to constrain modulation fraction of signal, and dark matter interpretation
  - ▶  $^{40}\text{K}$  also a background in other rare-event searches

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

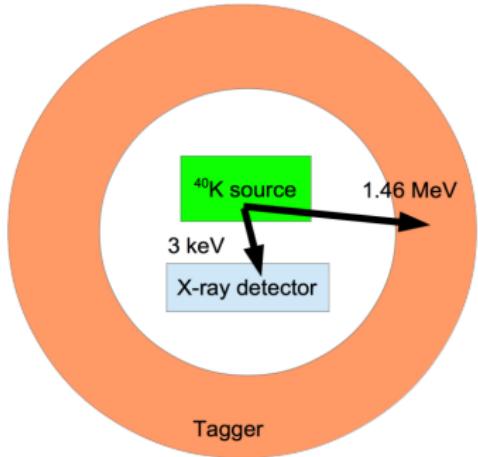
- $^{40}\text{K}$ : naturally occurring; 0.012% abundance
- $T_{1/2} = 1.2 \times 10^9$  years; main decay is  $\beta^-$  with branching ratio of 90%:



- Also electron capture (EC):
  - 3 keV X-rays and Auger electrons from K-shell electron capture:
$$^{40}\text{K} + e^- \rightarrow {}^{40}\text{Ar} + \nu_e.$$
  - Main contribution: EC\* to excited state of  $^{40}\text{Ar}$ , 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  $^{40}\text{K}$  to  $^{40}\text{Ar}$  as  $0.2 \pm 0.1\%$  (theory dependent)<sup>a</sup>, 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.

<sup>a</sup>Update:  $0.045 \pm 0.006\%$  [5]

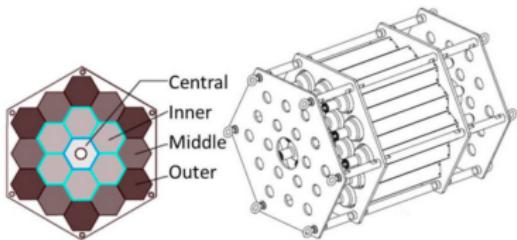
# Measuring EC with KDK [7]: X-ray detector and tagger



- ▶ 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  $1\ \mu\text{s}$  window is  $2.8 \times 10^{-3}$ )

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

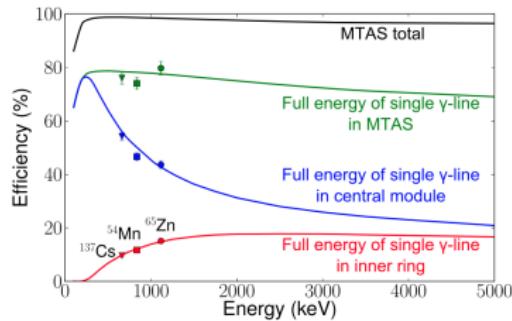
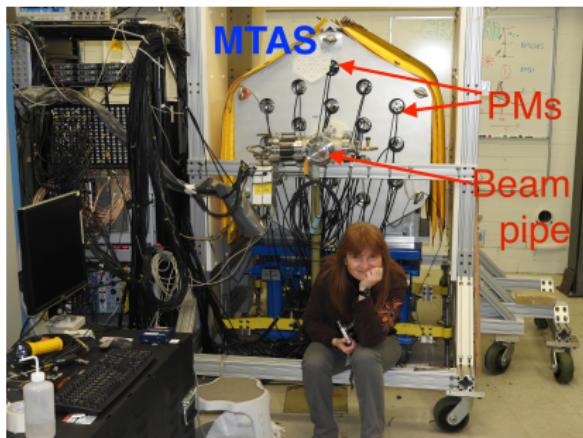


FIG. 3. The efficiencies of MTAS to detect single  $\gamma$ -ray transition are compared to GEANT4 simulations.

- ▶ 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



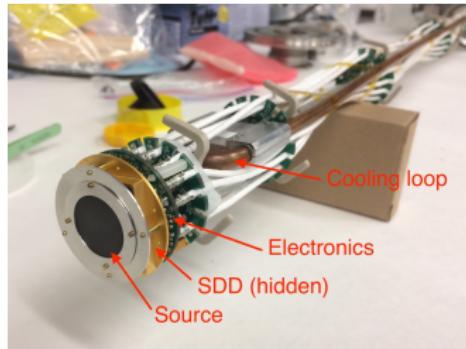
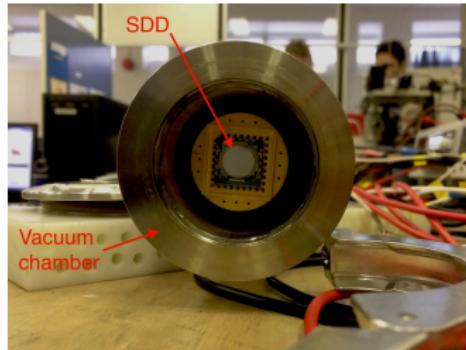
Vacuum insert with X-ray detector slides into beam pipe



Material minimized around source to avoid  $\gamma$  scattering

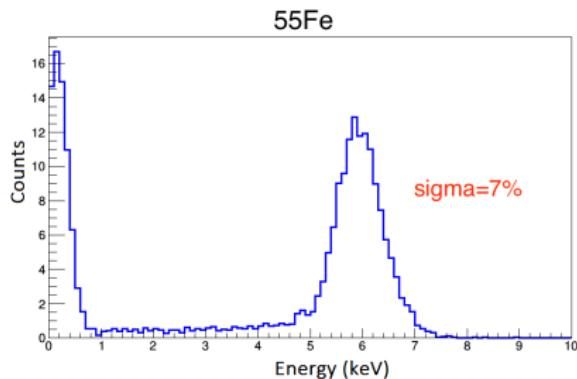
# X-ray detector

- ▶ Requirements include  $\lesssim 1$  keV threshold and  $1 \text{ cm}^2$  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.

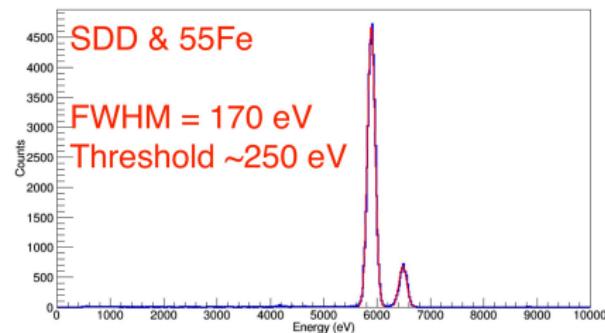


# APD vs SDD: $^{55}\text{Fe}$ calibration

APD

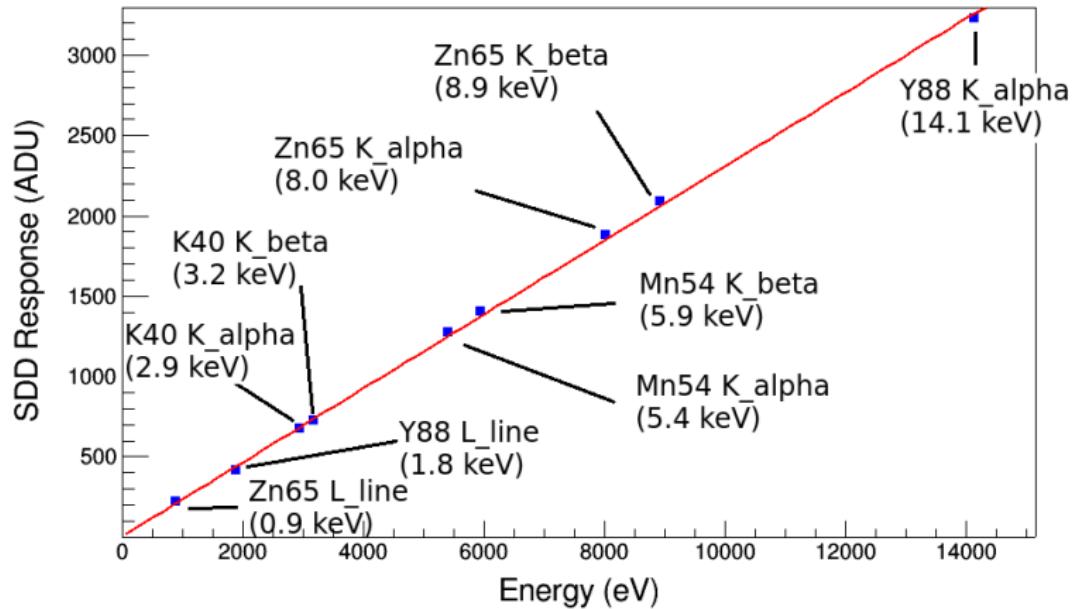


SDD



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

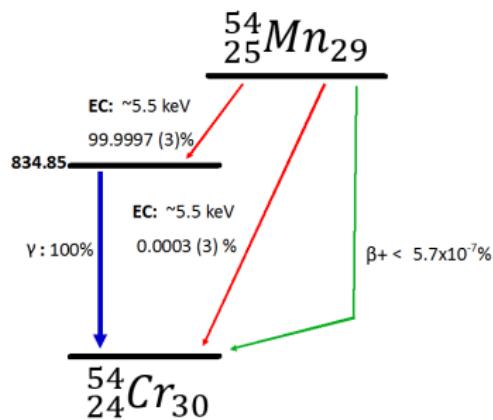
# All energy calibrations



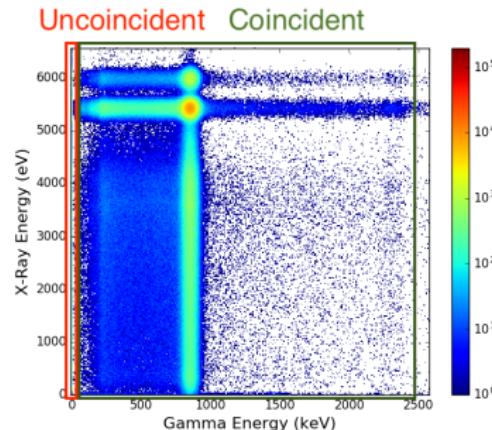
# Calibrating tagging efficiency with $^{54}\text{Mn}$

Overwhelmingly decays by EC\*

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

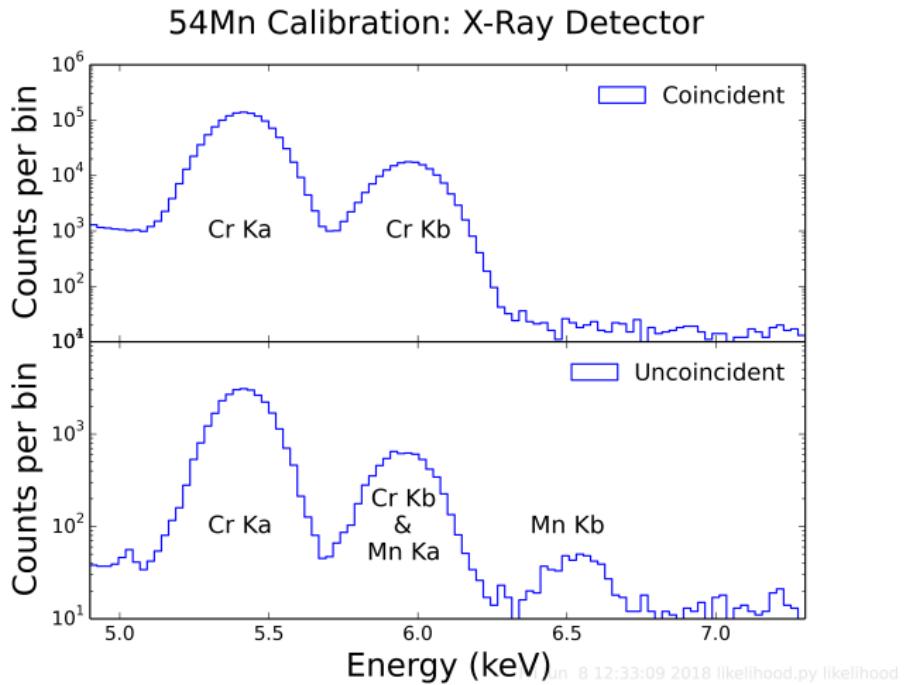


$E_X = 5.5 \text{ keV}$  (also 4–6 keV Augers),  $E_\gamma = 835 \text{ keV}$   
Standard geometry source



(spurious coinc. with  $^{40}\text{K}$  BG visible)  
Also using  $^{65}\text{Zn}$  ( $EC/EC^* \approx 1$ ),  
 $E_X = 8 \text{ keV}$ ,  $E_\gamma = 1115 \text{ keV}$ ),  
and Monte Carlos to extrapolate  
to  $E_\gamma = 1.46 \text{ MeV}$ .

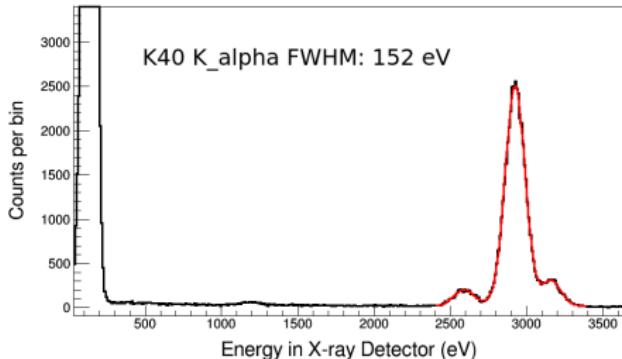
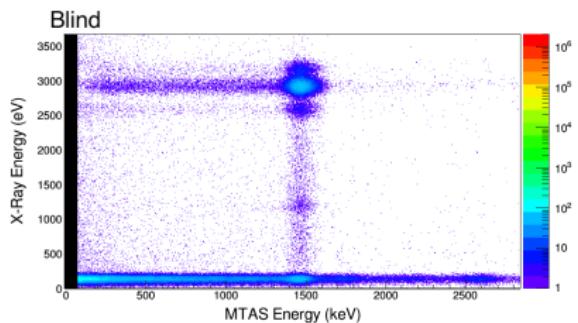
# $^{54}\text{Mn}$ efficiency calibration and background



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

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

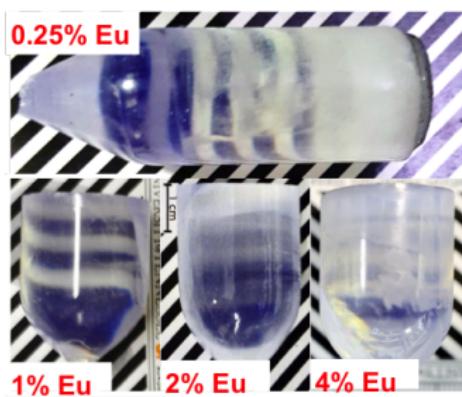
- ▶ Using a thermally deposited *enr* KCl source
- ▶ 33 days of usable data
- ▶  $^{40}\text{K}$  visible in MTAS and SDD



- ▶  $K_{\alpha,\beta}$  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: $\text{KSr}_2\text{I}_5:\text{Eu}$ scintillator (KSI)<sup>c</sup>

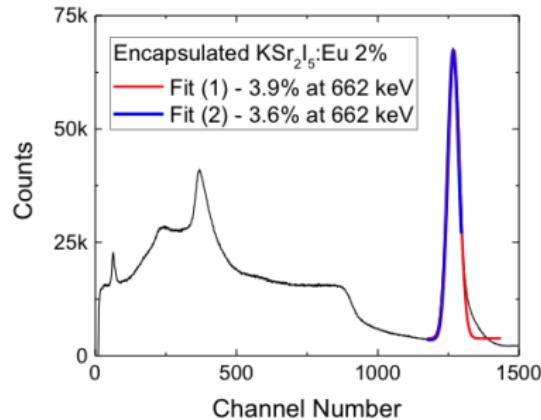
- ▶ Novel scintillator [9], high light yield  $\approx 100$  photons/keV,  $\lambda \approx 450$  nm
- ▶ Density  $4.4 \text{ g/cm}^3$ , total  ${}^{40}\text{K}$  activity  $6.6 \text{ Hz/cm}^3$
- ▶ Available in several  $\text{cm}^3$
- ▶ 1" diameter crystals:



- ▶ Hygroscopic  $\rightarrow$  encapsulate



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



<sup>c</sup>C. Goetz, E. Lukosi, C. Melcher, L. Stand — U. Tennessee

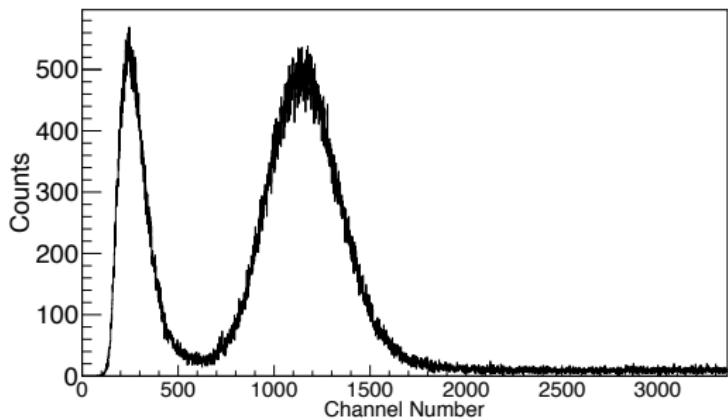
# KSI in MTAS (preliminary)

Setup inserted into  
MTAS



- ▶ 4 g KSI
  - ▶  $7 \times 7 \times 20 \text{ mm}^3$
  - ▶ Total  $^{40}\text{K}$  activity  
 $\sim 6 \text{ Hz}$
- ▶ 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  $^{40}\text{K}$  to ground state of  $^{40}\text{Ar}$  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  $^{40}\text{K}$ , in hand; coincidences visible
- ▶ Excellent performance of SDD X-ray detector
- ▶ Analysis progressing:  $\gamma$ -tagging efficiency, backgrounds, simulations, and  $^{40}\text{K}$  data
- ▶ Complementary analysis of  $\text{KSr}_2\text{I}_5$  data advancing in parallel



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