The KDK Experiment: A Measurement of ^{40}K Relevant for Rare-Event Searches and Geochronology

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On behalf of the KDK Collaboration

August 31, 2022

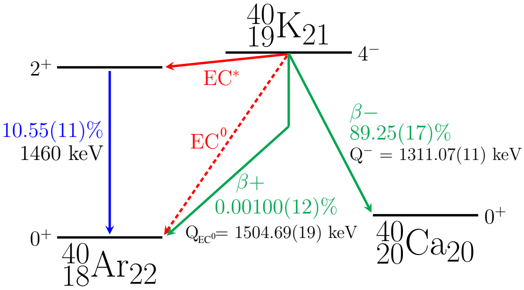
ICNFP 2022, Kolymbari, Crete

Potassium-40

- Naturally-occuring radioactive isotope (0.0117(1)%[2] ^{40}K in ^{nat}K)
- **E.C. → g.s. ($I_{\mathbf{EC^0}}$) is ill-known. Predictions: $\sim (\mathbf{0.0 - 0.3})\%$**

1. Rare-event searches

- Contaminant in NaI volumes (e.g. DAMA/LIBRA, SABRE, COSINUS)
- Irreducible background at $\sim 3\,$keV [3]



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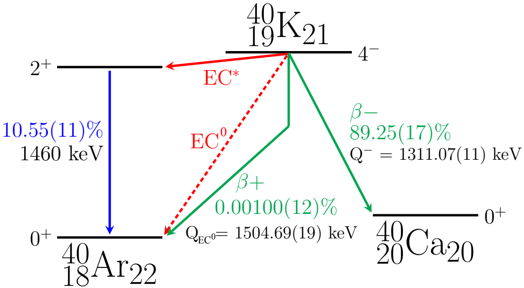
2. Geochronology

- Lifetime $\sim 10^9$ y
- K-Ar (& Ar-Ar) dating dependent on ^{40}K decay scheme [4]
- Ill-known I_{EC^0} becoming an important systematic



Potassium-40

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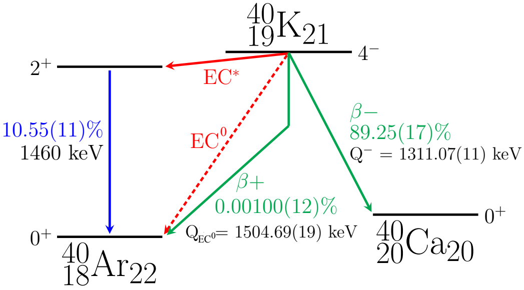
3. Nuclear Theory

- I_{EC^0} is the only known *third-forbidden unique* E.C. decay
- 3FU transition can inform calculated $0\nu bb$ half-lives (estimate quenching of weak axial-vector coupling).
- Theoretical predictions vary widely



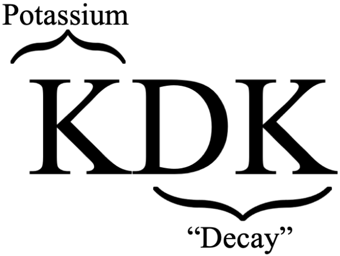
Potassium-40

- Naturally-occuring radioactive isotope
- **E.C. → g.s. (I_{EC^0}) is ill-known. Predictions: $\sim (\mathbf{0.0 - 0.3})\%$**

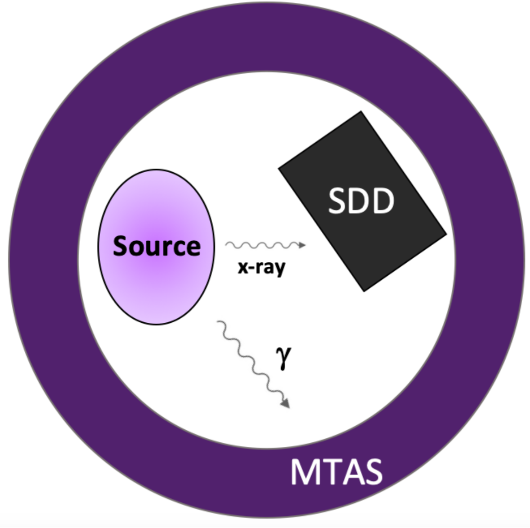
The KDK Collaboration

International collaboration making the **first measurement of Potassium-40's rare I_{EC^0} decay**

Instrumentation paper (NIM A, Stukel et al., 2021) available **here**



KDK Setup I



- I_{EC^0} event: X-ray/Auger
- I_{EC^*} event: X-ray/Auger & gamma

Inner **Silicon Drift Detector (SDD)**[†] *(MPP/HLL Munich)*; ~ 10 g

Outer **Modular Total Absorption Spectrometer (MTAS)** *(Oak Ridge National Laboratory)*; $\sim 1,000$ kg

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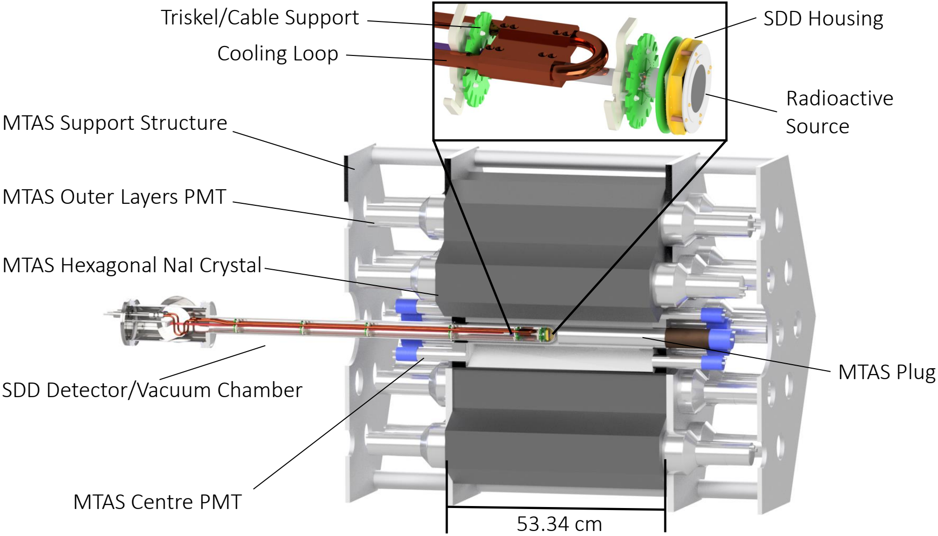
KDK measures $\rho = I_{\mathbf{EC}^0} / \, I_{\mathbf{EC}^*}$

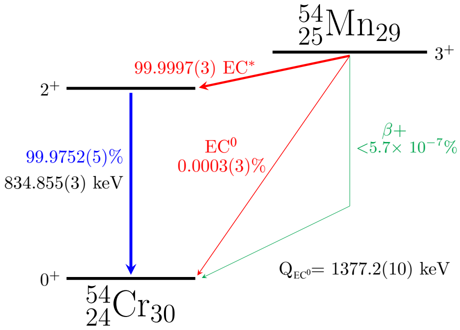
[†] or KSI

KDK Setup II (https://doi.org/10.1016/j.nima.2021.16559)



Leading Systematic - MTAS Gamma-Tagging Efficiency, ^{54}Mn

To discriminate I_{EC^0} from I_{EC^*} **γ-tagging efficiency must be very well-known.**



Measurement of ^{54}Mn γ efficiency is combined with ratio of Geant4-simulated values

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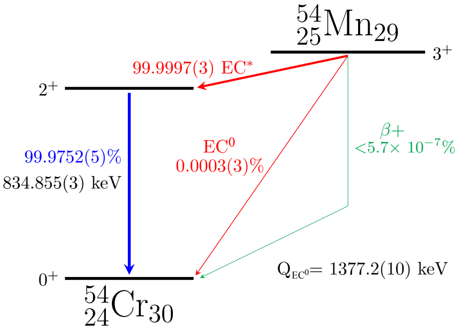

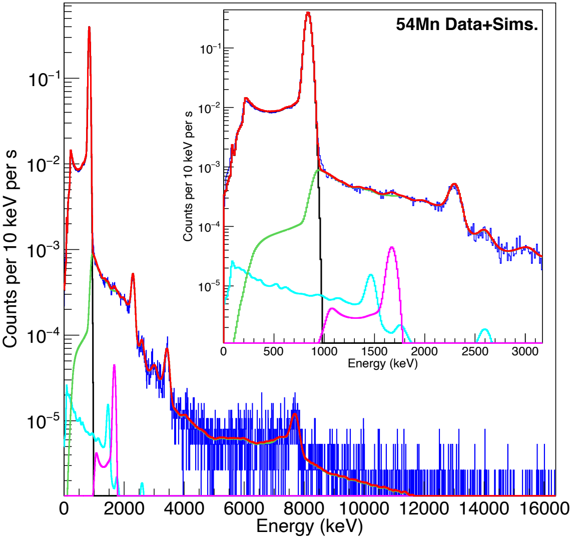

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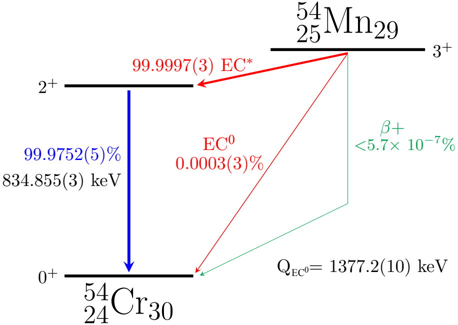


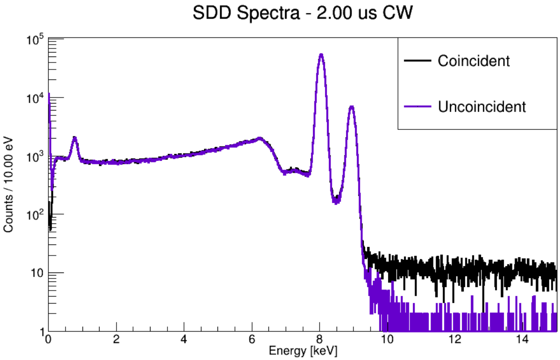
Measurement of ^{54}Mn γ efficiency is combined with Geant4-simulated values.

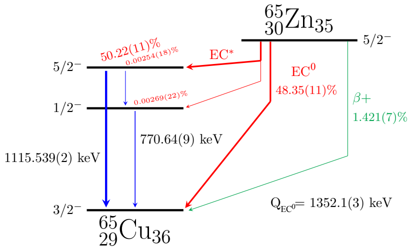
Scale 835 keV **gamma to** 1460 keV **(^{40}K), correct for dead time:**

(1 µs CW): Measured ^{54}Mn 97.75(1)% ⟶ ^{40}K **97.89(6)%**

Testing Methods - ^{65}Zn

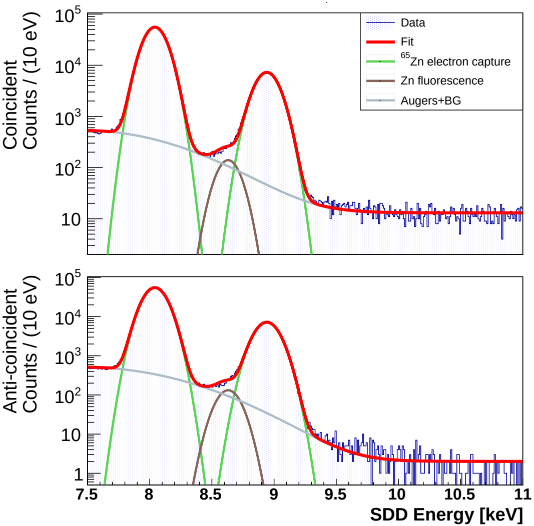
Test methodology for obtaining $\rho = I_{EC^0} / I_{EC^*}$ via ^{65}Zn, similar decay





Resolution 198 eV FWHM at 8 keV

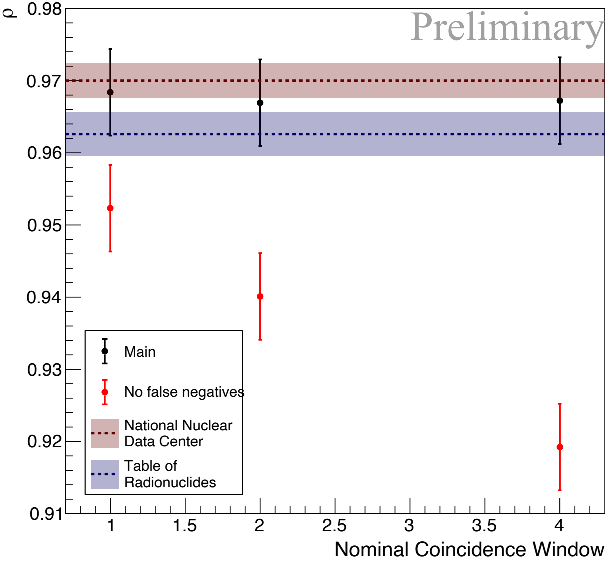
Testing Methods - ^{65}Zn



Fit coincident & uncoincident spectra (left) simultaneously

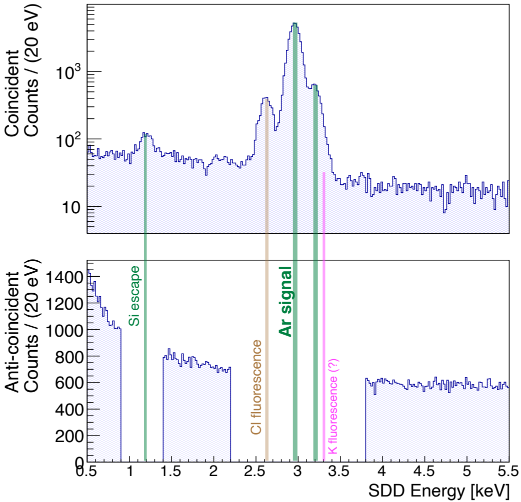
Fit accounts for false positives and negatives Notably: $<$ 100% MTAS efficiency, $I_{\mathbf{EC}^0}$ coincidence with MTAS background

Testing Methods - ^{65}Zn



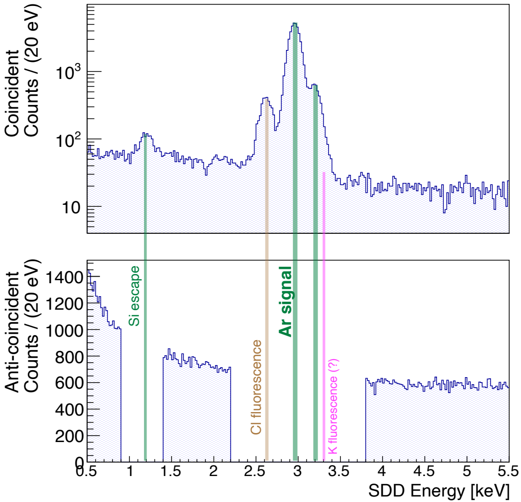
- False negative correction removes unphysical CW-dependency
- Finalizing systematics

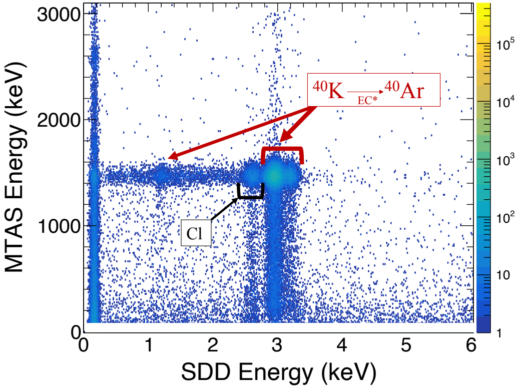
Main ^{40}K Analysis (blinded)



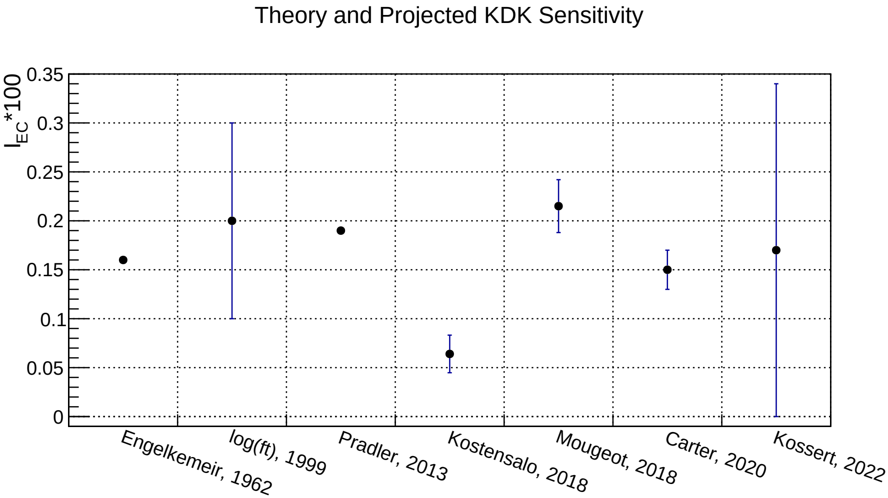
- Use ^{65}Zn analysis as a template
- See signal and fluorescence in coincident spectrum
- **Sensitivity depends on number of $I_{\mathbf{EC}^0}$ decays observed**

Main ^{40}K Analysis (blinded)

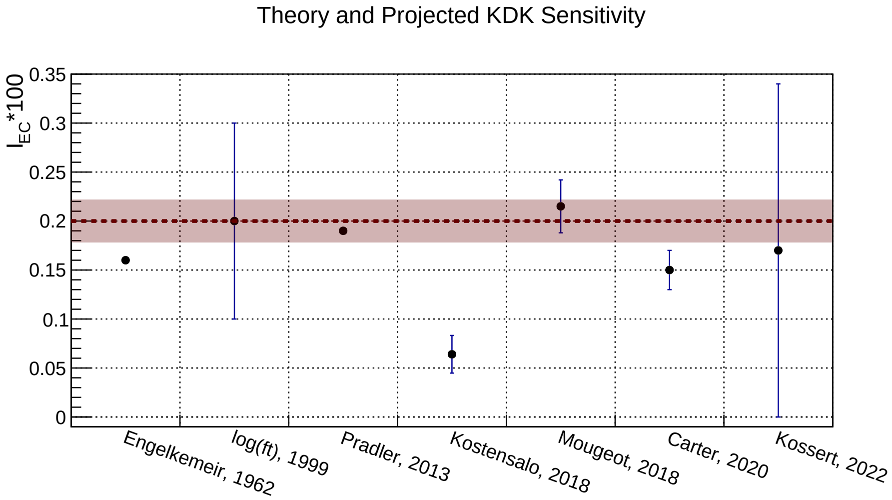




^{40}K: Predictions, Sensitivity



^{40}K: Predictions, Sensitivity



Takeaway

- ^{40}K measurement applicable to many fields: rare-event searches, geochronology, nuclear theory
- KDK is making a measurement of ^{40}K, along with other isotopes
- ^{40}K MEASUREMENT COMPLETED with result remaining internal, publication preparation in final stages
- Stay tuned for the final value in the coming weeks

Thank you to the KDK Collaboration

N. Brewer[1], J. Carter[2], H. Davis[3], P.C.F. Di Stefano[4], A. Fijałkowska[1,5,6], Z. Gai[1], R. Grzywacz[1,3,5], J. Kostensalo[7,8], P. Lechner[9], Y. Liu[1], E. Lukosi[3], M. Mancuso[10], J. Ninkovic[9], F. Petricca[10], B.C. Rasco[1,3], C. Rouleau[1], K.P. Rykaczewski[1], D. Stracener[1], M. Stukel[4], J. Suhonen[8], M. Wolińska-Cichocka[1,6]

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[7]Natural Resources Institute Finland, Joensuu, Finland
[8]University of Jyväskyla, Jyväskyla, Finland
[9]MPG Semiconductor Laboratory, Munich, Germany
[10]Max Planck Institute for Physics, Munich, Germany

Technical & Electronic Support: M. Constable, F. Retiere (TRIUMF), K. Dering[4], P. Davis, University of Alberta.

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.

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[4] Jack Carter, Ryan B Ickert, Darren F Mark, Marissa M Tremblay, Alan J Cresswell, and David CW Sanderson.

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[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.

Extra Slides

Impact of Background on Annual Modulation

Total rate:

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

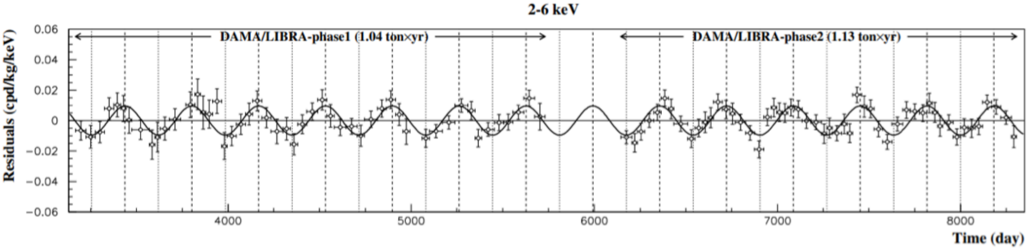
B_0: background, including ^{40}K
S_0: unmodulated dark matter
$S_m f(t)$: time-dependent dark matter signal
$R_0 \equiv B_0 + S_0$: measured time-independent rate

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

DAMA/LIBRA Modulation



Bernabei, Rita, Pierluigi Belli, Andrea Bussolotti, Fabio Cappella, Vincenzo Caracciolo, Riccardo Cerulli, Chang-Jiang Dai et al. “First model independent results from DAMA/LIBRA–phase2.” Universe 4, no. 11 (2018): 116.

Uniqueness, Forbidenness - I/II

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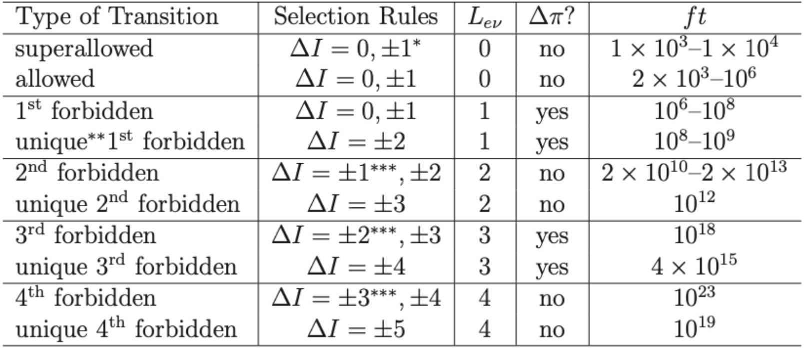

Type of Transition	Selection Rules	$L_{e\nu}$	$\Delta\pi$?	ft
superallowed	$\Delta I = 0, \pm 1^*$	0	no	1×10^3–1×10^4
allowed	$\Delta I = 0, \pm 1$	0	no	2×10^3–10^6
1^{st} forbidden	$\Delta I = 0, \pm 1$	1	yes	10^6–10^8
unique$^{**}1^{\text{st}}$ forbidden	$\Delta I = \pm 2$	1	yes	10^8–10^9
2^{nd} forbidden	$\Delta I = \pm 1^{***}, \pm 2$	2	no	2×10^{10}–2×10^{13}
unique 2^{nd} forbidden	$\Delta I = \pm 3$	2	no	10^{12}
3^{rd} forbidden	$\Delta I = \pm 2^{***}, \pm 3$	3	yes	10^{18}
unique 3^{rd} forbidden	$\Delta I = \pm 4$	3	yes	4×10^{15}
4^{th} forbidden	$\Delta I = \pm 3^{***}, \pm 4$	4	no	10^{23}
unique 4^{th} forbidden	$\Delta I = \pm 5$	4	no	10^{19}

${}^{40}\text{K} \to {}^{40}\text{Ar}$ g.s. or ${}^{40}\text{Ca}$ = unique 3rd forbidden; ${}^{40}\text{K} \to {}^{40}\text{Ar}$ exc. = unique 1st forbidden; ${}^{54}\text{Mn} \to {}^{54}\text{Cr}$ g.s. = unique 2nd forbidden; ${}^{54}\text{Mn} \to {}^{54}\text{Cr}$ exc. = allowed; ${}^{65}\text{Zn}$ all allowed.

Uniqueness, Forbidenness - II/II

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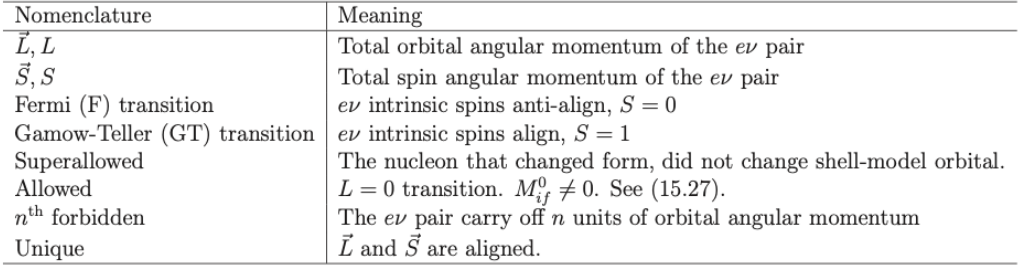

Nomenclature	Meaning
$\vec{L}, L$	Total orbital angular momentum of the $e\nu$ pair
$\vec{S}, S$	Total spin angular momentum of the $e\nu$ pair
Fermi (F) transition	$e\nu$ intrinsic spins anti-align, $S = 0$
Gamow-Teller (GT) transition	$e\nu$ intrinsic spins align, $S = 1$
Superallowed	The nucleon that changed form, did not change shell-model orbital.
Allowed	$L = 0$ transition. $M^0_{if} \neq 0$. See (15.27).
n^{th} forbidden	The $e\nu$ pair carry off n units of orbital angular momentum
Unique	$\vec{L}$ and $\vec{S}$ are aligned.

KSI

- Alternate configuration
- Combines x-ray detector + source
- Benefits from higher ^{40}K composition
- Currently, limitations in PMT modelling lead to difficulty in obtaining MTAS gamma-tagging efficiency

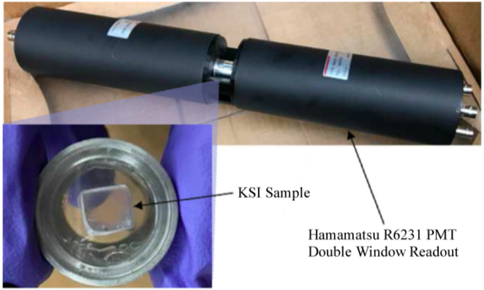

Fig. 11. $7 \times 7 \times 19.9$ mm^3 rectangular KSI sample wrapped in 400 μm of teflon sealed inside an aluminum housing with a nitrogen atmosphere placed in the center with a custom 3D printed polyethylene bracket holding the setup together.

Geochronology - K-Ar Dating

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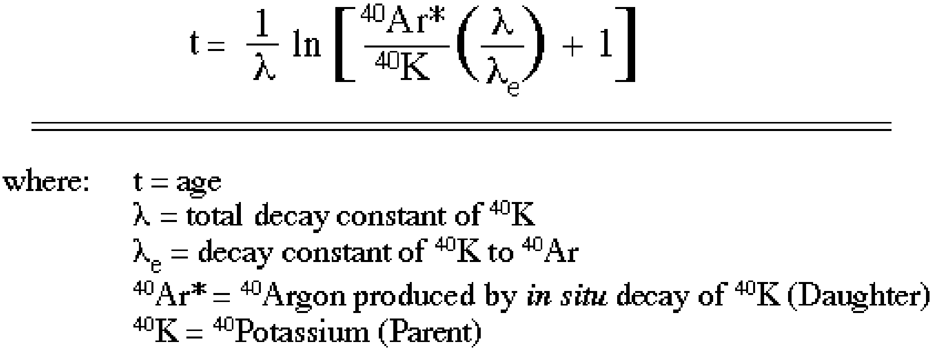

$$t = \frac{1}{\lambda} \ln\left[\frac{^{40}\mathrm{Ar}^*}{^{40}\mathrm{K}}\left(\frac{\lambda}{\lambda_e}\right) + 1\right]$$

where: t = age

λ = total decay constant of ^{40}K

λ_e = decay constant of ^{40}K to ^{40}Ar

^{40}Ar* = ^{40}Argon produced by *in situ* decay of ^{40}K (Daughter)

^{40}K = ^{40}Potassium (Parent)

Geochronology - Ar-Ar Dating

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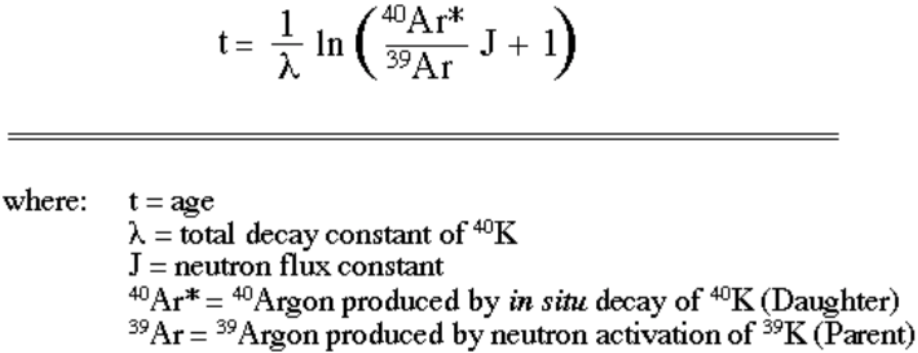
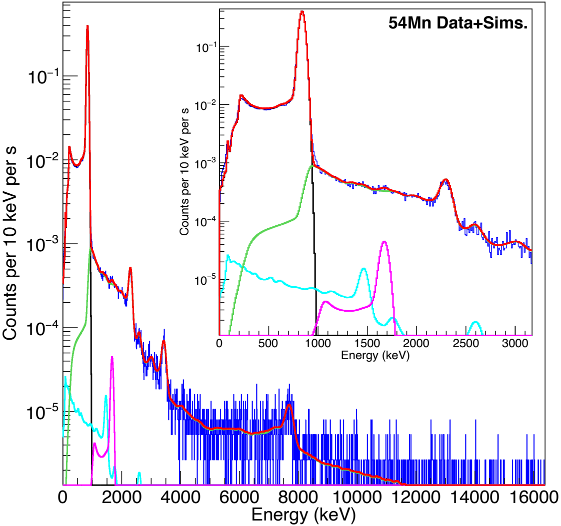


$$t = \frac{1}{\lambda} \ln\left(\frac{^{40}\mathrm{Ar}^*}{^{39}\mathrm{Ar}} J + 1\right)$$

where:
t = age
λ = total decay constant of ^{40}K
J = neutron flux constant
$^{40}\mathrm{Ar}^*$ = ^{40}Argon produced by *in situ* decay of ^{40}K (Daughter)
$^{39}\mathrm{Ar}$ = ^{39}Argon produced by neutron activation of ^{39}K (Parent)

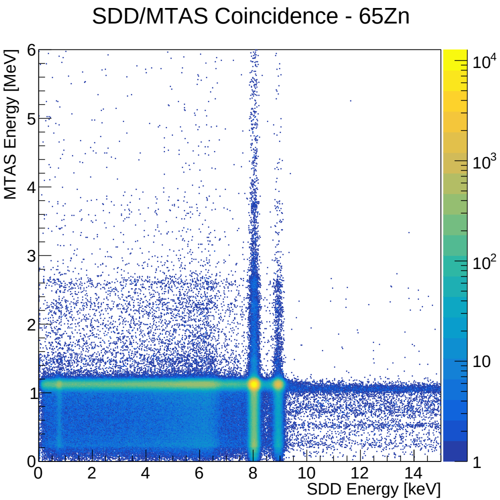
Note: total ^{40}K lifetime is calculated from partial half lives and branching ratios, thus λ is dependent on I_{EC^0}.

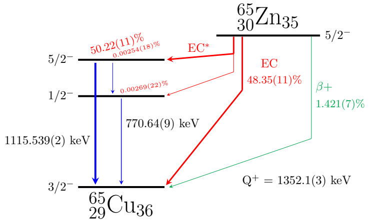
^{54}Mn MTAS Spectrum Fit



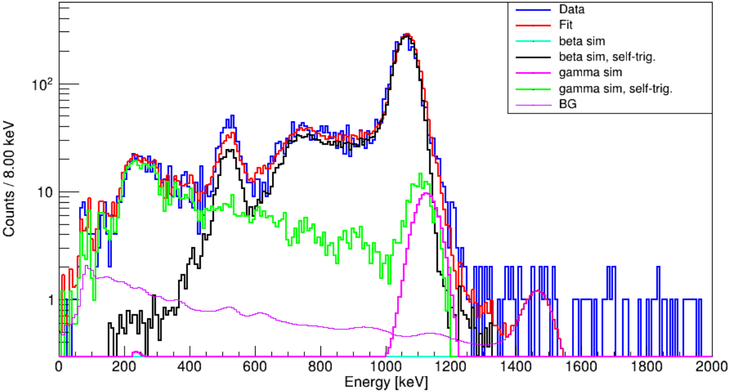
- Blue: ^{54}Mn 4 µs data
- Red: total fit, with components:
  - Black: simulated 835 keV spectrum
  - Teal: measured MTAS background
  - Green: gamma+BG convolution (black+teal)
  - Pink: gamma+gamma convolution (black+black)

^{65}Zn Coincidence Histogram



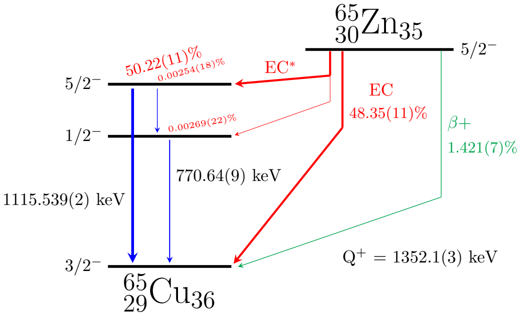


^{65}Zn fit to MTAS spectrum



^{65}Zn - 3rd Electron Capture Branch

- Electron capture branch to the 770 keV level
- Intensity per 100 for 770 keV = 0.00269(22)
- Intensity per 100 for 330 keV = 0.00254(18)
- This means decay directly to 770 keV occurs 0.00015(28) % of the time
- The systematic effect of the intermediate ^{65}Cu energy level on ρ is smaller than the statistical error



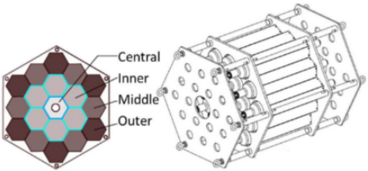
Implicit ^{65}Zn ρ Values from Literature

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

	National Nuclear Data Centre	Table of Radionuclides
I_{EC^0}	48.54(7)%	48.35(11)%
I_{EC^*}	50.04(10)%	50.23(11)%
ρ	**0.9700(24)**	**0.9626(30)**

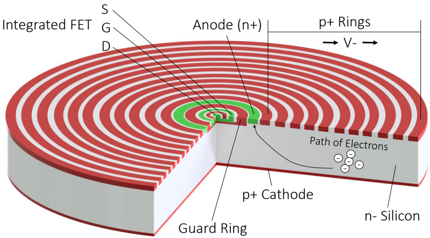
Agreement within 2σ between National Nuclear Data Center [5] and Table of Radionuclides [6].

MTAS Details



- 19 NaI(Tl) hexagonal volumes
- ~ 53 cm × 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
- $\sim 4\pi$ sr coverage
- surrounded by lead shielding

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

MTAS BG

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