Charged-current interactions on nuclei for low energy geoneutrino detection

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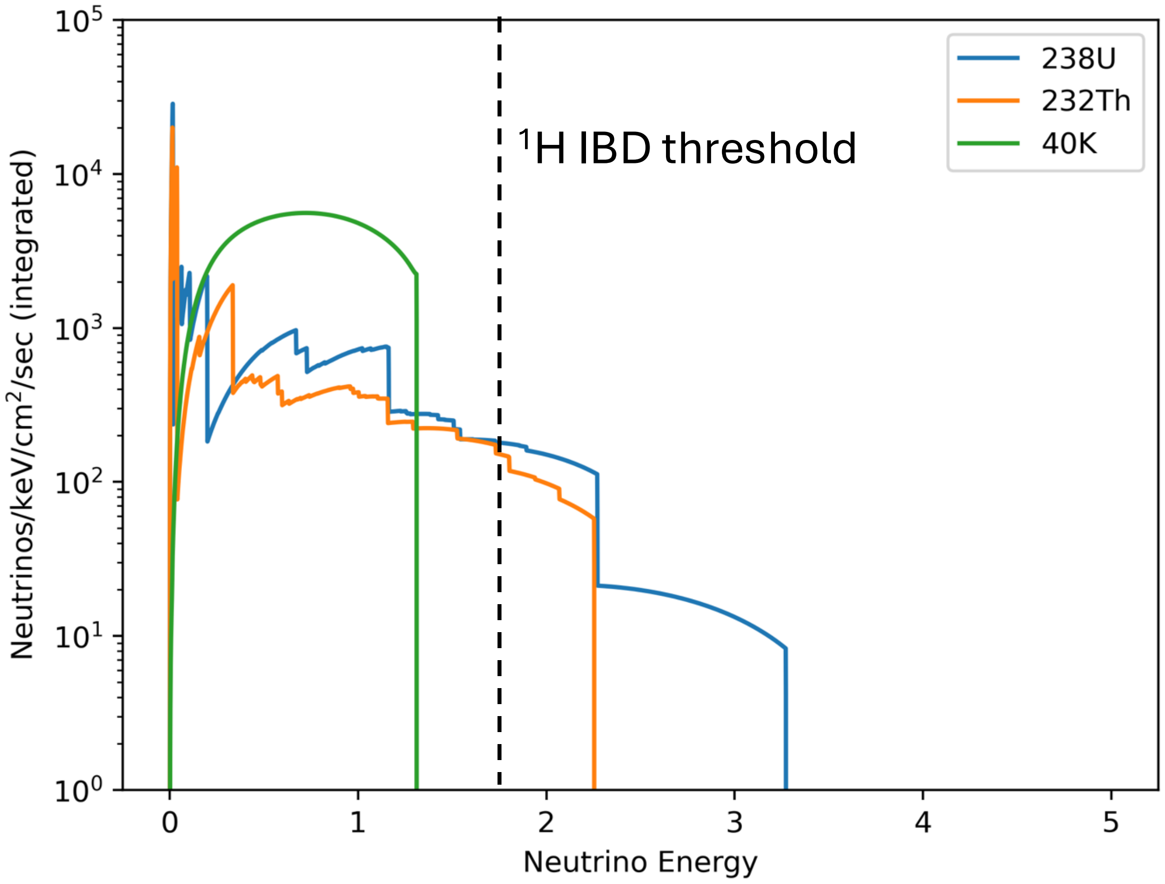
1/4/2025

Outline

1. Motivation
2. Review of existing literature
3. ^{63}Cu as a target
4. Measuring the *ft*-value of $^{63}Ni^{m}$
5. Summary

Motivation

- ^{40}K geoneutrinos unable to be detected with IBD on hydrogen
  - 1.8 MeV threshold for IBD on hydrogen, ^{40}K neutrino endpoint ~1.31 MeV
  - For an overview on the missing potassium problem, see talk: https://indico.cern.ch/event/825708/contributions/3550280/attachments/1931708/3199582/Serafini_NGS19.pdf
- Charged-current scattering on other nuclei can have lower thresholds



Two main processes

1. Inverse beta decay (IBD):

$$\overline{\nu}_e + {}^{A}_{Z}\mathrm{X} \rightarrow e^+ + {}_{Z-1}^{\ \ \ A}\mathrm{Y}^{(*)}$$

- Minimum threshold for stable nuclei is 1.022 MeV
- Pointed out that long-lived metastable states can have lower thresholds (see https://indico.phy.ornl.gov/event/433/contributions/1908/), but very small natural abundances
    - $^{180}\mathrm{Ta}^{m} \rightarrow {}^{180}\mathrm{Hf}$ has threshold of 0.2534 MeV, but cross section expected to be small due to spin-parity of transition
    - $^{180}\mathrm{Ta}^{m}$ is “nature’s rarest isotope” - https://www.sciencedirect.com/science/article/pii/S0375947403009539
- Cross section lower for heavy targets due to Pauli blocking
- Cross section inversely proportional to the *ft*-value of the corresponding beta decay

Two main processes

2. Resonant Orbital Electron Capture (ROEC)

$$\overline{\nu}_e + {}^{A}_{Z}\mathrm{X} + e^- \rightarrow {}^{A}_{Z-1}\mathrm{Y}^{(*)}$$

- Thresholds depend on the energy to capture an electron, can be significantly lower
- Cross section increases with heavier nuclei (more electrons)
- Only depends on neutrino flux within a small window around the required capture energies
- Only signature is the end nucleus, but can potentially capture to excited states as well
- Not yet measured

Review of existing work

- Krauss, Glashow, Schramm, Nature **310** (1984)
  - Focus on radiochemical approach
  - Consider IBD as well and ROEC

Takeaways

- ^{3}He the most promising target, but too costly to produce a large-scale detector
- ^{35}Cl mentioned as another interesting target
- Transitions to metastable states (e.g. ^{79}Br) can have larger cross sections, but does not work well for radiochemical approach
  - Make some assumptions about log(ft) values of these…

Table 3 Antineutrino targets with product lifetime ≥1 day and $Q_{ns} < 2$ MeV (in order of increasing log *ft*)

Target process	Q_B (MeV) (ground state transition)	log *ft*	Product lifetime	Interaction rate (TAU)	Sensitivity to terrestrial decay
$^{3}_{2}He \rightarrow ^{3}_{1}H$	0.0186	3.1	12 yr	0.32	^{238}U, ^{40}K, ^{232}Th
$^{33}_{16}S \rightarrow ^{33}_{15}P$	0.248	5.0	25 day	0.002	^{232}Th, ^{238}U, ^{87}Rb
$^{35}_{17}Cl \rightarrow ^{35}_{16}S$	0.167	5.0	88 day	0.004	^{232}Th, ^{238}U, ^{87}Rb
$^{121}_{51}Sb \rightarrow ^{121}_{50}Sn$	0.383	5.0	27 h	0.01	^{40}K, ^{238}U
$^{64}_{30}Zn \rightarrow ^{64}_{29}Cu \rightarrow ^{64}_{28}Ni$	0.573	5.3	Stable	0.02	^{40}K, ^{238}U, ^{232}Th
$^{77}_{34}Se \rightarrow ^{77}_{33}As$	0.68	5.7	1.6 day		
$^{175}_{71}Lu \rightarrow ^{175}_{70}Yb$	0.467	6.3	5.5 day	$\sim 10^{-2}$	
$^{169}_{69}Tm \rightarrow ^{169}Er$	0.34	6.4	9.4 day		
$^{185}_{75}Re \rightarrow ^{185}_{74}W$	0.49	6.5	75 day		
$^{177}_{72}Hf \rightarrow ^{177}_{71}Lu$	0.497	6.6	6.7 day		
$^{63}_{29}Cu \rightarrow ^{63}_{28}Ni$	0.067	6.7	92 yr	0.04* (0.15–0.2 MeV)	^{87}Rb, ^{232}Th
$^{153}_{63}Eu \rightarrow ^{153}_{62}Sm$	0.801	7.2	2 day		
$^{199}_{80}Hg \rightarrow ^{199}_{79}Au$	0.46	7.5	3.15 day		
$^{151}_{63}Eu \rightarrow ^{151}_{62}Sm$	0.076	7.6	87 yr	0.15 (0.15–0.23 MeV)	^{87}Rb, ^{232}Th
$^{141}_{59}Pr \rightarrow ^{141}_{58}Ce$	0.58	7.7	33 day		
$^{161}_{66}Dy \rightarrow ^{161}_{65}Tb$	0.58	7.8	7 day		
$^{155}_{64}Gd \rightarrow ^{155}_{63}Eu$	0.248	8.2	1.8 yr		
$^{14}_{7}N \rightarrow ^{14}_{6}C$	0.156	9.0	5×10^{3} yr		
$^{85}_{37}Rb \rightarrow ^{85}_{36}Kr$	0.67	9.1	10.7 yr		
$^{113}_{49}In \rightarrow ^{113}_{48}Cd$	0.58	9.2	14 yr		
$^{39}_{19}K \rightarrow ^{39}_{18}Ar$	0.565	9.9	269 yr		
$^{204}_{82}Pb \rightarrow ^{204}_{81}Tl$	0.765	9.9	3.8 yr		
$^{79}_{35}Br \rightarrow ^{79}_{34}Se$	0.154	10.8	6.5×10^{4} yr	0.08 (0.25 MeV)	^{87}Rb, ^{232}Th
$^{107}_{47}Ag \rightarrow ^{107}_{46}Pd$	0.035	10.8	7×10^{6} yr		

Estimate excited state transition interaction assuming log *ft* = 5.0 for allowed transition. Excited state Q_B given in parentheses.

N. Klay and F. Käppeler, Phys. Rev. C **38**, (1988) – $^{79}Se^{m}$ log(*ft*) = 4.7

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- Transitions to metastable states (e.g. ^{79}Br) can have larger cross sections, but does not work well for radiochemical approach
  - Make some assumptions about log(ft) values of these…
- ROEC can have large cross sections for heavy nuclei for specific energy neutrinos

Table 2 Two model detectors

		$^{3}_{2}He \to ^{3}_{1}H$	H_1 lifetime = 12.3 yr, $\log ft = 3.1$, $Q_B = 0.01861$ MeV	$^{209}Bi \to ^{209}Pb$	Pb lifetime = 3.3 h, $\log ft = 5.5$, $Q_B = 0.64$
		Rates		Rates	
Terrestrial process	E_ν max	Resonant (TAU)	Inverse (TAU)	Resonant (TAU)	Inverse (TAU)
^{40}K	1.31	1.8×10^{-9}	0.11	8.5×10^{-2}	0
^{87}Rb	0.274	3.1×10^{-7}	0	0	0
^{238}U					
^{234}Th	0.191	5.2×10^{-9}	0	0	0
^{234}Pa	2.29	2.3×10^{-9}	0.11	10^{-4}	1.2×10^{-5}
^{214}Pb	1.03	1.4×10^{-9}	0	8.5×10^{-2}	0
^{214}Bi	3.26	4×10^{-11}	5.3×10^{-2}	2.8×10^{-3}	9×10^{-6}
^{218}Pb	0.061	9×10^{-8}	0	0	0
^{210}Bi	1.16	1.2×10^{-9}	1.4×10^{-2}	1.1×10^{-2}	0
^{232}Th					
^{228}Ra	0.055	2.5×10^{-5}	0	0	0
^{278}Ac	2.18		1.4×10^{-2}	6×10^{-3}	10^{-7}
^{212}Pb	0.58	$0(10^{-9} - 10^{-11})$	0	0	0
^{212}Bi	2.25		3.1×10^{-2}	10^{-5}	6×10^{-6}
^{208}Tl	1.80		2.8×10^{-2}	10^{-4}	2×10^{-6}
Total from lithosphere		2.5×10^{-5}	0.36	0.2	2.6×10^{-5}

1 TAU = 10^{-36} interactions per target atom s^{-1} (and is equivalent to 1 SNU).

Review of existing work

- Kobayashi and Fukao, *Geophysical Research Lett*. **18** (1991)
  - Consider IBD and ROEC

Takeaways

- Two detectors considered:
  - Direct detection—with 10-tonnes of ^{3}He, one event detected in ~3 days
  - Indirect detection—detect product element in rocks by isotopic analysis
- Don't consider transitions to metastable states

Table 2. Candidates of target for terrestrial antineutrino detectic

Target	E_{th} [MeV]	Reaction Rate [TAU*]	Saturated P/T ratio	N_T^{**} [kg]
Elements with low ft values				
^{187}Os	1.025	6.3×10^{-8}	1.3×10^{-25}	5.6×10^{13}
^{3}He	1.041	2.1	1.2×10^{-27}	27000
^{107}Ag	1.055	3.3×10^{-7}	9.7×10^{-29}	6.3×10^{12}
^{131}Eu	1.098	1.2×10^{-3}	4.6×10^{-30}	2.5×10^{9}
^{93}Nb	1.114	7.3×10^{-8}	5.0×10^{-30}	2.5×10^{13}
^{171}Yb	1.119	9.1×10^{-3}	8.2×10^{-31}	3.6×10^{8}
^{14}N	1.179	7.5×10^{-7}	2.0×10^{-31}	3.6×10^{11}
^{79}Br	1.181	1.9×10^{-7}	5.7×10^{-31}	7.8×10^{12}
^{35}Cl	1.190	3.7×10^{-5}	4.0×10^{-34}	1.8×10^{10}
^{135}Ba	1.227	1.6×10^{-9}	2.1×10^{-31}	1.7×10^{15}
^{155}Gd	1.268	1.5×10^{-4}	3.3×10^{-32}	2.0×10^{10}
^{33}S	1.271	1.2×10^{-2}	3.8×10^{-32}	5.3×10^{7}
^{169}Tm	1.374	3.2×10^{-3}	3.7×10^{-33}	1.0×10^{9}
^{121}Sb	1.409	6.7×10^{-2}	9.4×10^{-33}	3.5×10^{7}
^{185}Re	1.454	7.1×10^{-3}	6.6×10^{-32}	5.0×10^{8}
^{199}Hg	1.475	9.1×10^{-4}	3.6×10^{-34}	4.2×10^{9}
^{175}Lu	1.490	1.8×10^{-2}	9.2×10^{-33}	1.9×10^{8}
^{177}Hf	1.519	9.2×10^{-3}	7.7×10^{-33}	3.7×10^{8}
^{64}Zn	1.600	7.6×10^{-3}	1.3×10^{-33}	1.6×10^{8}
^{141}Pr	1.602	3.3×10^{-4}	1.3×10^{-33}	8.2×10^{9}
^{113}In	1.608	9.2×10^{-6}	5.9×10^{-33}	2.4×10^{11}
^{161}Dy	1.613	1.9×10^{-4}	1.7×10^{-34}	1.6×10^{10}
^{77}Se	1.712	4.0×10^{-3}	8.1×10^{-34}	3.7×10^{8}
^{153}Eu	1.827	5.8×10^{-4}	1.4×10^{-34}	5.1×10^{9}
Elements abundant in the crust				
^{1}H	1.804	4.2×10^{-3}	3.8×10^{-36}	4.6×10^{6}
^{27}Al	3.631	4.4×10^{-7}	3.6×10^{-40}	1.2×10^{12}
^{43}Ca	2.839	6.3×10^{-6}	7.3×10^{-37}	1.3×10^{11}
^{31}P	2.513	4.0×10^{-4}	5.5×10^{-36}	1.5×10^{9}
^{39}K	1.587	4.5×10^{-7}	5.5×10^{-33}	1.7×10^{12}
^{47}Ti	1.623	1.1×10^{-2}	4.7×10^{-33}	8.2×10^{7}
^{63}Cu	1.087	8.1×10^{-4}	3.7×10^{-30}	1.5×10^{9}
^{95}Mo	1.948	1.0×10^{-4}	4.5×10^{-34}	1.8×10^{10}
^{204}Pb	1.785	5.9×10^{-6}	1.1×10^{-33}	6.6×10^{11}
^{206}Pb	2.548	5.8×10^{-3}	2.1×10^{-36}	6.8×10^{8}
^{207}Pb	2.444	1.1×10^{-2}	4.4×10^{-36}	3.8×10^{8}
Elements of which products are noble gases				
^{85}Rb	1.709	4.7×10^{-6}	2.3×10^{-33}	3.5×10^{11}
^{133}Cs	1.499	6.2×10^{-3}	4.1×10^{-33}	4.1×10^{8}

* 1 TAU=10^{-36}reactions/target atom· sec

** Necessary amount for one reaction per one day

Review of existing work

- A. Cabrera, et al. (LiquidO collaboration), *arXiv:2308.04154* (2023)
  - Focus on IBD
  - Real-time detection—can use event topology and de-excitation coincidences to tag interactions with opaque scintillator

Target process	IA [%]	E_{th} [MeV]	Log(*ft*)	Ref	S(U) [TNU]	S(Th) [TNU]	S(K) [TNU]
$^{1}H \rightarrow {}^{1}n$	99.99	1.806	3.0170	[26]	31.5 [24.0 ; 47.0]	9.0 [6.4 ; 14.1]	/
$^{63}Cu \rightarrow {}^{63}Ni$	69.15	1.089	6.7	[25]	0.85 [0.64 ; 1.26]	0.49 [0.35 ; 0.77]	0.10 [0.07 ; 0.13]
$^{63}Cu \rightarrow {}^{63}Ni^{*}$		1.176	5	[22]			
$^{35}Cl \rightarrow {}^{35}S$	75.76	1.189	5.0088	[27]	0.73 [0.56 ; 1.09]	0.43 [0.30 ; 0.67]	0.10 [0.07 ; 0.13]
$^{106}Cd \rightarrow {}^{106}Ag$	1.25	1.212	4.1	[28]	(1.7 [1.3 ; 2.6]) · 10^{-1}	(9.7 [6.9 ; 15.2]) · 10^{-2}	(5.1 [3.7 ; 6.6]) · 10^{-3}

Takeaways

- Identify ^{63}Cu, ^{35}Cl as most promising candidates, strong emphasis on ^{63}Cu
  - Assume log(ft) value of 5 for all metastable states, as done in Krauss, Glashow, & Schramm
  - Log(ft) of ^{79}Br measured to be 4.7 in Klay & Kappeler, Phys. Rev. C **38** (1988)

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$^{63}Cu \rightarrow {}^{63}Ni^{*}$		1.176	5
$^{35}Cl \rightarrow {}^{35}S$	75.76	1.189	5.0088
$^{106}Cd \rightarrow {}^{106}Ag$	1.25	1.212	4.1
$^{79}Br \rightarrow {}^{79}Se$	50.69	1.173	10.77
$^{79}Br \rightarrow {}^{79}Se^{*}$		1.268	5
$^{171}Yb \rightarrow {}^{171}Tm$	14.09	1.119	6.318
$^{151}Eu \rightarrow {}^{151}Sm$	47.81	1.099	7.51
$^{151}Eu \rightarrow {}^{151}Sm^{*}$		1.266	5
$^{45}Sc \rightarrow {}^{45}Ca$	100	1.282	6
$^{3}He \rightarrow {}^{3}H$	1.34 · 10^{-4}	1.041	3.0524
$^{33}S \rightarrow {}^{33}P$	0.75	1.271	5.022
$^{14}N \rightarrow {}^{14}C$	99.64	1.178	9.040
$^{107}Ag \rightarrow {}^{107}Pd$	51.839	1.056	9.9
$^{147}Sm \rightarrow {}^{147}Pm$	14.99	1.246	7.4
$^{187}Os \rightarrow {}^{187}Re$	1.96	1.024	11.195
$^{93}Nb \rightarrow {}^{93}Zr$	100	1.113	12.1
$^{155}Gd \rightarrow {}^{155}Eu$	14.80	1.274	8.62
$^{135}Ba \rightarrow {}^{135}Cs$	6.592	1.291	13.48
$^{87}Sr \rightarrow {}^{87}Rb$	7.00	1.304	17.514

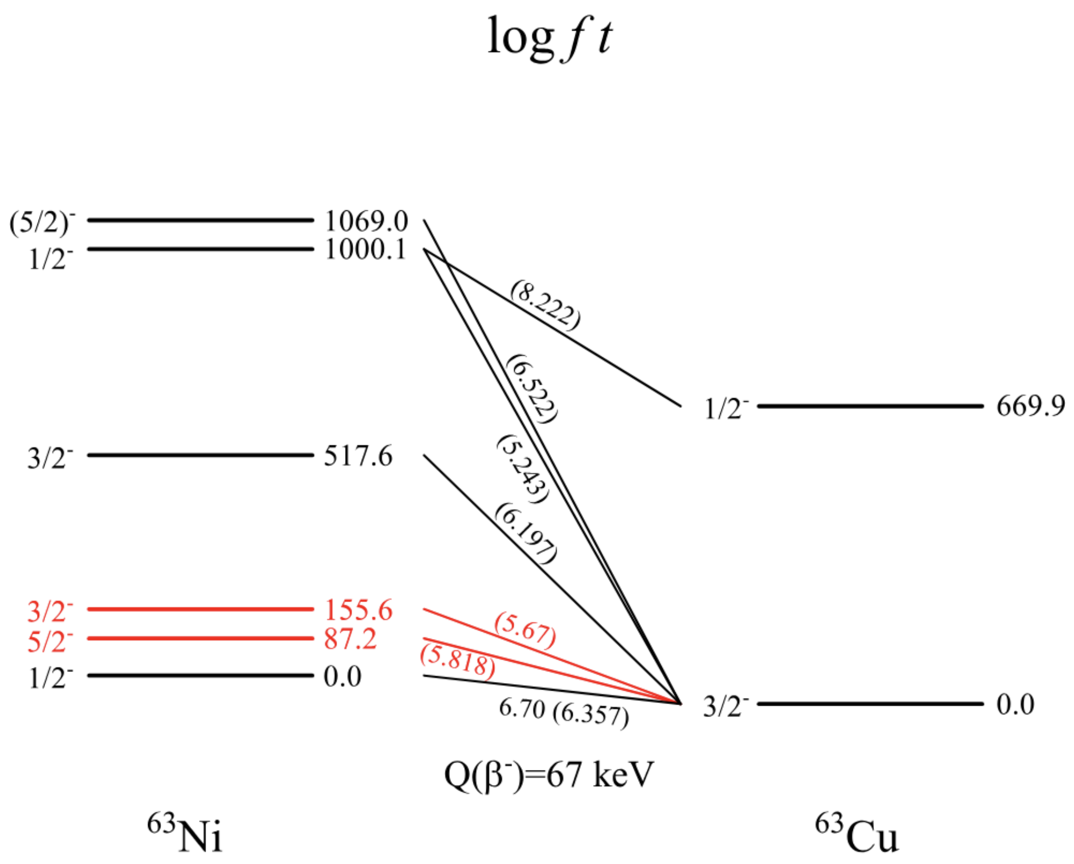
Why ^{63}Cu?

$$\bar{\nu}_e + {}^{63}\mathrm{Cu} \rightarrow e^+ + {}^{63}\mathrm{Ni}^{(m)}$$

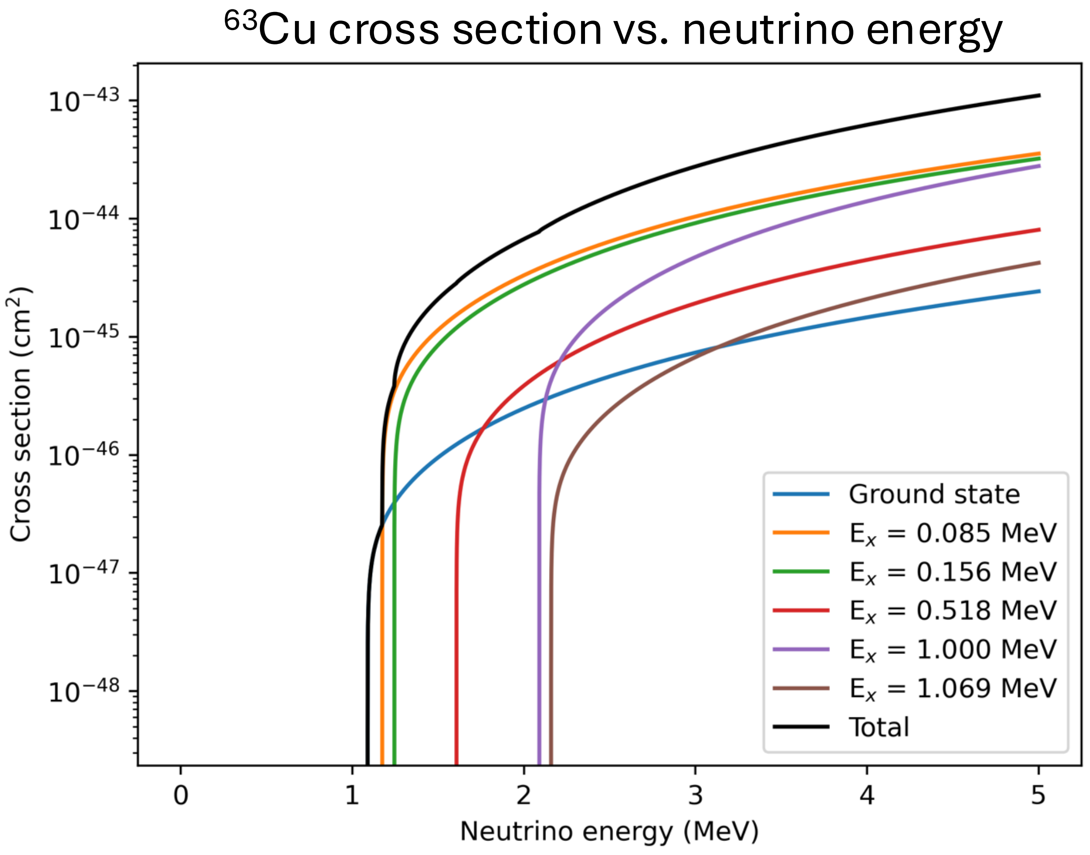
- Low threshold: 1.089 MeV to ground state in resulting ^{63}Ni
- Large natural abundance: 69.2% natural abundance
- Coincidence tagging: first excited state in ^{63}Ni has lifetime of 1.67μs, emits 87-keV gamma
- Both transitions to ground state and first excited state are allowed transitions

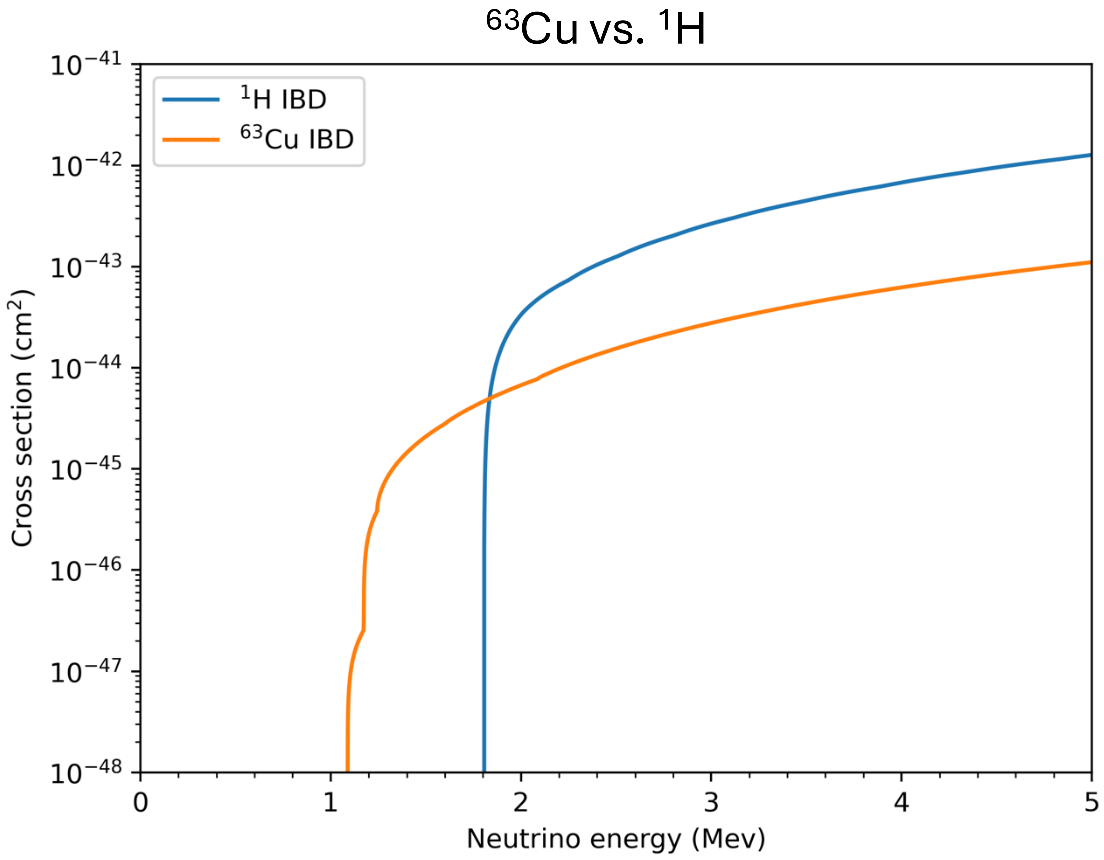
ft-values

- Charged-current cross section inversely proportional to the *ft*-value of corresponding beta decay
- *ft*-value of the first excited state of ^{63}Ni has never been measured
  - Critical first step for advancing detectors relying on this interaction
- For now, using ft-values from Chen and Wang, *Symmetry* (2023)



IBD cross section
(including ^{63}Ni excited states up to ~1 MeV)





Measuring the *ft*-value

- The ft-value is encoded in the branching ratio (R_β) of the first excited state of ^{63}Ni—how often it de-excites to ground state vs. direct decays
- Also impact isotopes produced in supernovae
  - ^{63}Ni has a long half-life, in supernovae temperatures can be high enough that many ^{63}Ni nuclei in first excited state
  - If decay from excited state is fast, affects the amount of ^{63}Cu produced
- Can potentially measuring the *ft*-value via neutron capture on ^{62}Ni with a pulsed neutron source
  - Requires ***large*** flux of neutrons, expected branching ratio is small (~10^{-12} to 10^{-14}) for log(ft) = 4.7-5.8
  - Beta decay half-life of ^{63}Ni^{m} corresponding to log(ft)=5 is 255 days
  - To produce 100 beta decays from excited state with this log(*ft*), would be left with μC-scale ^{63}Ni source

^{63}Ni Production

- Already enriched for ^{62}Ni production (96%) for safeguard applications

https://www.ornl.gov/news/making-radioactive-63ni-target-explosives

Menu

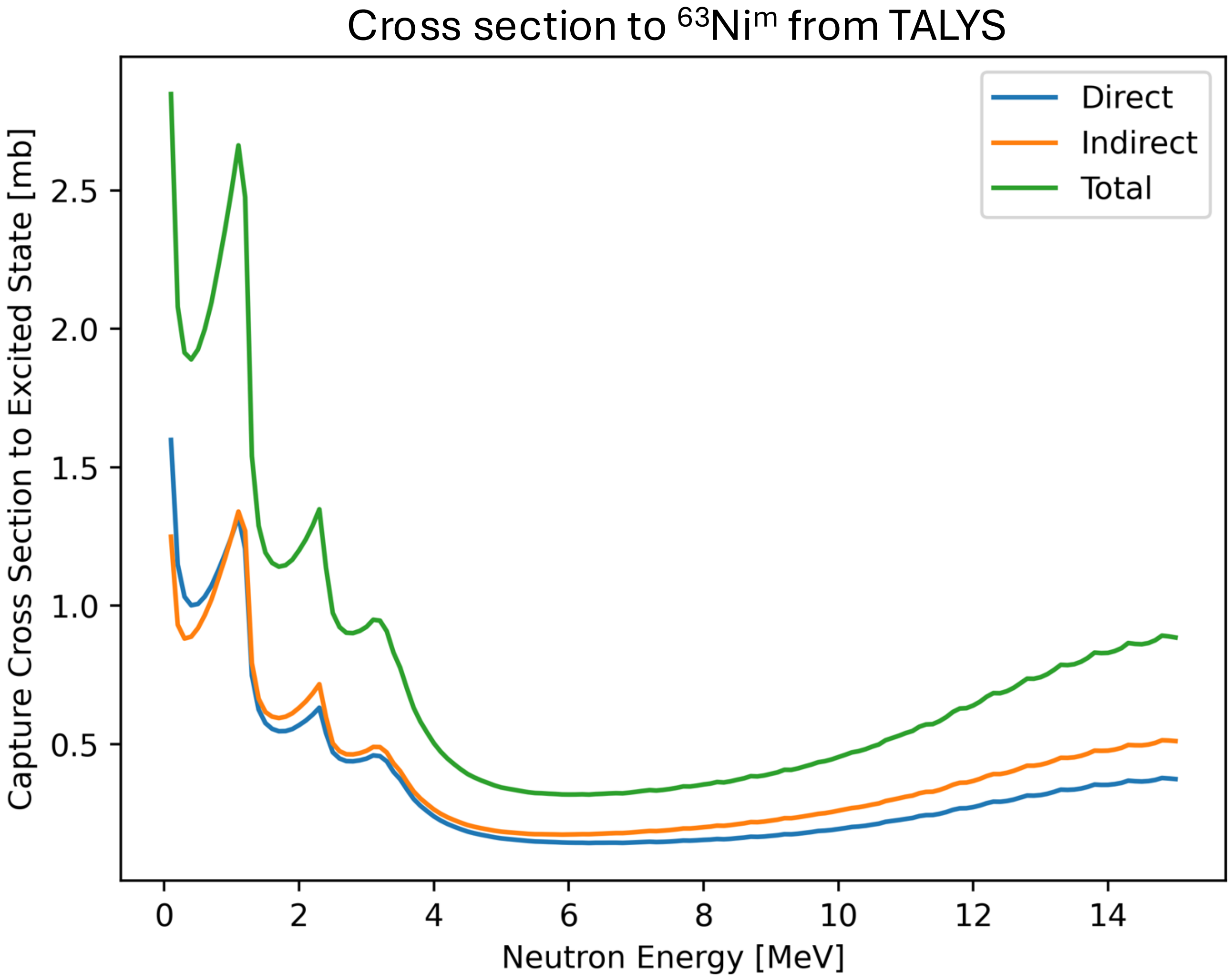
Oak Ridge National Laboratory

^{62}Ni is not naturally abundant, occurring at only 3.6% in nature. "The ^{62}Ni material we use for the target is 96% enriched," Ferren explained. "We increase the percentage of ^{62}Ni, compared to the other isotopes, to get more atoms of ^{62}Niper unit volume to hit with the neutrons." This stable isotope enrichment process was achieved with electromagnetic separators located at the Y-12 site. The irradiation of the highly enriched ^{62}Ni results in a high "specific activity" product, containing fewer impurities at the end of bombardment.

Industry specifications require the specific activity of the final product to be at least 15 curies (a measure of radioactivity) of ^{63}Ni per gram of enriched Ni target material. To achieve this, the ^{63}Ni is placed in the reactor for approximately 15 reactor cycles, where it becomes progressively more radioactive. Each target produces approximately 375 curies of ^{63}Ni.

What energy neutrons?

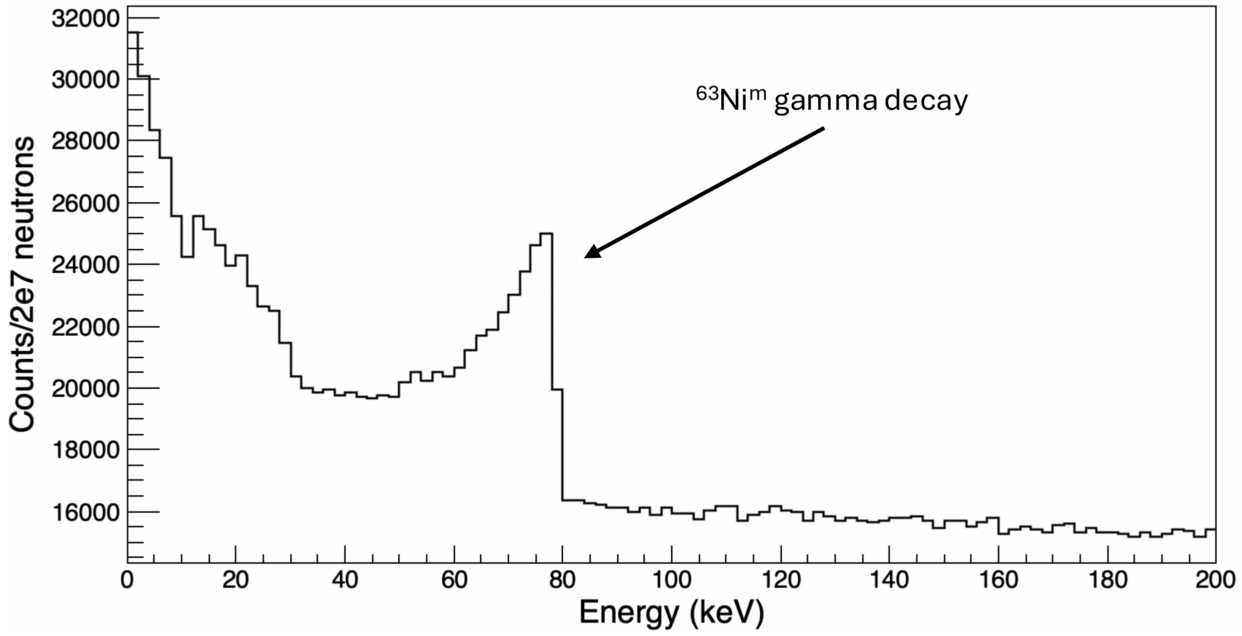
- Peak in capture cross section around 1.3 MeV
- Don’t really care how the metastable state is produced—can be produced from higher energy states de-exciting



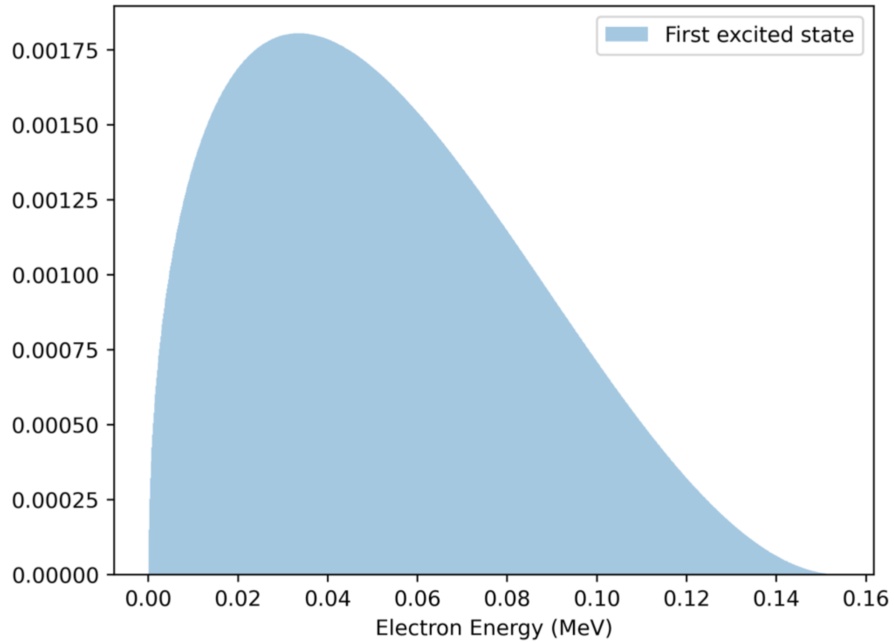
Neutron capture on ^{62}Ni

- Need a large array of ^{62}Ni-loaded scintillator (plastic or liquid) cells
  - Aim for 5+% loading in ^{62}Ni
  - Measure for ~2 weeks at Triangle Universities Nuclear Laboratory (TUNL)
  - Detector cell should be small—150 keV beta travels 0.2mm in plastic scintillator
- Neutron pulses are <10ns in width, separate pulses in time by 12.8μs (can change this)
  - This pulsing allows essentially all the produced ^{63}Ni^{m} to de-excite or decay
  - Signature of decay from excited state is a larger energy electron (end point of ~155 keV)
  - Focus on energy region from ~80 keV to 155 keV—above gamma de-excitation line
  - Signal should also occur outside of neutron beam window (between pulses), coincident only with a single cell, and want to maximize exposure while avoiding pile-up

Simulation of 1.25 MeV neutrons incident on ^{62}Ni-loaded LS cell



Calculated ^{63}Ni^{m} beta spectrum



Longer term objectives

- Assuming the log(ft) value is at least as low as predicted, next obstacle is loading scintillator with ^{63}Cu
  - Some existing formulas in literature, but not sure of properties
- Detector design would then be optimized via simulation—want to take advantage of 1.67μs metastable coincidence rejection
  - Simulate external backgrounds, backgrounds from IBD on hydrogen, ROEC as a signal and/or background
- Look into directionality of emitted positron to reduce backgrounds
  - Typically anticorrelated with the direction of the neutrino for other targets at low energies, but haven't seen calculations specifically for ^{63}Cu

Summary

- Charged-current interactions with nuclei one means to detect low energy electron antineutrinos
  - Little experimental work studying these interactions at this energy scale
- Copper-63 one of the most promising candidates
- Log(ft) of first excited state in Nickel-63 should be measured to better understand the cross section
  - Can potentially make this measurement at TUNL
- After measuring log(*ft*), can better evaluate the sensitivity of this technology and optimize a detector design