PTOLEMY

Neutrino–Nucleus Interactions in the Standard Model and Beyond, CERN

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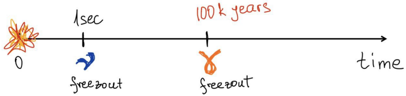
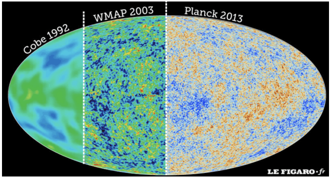
CνB and CMB

Similarly to how relic photons from **CMB**, relic neutrinos form **CνB**.



- In the **early Universe**, neutrinos are in *thermal equilibrium* with normal matter.
- **As the Universe expands** they *decouple* from matter creating a *''picture'' of the early Universe.*



- Right now, in your room, there are **411 relic photons** and **339 relic neutrinos** in every cm^3.
- Most of them are **relic** neutrinos.

Observation of the cosmological neutrinos would then provide a window into the first 0.1 second of creation

Requirements to the experiment

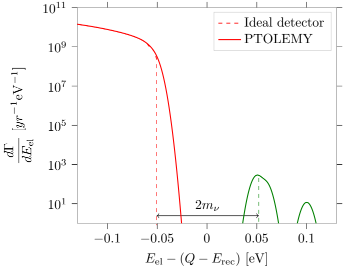
High enough activity

- Low emitter Q-value
- High number of emitters (order of 10^{25})
- Lifetime of emitter: small enough to have a high decay rate, but large enough not to decay instantly

o **Tritium** as a good β-decay emitter.

High enough precision

- Low emitter Q-value
- Low emitter densities - *electron free path bigger than the system size*
- Low volume



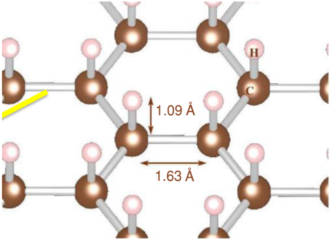
PTOLEMY - state of the art

CνB detection experiment challenge:

- High energy resolution combined with sufficient number of events.

- Gaseous source does not suit (0.93 eV resolution)
- A solid-state based experiment:
- **T on graphene sheets**.
- ≈ 4 CνB **events per year**.
- **energy resolution** $\approx 10\,\text{meV}$.

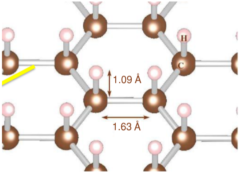
P on-
T ecorvo
O bservatory for
L ight,
E arly-universe,
M assive-neutrino
Y ield



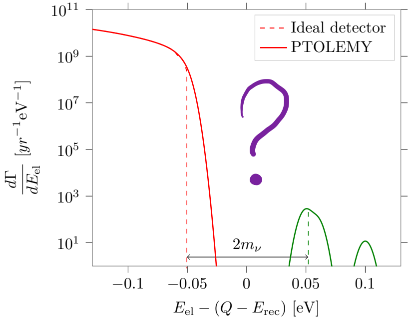
One needs to account for the intrinsic energy resolution

The **width of the peak** that serves as a signature of CνB is defined by

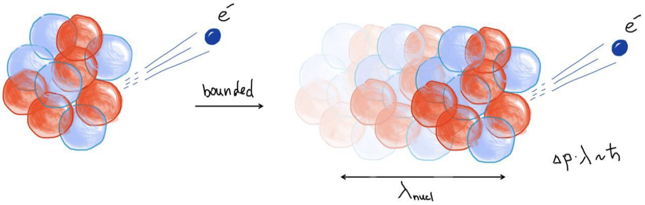
- *energy resolution* of the measurement
- physical *smearing* of the energies of individual electrons



- The presence of the substrate changes the intrinsic (before measurement) energy spectrum of the emitted electron.
- Introducing additional broadening of the electron spectrum.
- Which leads to intrinsic irreducible limitations on the energy resolution.



General mechanism of the broadening



- For a bonded system, recoil energy of the nucleus is not fixed by the kinematics but has some distribution.
- Uncertainty[1] in the velocity of the centre of mass of the nucleus

$$\Delta u \approx \frac{\hbar}{m_{\text{nucl}}\lambda_{\text{nucl}}}.$$

- The energy of the electron is measured in the laboratory frame of reference, where it acquires an uncertainty

$$\Delta E \approx m_e v_e \Delta u.$$

[1]from the Heisenberg uncertainty principle.

Energy broadening for the β-decay of the Tritium on graphene

$$\frac{\Delta E}{\sqrt{\hbar m_e}} \approx \underbrace{\varkappa^{1/4}}_{\text{potential}} \underbrace{\left[\frac{Q^2}{m_{\text{nucl}}^3}\right]^{\frac{1}{4}}}_{\text{nucleus}}$$

The uncertainty in the electron energy ΔE:

- Is of the order of 0.5 eV.
- Is 2 orders of magnitude greater than the resolution needed to see the CνB signal.
- Weakly depends on the potential stiffness.
- For molecular tritium the estimate is of the same order.
- Strongly depends on the radioactive nucleus.
- Agrees with the quantum calculation[2]

[2] Fermi Golden Rule.

Mechanisms of the intrinsic energy broadening

- **Chemical bonding of the atom to the substrate.**
- **Impurity screening by charges in the substrate.**
- **X-ray edge singularity.**
- Lattice vibrations
- Emission of plasmons and surface polaritons
- Creation of shock wave emission due to the motion of the emitted electron at grazing angles at speeds exceeding the Fermi velocity
- Inhomogeneous broadening
- ...

Solution

- Two ways to reduce ΔE:

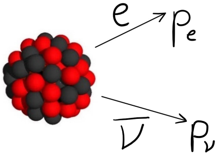
  1. **Modify the bounding potential**: decrease the stiffness constant
  $$\lambda_{\rm el} = (\hbar^2/m_e\kappa)^{1/4}$$

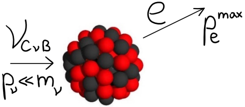
  2. **Use heavy β-emitter**: decrease the parameter
  $$\gamma = \left[\frac{Q^2 m_e}{m_{\rm nucl}^3 c^4}\right]^{\frac{1}{4}}$$

- A suitable β-emitter must have the following properties:
  1. small γ parameter: $\gamma/\gamma_{^3\rm H} \lesssim 0.1$ ($\Delta E \lesssim 50\,\rm meV$)
  2. lifetime $\tau \gtrsim 1$ year
  3. only β-decay. The daughter atom should be stable
  4. sufficiently large neutrino capture rate (?)

$$\Longrightarrow \qquad {}^{171}_{69}\mathrm{Tm}, \qquad {}^{151}_{61}\mathrm{Sm}$$

Naive capture rate





$$\frac{d\Gamma}{dE_e} = \frac{p_\nu E_\nu p_e E_e}{2\pi^3} \times \sum |\mathcal{M}_\mathcal{H}|^2 \qquad (\sigma v)_\nu = \frac{p_e^{\max} E_e^{\max}}{\pi} \times \frac{1}{2} \sum |\mathcal{M}_\mathcal{H}|^2$$

The simplest assumption: $\sum |\mathcal{M}_\mathcal{H}|^2 \approx$ const:

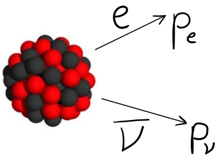
$$(\sigma v)_\nu \approx \frac{1}{\tau} \frac{p_e^{\max} E_e^{\max}}{\int_{m_e}^{m_e+Q} p_\nu E_\nu p_e E_e \, dE_e}$$

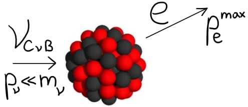
- For many known spectra [Cocco et al, 2007] this estimate is accurate within a factor of two

$$(\sigma v)_\nu = \delta \times (\sigma v)_{\text{est.}}$$

Isotope	Q, keV	τ, year	$(\sigma v)_\nu$, 10^{-46} cm^2	δ
^{3}H	18.591	17.8	39.2	0.86
^{63}Ni	66.945	145	$6.9 \cdot 10^{-2}$	0.57
^{93}Zr	60.63	$2.27 \cdot 10^6$	$1.20 \cdot 10^{-5}$	1.15
^{106}Ru	39.4	1.48	29.4	0.51
^{107}Pd	33	$9.38 \cdot 10^6$	$1.29 \cdot 10^{-5}$	0.83
^{187}Re	2.646	$6.28 \cdot 10^{10}$	$2.16 \cdot 10^{-6}$	0.48

Naive capture rate





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The simplest assumption: $\sum |\mathcal{M}_\mathcal{H}|^2 \approx$ const:

$$(\sigma v)_\nu \approx 5.3 \cdot 10^{-46}\,\mathrm{cm}^2 \times \frac{1\,\mathrm{year}}{\tau} \times \left(\frac{100\,\mathrm{keV}}{Q}\right)^3$$

allows to connect the neutrino capture rate and the lifetime

- For many known spectra [Cocco et al, 2007] this estimate is accurate within a factor of two

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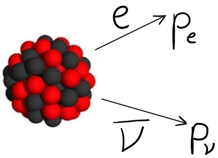
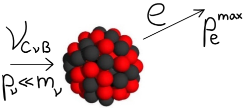




$$\frac{d\Gamma}{dE_e} = \frac{p_\nu E_\nu p_e E_e}{2\pi^3} \times \sum |\mathcal{M}_\mathcal{H}|^2 \qquad (\sigma v)_\nu = \frac{p_e^{\max} E_e^{\max}}{\pi} \times \frac{1}{2} \sum |\mathcal{M}_\mathcal{H}|^2$$

- The simplest assumption: $\sum |\mathcal{M}_\mathcal{H}|^2 \approx \text{const}$:

$$(\sigma v)_\nu \approx 5.3 \cdot 10^{-46}\,\text{cm}^2 \times \frac{1\,\text{year}}{\tau} \times \left(\frac{100\,\text{keV}}{Q}\right)^3$$

  allows to connect the neutrino capture rate and the lifetime

- For ^{171}Tm, ^{151}Sm this gives

$$\boxed{\Gamma^{^{171}\text{Tm}}_{\text{capture}} = 0.05 \times \Gamma^{^{3}\text{H}}_{\text{capture}}, \qquad \Gamma^{^{151}\text{Sm}}_{\text{capture}} = 0.002 \times \Gamma^{^{3}\text{H}}_{\text{capture}} \qquad \text{(crude estimate)}}$$

Problem with ^{171}Tm and ^{151}Sm [3]

In general, we cannot deduce the neutrino capture rate from the lifetime of the emitter

$$(\sigma v)_\nu = \frac{1}{\tau} \frac{p_e^{\max} E_e^{\max} \sum |\mathcal{M}_{\mathcal{H}}(p_e^{\max}, p_\nu \to 0)|^2}{\int_{m_e}^{m_e+Q} p_\nu E_\nu p_e E_e \sum |\mathcal{M}_{\mathcal{H}}(p_e, p_\nu)|^2 \, dE_e}$$

Unique

$$\sum |\mathcal{M}_{\mathcal{H}}|^2 = C \cdot f(p_e, p_\nu)$$

- one final state
- C - single nuclear constant
- f - known function of p_e, p_ν

Nonunique

$$\sum |\mathcal{M}_{\mathcal{H}}|^2 = \sum c_i \cdot f_i(p_e, p_\nu)$$

- *several* possible final states
- c_i - *several* nuclear constants
- f_i - known functions of p_e, p_ν

For nonunique transitions we cannot extract many constants c_i from lifetime τ only - **cannot predict** $\sum |\mathcal{M}_{\mathcal{H}}(p_e^{\max}, p_\nu \to 0)|^2 \propto (\sigma v)_\nu$!

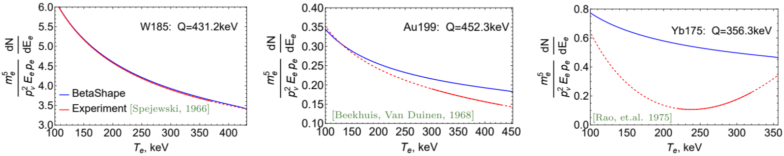
[3] [Mikulenko, Cheipesh, Cheianov, Boyarsky, 2021]

ξ-approximation

- For some isotopes with large parameter $\xi \equiv \frac{\alpha Z}{R_{\text{nucl}} Q} \gg 1$ the matrix element can be expanded in ξ:

$$\sum |\mathcal{M}_{\mathcal{H}}|^2 = C \cdot \xi^2 \cdot f(p_e, p_\nu) + O(\xi)$$

- Then the transition may be treated as unique. This is known as *ξ-approximation*
- We cannot be sure that some sort of interference and cancellation between various nuclear transitions does not happen $C \to 0$.



$$\xi \approx 40$$

- For Samarium the experimental spectrum [Loidl et al, 2020] shows perfect agreement with the ξ-approximation

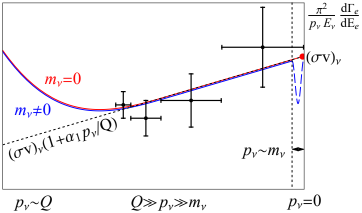
Neutrino capture rate from experimental spectrum

- for non-unique, $(\sigma v)_\nu$ cannot be predicted from lifetime τ **only**
- Strictly, we can not be 100% sure in the validity of ξ-approximation for ^{171}Tm
- Measure it directly from the spectrum! [Mikulenko, et.al. 2021]

$$\frac{\pi^2}{p_\nu^2}\frac{d\Gamma_\beta}{dE_e} = (\sigma v)_\nu \times \left[1 + \alpha_1 p_\nu/Q + O(p_\nu^2/Q^2)\right]$$

$$p_\nu = Q + m_e - E_e \ll Q$$

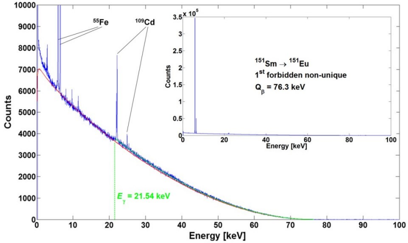
$$p_\nu \gg m_\nu$$



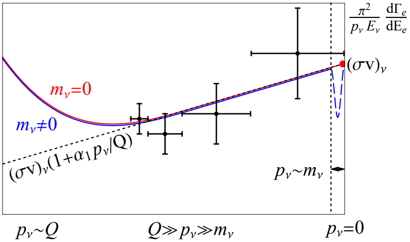
1. Measure the spectrum in several energy bins with width ΔE near the endpoint
2. Make a linear fit of $\frac{\pi^2}{p_\nu^2}\frac{d\Gamma_\beta}{dE_e}$
3. The endpoint value $= \sigma v$ for neutrino capture!

Alternative approach

- As was shown in [Brdar, Plestid, Rocco, 2022], if the ξ-approximation holds (spectrum is known up to $1/\xi$ corrections), the value of cross-section may be extracted directly from the lifetime with the theoretical uncertainty of 1% order
- *Alternative approach*: measure the spectrum in a wide kinematic range to verify the ξ-approximation
  1. if valid: the estimates of σv can be made without experimental error
  2. if not: we still need to extract σv from the end of the spectrum



^{151}Sm [Loidl, et.al. 2020].
Blue - exp., red - ξ-appr.



Results

- Before the actual measurement, let us make an estimate
- With the BetaShape spectra, which are computed under the ξ-approximation, the capture rates are:

$$\Gamma^{^{171}\mathrm{Tm}}_{\mathrm{capture}} = 3 \cdot 10^{-2} \Gamma^{^{3}\mathrm{H}}_{\mathrm{capture}}, \qquad \Gamma^{^{151}\mathrm{Sm}}_{\mathrm{capture}} = 10^{-3} \Gamma^{^{3}\mathrm{H}}_{\mathrm{capture}}$$

— consistent with the crude estimate up to a factor of two

- Assuming local relic neutrino concentration $\eta_\nu = 56\,\mathrm{cm}^{-3}$ and Majorana nature, we need

$$\boxed{N_{\text{atoms for event/year}} = \begin{cases} 2 \cdot 10^{24}, & ^{3}\mathrm{H} \\ 10^{26}, & ^{171}\mathrm{Tm} \\ 2 \cdot 10^{27}, & ^{151}\mathrm{Sm} \end{cases}}$$

Back-up

- Assuming local relic neutrino concentration $\eta_\nu = 56\,\mathrm{cm}^{-3}$ and Majorana nature, we need

$$\boxed{N_{\text{atoms for event/year}} = \begin{cases} 2 \cdot 10^{24}, & {}^{3}\mathrm{H} \\ 10^{26}, & {}^{171}\mathrm{Tm} \\ 2 \cdot 10^{27}, & {}^{151}\mathrm{Sm} \end{cases}}$$

- With atom density on a graphene sheet $3.8 \cdot 10^{15}\,\mathrm{cm}^{-2}$ and separation of mm between sheets, event/year targer would have the volume

$$\begin{aligned} {}^{3}\mathrm{H}: &\qquad V \approx 1\,\mathrm{m} \times 8\,\mathrm{m} \times 8\,\mathrm{m} \\ {}^{171}\mathrm{Tm}: &\qquad V \approx 10\,\mathrm{m} \times 16\,\mathrm{m} \times 16\,\mathrm{m} \\ {}^{151}\mathrm{Sm}: &\qquad V \approx 20\,\mathrm{m} \times 50\,\mathrm{m} \times 50\,\mathrm{m}. \end{aligned}$$