Neutrino Telescopes 2007

Probing Low Energy Neutrino Backgrounds with Neutrino Capture on Beta Decaying Nuclei

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The longstanding questions

1) Is it possible to make a measurement of the
Cosmological Relic Neutrino density ?

We know that CRN are non-relativistic and weakly-clustered

- UHE cosmic rays scattering (indirect, unknown sources)
- Torsion balance (polarization, strong ν-$\bar{\nu}$ asymmetry)

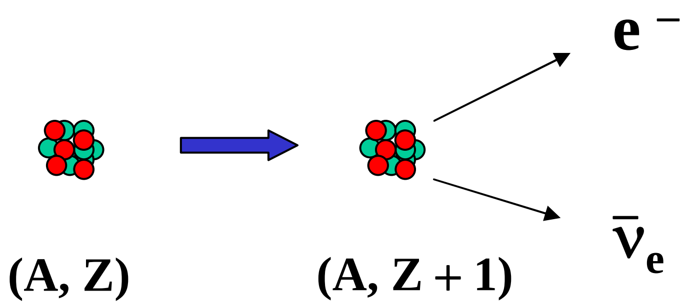
A.Ringwald “Neutrino Telescopes” 2005 – hep-ph/0505024
G.Gelmini hep-ph/0412305

2) How to measure very low energy ($<$ 1 keV) neutrino ?

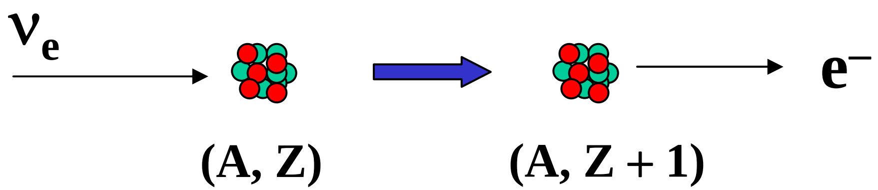
An old idea

S.Weinberg Phys.Rev. 128 (1962) 1457

Beta decay



Neutrino Capture on a Beta Decaying Nucleus (NCB)



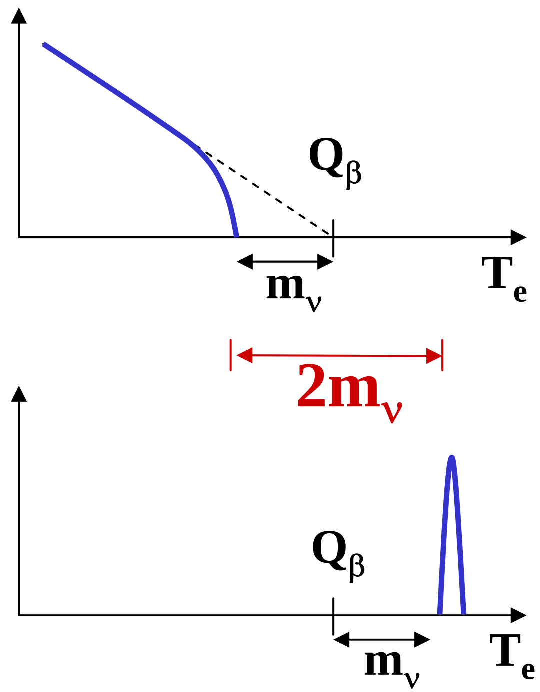
In the original idea a large neutrino chemical potential (μ) could distort the electron (positron) spectrum near the endpoint energy Today we know that $\mu/T_\nu \leq 0.1$ and the effect is too small to be detected. BUT……

A new fact: $m_\nu \neq 0$

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

Beta decay

NCB



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

The drawings however are not to scale…..

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

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

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

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

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)

NCB Cross Section

on 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

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

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

NCB Cross Section Evaluation

The case of Tritium

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

we obtain $$\sigma_{\rm NCB}(^3{\rm H}) \frac{v_\nu}{c} \underset{\lim \beta \to 1}{=} (\ 7.7 \pm 0.2\ ) \times 10^{-45}\ {\rm cm}^2$$

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

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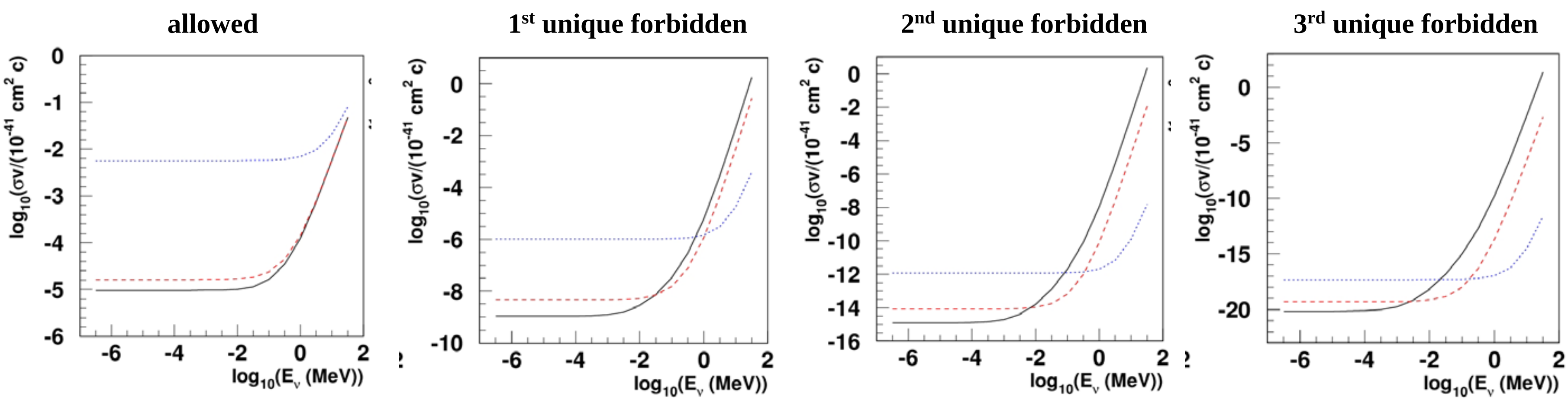
Using shape factors ratio $$\sigma_{\rm NCB} v_\nu = 2\pi^2 \ln 2 \frac{p_e E_e F(Z, E_e)}{f t_{1/2}}$$

$$\sigma_{\rm NCB}(^3{\rm H}) \frac{v_\nu}{c} \underset{\lim \beta \to 1}{=} (\ 7.84 \pm 0.03\ ) \times 10^{-45}\ {\rm cm}^2$$

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

NCB Cross Section Evaluation



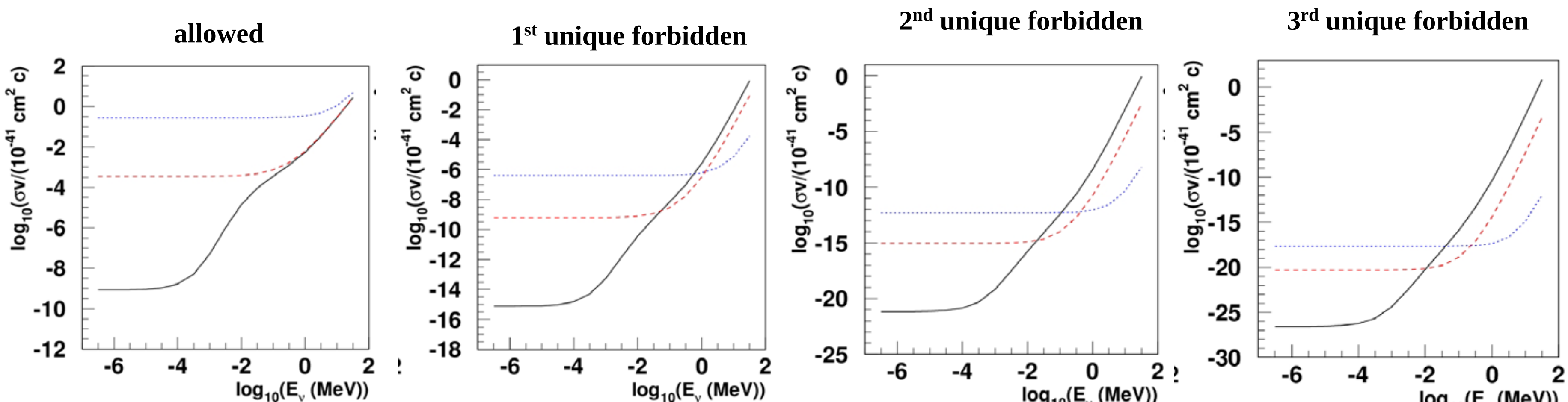
β^- (top)

β^+ (bottom)

Q_β = 1 keV

Q_β = 100 keV

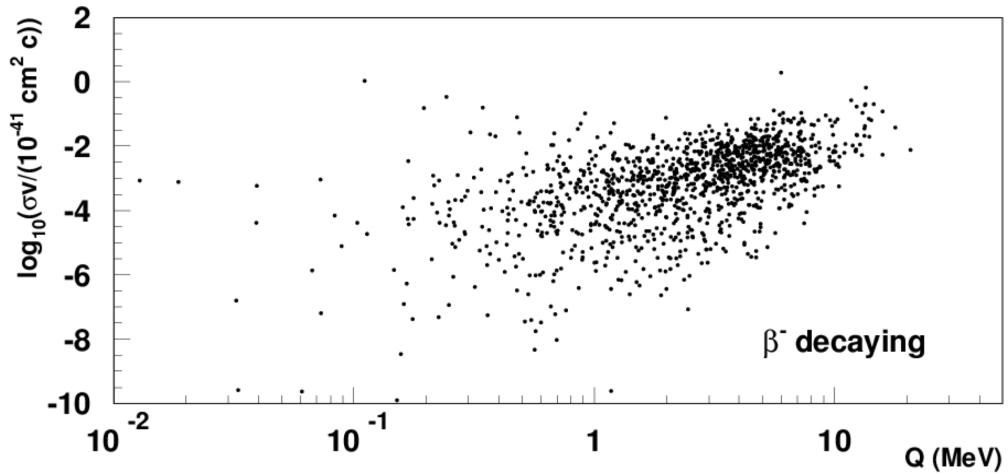
Q_β = 10 MeV



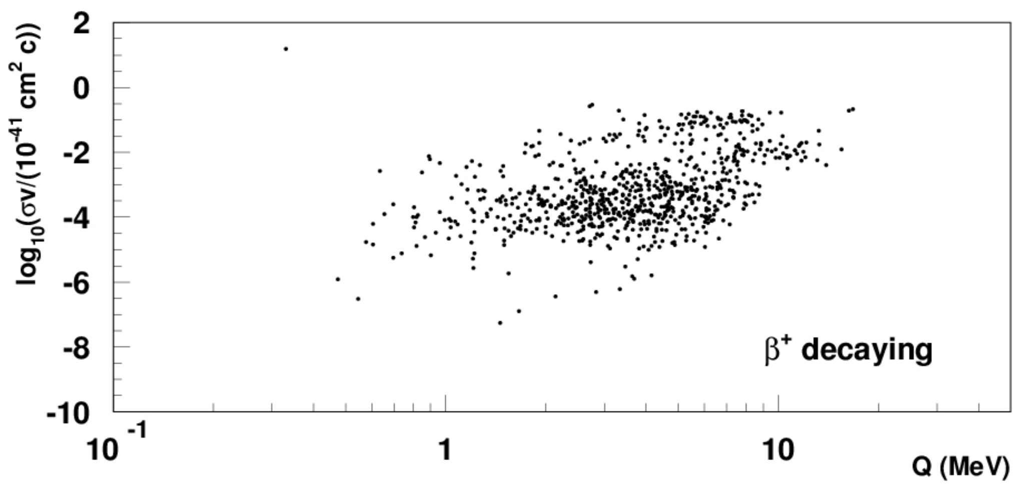
NCB Cross Section Evaluation

using measured values of Q_β and $t_{1/2}$

1272 β^- decays



799 β^+ decays



Beta decaying nuclei having BR($\beta^\pm$) > 5 %
selected from 14543 decays listed in the ENSDF database

NCB Cross Section Evaluation

specific cases

Isotope	Q_β (keV)	Half-life (sec)	$\sigma_{\rm NCB}(v_\nu/c)$ (10^{-41} cm^2)
^{10}C	885.87	1320.99	5.36×10^{-3}
^{14}O	1891.8	71.152	1.49×10^{-2}
^{26m}Al	3210.55	6.3502	3.54×10^{-2}
^{34}Cl	4469.78	1.5280	5.90×10^{-2}
^{38m}K	5022.4	0.92512	7.03×10^{-2}
^{42}Sc	5403.63	0.68143	7.76×10^{-2}
^{46}V	6028.71	0.42299	9.17×10^{-2}
^{50}Mn	6610.43	0.28371	1.05×10^{-1}
^{54}Co	7220.6	0.19350	1.20×10^{-1}

Superallowed $0^+ \rightarrow 0^+$ decays
used for CVC hypotesis testing
(very precise measure of Q_β and $t_{1/2}$)

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}

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

Relic Neutrino Detection

The cosmological relic neutrino capture rate is given by

$$\lambda_\nu = \int \sigma_{\mathrm{NCB}} v_\nu \frac{1}{\exp(p_\nu/T_\nu)+1} \frac{d^3 p_\nu}{(2\pi)^3}$$

$T_\nu = 1.7 \cdot 10^{-4}$ **eV**

after the integration over neutrino momentum and inserting numerical values we obtain

$$2.85 \cdot 10^{-2} \frac{\sigma_{\mathrm{NCB}} v_\nu / c}{10^{-45}\mathrm{cm}^2} \ \ \mathrm{yr}^{-1}\ \mathrm{mol}^{-1}$$

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

Relic Neutrino Detection

signal to background ratio

The ratio between capture (λ_ν) and beta decay rate (λ_β) is obtained using the previous expressions

$$\frac{\lambda_\nu}{\lambda_\beta} = \frac{2\pi^2 n_\nu}{\mathcal{A}}$$

In the case of Tritium we found that

$$\lambda_\nu(^3\mathrm{H}) = 0.66 \cdot 10^{-23} \lambda_\beta(^3\mathrm{H})$$

As a general result for a given experimental resolution Δ the signal to background ratio is given by

$$\frac{S}{B} = \frac{9}{2}\zeta(3)\left(\frac{T_\nu}{\Delta}\right)^3 \frac{1}{(1+2m_\nu/\Delta)^{3/2}} \left[\frac{1}{\sqrt{2\pi}} \int_{\frac{2m_\nu}{\Delta}-\frac{1}{2}}^{\frac{2m_\nu}{\Delta}+\frac{1}{2}} e^{-x^2/2} dx\right]^{-1}$$

where the last term is the probability for a beta decay electron at the endpoint to be measured beyond the $2m_\nu$ gap

Relic Neutrino Detection

discovery potential

As an example, given a neutrino mass of 0.7 eV and an energy resolution at the beta decay endpoint of 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

The same result holds in case of m_ν=0.3 eV and Δ=0.1 eV

Conclusions

The fact that neutrino has a nonzero mass has renewed the interest on Netrino Capture on Beta 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 uncertainty 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