Exploring the lowest neutrino energies

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MOTIVATION

- Look for unobserved physics and new processes
  -Weekend research hobbies.
- Use a fully ionized isotopes to produce a monochromatic anti-neutrino beam by neutrino capture (bound-beta decay)
  -Potential intermediate experimental step: show the process exist by counting $^3He^+$ produced in $^3H^+$ beam.
- Use stable isotopes with to detect the monochromatic anti-neutrino via resonant (anti-neutrino induced) electron capture: the incoming neutrino energy needs to match the Q_β energy of the target nucleus.
- Possible experimental signatures: observe photons from the atomic de-excitation, and/or observe the decay of the daughter nucleus of the target nucleus.
- Inspiration exist from pioneering work and discussions described in references listed below.
- Example: $^3H \leftrightarrow {}^3He$ System.
- Physics opportunities in a very long term
  -Demonstrate bound-beta decay in ^3H
  -Measure resonant anti-neutrino capture in ^3He
  -Apply to low-energy physics challenges.

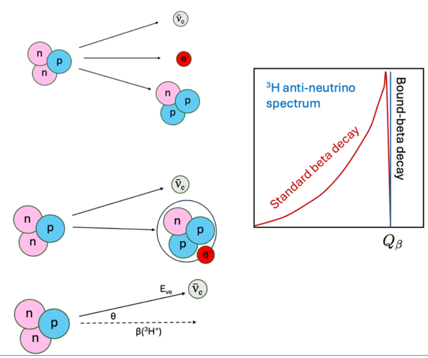
BOUND-BETA DECAY CONCEPT

Standard beta decay of ^3H:

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

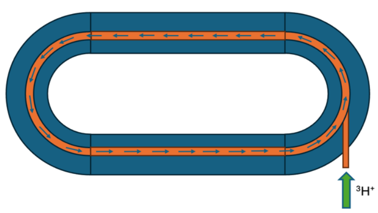
Bound-beta decay of ^3H in $^3H^+$ beam:

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



STORAGE RING

- Inject $^3H^+$ to the storage ring and have it go through the beta decay(s).



SOURCE: BOUND-BETA DECAY

$^3H \leftrightarrow {}^3He$ system

Anti-neutrino source — Anti-neutrino target

$^3H^+$ Bound-beta (Bβ) decay to ground state of ^3He

Standard β-decay: $^3H \rightarrow ^3He + e^- + \bar{\nu}_e$ $\quad n \rightarrow p + e^- + \bar{\nu}_e$

Bound β-decay of $^3H^+$: $^3H^+ \rightarrow ^3He^+ + \bar{\nu}_e$

^3H Bβ-decay fraction ^3He ground state (*): $p(B\beta) = 5.4 \times 10^{-3}$

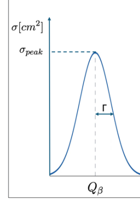
In bound β-decay the electron from nucleus does not leave the atom: it stay bound in atomic orbit.

(*)Reference: R. S. Raghavan. https://arxiv.org/pdf/hep-ph/0601079, L. Mikaelyan et al, Sov J. Nucl. Phys 6 (1968) 254.

TARGET: RESONANT ν_e CAPTURE

$^3H \leftrightarrow {}^3He$ system

Anti-neutrino source — Anti-neutrino target



Anti-neutrino induced electron capture on neutral atom:

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

(photon de-excitation)

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

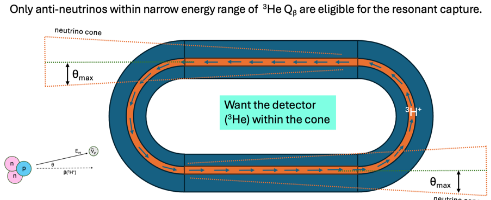
- Cross-section(*): σ_{peak} (^3He) = 3.66×10^{-38} cm^2

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

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

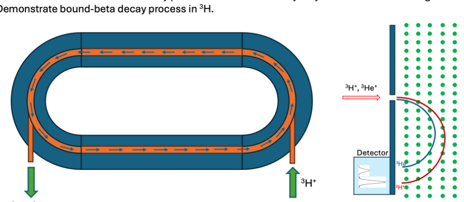
EXPERIMENTAL DESIGN

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



INDIRECT 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 $^3He^+$ ions as they stay in the beam orbit along with $^3H^+$
  -Demonstrate bound-beta decay process in ^3H.



INTERACTION RATES

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

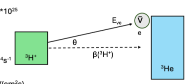
Source: ^3H

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

A_H=0.96 MCi
$p(B\beta) = 5.4 \times 10^{-3}$

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

Φ_{ve}(at 1m) = $1.53*10^9$ 1/(cm^{2}s)



Target: ^3He

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}

$\sigma_{peak} = 3.66 * 10^{-38}$ cm^2

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

Rate = $\Phi_{ve} * \sigma_{eff} * N_{target} * f_{target}$ = $1.53*10^9$ 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

PERSPECTIVE

- Needed to start discussing the above ideas.
- The first step would be a demonstration of $^3H^+$ storage
  -Use of an existing storage ring?
- One would follow up with a measurement of ^3H Bβ-decay fraction ^3He ground state
  -Current estimate $p(B\beta) = 5.4 \times 10^{-3}$.
- Assuming the above is done we would follow up with the design of an adequate $^3H^+$ source and ^3He target detectors for the measurement of the resonant anti-neutrino cross-section.
- Ideas exist to explore reverse problem in a very long term: accelerate ^3He to capture the lowest energy (relic) anti neutrinos.

ENERGY REQUIREMENTS

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

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

$$E_{\bar{\nu}_e(^3H)} = Q_{(^3H)} - \frac{Q^2_{(^3H)}}{2m_{(^3H)}}$$

account for the source atom recoil

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

$$E_{\bar{\nu}_e(^3He)} = Q_{(^3He)} + \frac{Q^2_{(^3He)}}{2m_{(^3He)}}$$

account for the target atom recoil

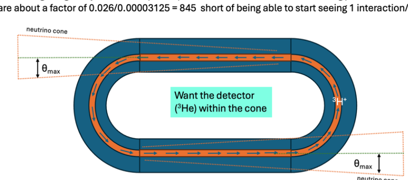
- Neutrino source velocity required to boost neutrinos from the source to resonant capture at target

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

  - Need accelerate source to velocity β

INTERACTION RATES

- "Realistic" case:
  - The unrealistic case above needs accelerate 100g of $^3H^+$ to get a signal of 3785 neutrino interactions/year This would correspond to ~0.026 g of $^3H^+$ for 1 anti-neutrino interaction per year (still in 1000 kg ^3He target.
  - Current storage rings may store ~1Amp ions (= 6.24 * 10^{18} 3H$^+$ ions = 3.125 * 10^{-5} g).
  - We are about a factor of 0.026/0.00003125 = 845 short of being able to start seeing 1 interaction/year.



- A "Typical" ion storage current is up to ~1 Amp for higher-energy, heavy ions.
  - Can we get a significantly higher ion-currents for the low-energy , light ions (such as $^3H^+$)?

REFERENCES

- Inspiration from many works, including the following references:
  - R. S. Raghavan. https://arxiv.org/pdf/hep-ph/0601079, L. Mikaelyan et al, Sov J. Nucl. Phys 6 (1968) 254.
  - R. G. C. Oldeman et al. Eur. Phys. J. C (2010) 65: 81-87.
  - https://link.springer.com/article/10.1140/epja/s10050-023-00985-x
  - Martin Bauer and Jack D. Shergold, https://arxiv.org/pdf/2104.12784

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