^{65}Zn: A Measurement of Electron-Capture Decays Using Data from the KDK Experiment

Lilianna Hariasz

(Queen's University)
On behalf of the KDK collaboration

Winter Nuclear & Particle Physics Virtual Conference
February 11, 2021

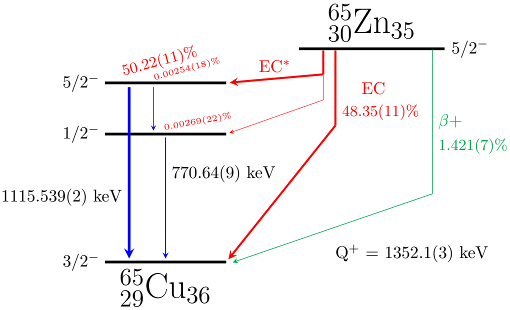
^{65}Zn

Uses

- Common gamma calibration source
- Tracer (medicine, biology)

Data, Advantages

- Data from KDK experiment
- Setup allows for measurement of EC branches
- **High gamma-tagging efficiency** ($\sim$ **98**%)
- KDK Instrumentation Paper Pre-Print Available At: **arXiv:2012.15232** [1]



Novel measurement of $\rho \equiv \mathbf{BR_{EC}/BR_{EC^*}}$

KDK: Potassium (K) Decay (DK)

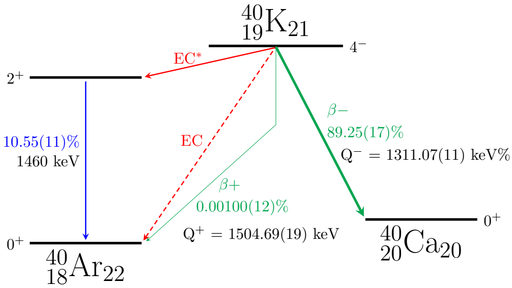
KDK is measuring ρ for ^{40}K

Datasets

- Data was obtained using ^{40}K, ^{54}Mn, ^{65}Zn, ^{88}Y sources
- all for energy calibration
- ^{54}Mn for efficiency calibration
- ^{40}K, ^{65}Zn, and ^{88}Y for physics results

^{40}K

- 0.0117(1)%[2] ^{40}K in ^{nat}K (in NaI)
- NaI commonly-used in dark matter searches, e.g. DAMA/LIBRA
- 3 keV X-ray/Auger from EC decay is in expected DM-detection signal region [3]
- ^{40}K also of interest in geochronology [4]



Unblinded ^{65}Zn dataset is being used to test methods for main ^{40}K analysis.

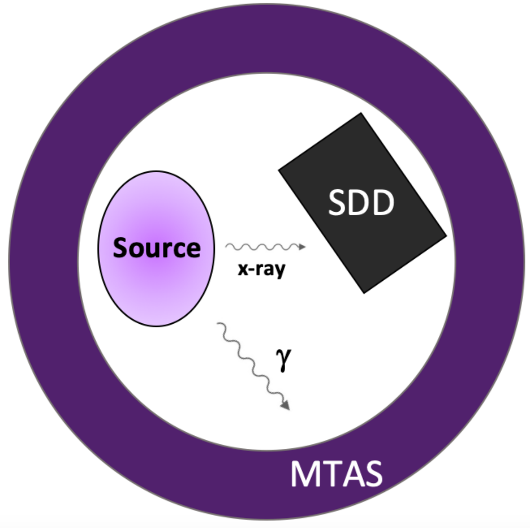
Implicit ^{65}Zn ρ Values from Literature

Branching ratios are calculated from measurements and theoretical values.
No experimental result has probed electron-capture to the ground state ($\equiv$EC) and excited state ($\equiv$EC*) branches simultaneously.

	National Nuclear Data Centre	Table of Radionuclides
BR_{EC}	48.54(7)%	48.35(11)%
BR_{EC^*}	50.04(10)%	50.23(11)%
ρ	**0.9700(24)**	**0.9626(30)**

Agreement within 2σ between National Nuclear Data Center [5] and Table of Radionuclides [6].

KDK Setup I



- EC event: x-ray
- EC* event: x-ray & gamma

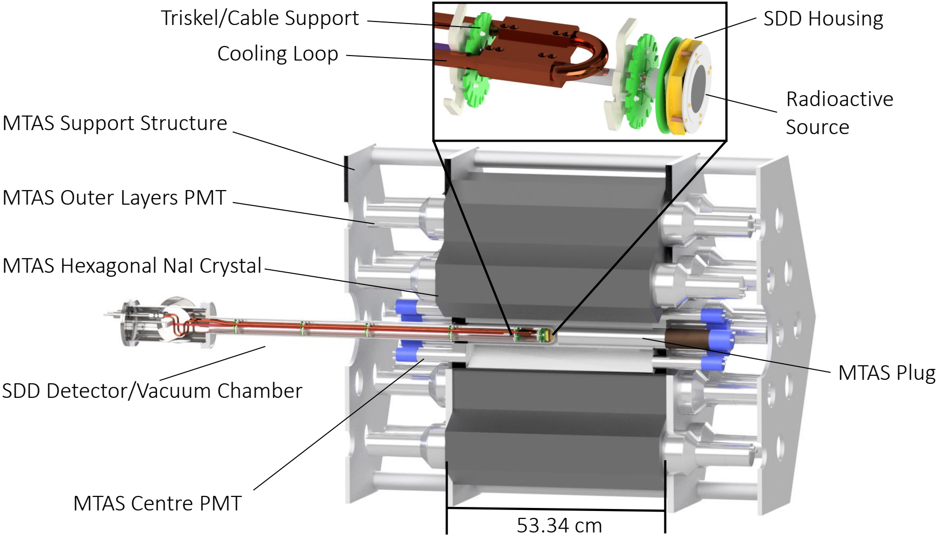
Inner **Silicon Drift Detector (SDD)** *(MPP/HLL Munich)* detects x-rays

Outer **Modular Total Absorption Spectrometer (MTAS)** *(Oak Ridge National Laboratory)* detects gammas

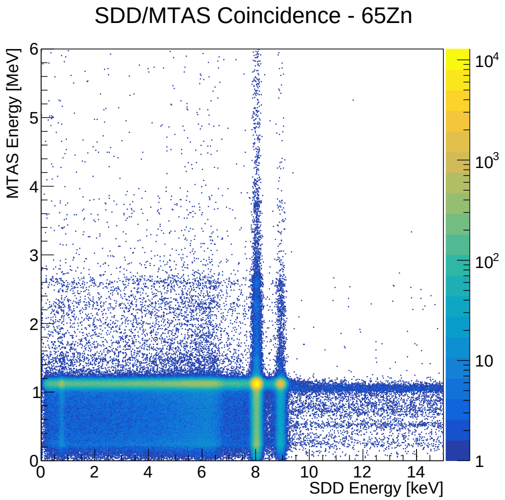
(Electronic support: TRIUMF)

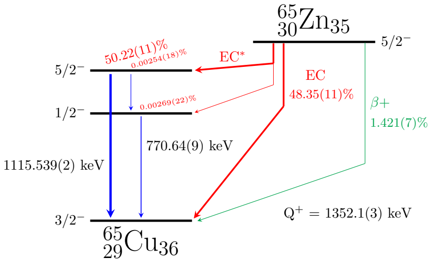
KDK measures $\rho = \mathbf{BR_{EC}/BR_{EC^*}}$

KDK Setup II (arXiv:2012.15232)



^{65}Zn Coincidence Histogram

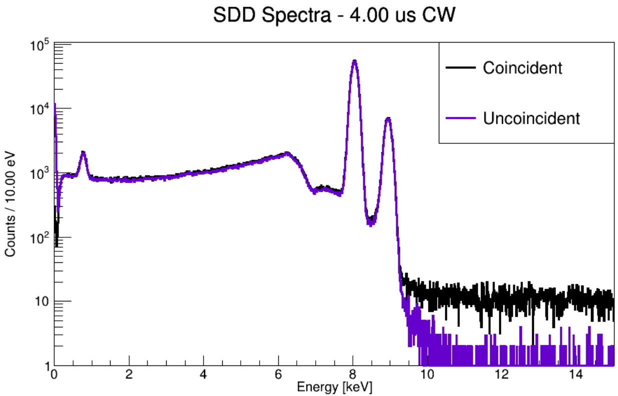




Analysis Procedure, SDD Spectra

1. Sort SDD data by checking for MTAS coincidence
2. Fit coincident & uncoincident spectra simultaneously
3. Divide signal counts in uncoincident & coincident spectra

SDD resolution: 198 eV FWHM at 8 keV

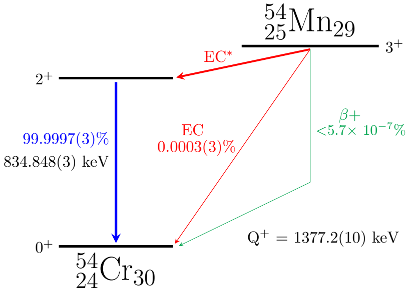


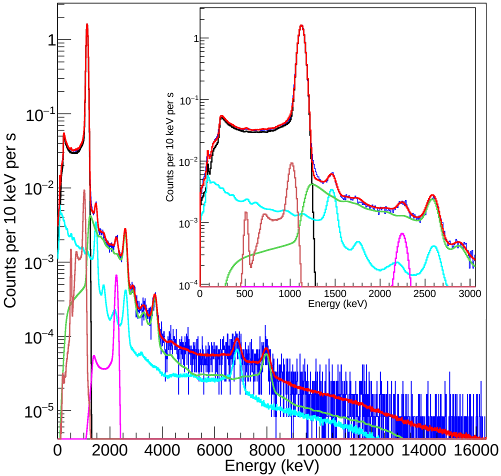
Fit accounts for false positives and negatives

Notably: $<100\%$ MTAS efficiency, EC coincidence with MTAS background

Simulating MTAS (Gamma-Tagging) Efficiencies, ^{54}Mn

Measured and simulated 835 keV (^{54}Mn) efficiencies are used to determine those of 1115 keV (^{65}Zn). Comparison of data + simulation for ^{65}Zn is shown.

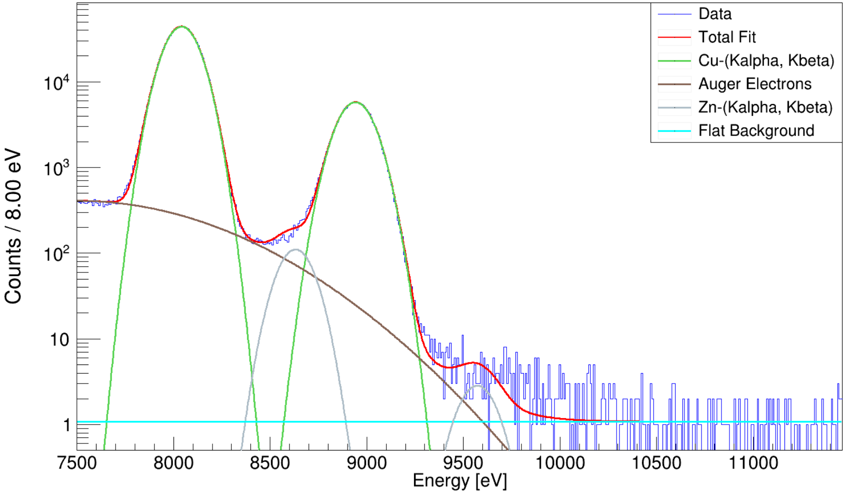




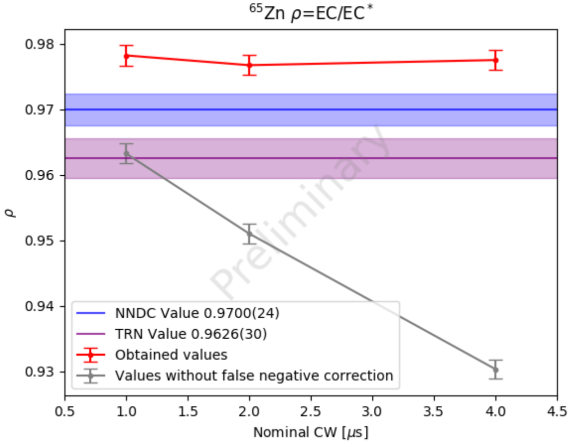
^{65}Zn efficiency = ^{65}Zn efficiency (sim.)/^{54}Mn efficiency (sim.) × ^{54}Mn efficiency (meas.).
97.96(4)% at the 4 μs **Coincidence Window (CW).**

^{65}Zn Spectrum Fit

Various background models are currently being studied.



Preliminary ^{65}Zn ρ Results



Coincidence window dependency

- ρ should be independent of coincidence window
- False negative corrections resolve unphysical CW-dependency

Currently finalizing false positives and & negatives

Summary

- KDK is measuring several rare decays, with results applicable to many fields
- The ^{65}Zn dataset obtained as part of KDK is being used to test analysis methods, and to obtain physics results
- The apparatus, featuring a high-efficiency gamma detector and high-resolution x-ray detector, provides a novel measurement method for ^{65}Zn decays
- False positive and false negative corrections are ongoing
- Final results to be published in the near future

Thank you to the KDK Collaboration

N. Brewer[1], H. Davis[2,3], P.C.F. Di Stefano[4], E. Lukosi[2,3], B.C. Rasco[1], K.P. Rykaczewski[1], M. Stukel[4], and the KDK Collaboration

[1]Oak Ridge National Laboratory Physics Division, Oak Ridge, TN, U.S.A, [2]Department of Nuclear Engineering, University of Tennessee, Knoxville, TN, USA, [3]Joint Institute for Nuclear Physics and Applications, Oak Ridge, TN, U.S.A, [4]Queen's University, Kingston, Ontario, Canada

References I

[1] 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, 2020.

[2] Jun Chen.
Nuclear data sheets for a= 40.
Nuclear Data Sheets, 140:1–376, 2017.

[3] 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, 2013.

[4] Jack Carter, Ryan B Ickert, Darren F Mark, Marissa M Tremblay, Alan J Cresswell, and David CW Sanderson.
Production of 40 Ar by an overlooked mode of 40 K decay with implications for K-Ar geochronology.
Geochronology, 2(2):355–365, 2020.

[5] E. Browne and J.K. Tuli.
Nuclear Data Sheets for A = 65.
Nuclear Data Sheets, 111(9):2425–2553, September 2010.

[6] M. M. Bé, V. Chisté, C. Dulieu, E. Browne, C. Baglin, V. Chechev, N. Kuzmenco, R. Helmer, F. Kondev, and D. MacMahon.
Table of Radionuclides (vol. 3–A= 3 to 244).
Monographie BIPM, 5, 2006.

[7] P. C. F. Di Stefano, N. Brewer, A. Fijalkowska, Z. Gai, K. C. Goetz, R. Grzywacz, D. Hamm, P. Lechner, Y. Liu, and E. Lukosi.
The KDK (potassium decay) experiment.
In *Journal of Physics: Conference Series*, volume 1342, page 012062. IOP Publishing, 2020.

[8] Marie-Martin Be, Venassa Chiste, C Dulieu, X Mougeot, V Chechev, F Kondev, A Nichols, X Huang, and B Wang.
Table of radionuclides (comments on evaluations).
Monographie BIPM-5, 7, 1999.

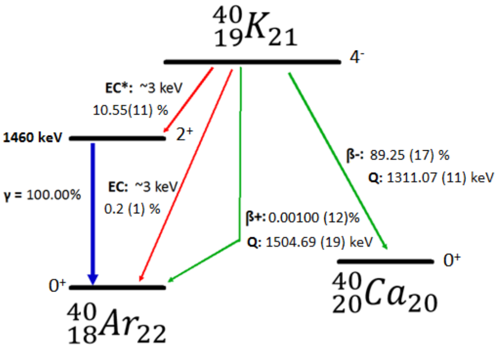
Extra Slides

Decay Channels:

- Primarily β^- to ^{40}Ca
- Electron capture to either excited or ground state of ^{40}Ar
- Small β^+ to ^{40}Ar branch

EC As A Background

- EC and EC* events emit low-energy x-rays/Auger electrons in expected DM-detection signal region
- **EC event: no high-energy gamma ray $\Longrightarrow$ difficult to veto the event**
- Need to accurately know $\mathrm{BR}_{\mathrm{EC}}$
- Never experimentally-measured



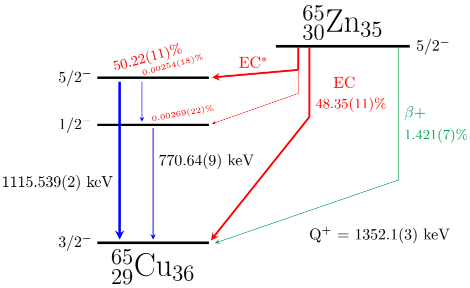
BR_{EC} value is theoretical

False-Negative Corrections

EC-triggered events in coincident spectrum

Sources

1. EC coincident with MTAS background
2. Source coincidence (EC + EC*)



Probability that EC "looks like" an EC*: 0.0245(1) at the 4 µs CW

Extra - Literature BR_{EC} Values for ^{40}K

Log(ft) is commonly-used, but disagrees with 2017 NNDC value.

Current half-life measurements are not precise enough to provide sufficient BR_{EC} estimation.

KDK measurement was suggested by Pradler et al.[1] .

Log(ft):	$\mathbf{BR_{EC}=0.2(1)\%}$[2]
NNDC:	$BR_{EC}=0.045(6)\%$[3]
From Half-Life Measurements:	$BR_{EC}=0.8(8)\%$[1]

---

[1] Pradler, Josef, Balraj Singh, and Itay Yavin. "On an unverified nuclear decay and its role in the DAMA experiment." Physics Letters B 720.4-5 (2013): 399-404.

[2] Be, Marie-Martin, et al. "Table of Radionuclides (Comments on evaluations)." Monographie BIPM-5 7 (1999).

[3] Chen, Jun. "Nuclear Data Sheets for A= 40." Nuclear Data Sheets 140 (2017): 1–376.

Extra - Impact of Background on Annual Modulation

Total rate:

$$R(t) = B_0 + S_0 + S_m f(t)$$

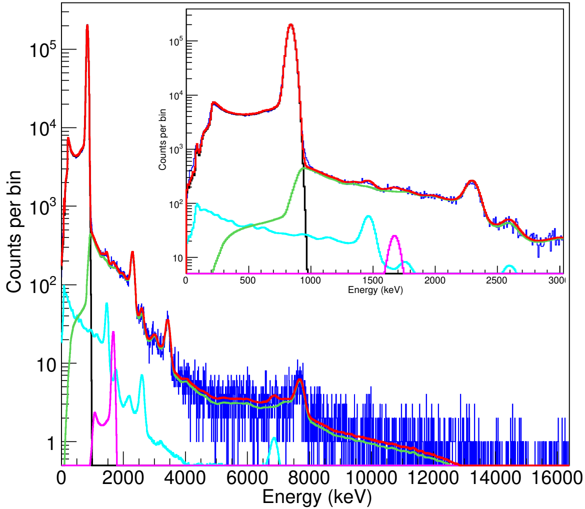
B_0: background
S_0: unmodulated dark matter
$S_m f(t)$: time-dependent dark matter signal
$R_0 \equiv B_0 + S_0$: measured time-independent rate

Modulation fraction:

$$s_m = \frac{S_m}{S_0} = \frac{S_m}{R_0 - B_0}$$

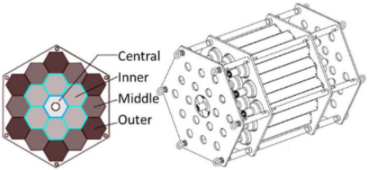
B_0 affects s_m result, while feasibility can be assessed via theoretical DM models

Extra - ^{54}Mn MTAS Spectrum Fit



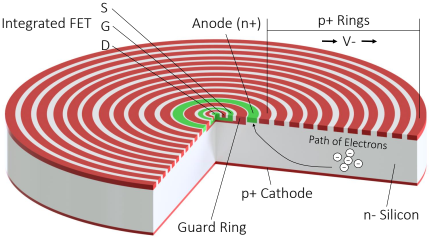
- Blue: ^{54}Mn 4 µs data
- Red: total fit, with components:
  - Black: simulated 835 keV spectrum
  - Teal: measured MTAS background
  - Green: gamma+BG convolution (black+teal)
  - Pink: gamma+gamma convolution (black+black)

Extra - MTAS Details



- 19 NaI(Tl) hexagonal volumes
- ~ 53 cm $\times$ 18 cm
- Inner, Middle Outer: one PMT at each end
- Center: 6 PMTs on each end, hole through center for source
- total mass ~ 1 ton
- $\sim 4\pi$ coverage
- surrounded by lead shielding

Extra - SDD Details

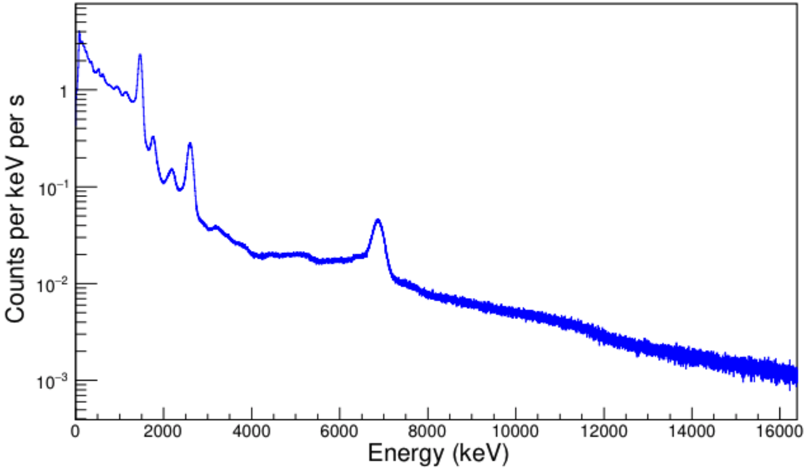


- Increasingly-biased p$^+$ rings
- Planar cathode
- Central n$^+$ anode is at potential minimum
- Gate of field-effect transistor (FET) connected to anode

MTAS Insert

- Contains SDD + source
- 2mm width except for endcap
- Endcap is 30cm long, 0.63mm thick to reduce scattering

Peaks: ^{40}K (1460 keV), ^{214}Bi (1760 keV), ^{208}Tl (2614 keV), ^{127}I & ^{23}Na neutron captures (6800 keV).



Extra - False Negatives

EC in coincidence with a background in MTAS:

$$\psi_B = BT \tag{1}$$

T=CW, $B = 2641.00(26)\,\mathrm{Hz}$ is the rate of background events in MTAS. Using convolutions of MTAS background with ^{54}Mn, a collaborator obtained ψ_B values.

Source (EC + EC*) coincidence:

$$\psi_{\mathrm{EC}*} = \epsilon A(\mathrm{BR}_{\mathrm{EC}*})\mu_x T \tag{2}$$

$A = 536(23)\,\mathrm{Bq}$ is source activity, $\mathrm{BR}_{\mathrm{EC}*} = 50.04(10)\,\%$, μ_x is probability of missing EC* x-ray (sims.).

Source (EC + β^+) coincidence:

$$\psi_{\beta+} = \epsilon \mathrm{A}(\mathrm{BR}_{\beta+})\mu_{\beta+} T \tag{3}$$

β^+ annihilates to two 511 keV gammas. $\mathrm{BR}_{\beta+} = 1.421(7)\,\%$, $\mu_{\beta+}$ is probability β^+ is missed by SDD (sims.). $\epsilon \approx 1$

Extra - False Negative Corrections Details

T' (µs)	$(1-\eta_x)$	T_{avg} (µs)	ψ_B	ψ_{EC^*}	Ψ
1	0.799(25)	2.66(5)	0.0071(1)	0.00057(1)	0.0076(1)
2	0.749(28)	4.64(3)	0.0123(1)	0.00093(1)	0.0132(1)
4	0.750(21)	8.67(4)	0.0227(1)	0.00174(1)	0.0245(1)