An idea for relic neutrino detection with MMC technique

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AMoRE Collaboration Meeting

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Introduction to relic neutrino

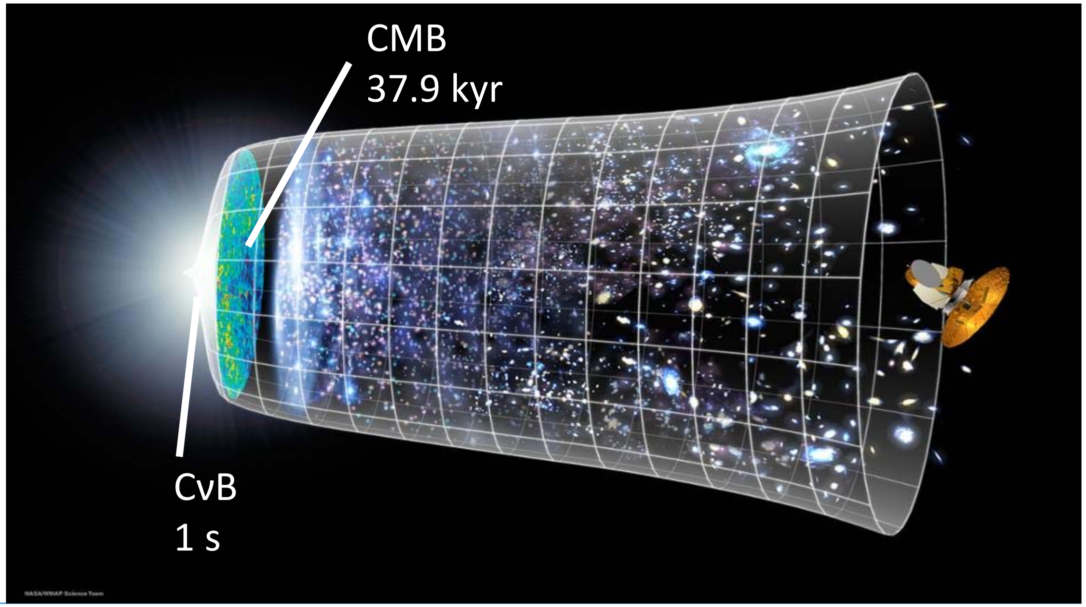
- The relic neutrino
  - The cosmic neutrino background (CνB)

  - Analogous to the cosmic microwave background radiation (CMB)
    - Relic of the Big Bang
    - Born at the very beginning of the universe
    - Cooled but little changed through billions of years

  - Very low average energy
    - 10^{10} K at birth
    - $E_\nu \approx 0.00055$ eV (corresponding to T = 1.95 K) at the present
    - (during the calculation, $E_\nu \approx 0.0005$ eV)

Introduction to relic neutrino

- Why so important?
  - Neutrino decoupled about 1 second after the Big Bang
  - A crucial role in nucleosynthesis, structure formation and the evolution of the universe as a whole.
  - Relic neutrino observation would give us the information of early epochs of our universe history, which were not allowed with CMB detection



Relic neutrino detection with beta decaying isotopes

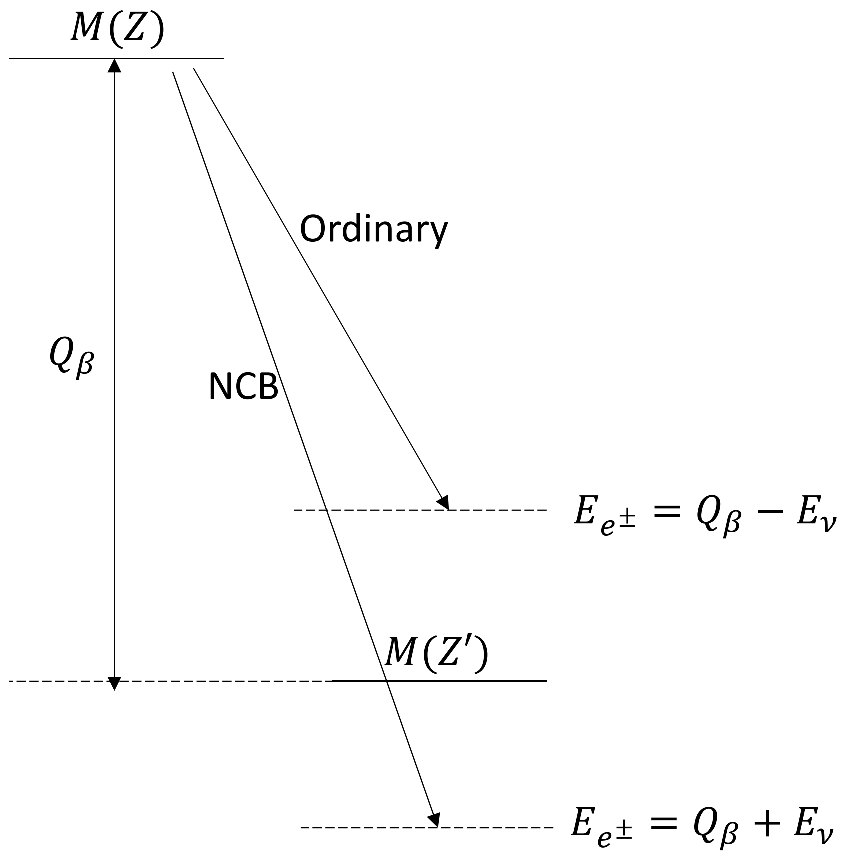
- Instead of ordinary beta(β^-) decay…
  - $n \to p^+ + e^- + \bar{\nu}_e$
  - $(A, Z) \to (A, Z+1) + e^- + \bar{\nu}_e$

- Neutrino absorption
  - $\nu_e + n \to e^- + p^+$
  - $\nu_e + (A, Z) \to (A, Z+1) + e^-$

- (or β^+ decay & antineutrino absorption)

Relic neutrino detection with beta decaying isotopes

- Between NCB (neutrino capture on beta decaying nuclei) interaction and ordinary beta decay, there exists minimum gap of $2m_\nu$ of $E_{e^\pm}$.



Relic neutrino detection with beta decaying isotopes

- Candidate isotopes' conditions:
  1. Long half-life
  2. Large cross-section – more frequent detection
  3. Small Q-value

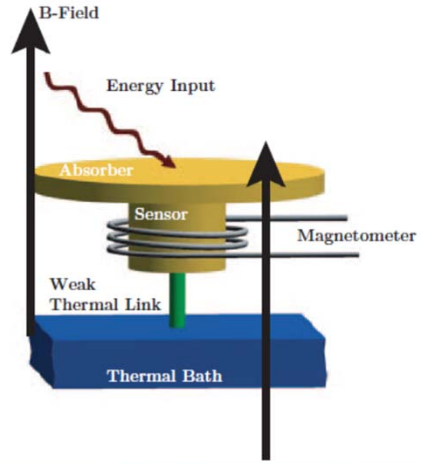
Isotope	Decay	Q_β (keV)	Half-life (sec)	$\sigma_{\rm NCB}(v_\nu/c)$ $(10^{-41}\ {\rm cm}^2)$
^{3}H	β^-	18.591	3.8878×10^8	7.84×10^{-4}
^{63}Ni	β^-	66.945	3.1588×10^9	1.38×10^{-6}
^{93}Zr	β^-	60.63	4.952×10^{13}	2.39×10^{-10}
^{106}Ru	β^-	39.4	3.2278×10^7	5.88×10^{-4}
^{107}Pd	β^-	33	2.0512×10^{14}	2.58×10^{-10}
^{187}Re	β^-	2.64	1.3727×10^{18}	4.32×10^{-11}
^{11}C	β^+	960.2	1.226×10^3	4.66×10^{-3}
^{13}N	β^+	1198.5	5.99×10^2	5.3×10^{-3}
^{15}O	β^+	1732	1.224×10^2	9.75×10^{-3}
^{18}F	β^+	633.5	6.809×10^3	2.63×10^{-3}
^{22}Na	β^+	545.6	9.07×10^7	3.04×10^{-7}
^{45}Ti	β^+	1040.4	1.307×10^4	3.87×10^{-4}

Rate ≈ 75 $\mathrm{yr}^{-1}\ \mathrm{kg}^{-1}$

A. Cocco, G. Mangano, and M. Messina, hep-ph/0703075 (2007).

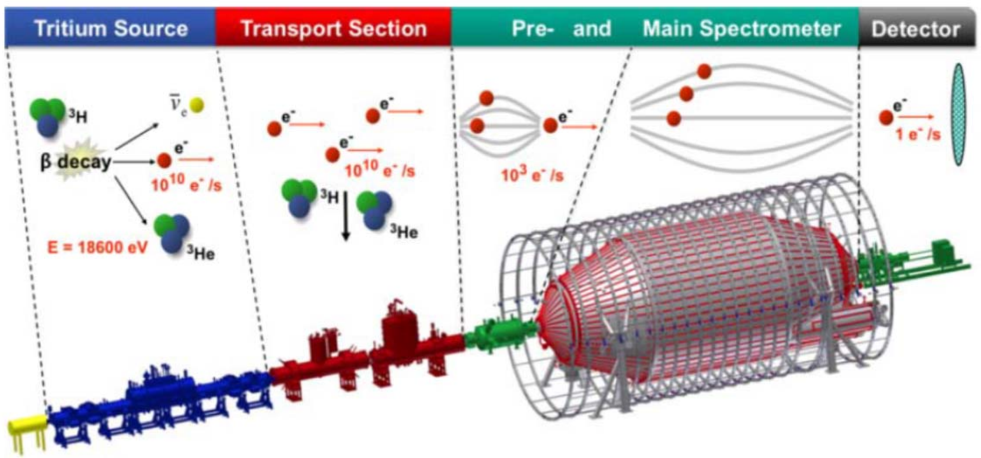
Proposed experiments for relic neutrino detection

1. MARE
   - Direct neutrino probe
   - ^{187}Re source – the lowest known Q-value
   - Magnetic calorimeter with Re-embedded absorber
   - 760 g -> 7.6 $\times 10^{-8}$ yr^{-1} relic neutrino events



Yu-Feng Li, Int.J.Mod.Phys. A30 (2015) no.12, 1530031

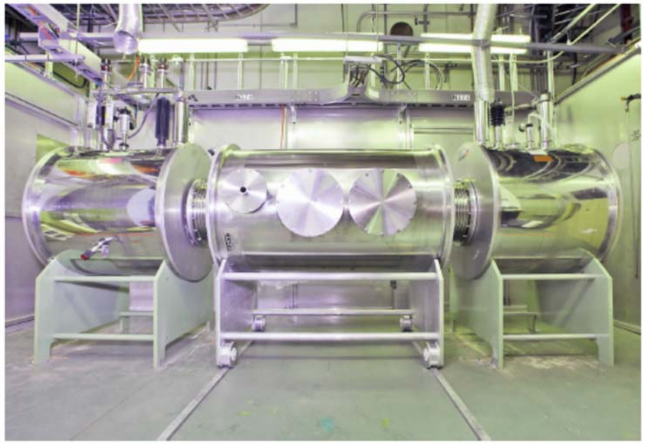
2. KATRIN
   - Molecular tritium source
   - MAC-E filter ($\Delta \sim 0.2$ eV)
   - Expectation:
     - Improve the upper limit of the mass down to: 2.3 eV/c^2 →~0.2 eV/c^2
     - Or discover the actual mass if it is larger than 0.35 eV/c^2
   - 50 μg -> 4.2 $\times 10^{-6}$ yr^{-1} relic neutrino events

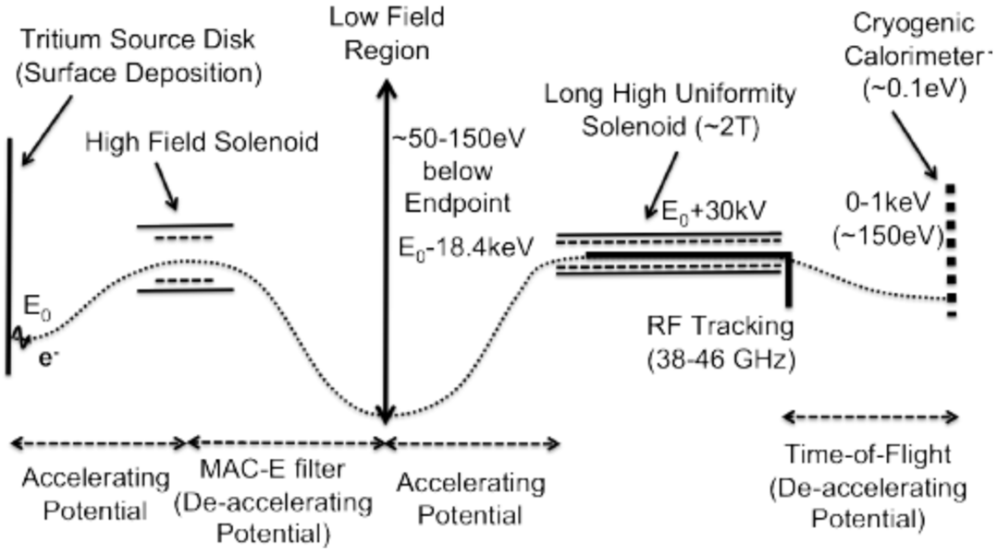


Proposed experiments for relic neutrino detection

3. PTOLEMY

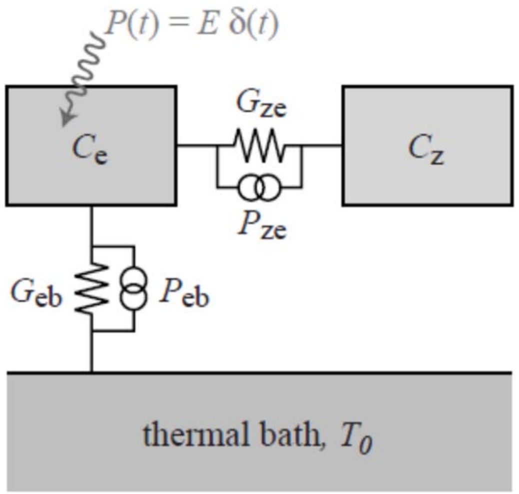
- Detection of relic neutrino
- 100 g of tritium – ~8 events/yr
  - Surface deposition of atomic tritium on graphene (hydaration of graphene)
- Expected to achieve a resolution of 0.15 eV





S. Betts, *et al.*, arXiv:1307.4738 [astro-ph.IM] (2013)

Energy resolution of MMC



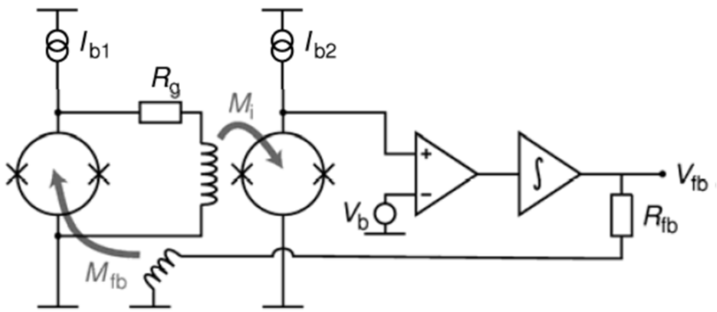
- 1. The fundamental limit of energy resolution
  - The thermal fluctuations of energy between the subsystems of the detector, and between the calorie meter and the thermal reservoir

$$\Delta E_{\mathrm{rms}} = \sqrt{4k_{\mathrm{B}}C_{\mathrm{e}}T^2}\left(\frac{1}{\beta(1-\beta)}\right)^{\frac{1}{4}}\left(\frac{\tau_0}{\tau_1}\right)^{\frac{1}{4}}$$

  - Consider the case in which $C_e = C_z = 0.2\ \mathrm{pJ/K}, \tau_0 = 0.1\ \mu\mathrm{s},\ \ \tau_1 = 100\ \mu\mathrm{s}, T = 10\ \mathrm{mK}.$

    Then we get $\Delta E_{rms} \approx 0.052\ \mathrm{eV}$

Energy resolution of MMC



- 2. Other noise contributions
  A. The magnetic Johnson noise

  $$S_\Phi \propto \sigma k_B T$$

  - Very small

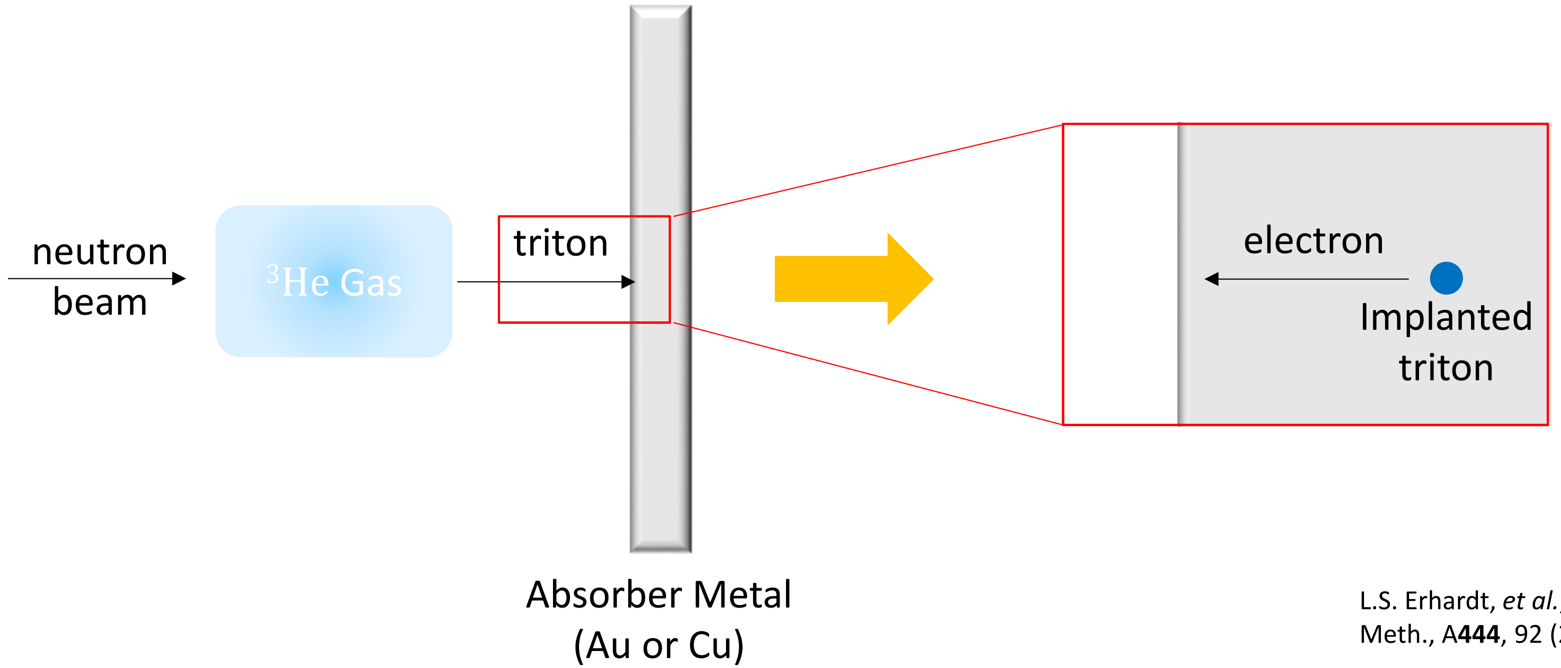
  B. The flux noise of the SQUID

  $$S_\Phi = S_{\Phi,1} + \frac{4k_B T R_g}{(\partial V_1 / \partial \Phi_1)^2_{R_g}} + \frac{S_{\Phi,2}}{G_\Phi^2} + \frac{S_{V,\mathrm{el}}}{(\partial V_1 / \partial \Phi_1)^2 G_\Phi^2}$$

  C. 1/f noise contribution
  - seems to be caused by the magnetic moments of the sensor and to be independent of the temperature

Tritium implantation into metal

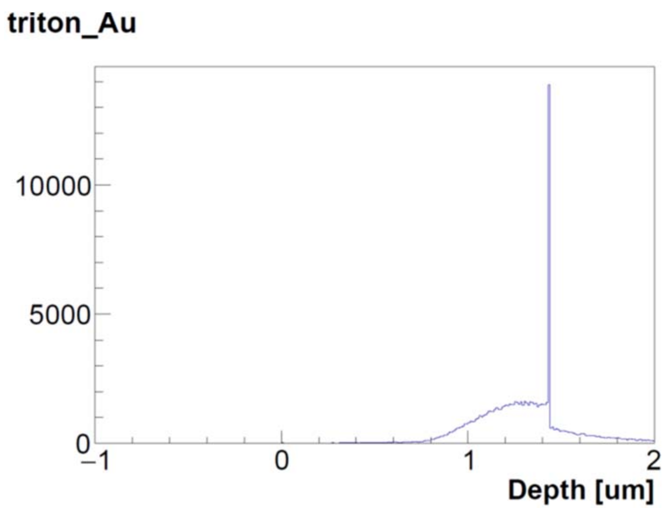
- Implantation – $^{3}He(n,p)^{3}H$ nuclear reaction
  - Neutron capture
  - $^{3}\mathrm{He} + n \rightarrow {}^{3}\mathrm{H} + p$
  - Q-value: 765 keV
  - Emitted tritium: 191 keV

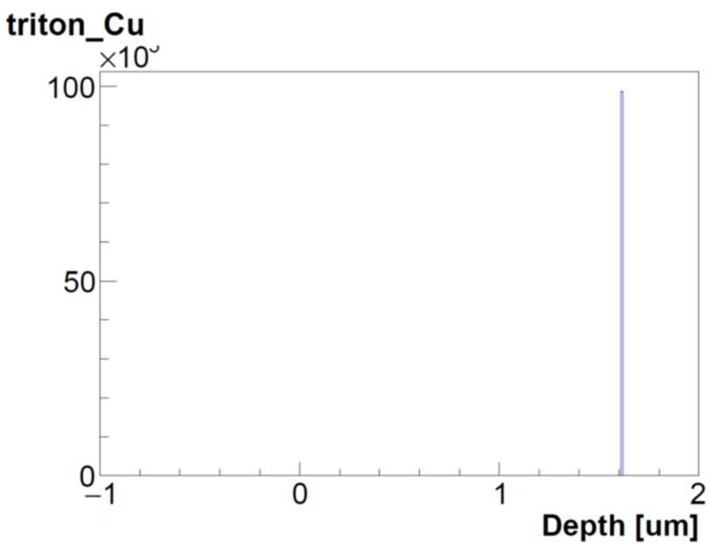


L.S. Erhardt, *et al.*, Nucl. Instrum. Meth., A**444**, 92 (2000)

Tritium implantation into metal

- GEANT4 Simulation (Preliminary)



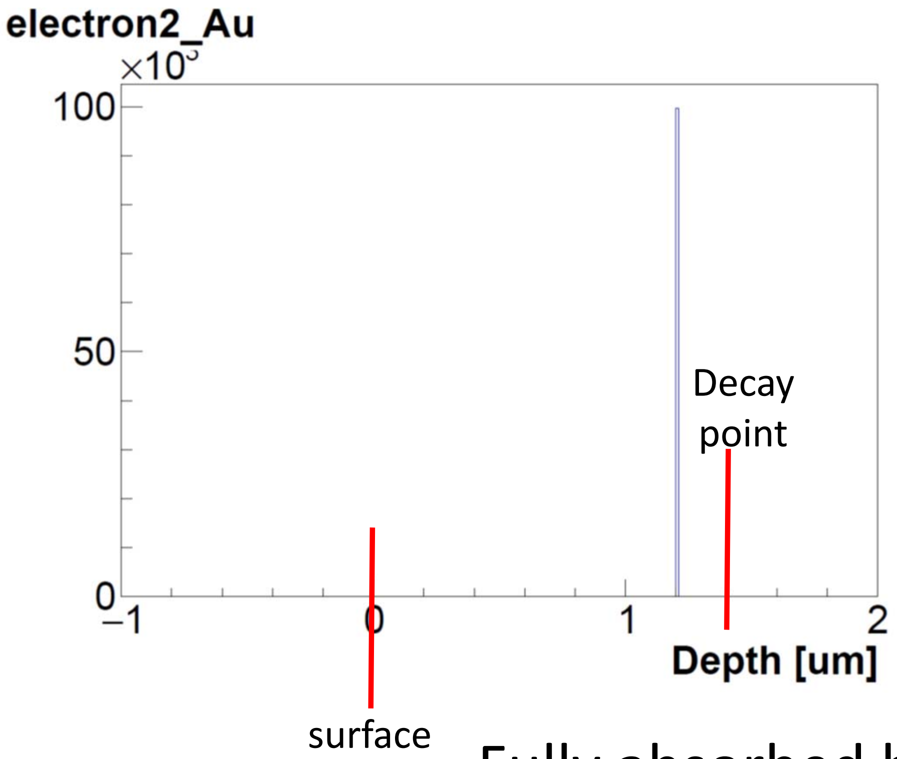


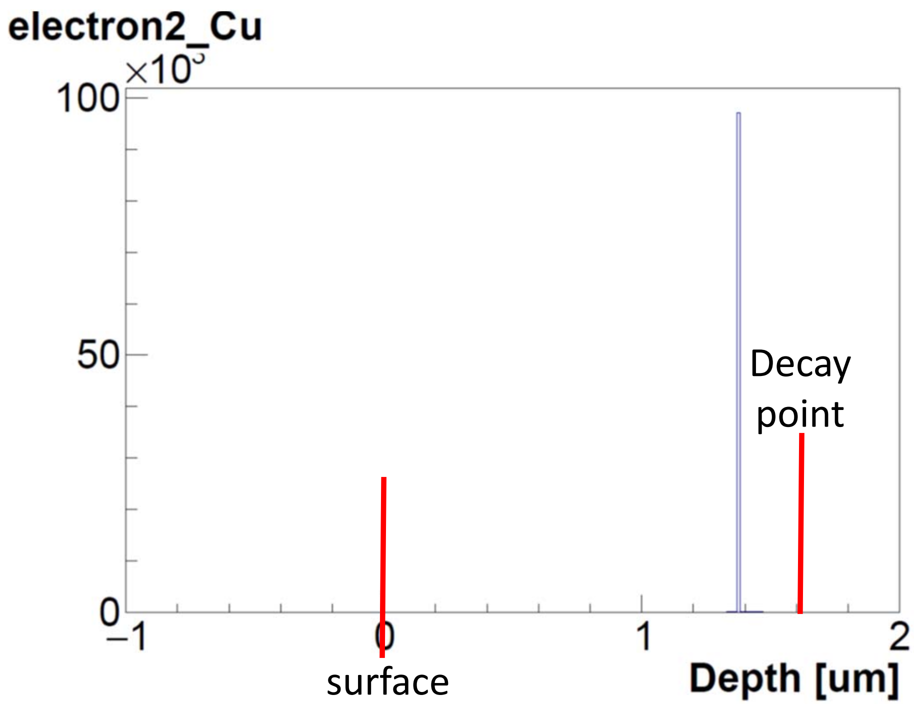
- Expected depth:

1.287 μm 1.618 μm

(Still under study)

18 keV electron: GEANT4 Simulation (Preliminary)





Fully absorbed by the absorber metal

Measurement of beta spectrum near end point

- Implant tritium directly to the gold absorber of MMC (rather than soldering)

- We have assumed the fall time to be 100 μs = measurement rate is 10 kHz

$$A_{Bq} = nN_A \frac{\ln(2)}{t_{1/2}}$$

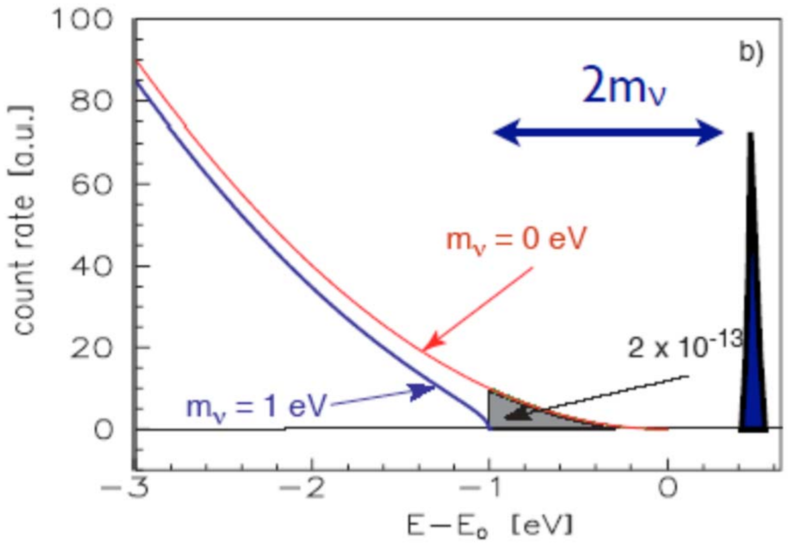
→ 9.3×10^{-12} mol = 2.8×10^{-11} g tritium for each sensor

- Compare with 100 g of PTOLEMY, it requires a huge number of devices!!

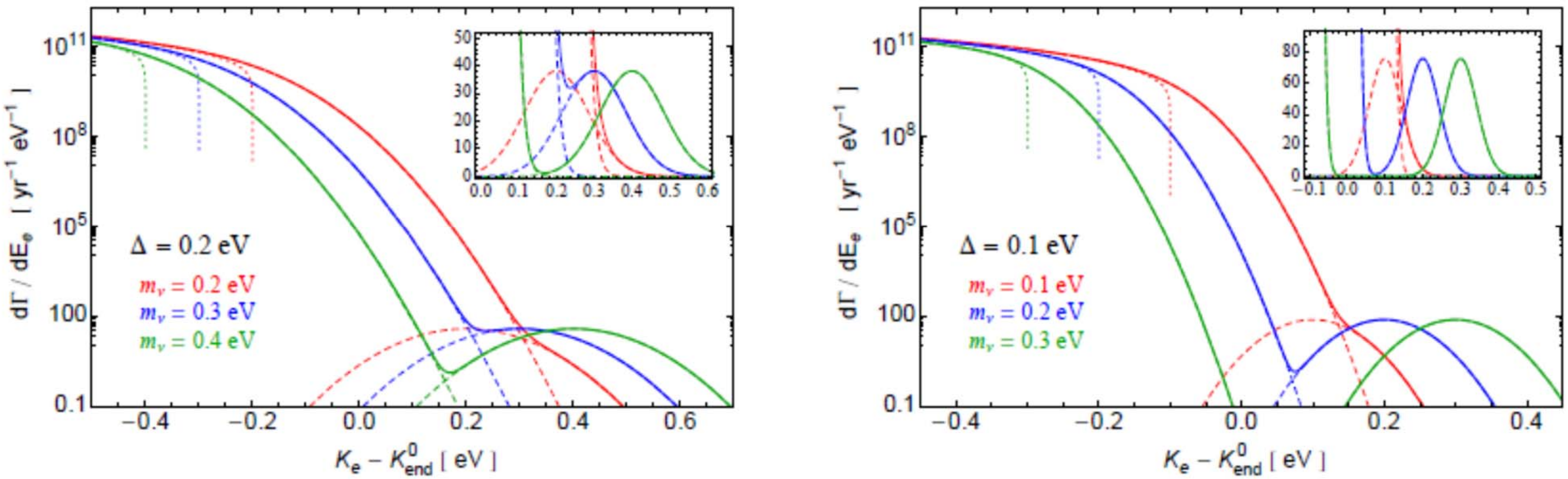
Measurement of beta spectrum near end point

- Low $T_{\nu}(\approx 1.95\text{ K})$ = narrow energy distribution

- To distinguish NCB and beta decay signal with minimum gap of $2m_{\nu}$, we need a resolution of $\Delta < 0.7m_{\nu}$.



Measurement of beta spectrum near end point



Expected spectrums with finite energy resolution and nonzero neutrino mass

A. J. Long, *et al.,* JCAP **1408** (2014) 038

Thank you

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Tritium implantation into metal