Potassium

# KDK

Decay

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

N. Brewer[2] J. Carter[9] H. Davis[3] **P. Di Stefano**[1b]
A. Fijalkowska[2,4,5] Z. Gai[2] R. Grzywacz[2,3,5] L. Hariasz[1]
J. Kostensalo[8] P. Lechner[7] Y. Liu[2] E. Lukosi[3]
M. Mancuso[6] J. Ninkovic[7] F. Petricca[6] B. C. Rasco[2]
C. Rouleau[2] K. Rykaczewski[2] D. Stracener[2] M. Stukel[1]
J. Suhonen[8] M. Wolińska-Cichocka[2,4,5]

(Student/Postdoc/RA)
[1]Queen's U, [2]Oak Ridge Nat Lab, [3]U Tennessee, [4]U Warsaw, [5]Joint Inst Nuclear Phys Application,
[6]Max Planck Inst Munich, [7]MPG Semiconductor Lab Munich, [8]U Jyväskylä, [9]Berkeley

*Tech. support: M. Constable, F. Retiere (TRIUMF), K. Dering (Queen's MRS), P. Davis (U Alberta MRS)*

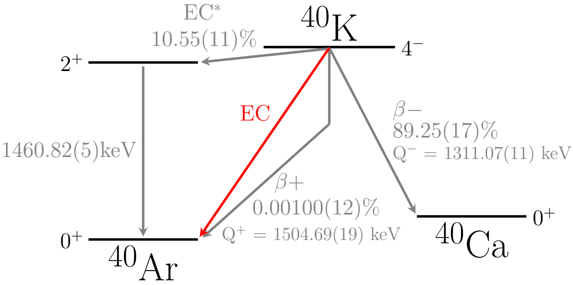
arXiv:2012.15232 NIM A 1012 (2021) 165593
arXiv:1711.04004 JPhys Conf Series 1342 2020

---

[b]distefan@queensu.ca

# Decays of $^{40}$K [1]

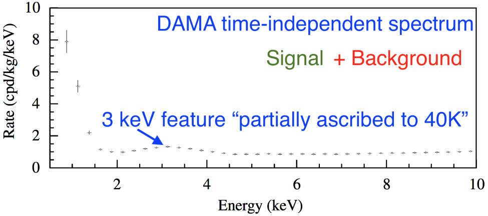
- $^{40}$K: naturally occurring; 0.012% abundance; $T_{1/2} = 1.2 \times 10^9$ years




- Electron capture (EC): ${}^{40}_{19}\text{K} + e^- \rightarrow {}^{40}_{18}\text{Ar} + \nu_e$
  - $\sim 3$ keV X-rays, Auger electrons from K-shell electron capture
  - Also 1.4 MeV $\gamma$ (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

- $\sim 3$ keV from EC/EC* is a BG in energy region expected for many dark matter models
- EC* can be tagged by 1.4 MeV $\gamma$, 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)

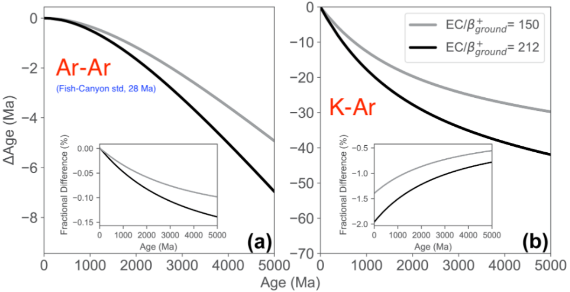
# $^{40}$K EC and geochronology

- 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.

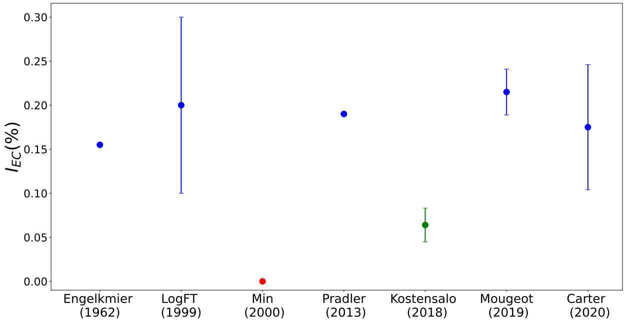
> Outstanding problems remaining to be addressed in evaluating the $^{40}$K decay constants include: (i) improving disintegration counting experiments to provide better data for $\beta$ and $\gamma$ activities and (ii) verifying the existence and magnitude of the hypothetical $\gamma$-less electron capture 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:

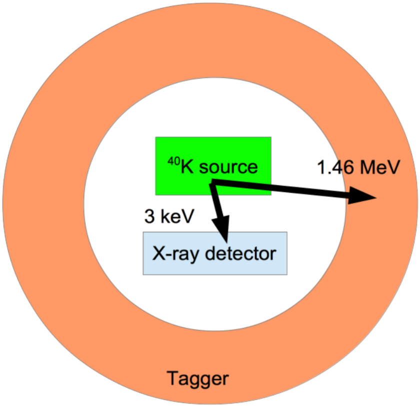



Neglecting EC tends to overestimate ages

# Theoretical predictions for the EC branching ratio



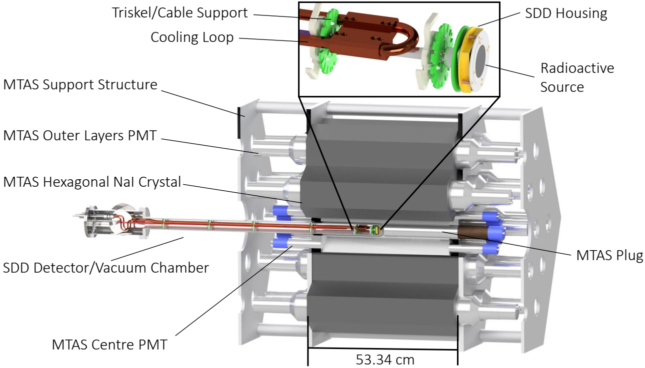
# Measuring EC with KDK [7, 8]: X-ray detector and tagger




- 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 $4\pi$ veto to tag EC* 1.46 MeV $\gamma$
  - For signal-to-noise of 1, need 98% efficiency
  - 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 $\rho$, ratio of EC to EC*.

# Modular Total Absorption Spectrometer (MTAS) tagger [9]

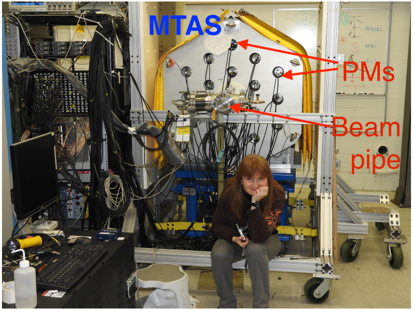
## MTAS and insert




- $\sim$ 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

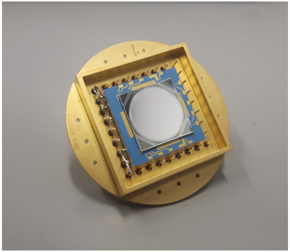


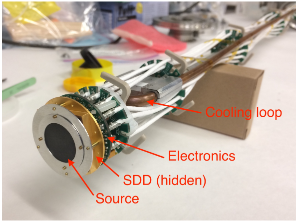

## Vacuum insert with X-ray detector slides into beam pipe

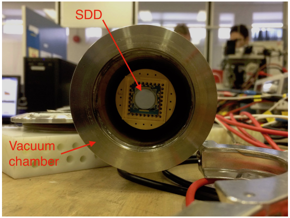
Material minimized around source to avoid $\gamma$ scattering

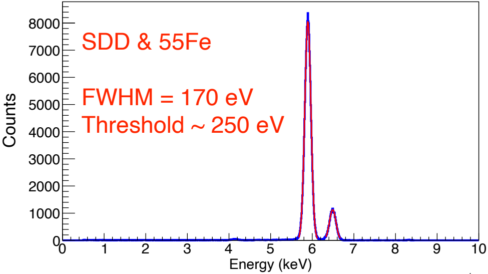
# X-ray detector

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

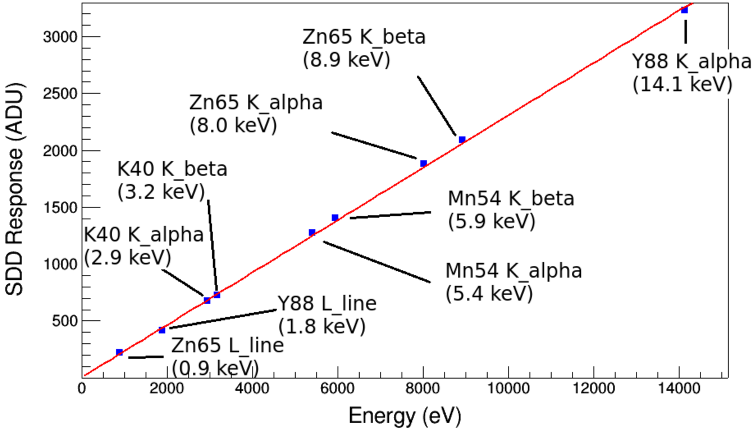




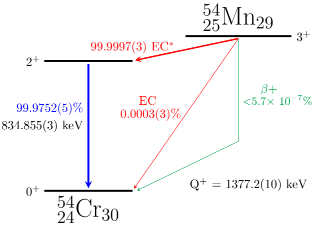



# SDD: all energy calibrations



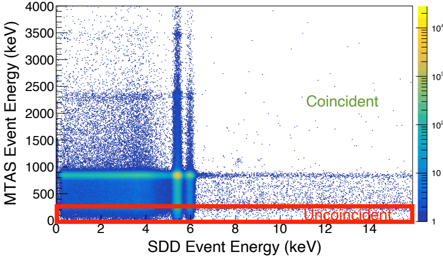
# Calibrating tagging efficiency with $^{54}$Mn

## Overwhelmingly decays by EC*




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

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

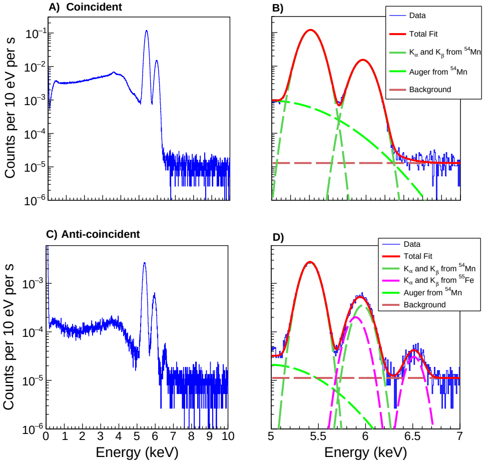



Something in MTAS: coincident

Nothing in MTAS: uncoincident

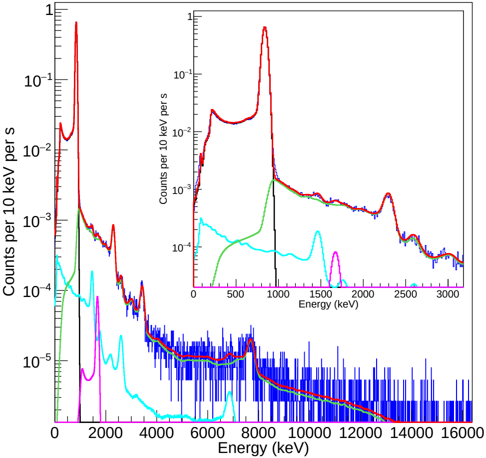
# $^{54}$Mn tagging efficiency calibration and background

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 $\mu$s 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 $\gamma$s [8]

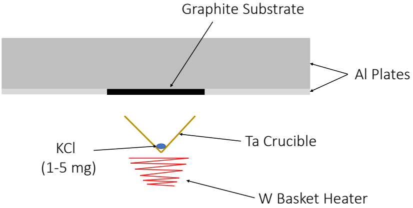
- Many additional ingredients for $^{54}$Mn 835 keV efficiency: source-BG pileup, source-source pileup, coincidence window, conversion electrons, deadtime... $\rightarrow$ likelihood function
- Scale up to $^{40}$K 1.4 MeV efficiency with GEANT 4 Monte-Carlos
  - Simulate **ratio** of efficiencies at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

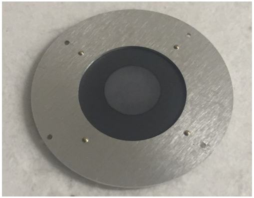
| Coin Win ($\mu$s) | Energy & Live Time Corrected Efficiency | | |
|---|---|---|---|
| | $^{54}$Mn | $^{40}$K | $^{65}$Zn |
| 1 | 0.9775 (1) | 0.9789 (6) | 0.9790 (6) |
| 2 | 0.9778 (1) | 0.9792 (6) | 0.9793 (6) |
| 4 | 0.9778 (1) | 0.9792 (6) | 0.9793 (6) |

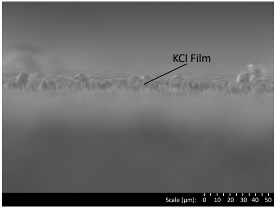
Numbers consistent across coinc. windows.

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

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



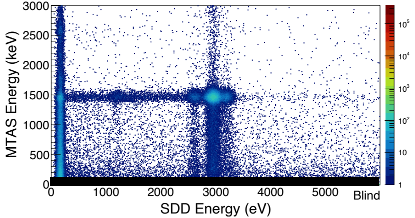



(test source)

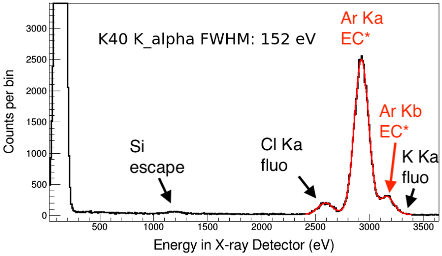
- 5 $\mu$m thick, $\sim 9 \times 10^{17}$ atoms $^{40}$K: activity equivalent to 

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

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

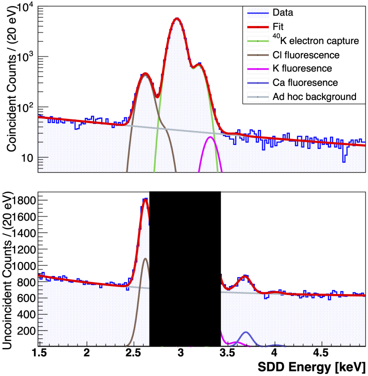



Coincident X-ray spectrum




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

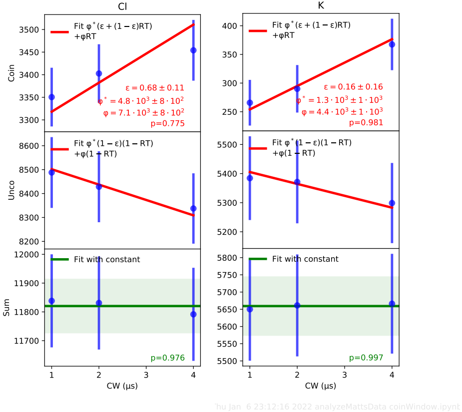
# $^{40}$K coincident and uncoincident spectra (blind)




$\rho = \frac{I}{I*}$ estimated from joint likelihood fit which also includes:

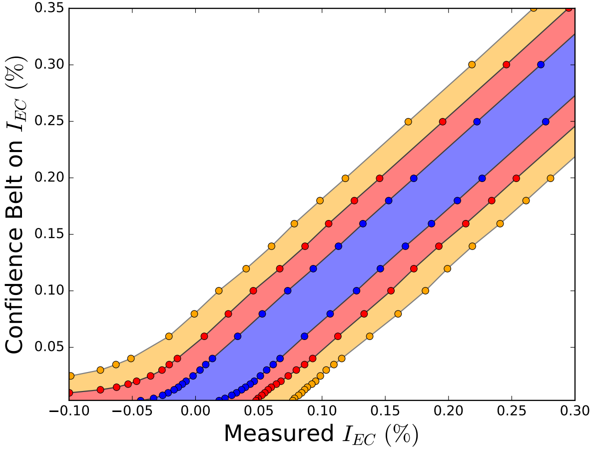
- Respective X-ray emission probabilities of EC, EC*
- $\gamma$-tagging efficiencies for EC*
- Spurious coincidences with $\gamma$ BG
- $\gamma$ interactions in SDD

# Confirming rate of spurious coincidences using Cl, K fluo




- $\beta^-$ and other mechanisms can fluoresce Cl, K in source
- These fluorescence events can also be in coincidence with MTAS BG
- Evolution of fluorescence count rate as a function of coincidence window is consistent with BG rate determined independently (2.8 kHz)
- Caveat stats

# Feldman and Cousins [10] expected sensitivity

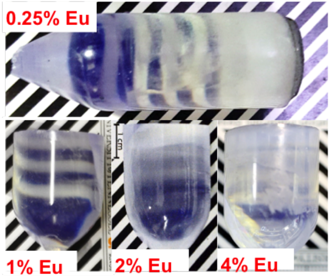



(68, 95, 99% CI)

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

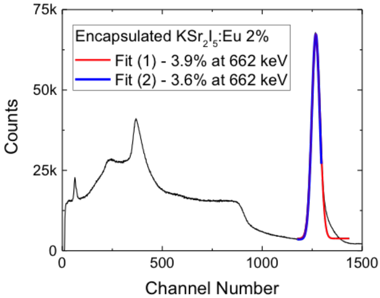
# Complementary approach: $KSr_2I_5$:Eu scintillator (KSI)[c]

- Novel scintillator [11], 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):



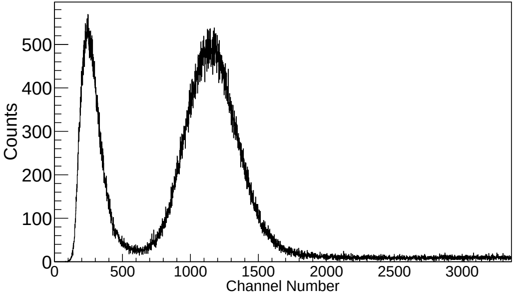

[c] C. Goetz, E. Lukosi, C. Melcher, L. Stand — U. Tennessee

# KSI in MTAS (preliminary)

## Setup inserted into MTAS


- 4 g KSI
  - $7 \times 7 \times 20\ \mathrm{mm}^3$
  - 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 $^{40}$K electron capture to $^{40}$Ar ground state will:
    - provide better understanding of backgrounds in dark matter searches, and in DAMA claim for discovery
    - resolve a longstanding question in geochronology
    - inform nuclear structure and beta decay models
- Detector fully characterized: $(97.89 \pm 0.06)\%$ tagging efficiency will allow target sensitivity (NIM A 1012 (2021) 165593)
- **$^{40}$K unblinded, analyzed; publication this summer**
- Also have $^{65}$Zn and $^{88}$Y data

# References I


[1] X. Mougeot and R. G. Helmer.
K-40_tables.pdf.

[2] R. Bernabei, P. Belli, S. d'ANGELO, A. Di Marco, F. Montecchia, F. Cappella, A. d'ANGELO, A. Incicchitti, V. Caracciolo, S. Castellano, R. Cerulli, C. J. Dai, H. L. He, X. H. Ma, X. D. Sheng, R. G. Wang, and Z. P. Ye.
DARK MATTER INVESTIGATION BY DAMA AT GRAN SASSO.
Int. J. Mod. Phys. A, 28(16):1330022, June 2013.

[3] Josef Pradler, Balraj Singh, and Itay Yavin.
On an unverified nuclear decay and its role in the DAMA experiment.
Phys. Lett. B, 720(4–5):399–404, March 2013.

[4] Kyoungwon Min, Roland Mundil, Paul R. Renne, and Kenneth R. Ludwig.
A test for systematic errors in 40Ar/39Ar geochronology through comparison with U/Pb analysis of a 1.1-Ga rhyolite.
Geochimica et Cosmochimica Acta, 64(1):73–98, January 2000.

[5] F. Begemann, K.R. Ludwig, G.W. Lugmair, K. Min, L.E. Nyquist, P.J. Patchett, P.R. Renne, C.-Y. Shih, I.M. Villa, and R.J. Walker.
Call for an improved set of decay constants for geochronological use.
Geochimica et Cosmochimica Acta, 65(1):111–121, January 2001.

[6] Jack Carter, Ryan B. Ickert, Darren F. Mark, Marissa M. Tremblay, Alan J. Cresswell, and David C. W. Sanderson.
Production of $^{40}$Ar by an overlooked mode of $^{40}$K decay with implications for K-Ar geochronology.
Geochronology, 2(2):355–365, November 2020.
Publisher: Copernicus GmbH.

# References II


[7] P. C. F. Di Stefano, N. Brewer, A. Fijałkowska, Z. Gai, K. C. Goetz, R. Grzywacz, D. Hamm, P. Lechner, Y. Liu, E. Lukosi, M. Mancuso, C. Melcher, J. Ninkovic, F. Petricca, B. C. Rasco, C. Rouleau, K. P. Rykaczewski, P. Squillari, L. Stand, D. Stracener, M. Stukel, M. Wolińska-Cichocka, and I. Yavin.
The KDK (potassium decay) experiment.
arXiv:1711.04004 [nucl-ex, physics:physics], November 2017.
arXiv: 1711.04004.

[8] M. Stukel, B. C. Rasco, N. T. Brewer, P. C. F. Di Stefano, K. P. Rykaczewski, H. Davis, E. D. Lukosi, L. Hariasz, M. Constable, P. Davis, K. Dering, A. Fijałkowska, Z. Gai, K. C. Goetz, R. K. Grzywacz, J. Kostensalo, J. Ninkovic, P. Lechner, Y. Liu, M. Mancuso, C. L. Melcher, F. Petricca, C. Rouleau, P. Squillari, L. Stand, D. W. Stracener, J. Suhonen, M. Wolińska-Cichocka, and I. Yavin.
A novel experimental system for the KDK measurement of the \$^{40}\$K decay scheme relevant for rare event searches.
arXiv:2012.15232 [nucl-ex, physics:physics], December 2020.
arXiv: 2012.15232.

[9] M. Karny, K.P. Rykaczewski, A. Fijałkowska, B.C. Rasco, M. Wolińska-Cichocka, R.K. Grzywacz, K.C. Goetz, D. Miller, and E.F. Zganjar.
Modular total absorption spectrometer.
Nucl. Instr. Meth. Phys. Res. A, 836:83–90, November 2016.

[10] Gary J. Feldman and Robert D. Cousins.
Unified approach to the classical statistical analysis of small signals.
Physical Review D, 57(7):3873–3889, 1998.

[11] L. Stand, M. Zhuravleva, G. Camarda, A. Lindsey, J. Johnson, C. Hobbs, and C.L. Melcher.
Exploring growth conditions and Eu2+ concentration effects for KSr2I5:Eu scintillator crystals.
Journal of Crystal Growth, 439:93–98, April 2016.

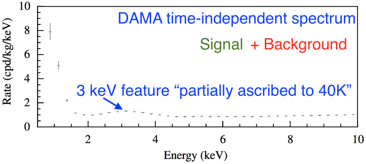
# References III

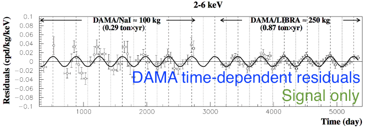
[12] V.A. Kudryavtsev, M. Robinson, and N.J.C. Spooner.
The expected background spectrum in NaI dark matter detectors and the DAMA result.
Astropart. Phys., 33(2):91–96, March 2010.

[13] R. Bernabei, P. Belli, A. Bussolotti, F. Cappella, R. Cerulli, C. J. Dai, A. d'Angelo, H. L. He, A. Incicchitti, H. H. Kuang, J. M. Ma, A. Mattei, F. Montecchia, F. Nozzoli, D. Prosperi, X. D. Sheng, and Z. P. Ye.
The DAMA/LIBRA apparatus.
arXiv:0804.2738, April 2008.
Nucl.Instrum.Meth.A592:297-315,2008.

# 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:




- $\dfrac{\overbrace{\text{modulation amplitude}}^{\text{signal}}}{\underbrace{\text{time-independent amplitude}}_{\text{signal} + \text{background}}} \approx \dfrac{1}{100}$
- DAMA controversial:
  - tension with other experimental results
  - disagreement on background model, eg [12]
- 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

# $^{40}$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 [13].
- 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 [13], and Sec. 5.4 of [2]).
- 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 [3]

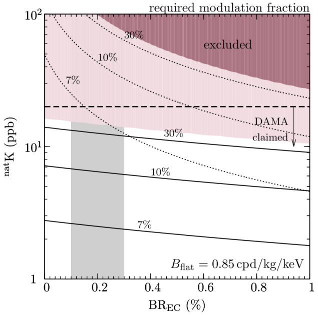
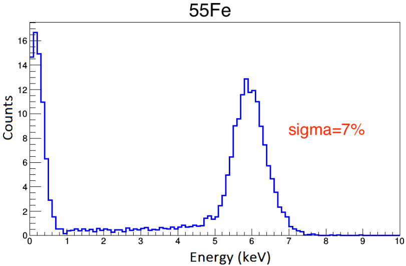



Figure 1: Solid: assuming some vetoed EC*. Dashed: no EC* at all. For fixed BR, as K concentration increases, one squeezes out signal DC, resulting in larger signal modulation fractions. For fixed K concentration, as BR increases , one squeezes the signal DC, and increases signal modulation fraction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

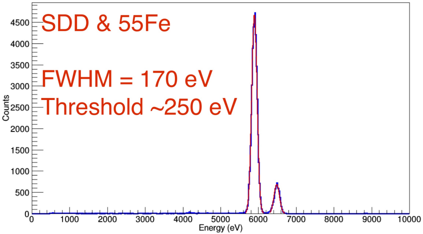
- In region of interest, DAMA observes a $\sim$ 1% modulation (AC — signal only) over a constant level (DC — signal and BG).
- Level of BG will squeeze level of DC signal
- This may push signal AC/DC to values $\geq$ 20% diffcult to reconcile with usual halo assumptions.
- Assuming 90% tagging of EC*, BG contribution of EC* relative to that of EC is $5 \times 0.2\%/\text{BR}$ [3].
- Also depends on level of other BGs

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

## APD




## SDD




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