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

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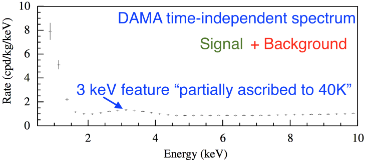
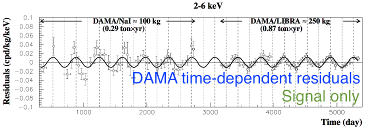
Dark matter, DAMA/LIBRA, and ^{40}K [2, 3]

- 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:

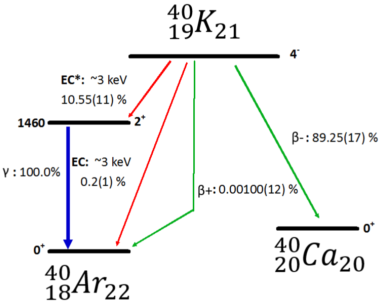




- $$\frac{\overbrace{\text{modulation amplitude}}^{\text{signal}}}{\underbrace{\text{time-independent amplitude}}_{\text{signal} + \text{background}}} \approx \frac{1}{100}$$
- DAMA controversial:
  - tension with other experimental results (cf many talks at TAUP)
  - disagreement on background model, 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

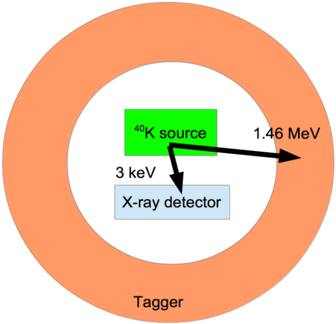
Decays of ^{40}K [5]

- ^{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: $^{40}\text{K} + e^- \rightarrow {}^{40}\text{Ar} + \nu_e$.
  - Main contribution: EC* to excited state of ^{40}Ar, which decays in ps, 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 [4] 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.

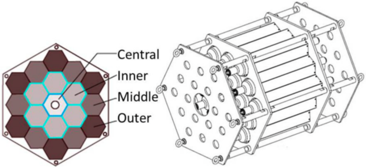
Measuring direct EC with KDK: X-ray detector and tagger



- Trigger on small inner detector
  - Low threshold (~ 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_{β^+}).
  - 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, $\approx$ 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 μs window is 2.8×10^{-3})

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

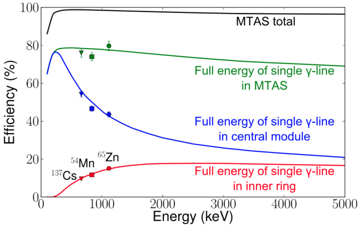
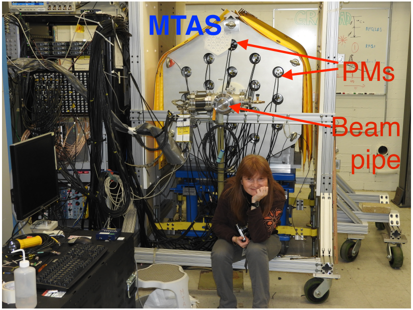


FIG. 3. The efficiencies of MTAS to detect single γ-ray transition are compared to GEANT4 simulations.

- 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

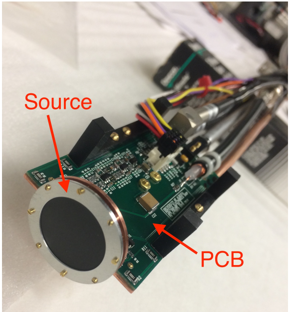


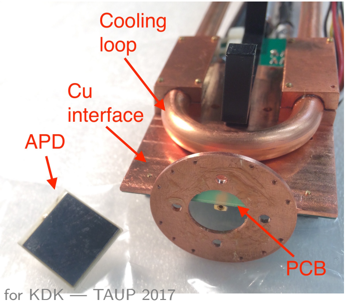
Vacuum insert with X-ray detector slides into beam pipe

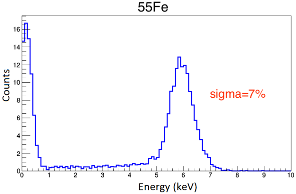
Material minimized around source to avoid γ scattering

X-ray detector

- 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

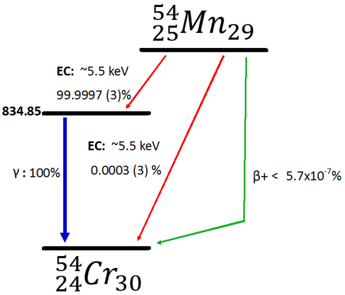






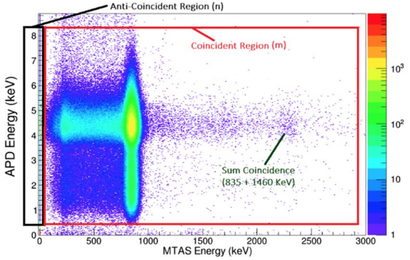
Calibrating tagging efficiency with ^{54}Mn

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: efficiency to tag 835 keV γ when 5.5 keV X-ray trigger is $(98.89 \underset{stat}{\pm} 0.01)\%$

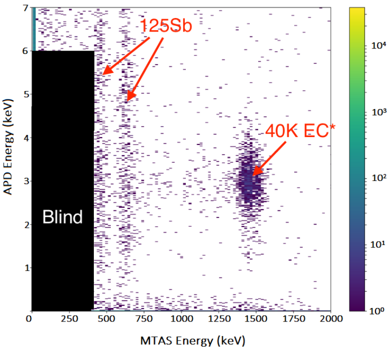
Also using ^{65}Zn ($EC/EC* \approx 1$, $E_X = 8$ keV, $E_\gamma = 1115$ keV), and Monte Carlos to extrapolate to $E_\gamma = 1.46$ MeV.

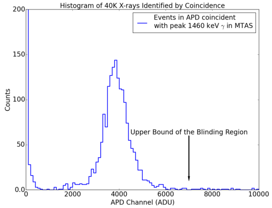
Preparing ^{40}K source (Y.Liu, ORNL)

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

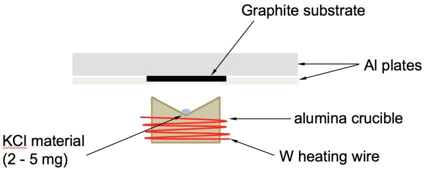


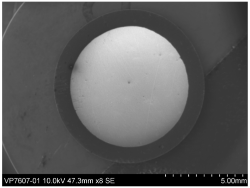


- **^{40}K visible in MTAS and APD!**
  Technique is viable
- Rate an order of magnitude lower than expected (only $\approx 10^{17}$ ^{40}K atoms)
  - Measured independently by MTAS, by APD, and by HPGe
  - Missing ^{40}K found in ion beam line by MTAS
  - Self-sputtered ^{40}K away?
- ^{125}Sb contamination 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: 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

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, new July ^{40}K sources
- Other ongoing work:
  - 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)

References I

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

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

[3] 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.
International Journal of Modern Physics A, 28(16):1330022, June 2013.

[4] D. W. Engelkemeir, K. F. Flynn, and L. E. Glendenin.
Positron Emission in the Decay of K 40.
Physical Review, 126(5):1818, 1962.

[5] K-40_tables.pdf.

[6] 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.
Nuclear Instruments and Methods in Physics Research Section A: Accelerators, Spectrometers, Detectors and Associated Equipment, 836:83–90, November 2016.

References II

[7] 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.

[8] X. Mougeot.
Reliability of usual assumptions in the calculation of β and ν spectra.
Physical Review C, 91(5), May 2015.

[9] Marc Diepold, Luis M. P. Fernandes, Jorge Machado, Pedro Amaro, Marwan Abdou-Ahmed, Fernando D. Amaro, Aldo Antognini, François Biraben, Tzu-Ling Chen, Daniel S. Covita, Andreas J. Dax, Beatrice Franke, Sandrine Galtier, Andrea L. Gouvea, Johannes Götzfried, Thomas Graf, Theodor W. Hänsch, Malte Hildebrandt, Paul Indelicato, Lucile Julien, Klaus Kirch, Andreas Knecht, Franz Kottmann, Julian J. Krauth, Yi-Wei Liu, Cristina M. B. Monteiro, Françoise Mulhauser, Boris Naar, Tobias Nebel, François Nez, José Paulo Santos, Joaquim M. F. dos Santos, Karsten Schuhmann, Csilla I. Szabo, David Taqqu, João F. C. A. Veloso, Andreas Voss, Birgit Weichelt, and Randolf Pohl.
Improved x-ray detection and particle identification with avalanche photodiodes.
Review of Scientific Instruments, 86(5):053102, May 2015.

[10] Recommended data.

[11] Glenn F. Knoll.
Radiation Detection and Measurement.
Wiley, 3 edition, January 2000.

[12] B. Smaller, J. May, and M. Freedman.
Scintillation studies on potassium iodide.
Physical Review, 79(6):940, 1950.

References III

[13] J. Bonanomi and J. Rossel.
Scintillations de luminescence dans les iodures d'alcalins.
Helvetica Physica Acta, 25(VII):725–752, 1952.

[14] H. V. Watts, L. Reiffel, and M. D. Oestreich.
Scintillation properties of pure alkali halides at low temperatures.
1962.

[15] E. V. D. van Loef, P. Dorenbos, C. W. E. van Eijk, K. W. Krämer, and H. U. Güdel.
Scintillation properties of K2lax5:Ce3+ (X=Cl, Br, I).
Nuclear Instruments and Methods in Physics Research Section A: Accelerators, Spectrometers, Detectors and Associated Equipment, 537(1–2):232–236, January 2005.

[16] 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.