The KDK Experiment

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

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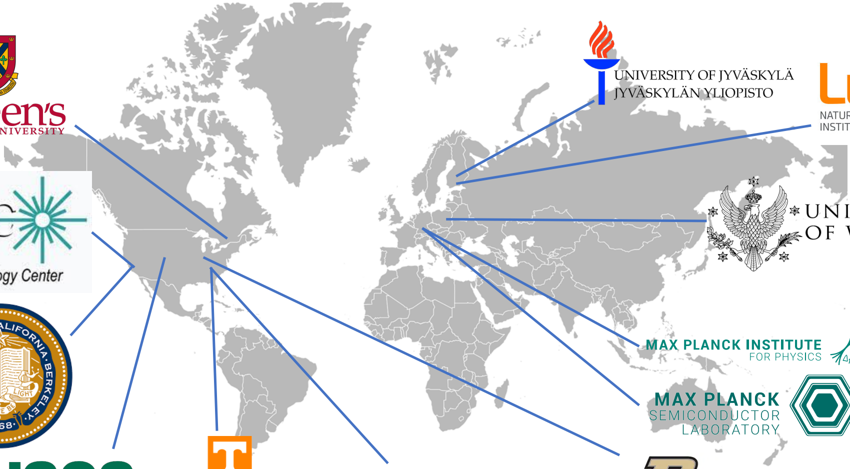
Banff, AB, Canada

The KDK collaboration



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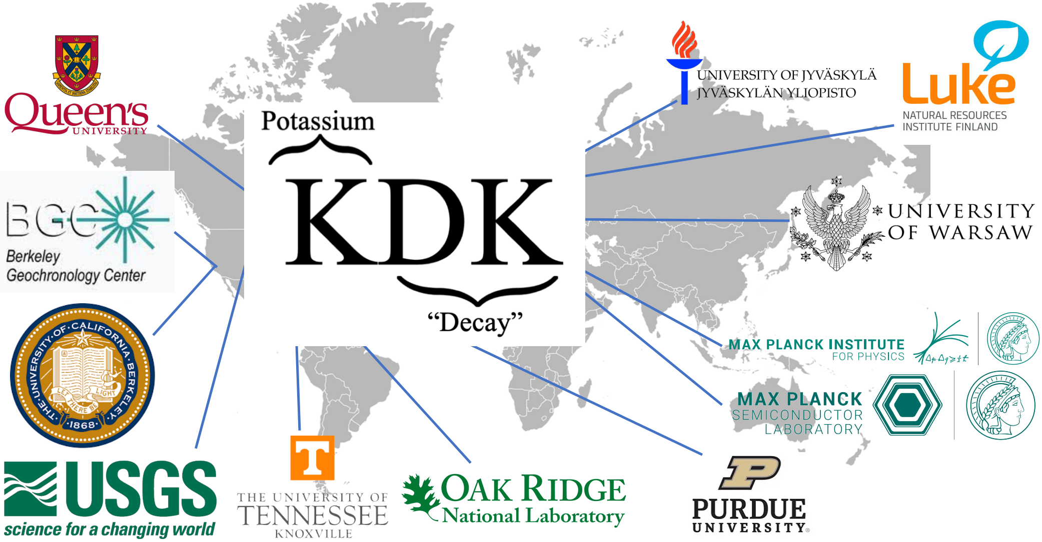
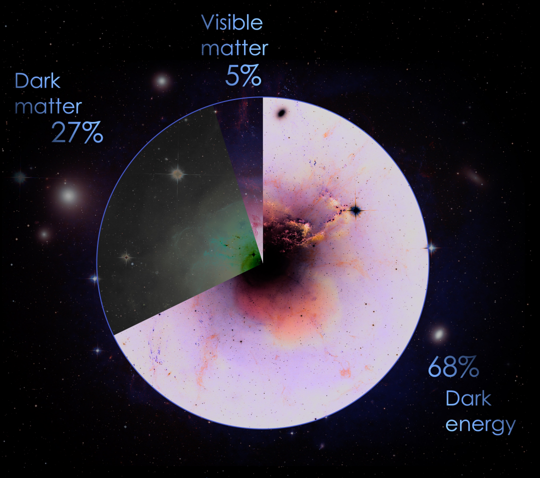


Dark matter

- Various searches for dark matter, particularly for **WIMPs**
- Direct-detection with **NaI** (DAMA/LIBRA[1], SABRE[2], COSINUS[3],...): $\mathcal{O}$(keV) signal
- **K in NaI; ^{40}K$\longrightarrow$ Ar electron captures: irreducible 3 keV background**



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https://svs.gsfc.nasa.gov/12307

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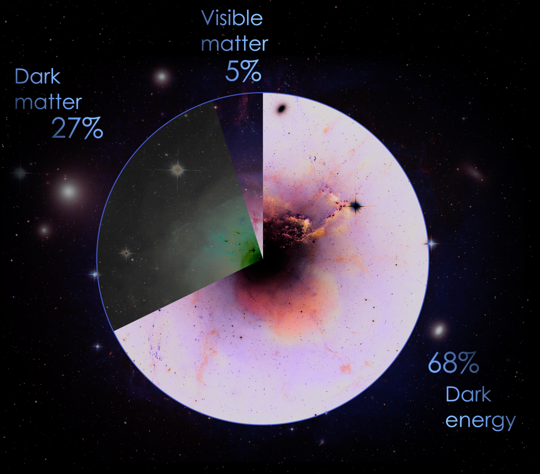

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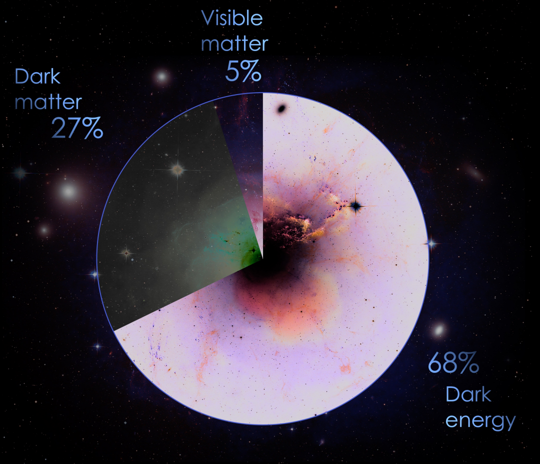

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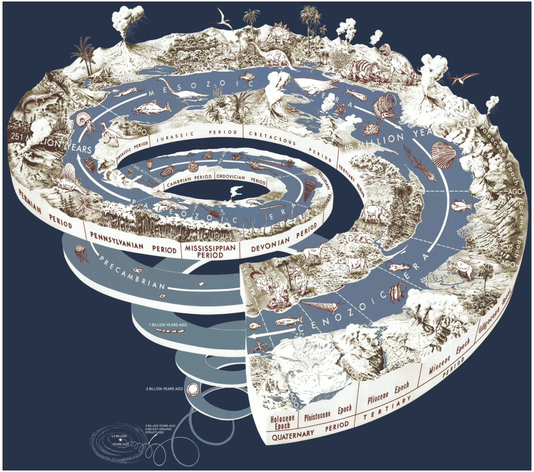
Geochronology



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

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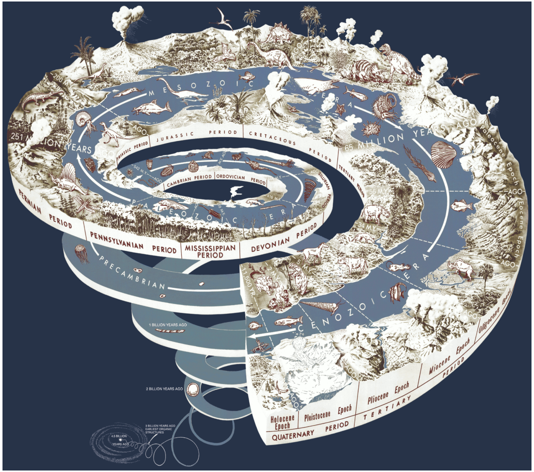

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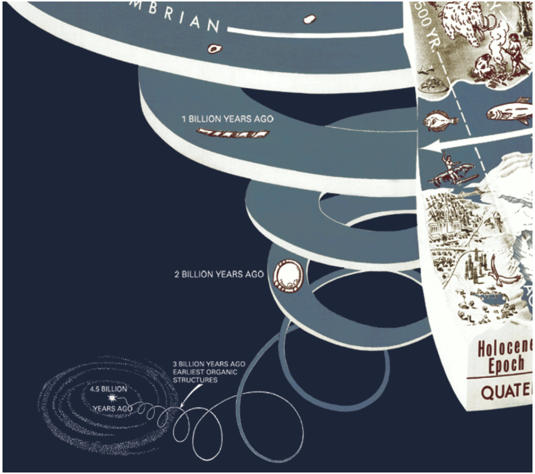

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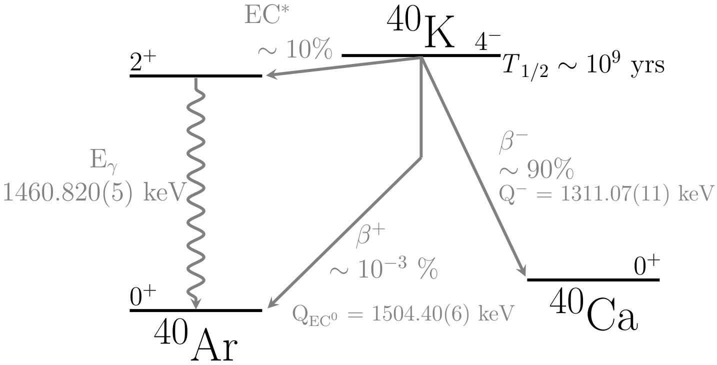
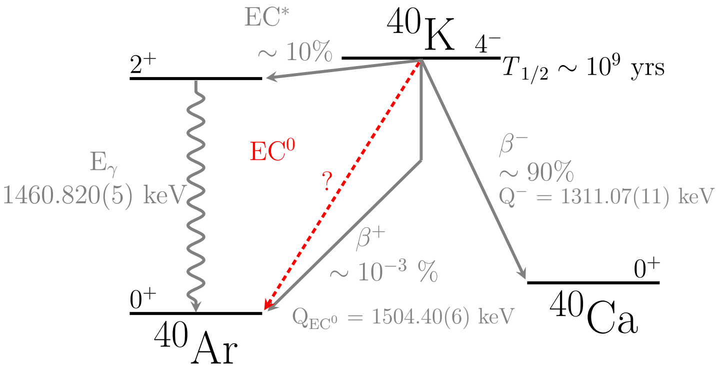


- EC^0: rare *third-forbidden unique* transition
- Assumed $I_{EC^0} \sim (0 - 0.8)\%$
- 3FU: effective weak-axial vector coupling constant $\rightarrow$ $0\nu\beta\beta$ half-life (^{48}Ca)



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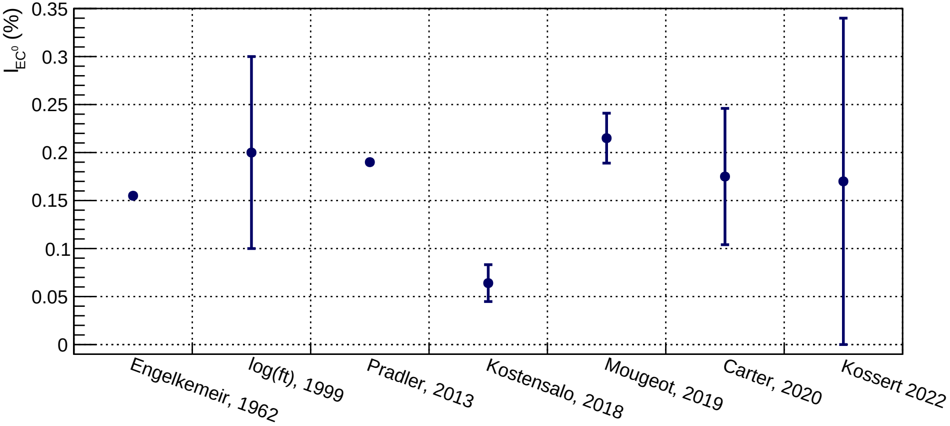

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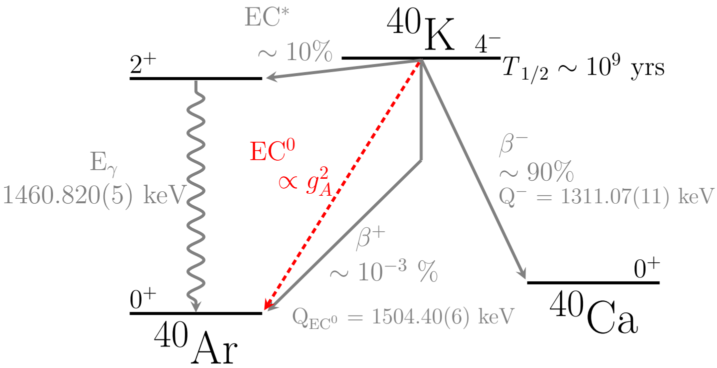

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The EC^0 branch

Direct-detection

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

Geochronology

Common exclusion[1a] of EC^0 branch can shift calculated ages by $> 10,000,000$ years (order of error)[1b]

Nuclear theory

No existing 3FU electron capture measurements[2]: avenue to quantify uncertainties and inform $0\nu\beta\beta$ calculations

KDK obtained first EC^0 measurement of ^{40}K

[1] Exclusion in [a] Min et al., *Geochim. Cosmochim. Acta* **64**(1), 111-121 (2001), as shown in [b] Carter at al., *Geochronology* **2**(2), 355-365 (2020)

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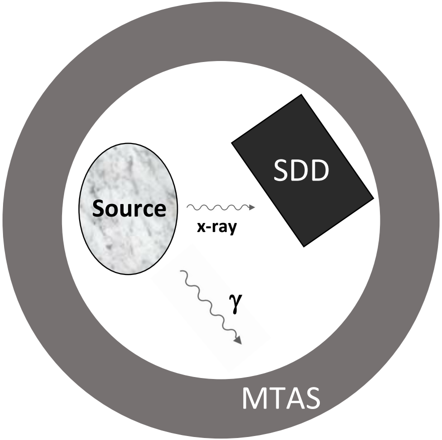
Coincidence technique



Coincident ($\sim$ EC*)

SDD signal + MTAS detection

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

SDD signal *only*

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

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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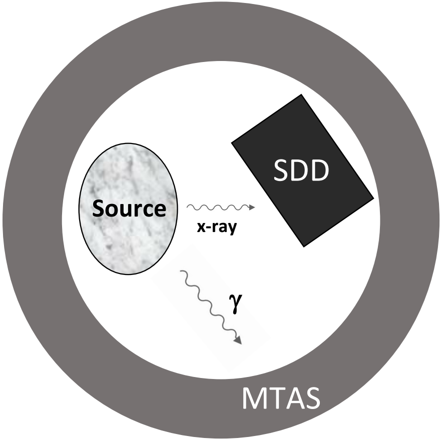

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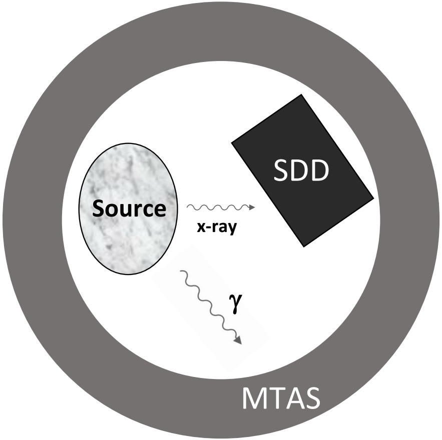

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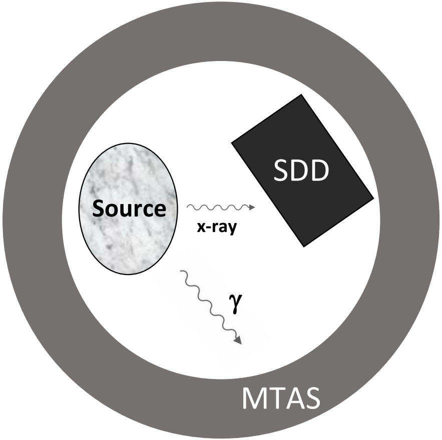

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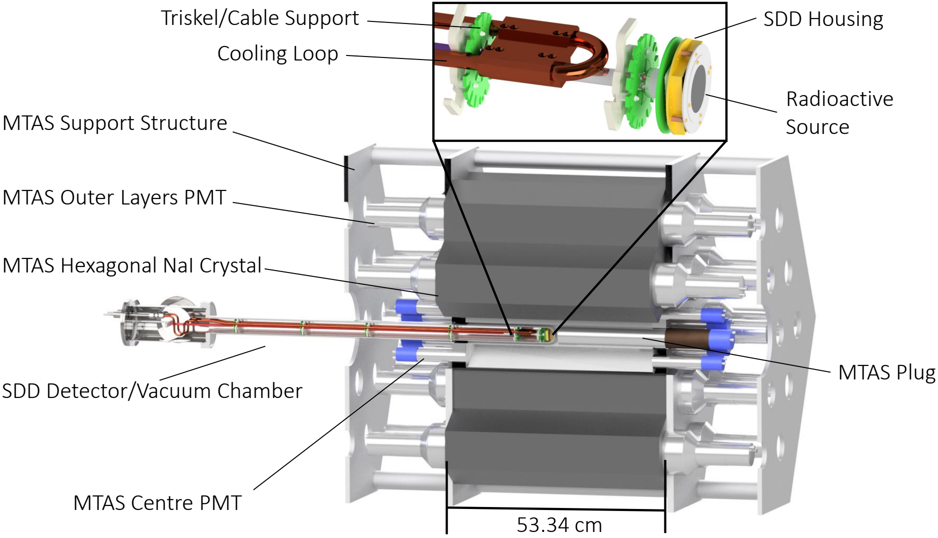
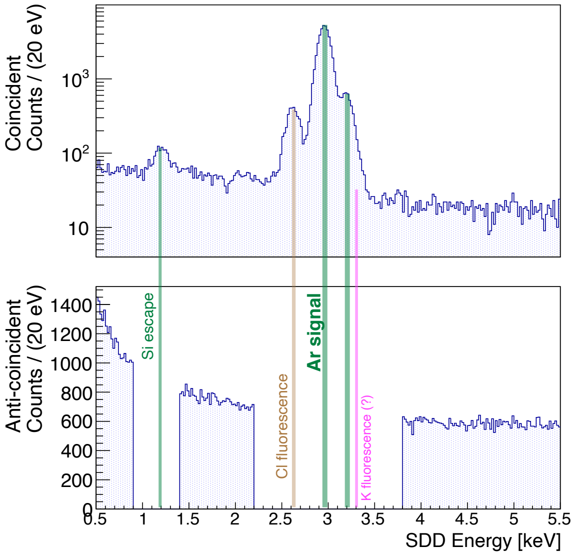
Schematic



Instrumentation paper available: `https://doi.org/10.1016/j.nima.2021.165593`

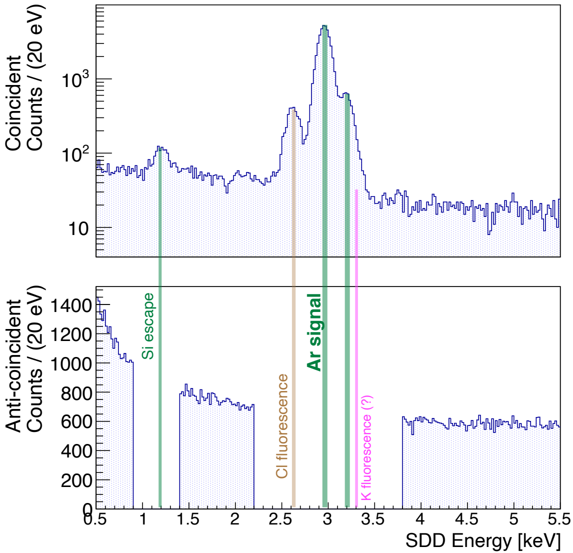
Blinded ^{40}K SDD data



Blinded analysis:

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

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



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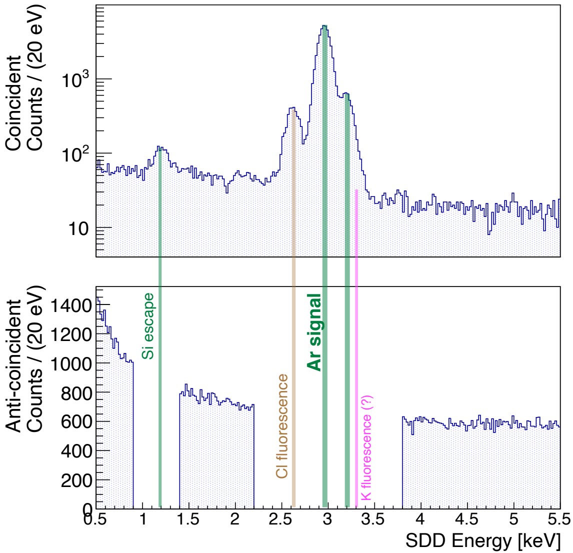

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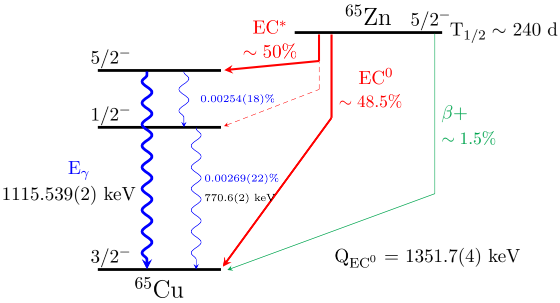
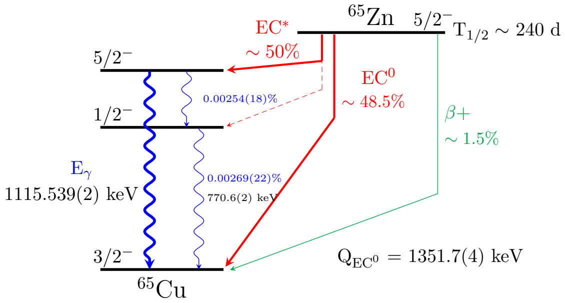
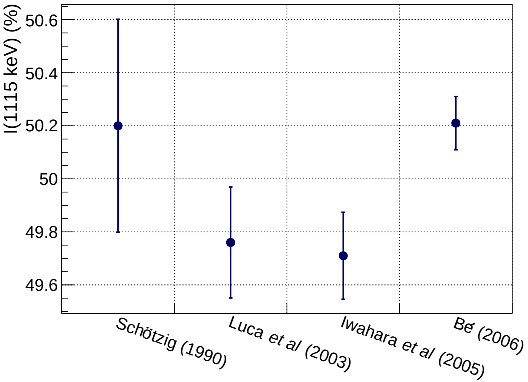
^{65}Zn complementary measurement



1. Some variability in 1115 keV intensity measurements
2. Test SDD fits

^{65}Zn complementary measurement





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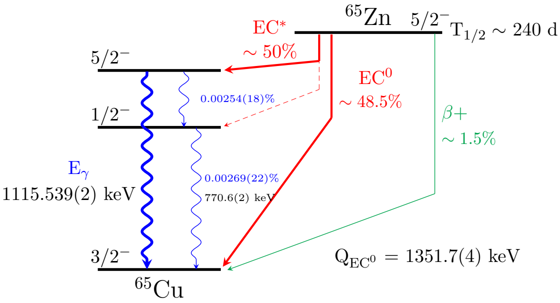

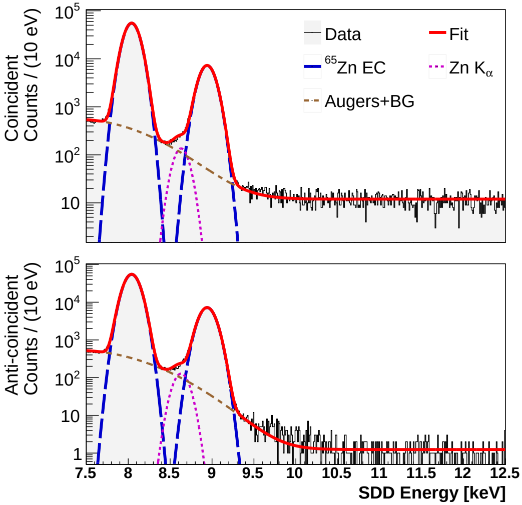

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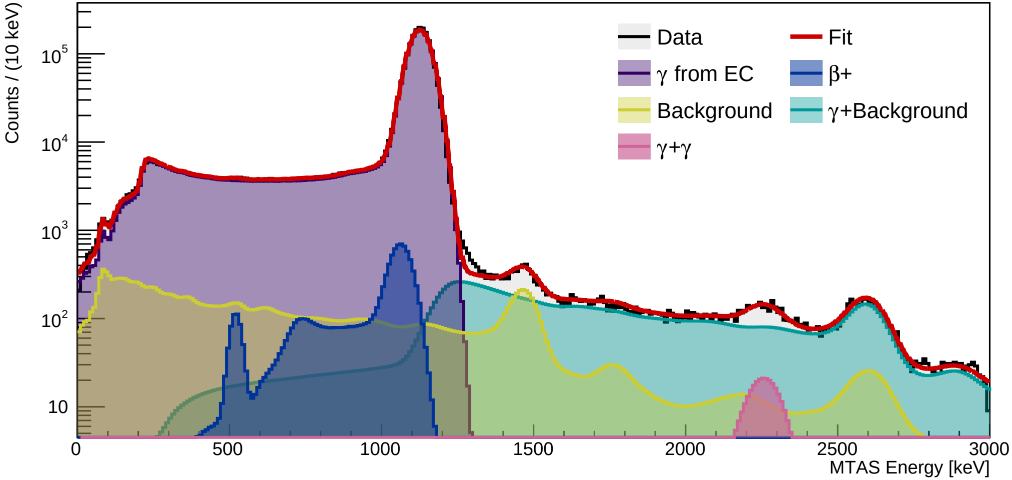
^{65}Zn MTAS events; coincidence considerations



Values at 2 μs SDD+MTAS coincidence window

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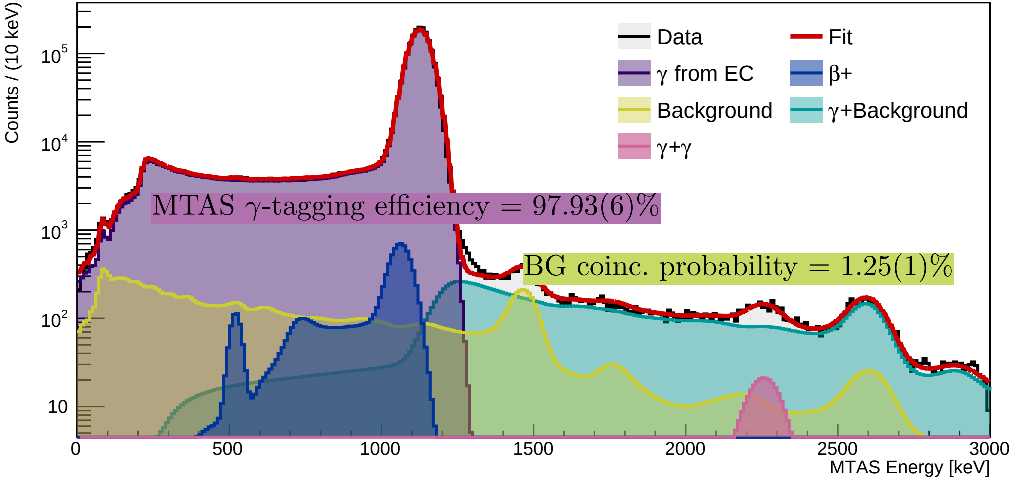

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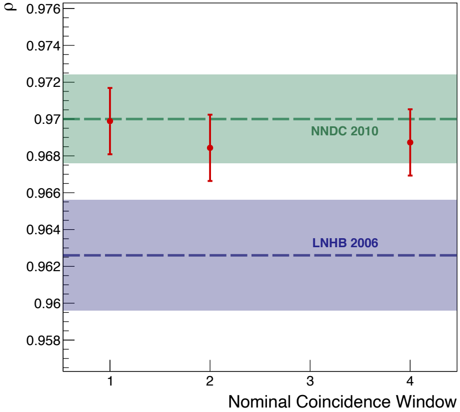
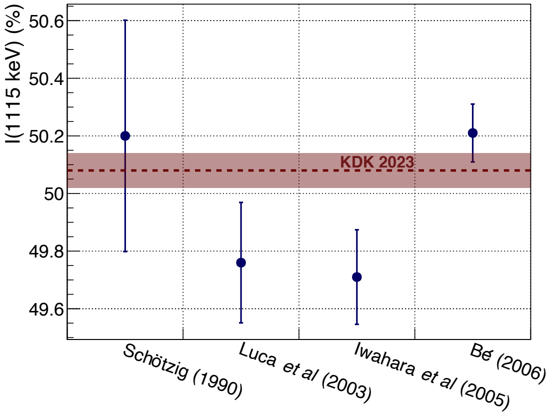
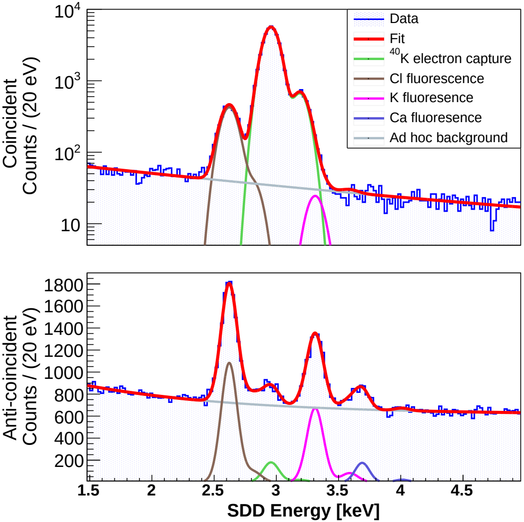
^{65}Zn results



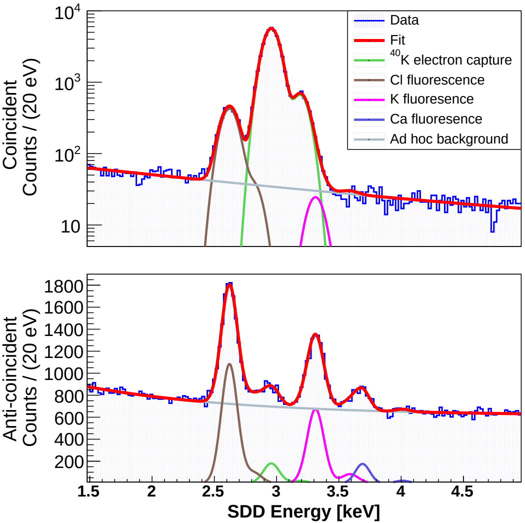


^{40}K fits



Data
Fit
40K electron capture
Cl fluorescence
K fluoresence
Ca fluoresence
Ad hoc background
Coincident
Counts / (20 eV)
10
10^2
10^3
10^4
Anti-coincident
Counts / (20 eV)
200
400
600
800
1000
1200
1400
1600
1800
1.5
2
2.5
3
3.5
4
4.5
SDD Energy [keV]

^{40}K fits



Data
Fit
40K electron capture
Cl fluorescence
K fluorescence
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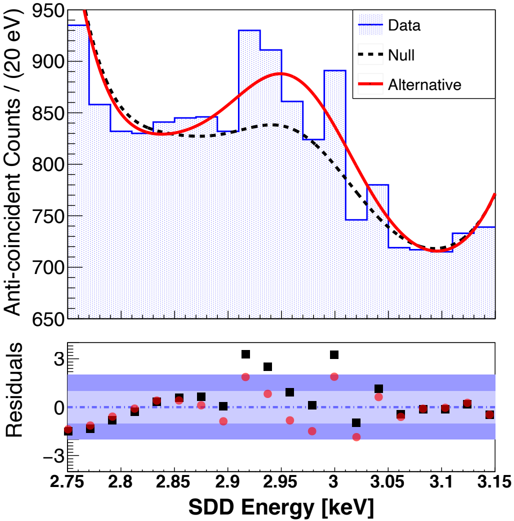
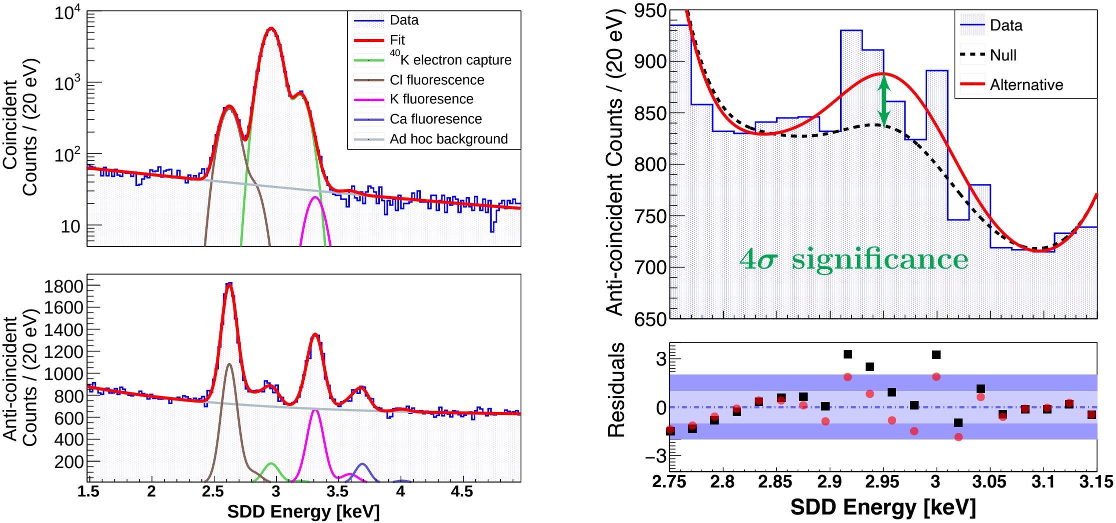
Ad hoc background
Coincident Counts / (20 eV)
Anti-coincident Counts / (20 eV)
SDD Energy [keV]



Data
Null
Alternative
Anti-coincident Counts / (20 eV)
Residuals
SDD Energy [keV]

^{40}K fits



Data
Fit
40K electron capture
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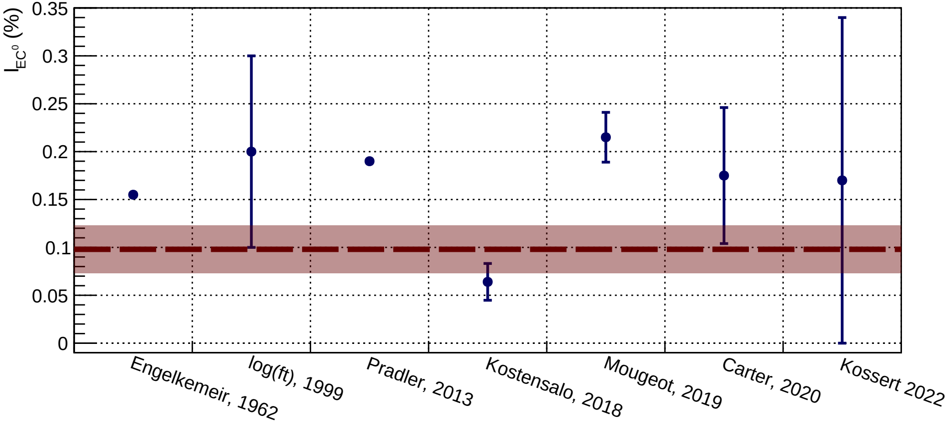
Ca fluoresence
Ad hoc background
Coincident Counts / (20 eV)
Anti-coincident Counts / (20 eV)
SDD Energy [keV]
Data
Null
Alternative
4σ significance
Anti-coincident Counts / (20 eV)
Residuals
SDD Energy [keV]

^{40}K Result

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



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 →K/Ar ages overestimated
- Indirect effect on ^{40}Ar/^{39}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^{+3}_{-2}

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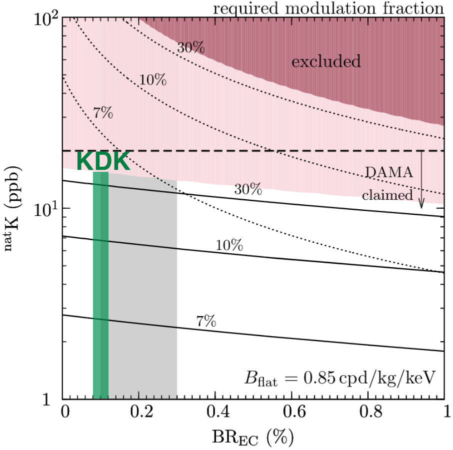

From Pradler *et al* (2013) arXiv:1210.5501

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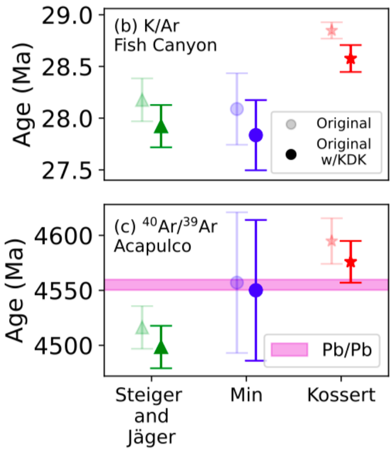

From Stukel *et al* (KDK) arXiv:2211.10319

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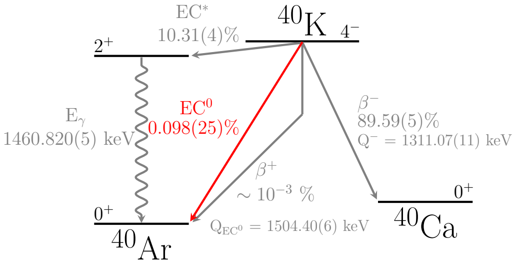
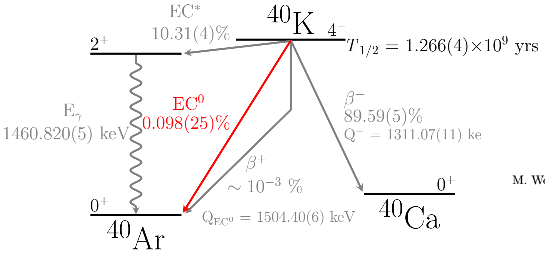


Summary



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

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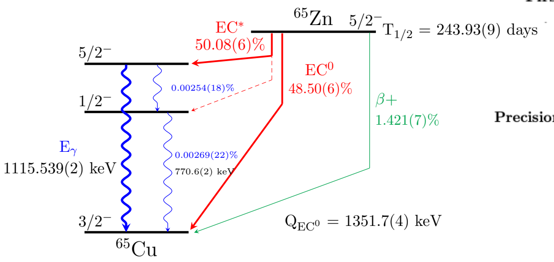
(KDK Collaboration)

(Submitted to PRL; Stukel *et al* arXiv:2211.10319)

First observation of the ground-state electron-capture of ^{40}K

(Submitted jointly to PRC; Hariasz *et al* arXiv: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. Fijałkowska,[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] M. Mancuso,[14] L.E. Morgan,[15] J. Ninkovic,[13] F. Petricca,[14] B.C. Rasco,[1] P.R. Renne,[3,16] C. Rouleau,[8] K.P. Rykaczewski,[1] D.W. Stracener,[1] M. Stukel,[6] J. Suhonen,[17] M. Wolińska-Cichocka,[1,2,18] and I. Yavin

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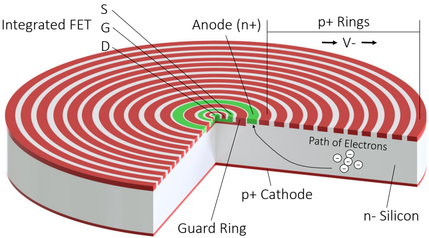
SDD Details

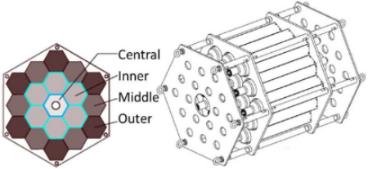


- Increasingly-biased p^+ rings
- Planar cathode
- Central n^+ anode is at potential minimum
- Gate of field-effect transistor (FET) connected to anode

MTAS Insert

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

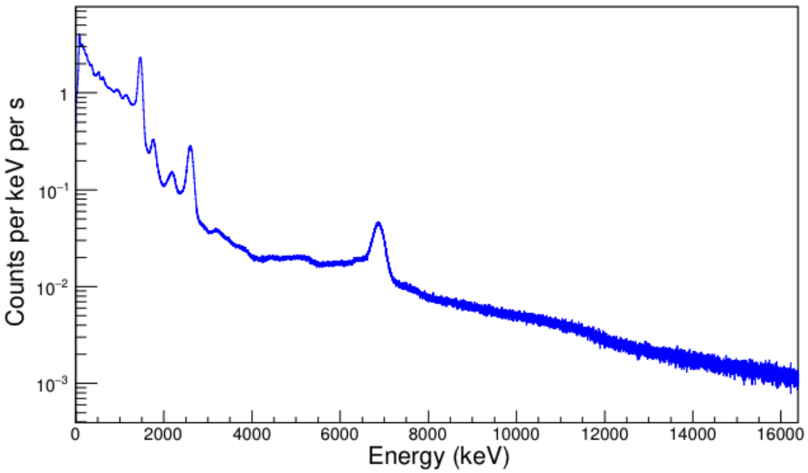
MTAS Details



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

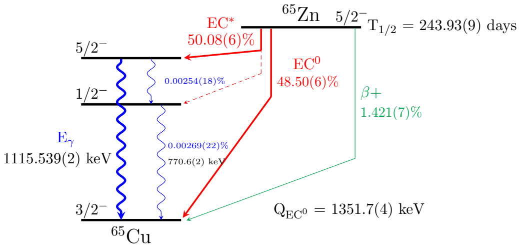
MTAS BG

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	1×10^3–1×10^4
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^{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}

$^{40}\mathrm{K} \xrightarrow{\mathrm{EC}^0/\beta^+} {}^{40}\mathrm{Ar}$ (3FU); $^{40}\mathrm{K} \xrightarrow{\beta^-} {}^{40}\mathrm{Ca}$ (3FU); $^{40}\mathrm{K} \xrightarrow{\mathrm{EC}^*} {}^{40}\mathrm{Ar}$ (1FU)

$^{54}\mathrm{Mn} \xrightarrow{\mathrm{EC}^*} {}^{54}\mathrm{Cr}$ (A); $^{54}\mathrm{Mn} \xrightarrow{\mathrm{EC}^0/\beta^+} {}^{54}\mathrm{Cr}$ (2FU)

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

Uniqueness, Forbidenness - 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. $M^0_{if} \neq 0$. 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.

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