Relic Neutrino detection using neutrino capture on beta decaying nuclei

Alfredo G. Cocco
Istituto Nazionale di Fisica Nucleare
(Italy)

The longstanding question

Is it possible to detect/measure the Cosmological
Relic Neutrino background (CνB) ?

We know that neutrino of CνB are non-relativistic
and weakly-clustered

- UHE cosmic rays scattering (indirect, unknown sources)
- Torsion balance (target polarization, strong ν-$\bar{\nu}$ asymmetry)
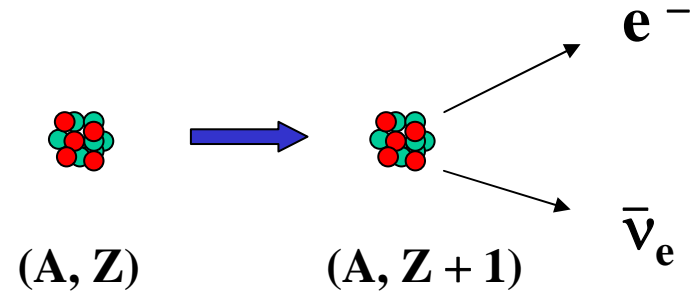
Short answer: NO !!

All the methods proposed so far require either strong
theoretical assumptions or experimental apparatus having
unrealistic performances

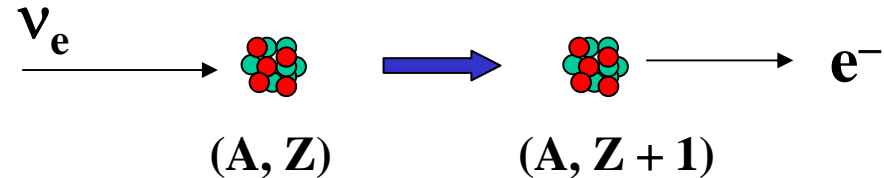A.Ringwald "Neutrino Telescopes" 2005 – hep-ph/0505024
G.Gelmini hep-ph/0412305

Neutrino capture on $\beta^{\pm}$ decaying nuclei

Beta decay

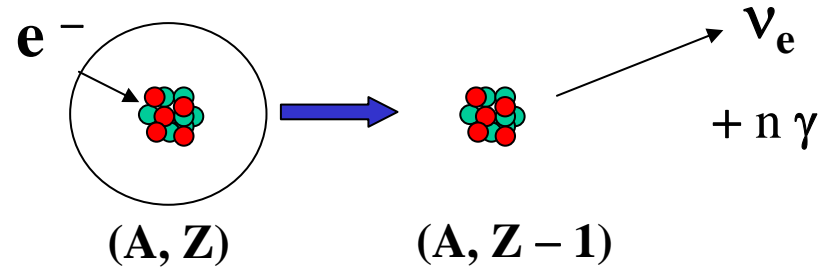$$(A, Z) \longrightarrow (A, Z+1) \quad \begin{array}{c} e^- \\ \bar{\nu}_e \end{array}$$

Neutrino Capture on a
Beta Decaying Nucleus
(NCB)

$$\nu_e \longrightarrow (A, Z) \longrightarrow (A, Z+1) \longrightarrow e^-$$

This process has no energy threshold !

Antineutrino capture on EC decaying nuclei

Electron Capture

e^-

ν_e

$+\, n\,\gamma$

(A, Z) $(A, Z-1)$

$\overline{\nu}$ and electron Capture

$\overline{\nu}_e$ e^-

$+\, n\,\gamma$

(A, Z) $(A, Z-1)$

This process has no energy threshold !

Antineutrino Capture

$\overline{\nu}_e$

e^+

(A, Z) $(A, Z-1)$
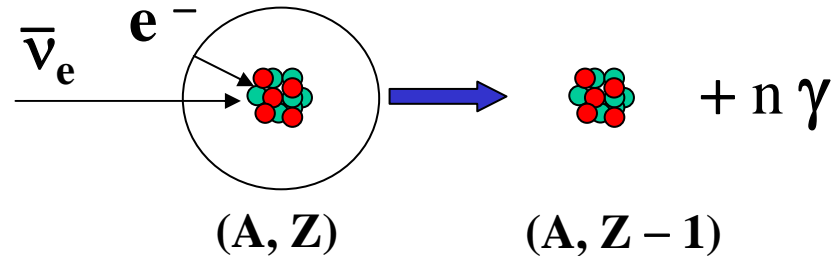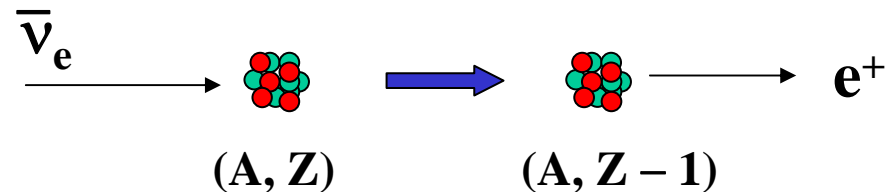
E_ν **threshold** $= 2m_e - Q_{EC}$

The effect of $m_\nu \neq 0$

Neutrino masses of the order of 1 eV are compatible with the present picture of our Universe

Neutrino capture on $\beta^{\pm}$ decaying nuclei
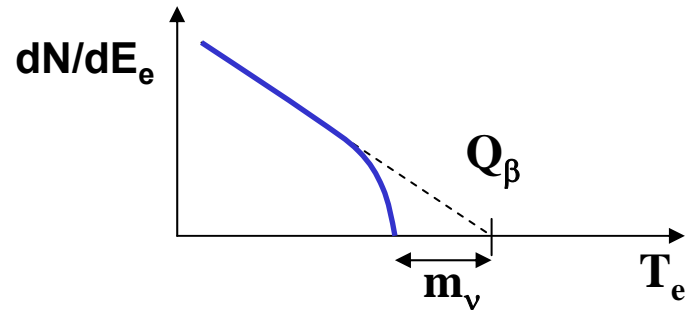## (exploiting $m_\nu \neq 0$)

Beta decay
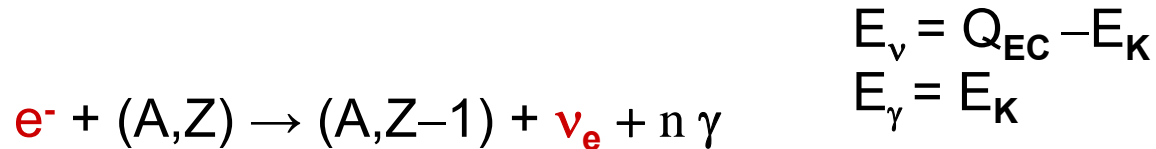
Neutrino Capture on a
Beta Decaying Nucleus

dN/dE_e

Q_β

m_ν

T_e

$2m_\nu$

dN/dE_e

Q_β

m_ν

T_e
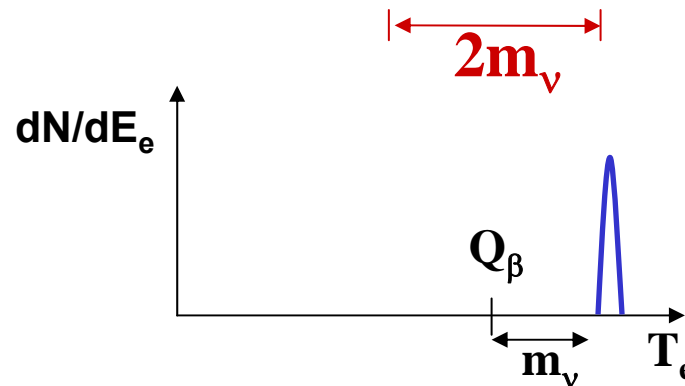
The events induced by Neutrino Capture have a unique
signature provided by a gap of $2m_\nu$ centered at Q_β

Antineutrino capture on EC decaying nuclei
(exploiting $m_\nu \neq 0$)

Electron Capture

$$E_\nu = Q_{EC} - E_K$$
$$E_\gamma = E_K$$

$$e^- + (A,Z) \rightarrow (A,Z-1) + \nu_e + n\,\gamma$$

E_K = captured electron binding energy

$$\overline{\nu}_e + e^- + (A,Z) \rightarrow (A,Z-1) + X \qquad \text{Always energetically allowed}$$

$$\text{IF: } E_K - m_\nu \leq Q_{EC} < E_K + m_\nu \qquad (\text{ in the limit } E_\nu \rightarrow m_\nu)$$

the EC decay is forbidden (no background)

$$\overline{\nu}_e + (A,Z) \rightarrow (A,Z-1) + e^+ \qquad E_{thr} = 2m_e - Q_{EC}$$
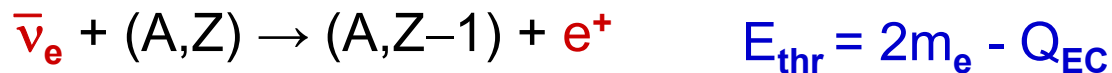
$$\text{IF: } 2m_e - m_\nu \leq Q_{EC} < 2m_e + m_\nu$$

no threshold and the β^+ decay is forbidden (no background)

NCB Cross Section
a new parametrization

Beta decay rate
$$\lambda_\beta = \frac{G_\beta^2}{2\pi^3} \int_{m_e}^{W_o} p_e E_e F(Z, E_e) C(E_e, p_\nu)_\beta E_\nu p_\nu \, dE_e$$

NCB
$$\sigma_{\text{NCB}} v_\nu = \frac{G_\beta^2}{\pi} p_e E_e F(Z, E_e) C(E_e, p_\nu)_\nu$$

The nuclear shape factors C_β and C_ν both depend on the same nuclear matrix elements

It is convenient to define
$$\mathcal{A} = \int_{m_e}^{W_o} \frac{C(E_e', p_\nu')_\beta}{C(E_e, p_\nu)_\nu} \frac{p_e'}{p_e} \frac{E_e'}{E_e} \frac{F(E_e', Z)}{F(E_e, Z)} E_\nu' p_\nu' \, dE_e'$$

$$\boxed{\sigma_{\text{NCB}} v_\nu = \frac{2\pi^2 \ln 2}{\mathcal{A} \, t_{1/2}}}$$

More details in: AGC, M.Messina and G.Mangano JCAP 06(2007)015

NCB Cross Section
a new parametrization

$$\sigma_{\mathrm{NCB}} v_\nu = \frac{2\pi^2 \ln 2}{\mathcal{A} \, t_{1/2}}$$

This is valid for both $\beta^\pm$ and EC decaying nuclei

$$\mathcal{A} = \int_{m_e}^{W_o} \frac{C(E'_e, p'_\nu)_\beta}{C(E_e, p_\nu)_\nu} \frac{p'_e}{p_e} \frac{E'_e}{E_e} \frac{F(E'_e, Z)}{F(E_e, Z)} E'_\nu p'_\nu dE'_e$$

$\overset{(\overline{})}{\nu}$ capture on $\beta^\pm$ nuclei

$$\mathcal{A} = \frac{\sum_x n_x C_x(q_\nu) f_x(q_\nu)}{p_e E_e F(Z, E_e) C(p_e, p_\nu)_\nu}$$

$\overline{\nu}$ capture on EC nuclei

$$\mathcal{A}' = \frac{\sum_x n_x C_x(q_\nu) f_x(q_\nu)}{\sum_x n_x C_x(E_\nu) g_x \rho_x(E_\nu)}$$

$\overline{\nu}$ + e$^-$ capture on EC nuclei

In a large number of cases $\mathcal{A}$ can be evaluated in an exact way and NCB cross section depends only on Q_β and $t_{1/2}$ (measurable)

Example: NCB Cross Section
on β± nuclei for different types of decay transitions

- Superallowed transitions

$$\sigma_{\mathrm{NCB}} v_\nu = 2\pi^2 \ln 2 \frac{p_e E_e F(Z, E_e)}{f t_{1/2}}$$

- This is a very good approximation also for allowed transitions since

$$\frac{C(E_e, p_\nu)_\beta}{C(E_e, p_\nu)_\nu} \simeq 1$$

- *i-th* unique forbidden

$$C(E_e, p_\nu)_\beta^i = \left[\frac{R^i}{(2i+1)!!} \right]^2 \left| {}^A F_{(i+1)\,i\,1}^{(0)} \right|^2 u_i(p_e, p_\nu)$$

$$\mathcal{A}_i = \int_{m_e}^{W_o} \frac{u_i(p_e', p_\nu') p_e' E_e' F(Z, E_e')}{u_i(p_e, p_\nu) p_e E_e F(Z, E_e)} E_\nu' p_\nu' \mathrm{d} E_e'$$

NCB Cross Section Evaluation
The case of Tritium

Using the expression $\qquad \sigma_{\text{NCB}} v_\nu = \dfrac{G_\beta^2}{\pi} p_e E_e F(Z, E_e) C(E_e, p_\nu)_\nu$

we obtain $\qquad \sigma_{\text{NCB}}(^3\text{H}) \dfrac{v_\nu}{c} \underset{\lim \beta \to 0}{=} (7.7 \pm 0.2) \times 10^{-45} \text{ cm}^2$

where the error is due to Fermi and Gamow-Teller matrix element uncertainties

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Using shape factors ratio $\quad \sigma_{\text{NCB}} v_\nu = 2\pi^2 \ln 2 \dfrac{p_e E_e F(Z, E_e)}{ft_{1/2}}$

$$\sigma_{\text{NCB}}(^3\text{H}) \dfrac{v_\nu}{c} \underset{\lim \beta \to 0}{=} (7.84 \pm 0.03) \times 10^{-45} \text{ cm}^2$$

where the error is due only to uncertainties on Q_β and $t_{1/2}$

NCB Cross Section Evaluation
specific cases

β±

Isotope	Decay	Q (keV)	Half-life (sec)	$\sigma_{\rm NCB}(v_\nu/c)$ (10^{-41} 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}

EC

Isotope	Decay $(J_i \to J_f)$	$E_\nu^{\rm thr}$ (keV)	Half-life (sec)	$\sigma_{\rm NCB}$ (10^{-41} cm^2)
^{7}Be	$\frac{3}{2}^- \to \frac{1}{2}^-$	637.80	4.40×10^7	6.80×10^{-3}
^{7}Be	$\frac{3}{2}^- \to \frac{3}{2}^-$	160.18	5.13×10^6	1.16×10^{-2}
^{55}Fe	$\frac{3}{2}^- \to \frac{5}{2}^-$	790.62	8.64×10^7	1.55×10^{-5}
^{68}Ge	$0^+ \to 1^+$	916.00	2.34×10^7	1.39×10^{-4}
^{178}W	$0^+ \to 1^+$	930.70	1.87×10^6	5.14×10^{-4}
^{41}Ca	$\frac{7}{2}^- \to \frac{3}{2}^+$	600.61	3.22×10^{12}	8.35×10^{-9}
^{81}Kr	$\frac{7}{2}^+ \to \frac{3}{2}^-$	741.30	7.23×10^{12}	2.40×10^{-9}
^{100}Pd	$0^+ \to 2^-$	693.68	3.14×10^5	4.17×10^{-4}
^{123}Te	$\frac{1}{2}^+ \to \frac{7}{2}^+$	970.70	1.89×10^{22}	5.40×10^{-15}

**$E_\nu = E_{\rm thr} + 1$ MeV
K capture**

Nuclei having the highest product
$$\sigma_{\rm NCB}\ t_{1/2}$$

Relic Neutrino Detection
using $\beta^{\pm}$ decaying nuclei

In the case of Tritium we estimate that 7.5 neutrino capture events per year are obtained using a total mass of 100 g

Signal to background ratio depends crucially on the energy resolution (Δ) at the beta decay endpoint (It works only if $\Delta < m_\nu$)

As an example, given a neutrino mass of 0.7 eV and an energy resolution at the beta decay endpoint of Δ=0.2 eV a signal to background ratio of 3 is obtained. In the case of 100 g mass target of Tritium it would take one and a half year to observe a 5σ effect
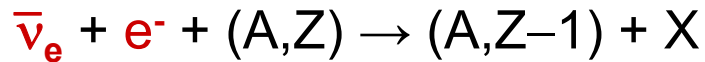
In case of CνB gravitational clustering we expect a significant signal enhancement

m_ν (eV)	FD (events yr^{-1})	NFW (events yr^{-1})	MW (events yr^{-1})
0.6	7.5	90	150
0.3	7.5	23	33
0.15	7.5	10	12

FD = Fermi-Dirac NFW= Navarro,Frenk and White
MW=Milky Way (Ringwald, Wong)

Relic Neutrino Detection
using EC decaying nuclei

$\overline{\nu}_e + e^- + (A,Z) \rightarrow (A,Z-1) + X$

The lack of a suitable final state prevents the use of this reaction to detect CνB unless either:

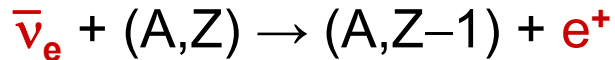1) there exist an excited level (either atomic or nuclear) with energy
$$E_o = Q_{EC} - E_K + m_\nu$$

2) the captured electron is "off-mass" shell $m_{eff} = m_e - E_o$

3) it exist a nucleus A (stable) for which $Q_{EC} = E_K - m_\nu$

Relic Antineutrino Detection
using EC decaying nuclei

$$\overline{\nu}_e + (A,Z) \rightarrow (A,Z-1) + e^+$$

The energy threshold prevents the use of this reaction to detect CνB unless:

1) use CνB as a target for accelerated fully ionized beam
   - EC decay is inhibited (no electrons to be captured)

   - Ions should have $\quad \gamma_{\min} = \dfrac{E_{\text{thr}}}{m_\nu}$

   - Interaction rate is given by $\quad \lambda_{\text{NCB}} = \dfrac{n_{\bar{\nu}} \, 2\pi^2 \ln 2}{\mathcal{A} \cdot t^{\text{EC}}_{1/2}} \, \mathcal{N}$

For allowed transitions and using $n_\nu = 56$, $E_{\text{thr}} = 10$ eV :
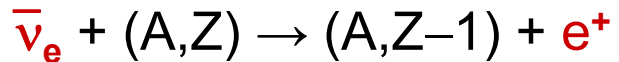
$$\mathcal{N} = 10^{13}$$
$$\gamma = 100$$

$$\lambda_{\text{NCB}} \simeq 10^{-18} \text{ s}^{-1}$$

Too slow to be detected !

Relic Antineutrino Detection
using EC decaying nuclei

$\overline{\nu}_e$ + (A,Z) $\rightarrow$ (A,Z–1) + e^+

2) there exist a nucleus for which

$$2m_e - m_\nu < Q_{EC} < 2m_e + m_\nu$$

In this case:

- the reaction has no energy threshold on the incoming antineutrino

- unique signature since β^+ decay is forbidden

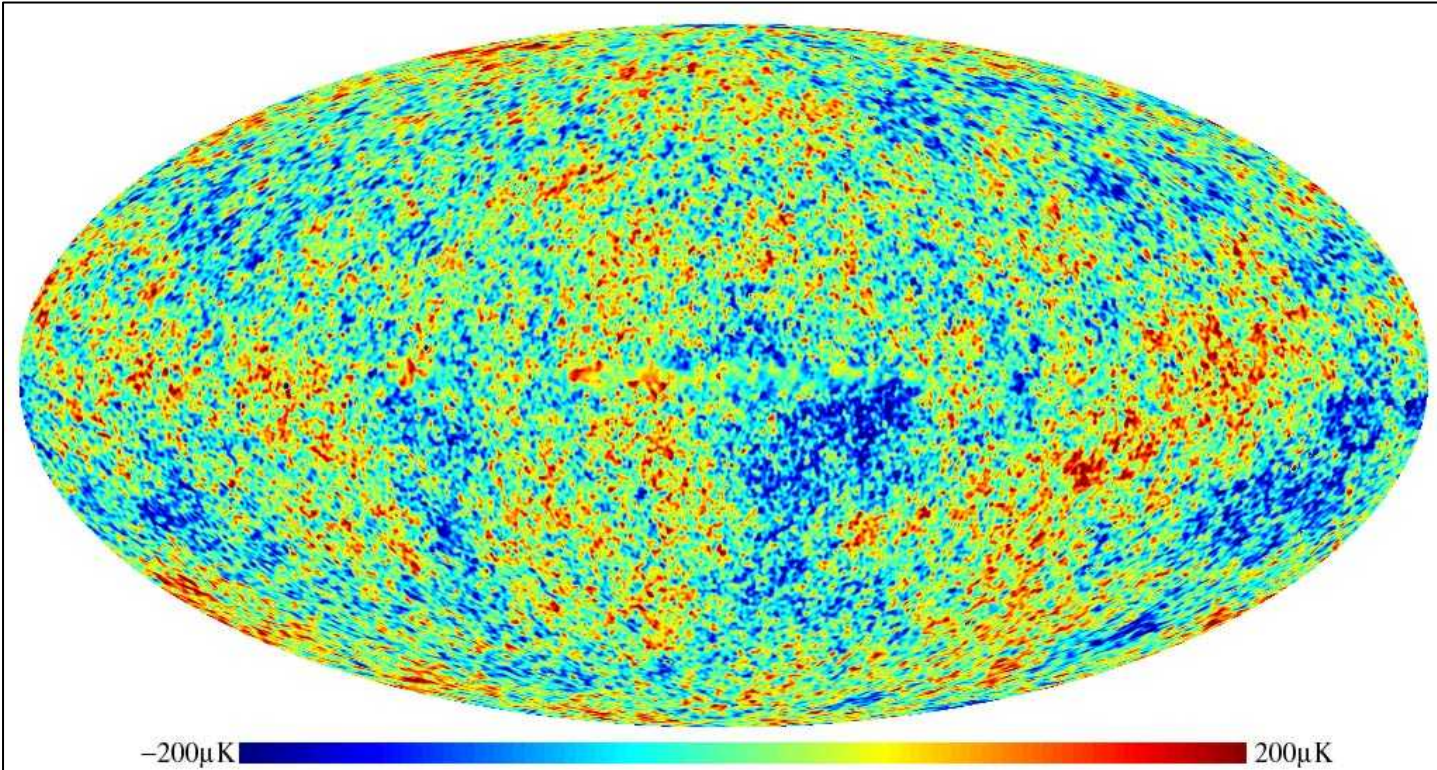- cross section is evaluated using EC decay observables

Conclusions

The fact that neutrino has a nonzero mass has renewed the interest on Netrino Capture on $\beta^{\pm}$ and EC decaying nuclei as a tool to measure very low energy neutrino

A detailed study of NCB cross section has been performed for a large sample of known beta decays avoiding the uncertainties due to nuclear matrix elements evaluation

The relatively high NCB cross section when considered in a favourable scenario could bring cosmological relic neutrino detection within reach in a few years using $\beta^{\pm}$ decaying nuclei

The energy threshold in one case and the absence of a suitable final state in the other prevent the use of EC decaying nuclei unless very specific conditions are fulfilled (difficult, but worth searching further…)

ν Anisotropy Probe Collaboration

CνB map in 20??