

The KDK Experiment

A novel measurement of ^{40}K for rare-event searches and geochronology

Lilianna Hariasz

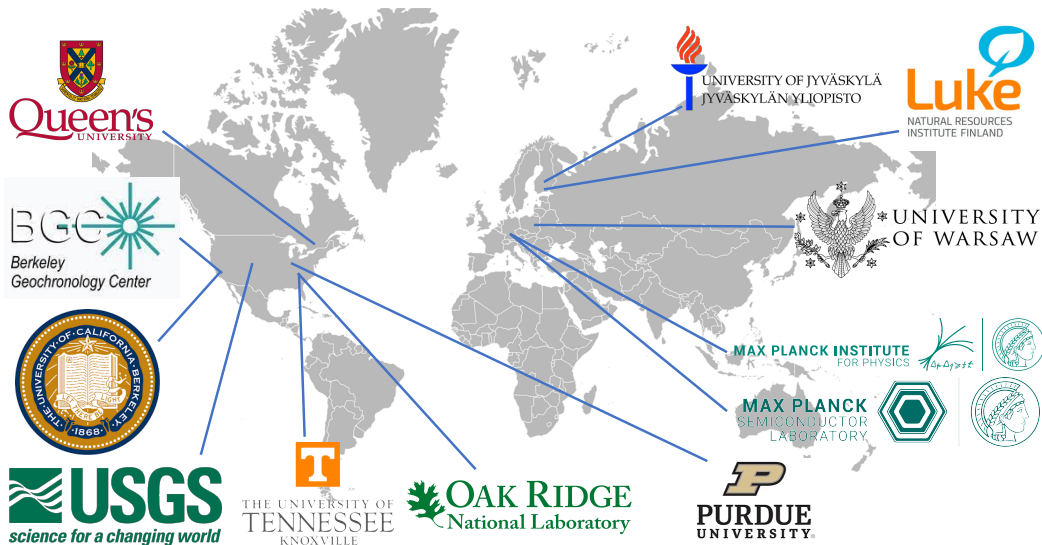
Queen's University, Kingston, ON

February 21, 2023

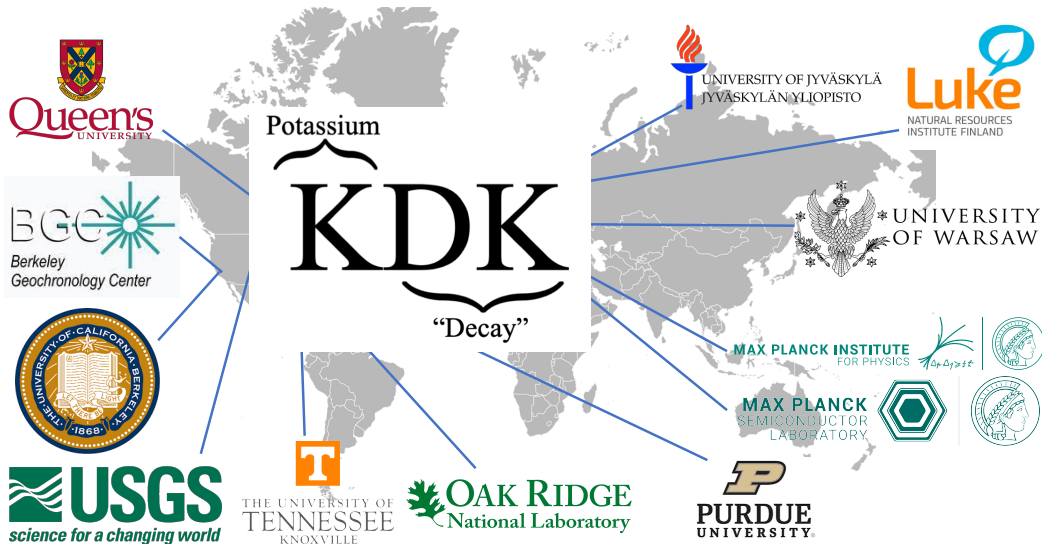
LAKE LOUISE WINTER INSTITUTE 2023

Lake Louise, AB, Canada

The KDK collaboration

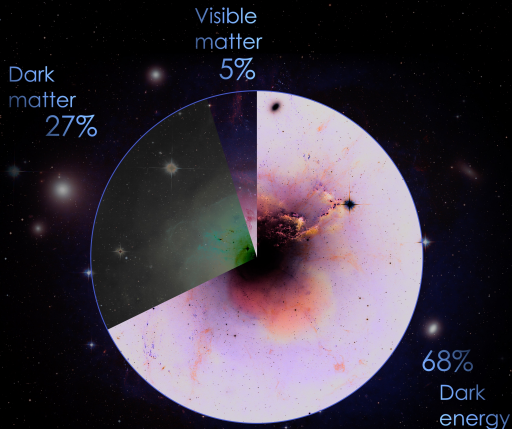


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Dark matter

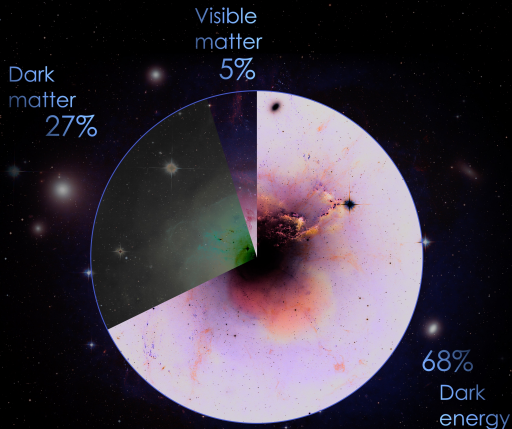
- Various searches for dark matter, particularly for **WIMPs**
- Direct-detection with NaI (DAMA/LIBRA¹, SABRE², COSINUS³,...): $\mathcal{O}(\text{keV})$ signal
- **K in NaI; $^{40}\text{K} \rightarrow \text{Ar}$ electron captures: irreducible 3 keV background**



¹Bernabei et al., *Universe* 4(11), 116 (2018), ²Antonello et al., *Astropart. Phys.* 106, 1-9 (2019), ³Angloher et al., *Eur. Phys. J. C* 82(3), 1-11 (2022)

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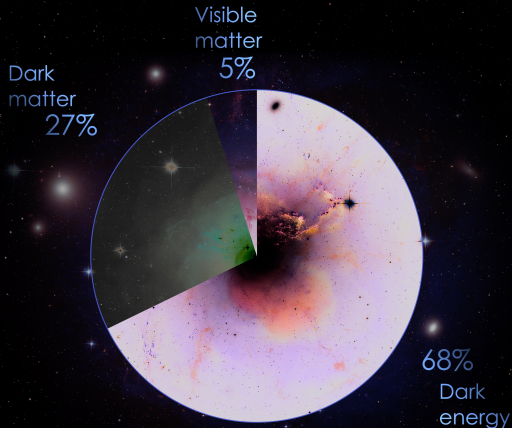
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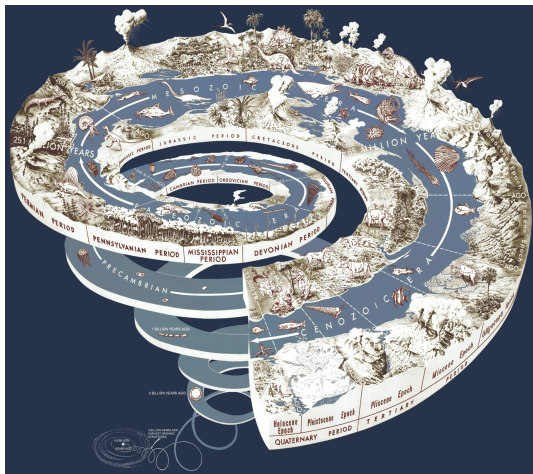
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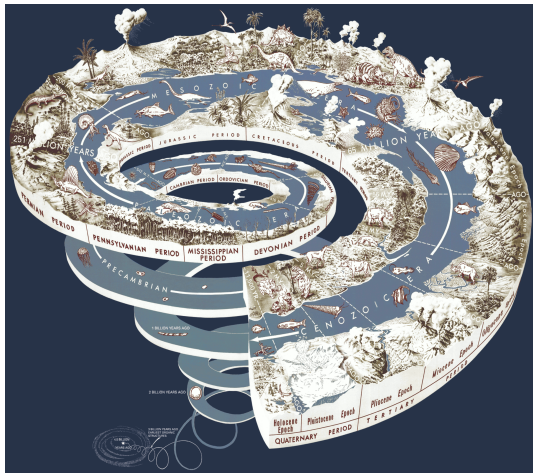
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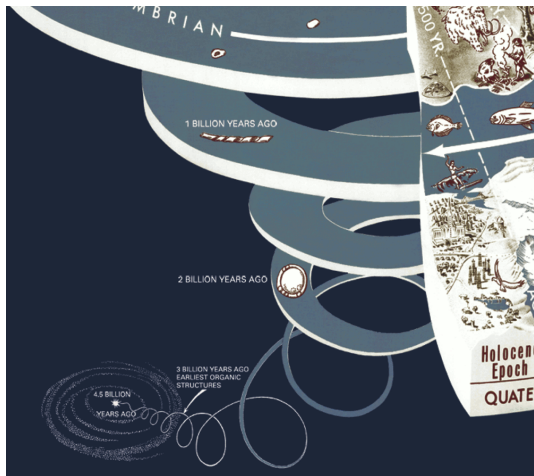


- Various dating techniques, including radioisotopic
- K/Ar and $^{40}\text{Ar}/^{39}\text{Ar}$ techniques use knowledge of $^{40}\text{K} \rightarrow \text{Ar}$ decays
- Long-lived ^{40}K ($t_{1/2} \sim 10^9 \text{ y}$) used to access timescales as old as the Earth



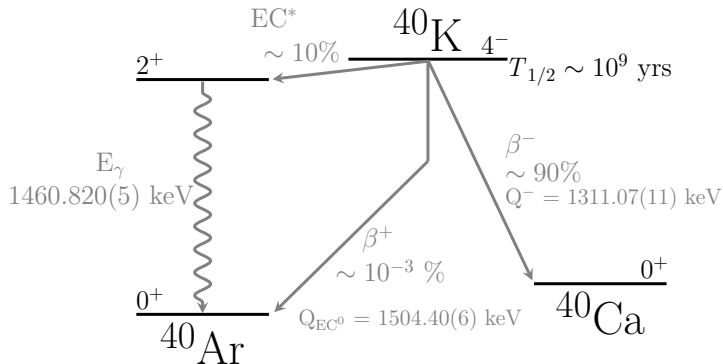
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Geochronology



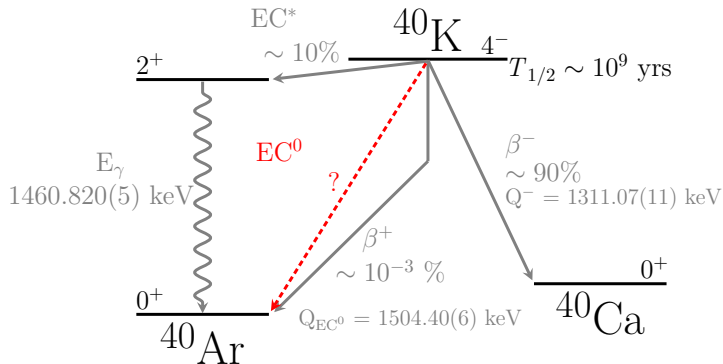
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Nuclear Theory & $0\nu\beta\beta$



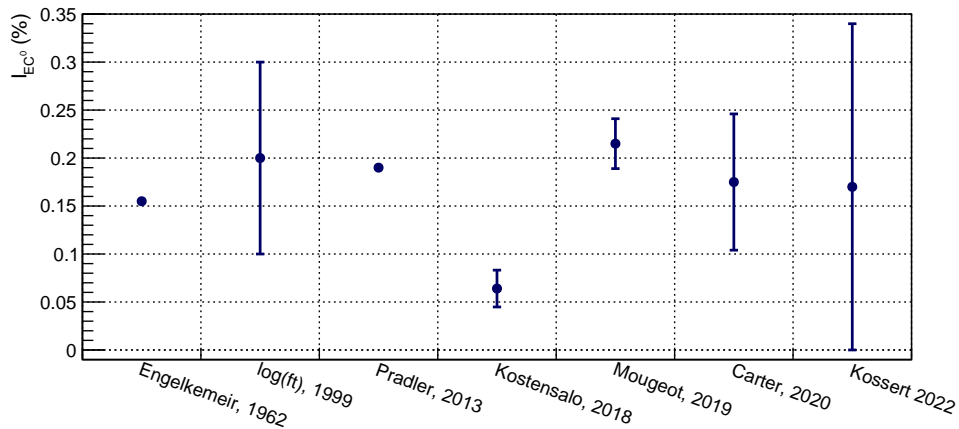
- EC^0 : rare *third-forbidden unique* transition
- Assumed $I_{\text{EC}^0} \sim (0 - 0.8)\%$
- 3FU: effective weak-axial vector coupling constant $\rightarrow 0\nu\beta\beta$ half-life (^{48}Ca)

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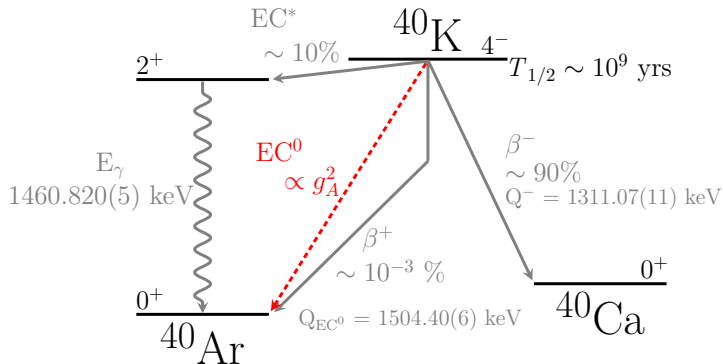
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Direct-detection

3 keV events *with no high-energy veto available*

Geochronology

Common exclusion^[1a] of EC⁰ branch can shift calculated ages by
> 10,000,000 years (order of error)^[1b]

Nuclear theory

No existing 3FU electron capture measurements²: avenue to quantify uncertainties
and inform $0\nu\beta\beta$ calculations

KDK obtained first EC⁰ measurement of ⁴⁰K

¹Exclusion in ^aMin et al., *Geochim. Cosmochim. Acta* **64**(1), 111-121 (2001), as shown in ^bCarter et al., *Geochronology* **2**(2), 355-365 (2020)

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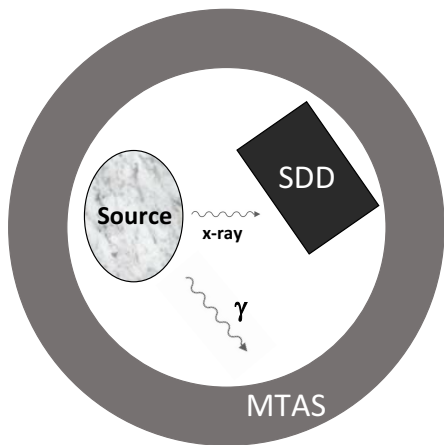
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Coincidence technique



Coincident ($\sim EC^*$)

SDD signal + MTAS detection

Anti-coincident ($\sim EC^0$)

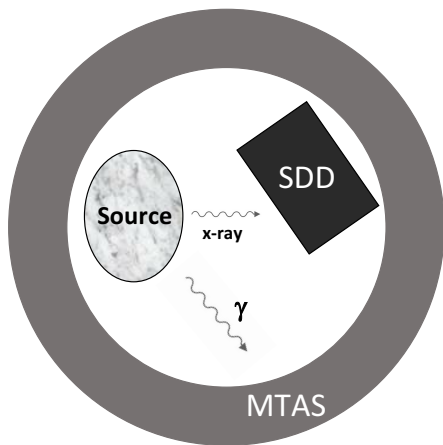
SDD signal *only*

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

Silicon Drift Detector (*MPP/HLL Munich*); < 1 g

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

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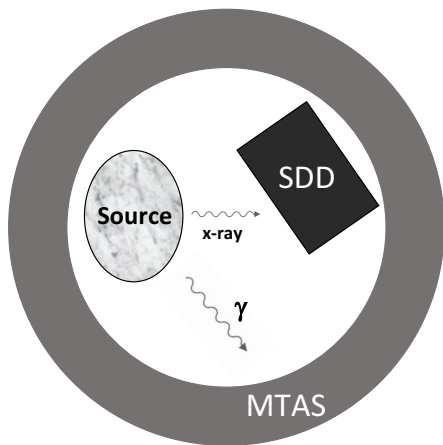
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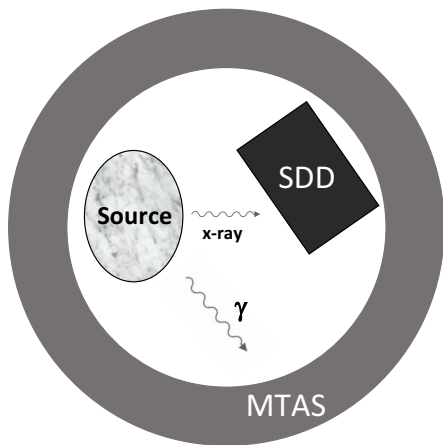
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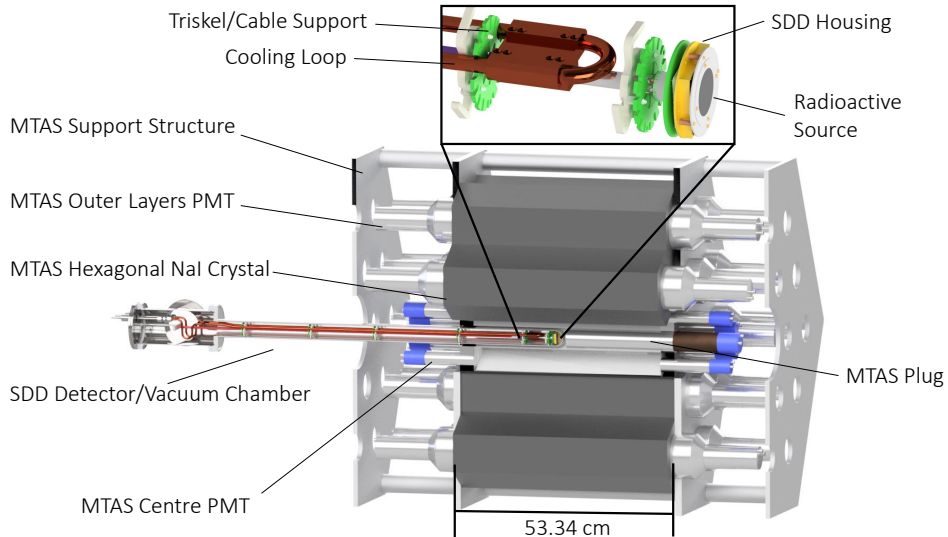
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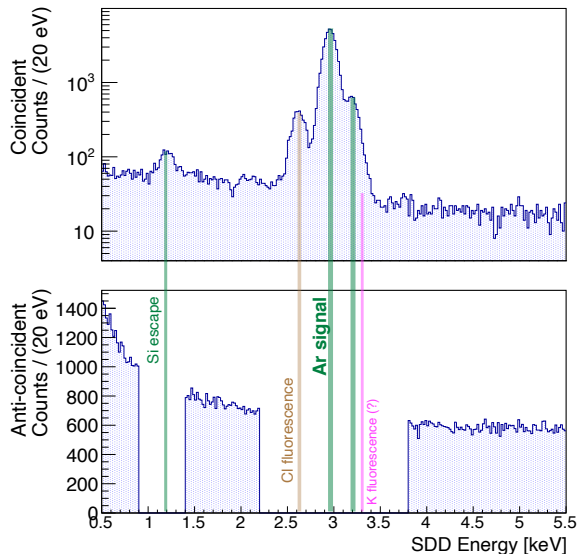
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Schematic



Blinded ^{40}K SDD data

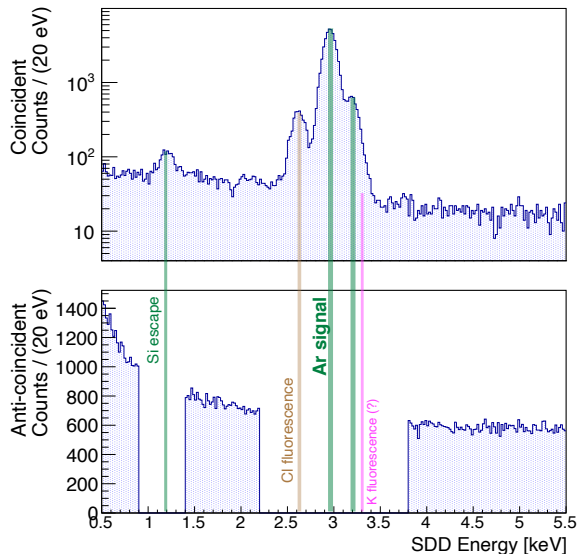


Blinded analysis:

- Likelihood method, statistical procedure
- Coincidence-categorization physics (e.g. γ -tagging efficiency)

Testing methods:
open analysis of ^{65}Zn data

Blinded ^{40}K SDD data

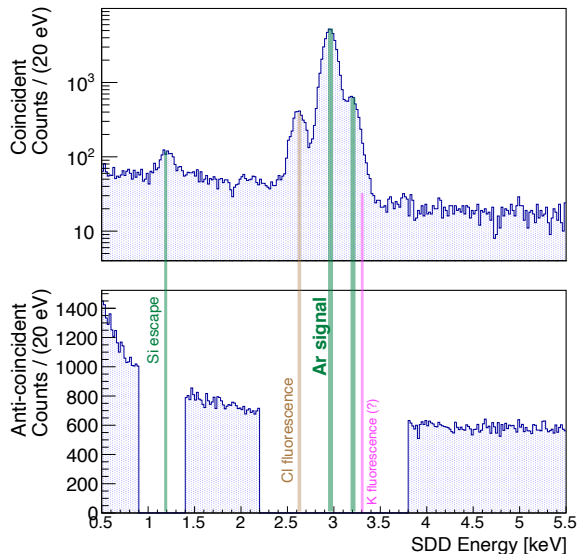


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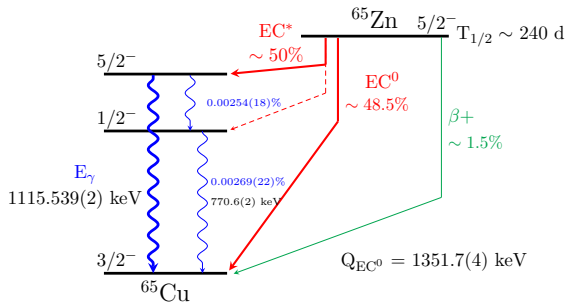


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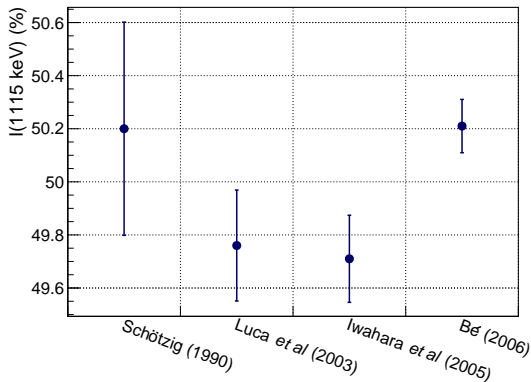
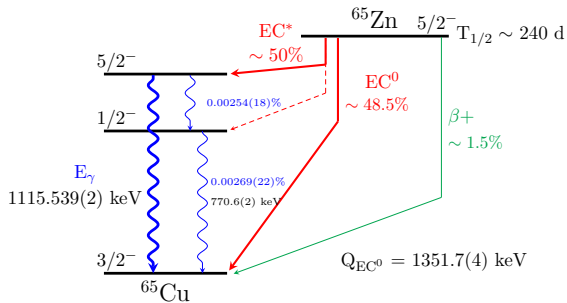
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^{65}Zn complementary measurement



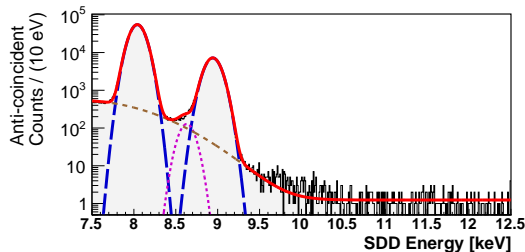
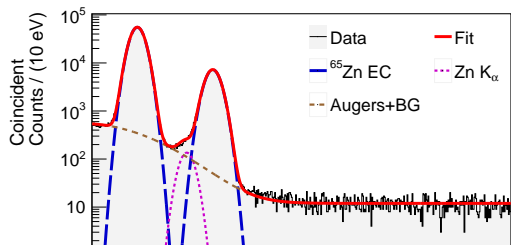
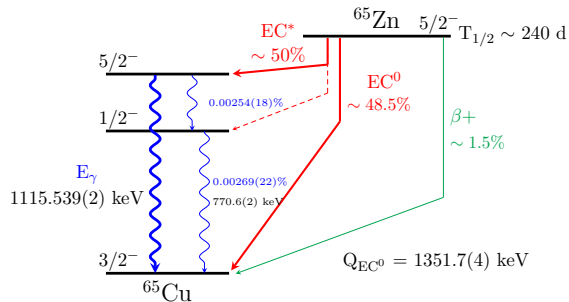
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- 2 Test SDD fits

^{65}Zn complementary measurement



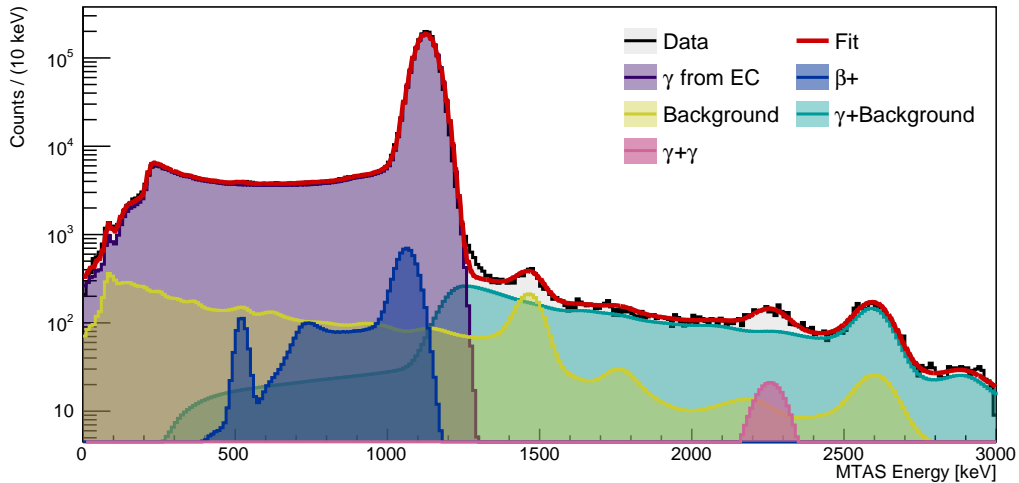
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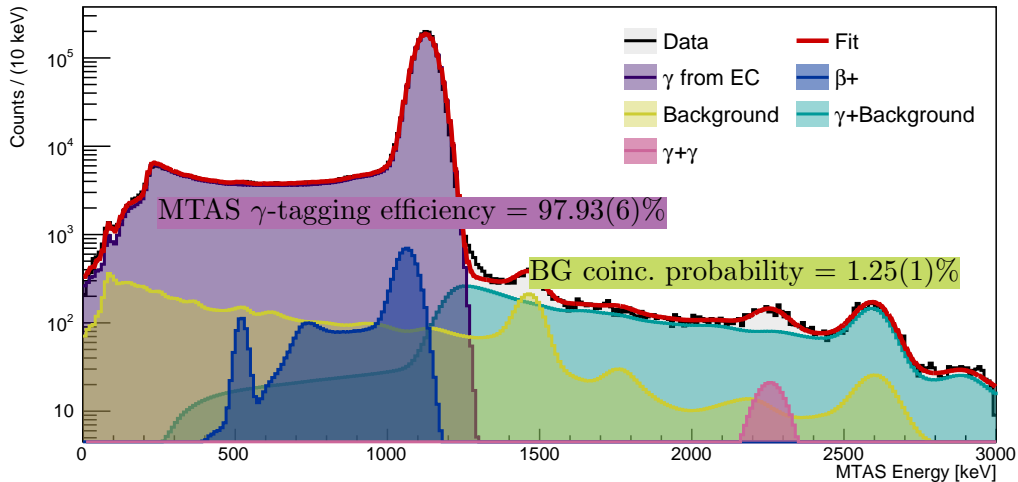


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^{65}Zn MTAS events; coincidence considerations

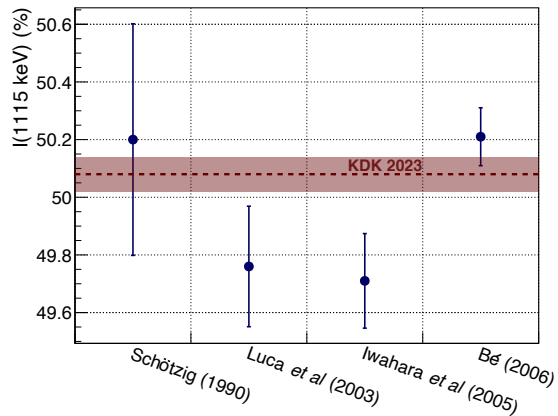
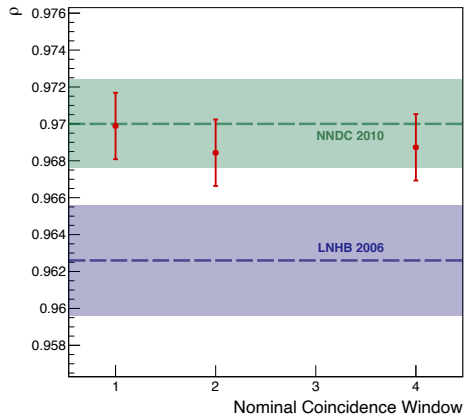


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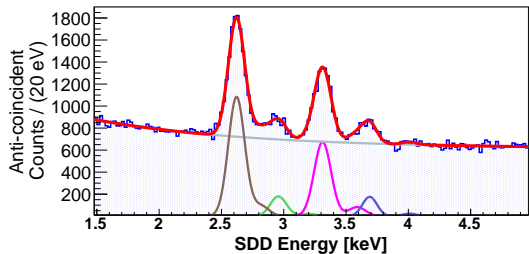
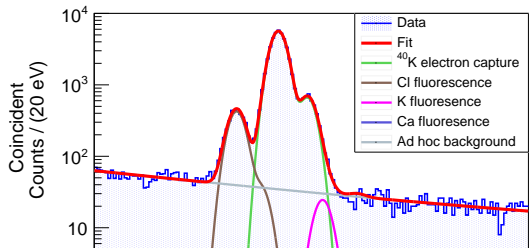


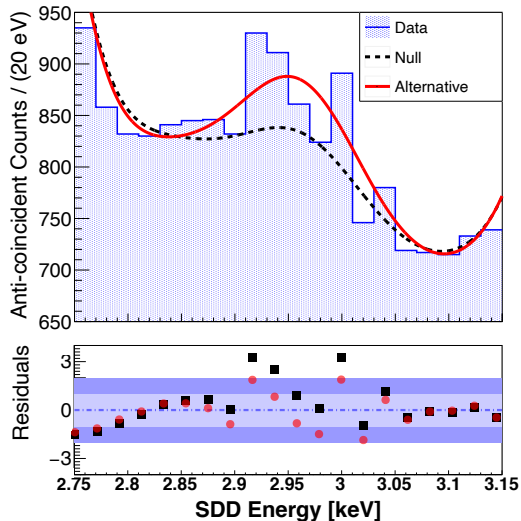
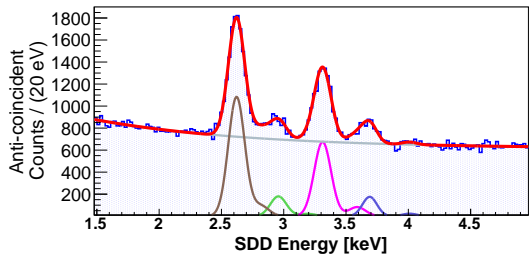
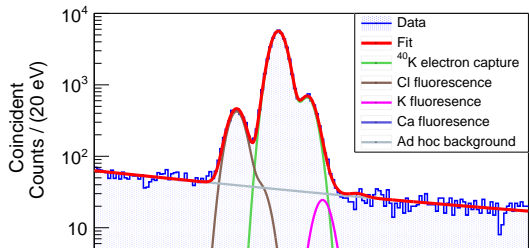
Values at 2 μs SDD+MTAS coincidence window

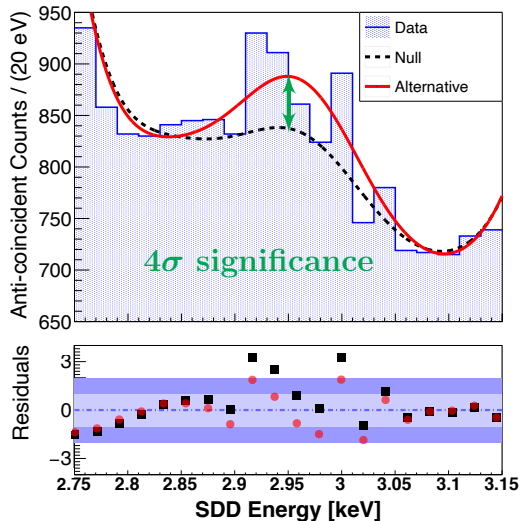
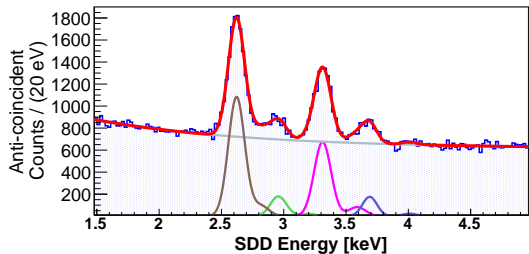
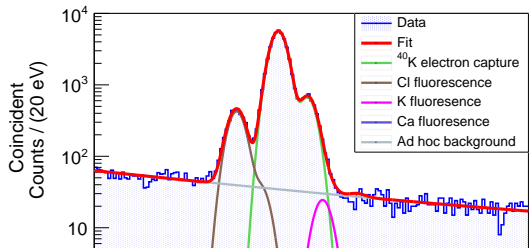
^{65}Zn results



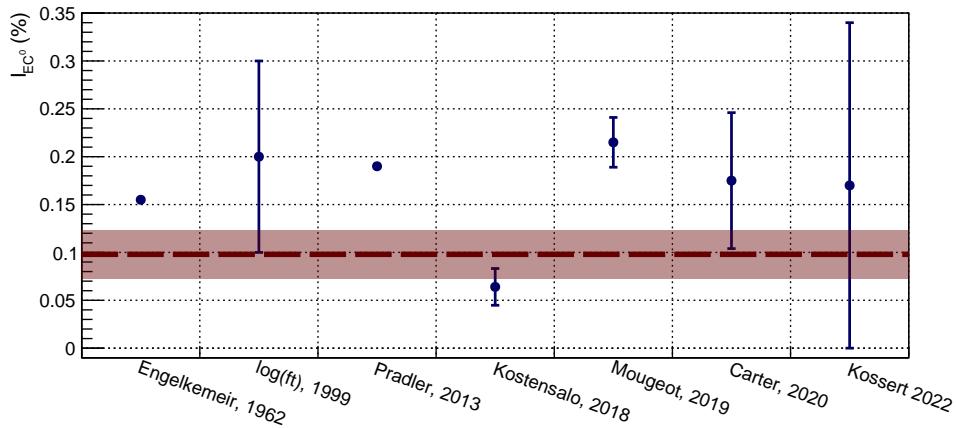
^{40}K fits







$$\rho = I_{\text{EC}^0}/I_{\text{EC}^*} = \left(0.95^{\text{stat}} \pm 0.22^{\text{syst}} \pm 0.10 \right) \times 10^{-2} \rightarrow \boxed{I_{\text{EC}^0} = (0.098 \pm 0.025)\%}$$



Implications of ^{40}K result

DM direct-detection

- Quantified 3 keV background in NaI
- DAMA/LIBRA: tends to loosen constraints on result interpretation

Geochronology

- I_{EC^0} omission \rightarrow K/Ar ages overestimated
- Indirect effect on $^{40}\text{Ar}/^{39}\text{Ar}$

Nuclear theory

- First 3FU EC measurement
- Significant g_A quenching from g_A^{bare}
- ^{48}Ca $0\nu\beta\beta$ half-life suppressed by 7_{-2}^{+3}

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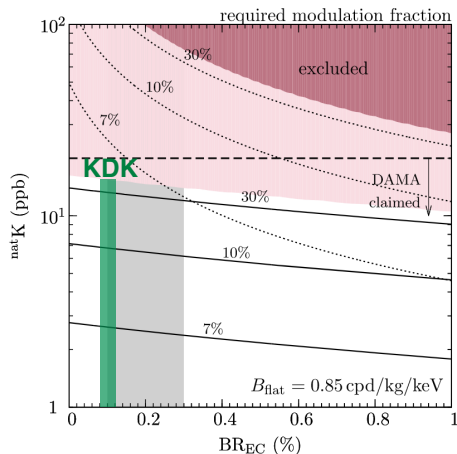
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From Pradler *et al* (2013) [arXiv:1210.5501](https://arxiv.org/abs/1210.5501)

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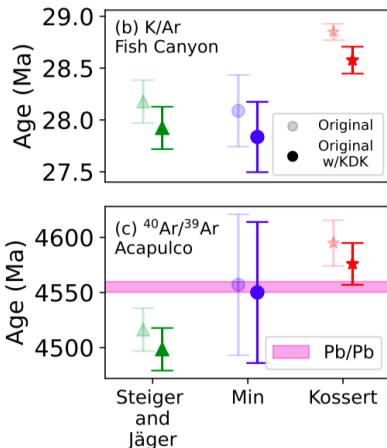
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From Stukel *et al* (KDK) [arXiv:2211.10319](https://arxiv.org/abs/2211.10319)

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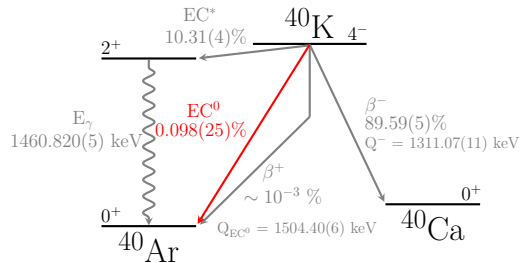
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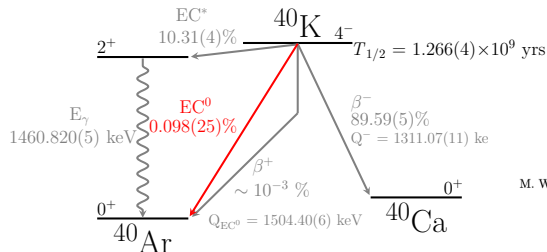
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Summary



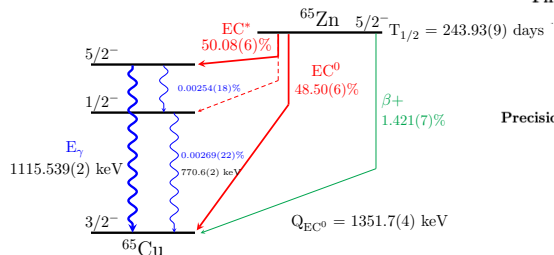
Rare ^{40}K decay with implications for fundamental physics and geochronology

M. Stukel,¹ L. Hariasz,¹ P.C.F. Di Stefano,^{1,*} B.C. Rasco,² K.P. Rykaczewski,² N.T. Brewer,^{2,3}
 D.W. Stracener,² Y. Liu,² Z. Gai,⁴ C. Rouleau,⁴ J. Carter,⁵ J. Kostensalo,⁶ J. Suhonen,⁷ H. Davis,^{8,9}
 E.D. Lukosi,^{8,9} K.C. Goetz,¹⁰ R.K. Grzywacz,^{2,3,11} M. Mancuso,¹² F. Petricca,¹² A. Fijałkowska,¹³
 M. Wolińska-Cichońska,^{2,3,14} J. Ninkovic,¹⁵ P. Lechner,¹⁵ R.B. Ickert,¹⁶ L.E. Morgan,¹⁷ P.R. Renne,^{5,18} and I. Yavin
 (KDK Collaboration)

(Submitted to PRL; Stukel *et al* [arXiv:2211.10319](https://arxiv.org/abs/2211.10319))

First observation of the ground-state electron-capture of ^{65}Zn

(Submitted jointly to PRC; Hariasz *et al* [arXiv:2211.10343](https://arxiv.org/abs/2211.10343))



Precision measurement of ^{65}Zn electron-capture decays with the KDK coincidence setup

(Hariasz *et al* in prep. for NDS)

Thank you

N.T. Brewer,^{1,2} J. Carter,³ H. Davis,^{4,5} P.C.F. Di Stefano,⁶ A. Fijalkowska,⁷ Z. Gai,⁸ K.C. Goetz,⁹
R.K. Grzywacz,^{1,2,10} L. Hariasz,⁶ R.B. Ickert,¹¹ J. Kostensalo,¹² P. Lechner,¹³ Y. Liu,¹ E.D. Lukosi,^{4,5}
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²*Joint Institute for Nuclear Physics and Application, Oak Ridge National Laboratory, Oak Ridge, Tennessee 37831, USA*

³*Berkeley Geochronology Center, Berkeley, California 94709, USA*

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⁵*Joint Institute for Advanced Materials, University of Tennessee, Knoxville, Tennessee 37996, USA*

⁶*Department of Physics, Engineering Physics & Astronomy, Queen's University, Kingston, Ontario K7L 3N6 Canada*

⁷*Faculty of Physics, University of Warsaw, Warsaw PL-02-093*

⁸*Center for Nanophase Materials Sciences, Oak Ridge National Laboratory, Oak Ridge, Tennessee 37831, USA*

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¹³*MPG Semiconductor Laboratory, Munich D-80805, Germany*

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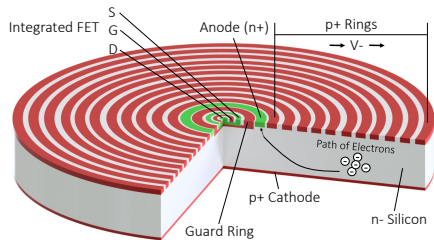
¹⁵*U.S. Geological Survey, Geology, Geophysics, and Geochemistry Science Center, Denver, Colorado 80225, USA*

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¹⁷*Department of Physics, University of Jyväskylä, Jyväskylä FI-40014, Finland*

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SDD Details

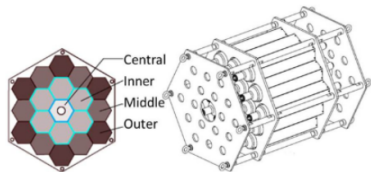


- Increasingly-biased p^+ rings
- Planar cathode
- Central n^+ anode is at potential minimum
- Gate of field-effect transistor (FET) connected to anode

MTAS Insert

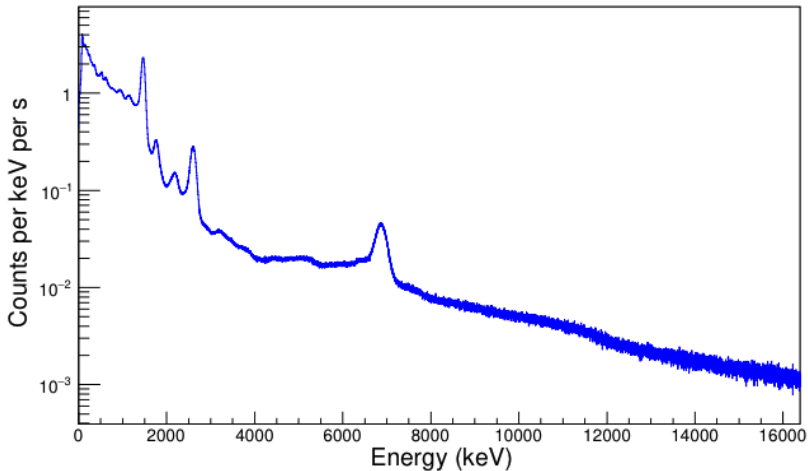
- Contains SDD + source
- 2mm width except for endcap
- Endcap is 30cm long, 0.63mm thick to reduce scattering

MTAS Details



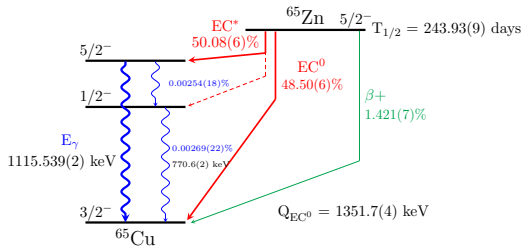
- 19 NaI(Tl) hexagonal volumes
- $\sim 53 \text{ cm} \times 18 \text{ cm}$
- Inner, Middle Outer: one PMT at each end
- Center: 6 PMTs on each end, hole through center for source
- total mass $\sim 1 \text{ ton}$
- $\sim 4\pi \text{ sr}$ coverage
- surrounded by lead shielding

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



^{65}Zn - 3rd Electron Capture Branch

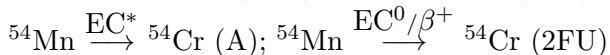
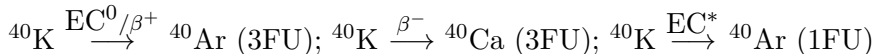
- Electron capture branch to the 770 keV level
- Intensity per 100 for 770 keV = 0.00269(22)
- Intensity per 100 for 330 keV = 0.00254(18)
- This means decay directly to 770 keV occurs 0.00015(28) % of the time
- The systematic effect of the intermediate ^{65}Cu energy level on ρ is smaller than the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



Uniqueness, Forbiddenness - I/II

From [this link](#)

Type of Transition	Selection Rules	$L_{e\nu}$	$\Delta\pi?$	ft
superallowed	$\Delta I = 0, \pm 1^*$	0	no	$1 \times 10^3 - 1 \times 10^4$
allowed	$\Delta I = 0, \pm 1$	0	no	$2 \times 10^3 - 10^6$
1 st forbidden	$\Delta I = 0, \pm 1$	1	yes	$10^6 - 10^8$
unique**1 st forbidden	$\Delta I = \pm 2$	1	yes	$10^8 - 10^9$
2 nd forbidden	$\Delta I = \pm 1^{***}, \pm 2$	2	no	$2 \times 10^{10} - 2 \times 10^{13}$
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}



${}^{65}\text{Zn}$ all allowed.

Uniqueness, Forbiddenness - II/II

From [this link](#)

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. $M_{if}^0 \neq 0$. 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.

“Unique transitions are Gamow-Teller transitions where L and S are aligned.”