Resonant Antineutrino Capture with Low-Energy Bound-β Beams

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MOTIVATION

- We study the feasibility of producing monochromatic, low-energy electron antineutrinos via bound-β decay of fully stripped radioactive ions and detecting them via resonant anti-neutrino induced electron capture.

  - Bound-β decay: fully stripped parent ion decays with the emitted electron created directly into a bound K orbital of the daughter ion.
  - Produces a monochromatic anti-ν_e of energy $E_{\nu e} \simeq Q_\beta - B_{src}$, up to small recoil and atomic corrections.
  - Time-reverse: resonant anti-ν EC on the isobaric mirror nucleus.
  - Experimentally demonstrated for ^{163}Dy (Jung 1992) and ^{187}Re (Bosch 1996) at GSI ESR.

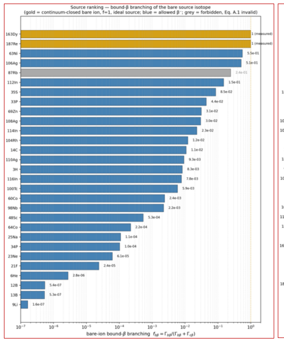
- Resonance gain over IBD
  $\sigma_{peak} = 4\pi(\hbar c)^2/Q^2_t \; \Gamma_{b\beta}/\Gamma_{total}$
  For ^{6}He→^{6}Li: $\sigma_{peak} = 7 \times 10^{-38}$ cm^2
  For comparison IBD on p:
  $\sigma_{IBD} \lesssim 10^{-42}$ cm^2 at MeV.
  Resonance gain: $\gtrsim 10^4$.

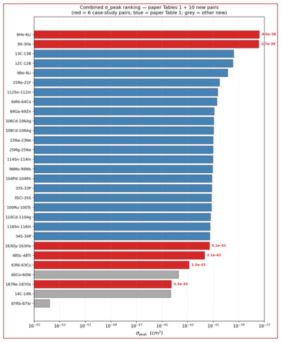
- Any rate asymmetry between bound-β emission and the inverse resonant capture on the same nuclear pair constrains beyond-the-SM charged-current physics
  - ❑ Example of a potential physics test: Bound-β rate (emission) and resonant anti-ν EC rate (absorption) on the same isobaric pair share the same nuclear matrix element => detailed-balance / CPT consistency test
- May consider an experiment with non-isobaric pairs as well
  - ❑ Apply to low-energy neutrino physics challenges.

REVISIT AND RECALCULATE PHYSICS PARAMETERS

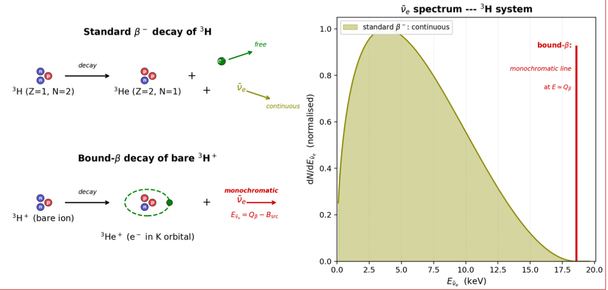
Source	Target	Q_t	$Q^{b\beta}_{src}$	$\Gamma_{b\beta}$	$\Gamma^{Eq.3}_K$	Γ^{meas}_K	σ ours (Eq.3)	σ ours (meas)	σ Oldeman	$\frac{ours}{pap}$	Trk
^{3}H	^{3}He	18.6	18.6	9.63×10^{-27}	2.64×10^{-6}	2.01×10^{-2}	5.15×10^{-38}	6.77×10^{-42}	3.66×10^{-38}	1.408	EqA1
^{6}He	^{6}Li	3508.3	3508.3	1.56×10^{-21}	8.64×10^{-6}	2.69×10^{-2}	7.16×10^{-38}	2.30×10^{-41}	4.04×10^{-38}	1.772	EqA1
^{9}Li	^{9}Be	13606.7	13606.6	1.02×10^{-22}	4.27×10^{-5}	3.60×10^{-2}	6.30×10^{-41}	7.47×10^{-44}	1.35×10^{-40}	0.466	EqA1
^{12}B	^{12}C	13369.1	13369.0	1.19×10^{-20}	5.05×10^{-4}	6.47×10^{-2}	6.42×10^{-40}	5.01×10^{-42}	3.46×10^{-40}	1.854	EqA1
^{13}B	^{13}C	13437.3	13437.3	1.19×10^{-20}	5.05×10^{-4}	6.47×10^{-2}	6.43×10^{-40}	5.02×10^{-42}	3.93×10^{-40}	1.637	EqA1
^{21}F	^{21}Ne	5684.9	5684.8	1.96×10^{-21}	6.93×10^{-3}	2.09×10^{-1}	4.28×10^{-41}	1.42×10^{-42}	3.11×10^{-41}	1.376	EqA1
^{23}Ne	^{23}Na	4376.7	4376.5	3.37×10^{-22}	1.08×10^{-2}	2.40×10^{-1}	7.96×10^{-42}	3.59×10^{-43}	9.86×10^{-42}	0.807	EqA1
^{25}Na	^{25}Mg	3836.1	3835.9	3.24×10^{-22}	1.64×10^{-2}	3.00×10^{-1}	6.58×10^{-42}	3.59×10^{-43}	9.61×10^{-42}	0.684	EqA1
^{33}P	^{33}S	250.7	250.4	9.33×10^{-24}	6.57×10^{-2}	5.30×10^{-1}	1.10×10^{-41}	1.37×10^{-42}	7.70×10^{-42}	1.431	EqA1
^{34}P	^{34}S	5376.3	5376.1	2.73×10^{-21}	6.57×10^{-2}	5.30×10^{-1}	7.01×10^{-42}	8.70×10^{-43}	5.34×10^{-42}	1.313	EqA1
^{35}S	^{35}Cl	169.7	169.4	5.50×10^{-24}	8.73×10^{-2}	5.90×10^{-1}	1.07×10^{-41}	1.58×10^{-42}	7.35×10^{-42}	1.452	EqA1
^{64}Co	^{64}Ni	7314.3	7313.9	2.93×10^{-19}	8.49×10^{-1}	1.33×10^{0}	3.16×10^{-41}	2.02×10^{-41}	1.93×10^{-41}	1.637	EqA1
^{69}Zn	^{69}Ga	919.4	919.0	4.40×10^{-21}	1.33×10^{0}	1.67×10^{0}	1.91×10^{-41}	1.53×10^{-41}	1.18×10^{-41}	1.622	EqA1
^{98}Nb	^{98}Mo	4602.2	4601.5	1.18×10^{-19}	5.15×10^{0}	4.14×10^{0}	5.32×10^{-42}	6.61×10^{-42}	8.78×10^{-42}	0.605	EqA1
^{100}Tc	^{100}Ru	3223.8	3223.1	1.53×10^{-19}	6.32×10^{0}	4.91×10^{0}	1.14×10^{-41}	1.47×10^{-41}	7.22×10^{-42}	1.577	EqA1
^{104}Rh	^{104}Pd	2463.4	2462.7	1.26×10^{-19}	7.70×10^{0}	5.77×10^{0}	1.32×10^{-41}	1.77×10^{-41}	8.02×10^{-42}	1.650	EqA1
^{106}Ag	^{106}Cd	220.7	219.9	3.47×10^{-23}	9.30×10^{0}	6.75×10^{0}	3.74×10^{-43}	5.15×10^{-43}	1.09×10^{-41}	0.034	EqA1
^{108}Ag	^{108}Cd	1676.0	1675.3	9.08×10^{-20}	9.30×10^{0}	6.75×10^{0}	1.69×10^{-41}	2.33×10^{-41}	1.08×10^{-41}	1.569	EqA1
^{110}Ag	^{110}Cd	2918.0	2917.2	1.60×10^{-19}	9.30×10^{0}	6.75×10^{0}	9.85×10^{-42}	1.36×10^{-41}	6.12×10^{-42}	1.610	EqA1
^{112}In	^{112}Sn	693.1	692.4	1.27×10^{-20}	1.11×10^{1}	7.91×10^{0}	1.16×10^{-41}	1.63×10^{-41}	2.25×10^{-41}	0.515	EqA1
^{114}In	^{114}Sn	2016.7	2015.9	1.48×10^{-19}	1.11×10^{1}	7.91×10^{0}	1.59×10^{-41}	2.24×10^{-41}	9.34×10^{-42}	1.699	EqA1
^{116}In	^{116}Sn	3306.0	3305.3	2.53×10^{-19}	1.11×10^{1}	7.91×10^{0}	1.01×10^{-41}	1.43×10^{-41}	5.72×10^{-42}	1.773	EqA1
New source/target pairs (this work) — no Oldeman entry											
^{14}C	^{14}N	156.8	156.7	2.77×10^{-29}	1.15×10^{-3}	8.68×10^{-2}	4.78×10^{-45}	6.35×10^{-47}	—	—	EqA1
^{48}Sc	^{48}Ti	3996.1	3995.8	1.98×10^{-21}	2.88×10^{-1}	8.60×10^{-1}	2.11×10^{-42}	7.06×10^{-43}	—	—	EqA1
^{60}Co	^{60}Ni	2830.8	2830.4	2.67×10^{-23}	8.49×10^{-1}	1.33×10^{0}	1.92×10^{-44}	1.22×10^{-44}	—	—	EqA1
^{63}Ni	^{63}Cu	75.3	74.9	1.51×10^{-25}	9.92×10^{-1}	1.44×10^{0}	1.31×10^{-43}	9.05×10^{-44}	—	—	EqA1
^{87}Rb	^{87}Sr	297.8	302.7	9.64×10^{-35}	3.30×10^{0}	2.99×10^{0}	$1.61 \times 10^{-54‡}$	1.78×10^{-54}	—	—	EqA1
^{163}Dy	^{163}Ho	51.2	50.2	1.12×10^{-22}	4.13×10^{1}	2.52×10^{1}	5.07×10^{-42}	8.31×10^{-42}	—	—	GSI
^{187}Re	^{187}Os	74.1	88.3	4.40×10^{-25}	7.34×10^{1}	—	5.33×10^{-45}	—	—	—	GSI

SOURCE AND TARGET RANKING

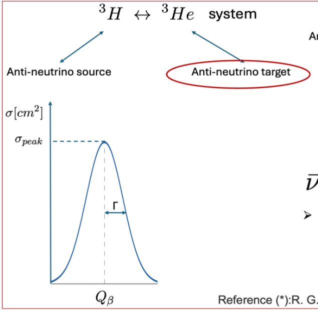

Source ranking — bound-β branching of the bare source isotope
(gold = continuum-closed bare ion, f=1, ideal source; blue = allowed β⁻; grey = forbidden, Eq. A.1 invalid)


Combined σ_peak ranking — paper Tables 1 + 10 new pairs
(red = 6 case-study pairs; blue = paper Table 1; grey = other new)

SOURCE: BOUND-BETA DECAY CONCEPT


Bound-β decay vs standard β^- decay --- ^{3}H example (adapted from Djurcic et al., Nu2024)

TARGET: RESONANT ν_e CAPTURE



Anti-neutrino induced electron capture on neutral atom:

photon de-excitation

$$\bar{\nu}_e + {}^A_{Z+1}Y_N \rightarrow {}^A_Z X^*_{N+1}$$

$$\bar{\nu}_e + {}^3He \rightarrow {}^3H^*$$

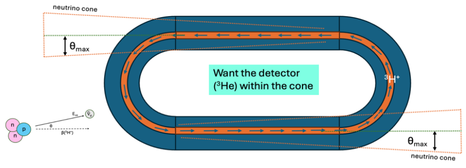
- Cross-section(*): σ_{peak} (^{3}He) = 3.66 x 10^{-38} cm^2

  $\bar{\nu}_e$ energy to match the target Q_β

Reference (*):R. G. C. Oldeman et al. Eur. Phys. J. C (2010) 65: 81-87.

EXPERIMENTAL DESIGN

- Only anti-neutrinos within narrow energy range of ^{3}He Q_β are eligible for the resonant capture.



ENERGY REQUIREMENTS

- Need neutrinos from the source reach the resonant neutrino energy of the target.

- Neutrino energy at source (^{3}H$^+$)

$$E_{\bar{\nu}_e(^3H)} = Q_{(^3H)} - \underbrace{\frac{Q^2_{(^3H)}}{2m_{(^3H)}}}_{\text{account for the source atom recoil}}$$

- Neutrino energy required at the target (^{3}He)

$$E_{\bar{\nu}_e(^3He)} = Q_{(^3He)} + \underbrace{\frac{Q^2_{(^3He)}}{2m_{(^3He)}}}_{\text{account for the target atom recoil}}$$

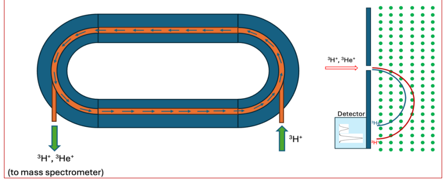
- Neutrino source velocity required to boost neutrinos from the source to resonant capture at target

$$\beta_{(^3H)} = \frac{E^2_{\bar{\nu}_e(^3He)} - E^2_{\bar{\nu}_e(^3H)}}{E^2_{\bar{\nu}_e(^3He)} + E^2_{\bar{\nu}_e(^3H)}}$$

- Need accelerate source to velocity β

INDIRECT BOUND-BETA MEASUREMENT

- There is an opportunity to indirectly observe the bound-beta decay (without observing the resonant anti-neutrino capture)
  -Extract and count bound-beta decay produced ^{3}He$^+$ ions as they stay in the beam orbit along with ^{3}H$^+$
  -Demonstrate bound-beta decay process in ^{3}H.



STUDY CASES

Production → ionisation → storage → target → detector chains
(6 case-study pairs; per-stage facility / parameter)

	Production	Charge state	Storage	Target	Detector
3H → 3He	^{6}Li(n,α)^{3}H HFIR commercial	1+ trivial (gas source)	CRYRING@FAIR electron cooling	liquid ^{3}He 4 K, 0.125 g/cm³	HPGe silicon PIN
6He → 6Li	^{9}Be(n,α)^{6}He ISAC/SPIRAL2	2+ direct ECRIS	CRYRING@FAIR laser cooling needed	Li metal 0.534 g/cm³	Si strip + HPGe recoil + X-ray
63Ni → 63Cu	^{62}Ni(n,γ)^{63}Ni HFIR commercial	Ni^{28+} EBIS + stripper foil	GSI ESR standard cooling	Cu metal 8.96 g/cm³	HPGe array Cu K_α 8.0 keV
48Sc → 48Ti	^{48}Ca(p,n)^{48}Sc FRIB / SPIRAL2	Sc^{21+} EBIS + foil	CRYRING@FAIR e-cooling	Ti metal 4.5 g/cm³ (enriched)	HPGe + Si Ti K_α 4.5 keV
163Dy → 163Ho	^{162}Dy(n,γ)^{163}Dy BR2 reactor	Dy^{66+} GSI HLI full strip	GSI ESR (historical site)	^{163}Ho enriched shared w/ ECHo	HPGe + bolometer saturated cone
187Re → 187Os	natural Re (no production needed)	Re^{75+} GSI HLI demo	GSI ESR (Bosch 1996 site)	^{187}Os enriched 22.6 g/cm³ (densest)	HPGe + TPC saturated cone

PERSPECTIVE

Why revisit?

A reach-physics / outreach interest revived these 2010 ideas — and two things have changed since: the closed-form framework is now reproduced and extended end-to-end with documented systematics, and the enabling technology is operational or near-term (cooler/storage rings CRYRING@FAIR & GSI ESR; cryogenic micro-calorimeters ECHo/HOLMES). Only the extreme beam cooling for the lightest pairs is still R&D.

Is there a promise?

The source figure of merit is the bound-β branching per source lifetime; the fully stripped ^{163}Dy ion (100% bound-β) tops it. By role:

Best now (^{63}Ni → ^{63}Cu): every link operational at GSI ESR today, no R&D — the natural precursor pair, despite a low rate.

Best physics (^{163}Dy → ^{163}Ho): the bare ion is a 100% bound-β source (top of the source ranking) and detection plugs into existing bolometers. Conditional on a re-derivation of the rate in the saturated-cone (β→0) limit — the one pair whose acceptance opens to the full 4π.

Brightest cross-section (^{6}He → ^{6}Li): the largest σ_{peak} (7×10^{-38} cm^2), but ^{6}He's own bound-β branch is tiny, its realistic rate is no better than ^{163}Dy's; needs ISOL + cooler-ring co-location and cooling to δp/p ≈ 10^{-9}.

Mid-term (^{48}Sc → ^{48}Ti): FRIB production + CRYRING@FAIR cooling (1–5 yr).

Source demonstrator (^{3}H → ^{3}He): brightest class σ_{peak} (5×10^{-38} cm^2), but the 0.06 eV ^{3}He recoil is unresolvable and the rate is far below 1/yr. Its value is the cheapest, lightest system to prove bound-β beam storage and measure the bound-β branching.

The long-term physics goal throughout is the **detailed balance / CPT consistency test** on a matched isobaric pair.

Rate reality

The realistic stored-ion event-rate ceiling is ≈ 10^{-5}/yr (^{163}Dy → ^{163}Ho); the rate-optimal configuration would instead boost ^{163}Dy onto the brightest target, ^{6}Li (γ ≈ 35) — ~70× higher (~10^{-3}/yr, the best in the study) — but it needs an SPS-class ring (Bρ ≈ 270 T·m) and gives up the matched-isobar CPT test.

Roadmap

Now: store a ^{3}H$^+$ beam and demonstrate bound-β indirectly by counting the ^{3}He^{2+} daughters in the orbit → measure the bound-β branching (closed-form prediction ≈ 8×10^{-3}). Cheapest concrete step.

Parallel: numerical evaluation of the bound/continuum ratio with Dirac wave functions to close the ±30% closed-form systematic.

Multiyear: re-derive the rate in the matched-isobar (β→0), full-4π stationary limit → realistic rates for the matched pairs (where ^{163}Dy → ^{163}Ho lives).

Multiyear: ^{63}Ni → ^{63}Cu at GSI ESR with existing components.

Reach pairs: ^{163}Dy → ^{163}Ho (bolometers), ^{48}Sc → ^{48}Ti (FRIB+CRYRING), ^{6}He → ^{6}Li (beam-cooling R&D).

INTERACTION RATES

- Idealized (unrealistic upper-bound) case:
  - Assume unrealistic case where the "concentrated" source (^{3}H$^+$) provides antineutrinos at resonant energy of the source (^{3}He) at L = 100 cm distance.
  - How much source and target is needed to start seeing anti-neutrino captures with a 100% detection efficiency?

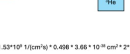
Source: ^{3}H

m(^{3}H) = 100 g: $N_{source} = 2*10^{25}$

A_H=0.96 MCi
p(Bβ) = 5.4 x 10^{-3}

$N_{\nu e} = A_H * p(B\beta) = 1.92*10^{14} s^{-1}$

$\Phi_{\nu e}$(at 1m) = $1.53*10^9$ 1/(cm^{2}s)



Target: ^{3}He

cosθ = 0.999957
Neutrino cone θ = 9.5 mrad: f_{target} (fraction of anti-nu that traverses the target) : $2.15*10^{-5}$

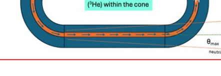
σ_{eff} (fraction of peak cross-section): 0.498 * σ_{peak}

σ_{peak} = 3.66 * 10^{-38} cm^2

m(^{3}He) = 1000 kg: $N_{target} = 2*10^{29}$

Rate = $\Phi_{\nu e} * \sigma_{eff} * N_{target} * f_{target}$ = $1.53*10^9$ 1/(cm^{2}s) * 0.498 * 3.66 * 10^{-38} cm^2 * $2*10^{29}$ * $2.15*10^{-5}$ = 12 * 10^{-5} s^{-1} = 10.3/day
=3785/year

- Realistic (stored-beam) case:
  - ~10^{12} ^{3}H$^+$ stored (light-ion current, GSI ESR); ^{3}H is a weak source (12.3 yr life, ~0.8% bound-β).
  - Realistic ^{3}H→^{3}He rate ~10^{-9}/yr; program ceiling ~10^{-5}/yr (^{163}Dy→^{163}Ho) — see PERSPECTIVE.
  - Source-limited, not geometry-limited → proof-of-principle. Near-term goal: indirect bound-β demo. (count ^{3}He^{2+}).



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