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

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A.G. Cocco, G.Mangano and M.M., JCAP06(2007)015

The longstanding question

Is it possible to make a measurement of the Cosmological Relic Neutrinos?

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

- Observation of absorption dips in the Extremely Energetic Cosmic neutrino (EECν) spectra ($E_\nu > 10^{22}$ eV to reach the Z^0 resonance) or ultra-GZK events (Z bursts)
  Neutrino or cosmic ray sources of such a high energy are not even foreseen yet.

- Observation of macroscopic forces due to coherent elastic scattering of CRN off target material in torsion balances (effect at second order in G_F^2)
  N.Cabibbo and L. Maiani, Phys.Lett. B 114, 115 (1982).
  This approach requires strong ν-$\bar{\nu}$ asymmetry or neutrino and target polarization and accelerometers need a sensitivity improvement of 10 orders of magnitude .

Is it possible to make a measurement of the Cosmological Relic Neutrinos?

- Observation of interactions of extremely high energy particles from terrestrial accelerator beams with the relic neutrino.
  In this case energy beam required is of $E_{beam} > 10^7$ TeV

Summarizing: none of the proposed methods appear realistic

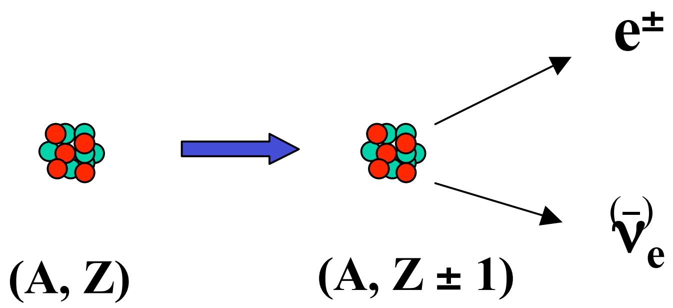
For recent reviews on this subject see:
A.Ringwald "Neutrino Telescopes" 2005 – hep-ph/0505024
G.Gelmini hep-ph/0412305

The long list of ideas that physicists have proposed so far miss the simplest one: a process where the ν can contribute only via its flavour quantum number and no additional energy is required!

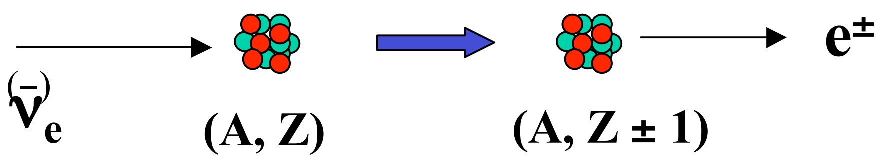
Our proposal

is to use a process without energy threshold

Beta decay



Neutrino Capture on a Beta Decaying Nucleus (NCB)

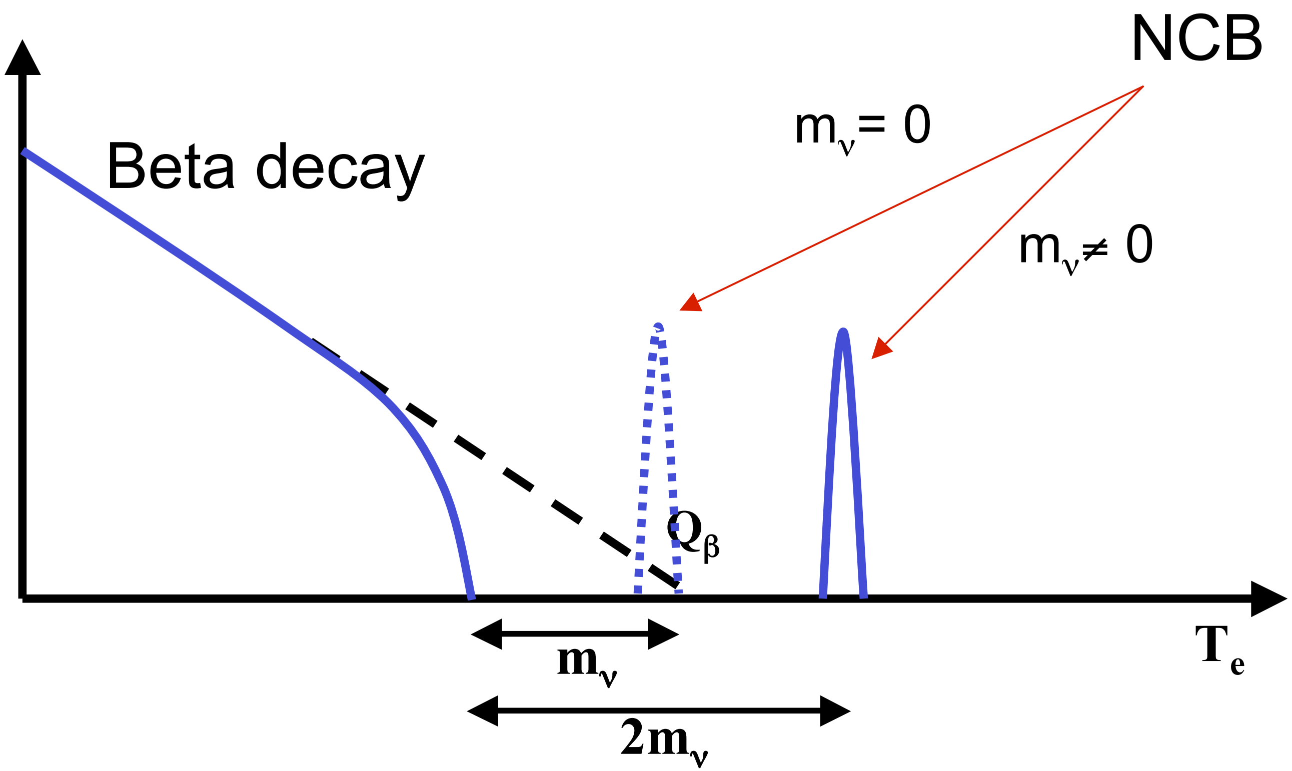


Since the nucleus decays spontaneously also a neutrino with vanishing energy can make the NCB process happens.

The NCB is a process with no energy threshold

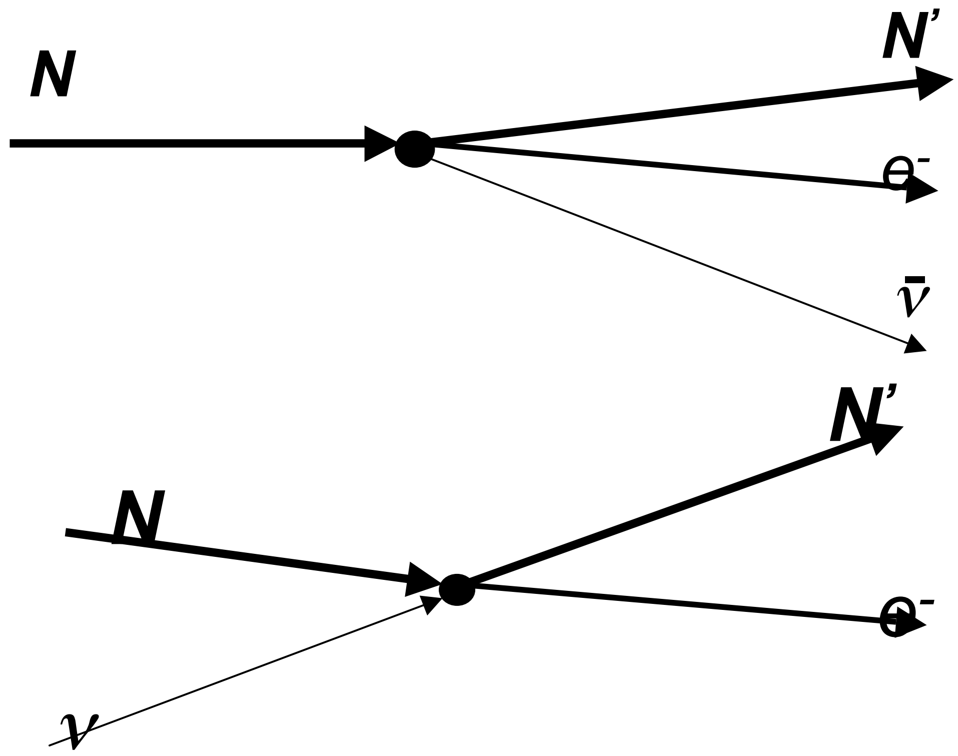
NCB signature

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



The events induced by Neutrino Capture have a unique signature: there is a gap of $2m_\nu$ between the NCB electron energy and the energy of beta decay electrons at the endpoint.

How to evaluate NCB cross section



The amplitudes of the two processes are identical (due to ν crossing)

This fact allows to evaluate the NCB cross section in an easy way

NCB Cross Section

a new parameterization

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

The nuclear shape factors C_β and C_ν depend on nuclear matrix elements but it can be shown that a simple relation holds:

$$C(E_e,p_\nu)_\nu = C(E_e,-p_\nu)_\beta$$

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

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

NCB Cross Section

on different types of decaying nuclei

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

we obtain $$\sigma_{\mathrm{NCB}}(^3\mathrm{H}) \frac{v_\nu}{c} = (\ 7.7 \pm 0.2\ ) \times 10^{-45}\ \mathrm{cm}^2$$

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

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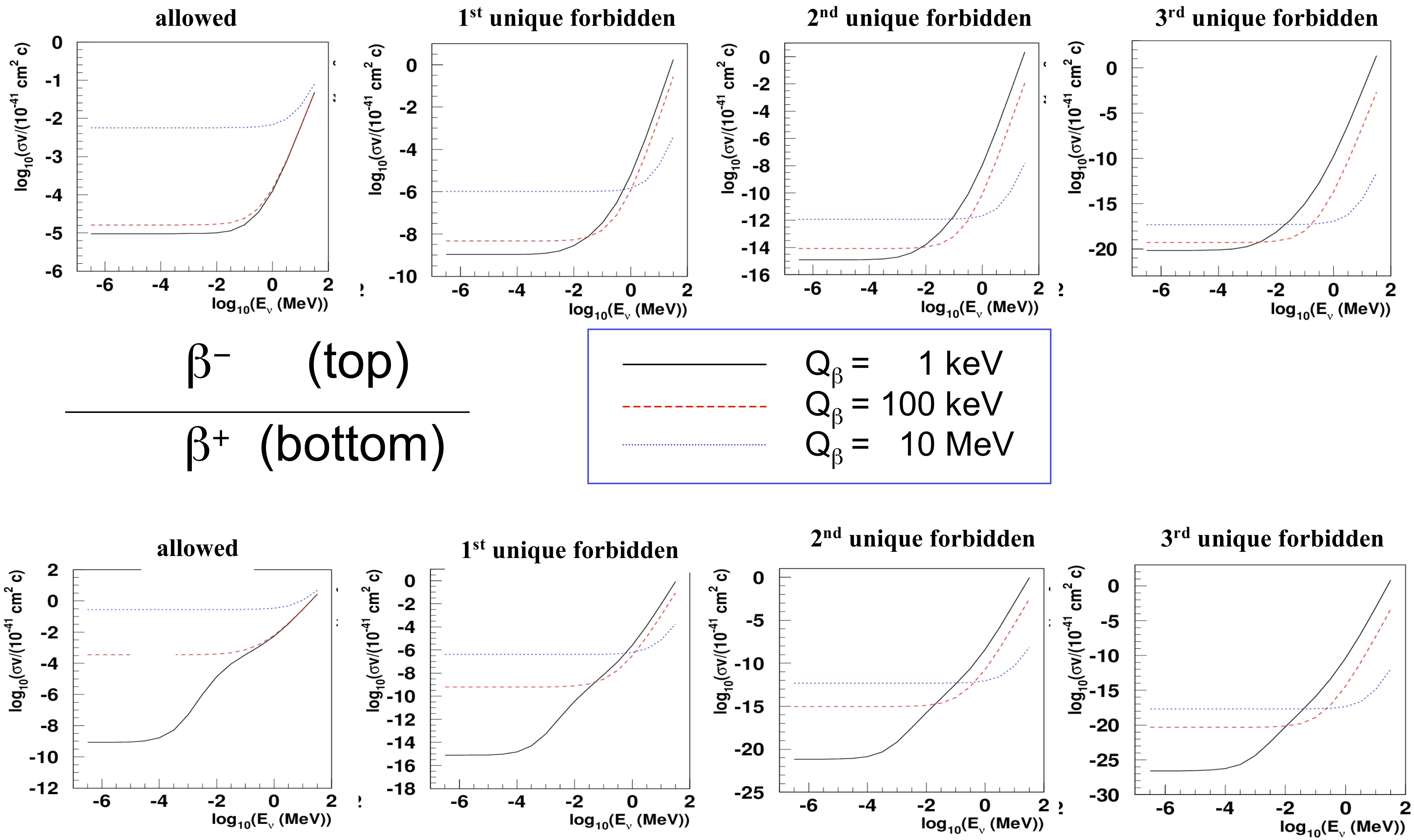
Using shape factors ratio $$\sigma_{\mathrm{NCB}} v_\nu = \frac{2\pi^2 \ln 2}{\mathcal{A}\, t_{1/2}}$$

$$\sigma_{\mathrm{NCB}}(^3\mathrm{H}) \frac{v_\nu}{c} = (\ 7.84 \pm 0.03\ ) \times 10^{-45}\ \mathrm{cm}^2$$

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

NCB Cross Section

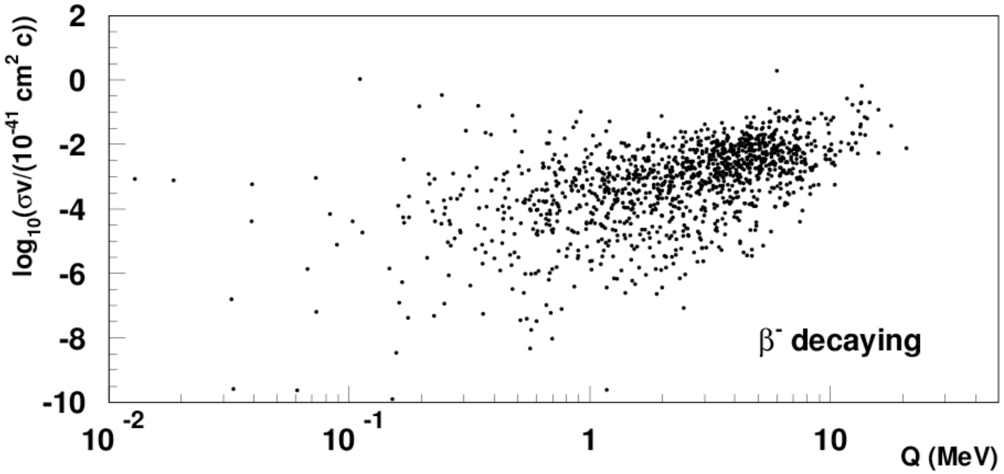
as a function of E_ν, Q_β and forbiddance level



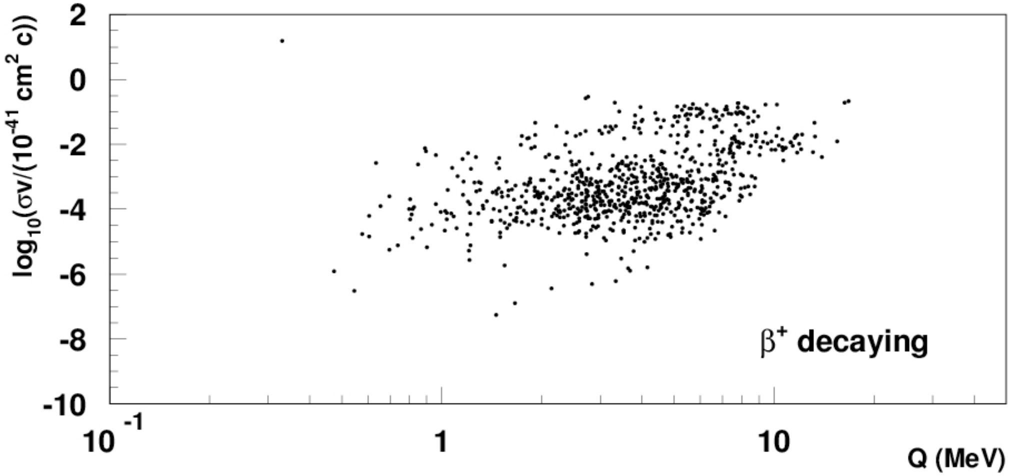
An important result is that the cross section does not vanish when the neutrino energy becomes negligible.

NCB Cross Section Evaluation
using measured values of Q_β and $t_{1/2}$

1272 β⁻ nuclei



799 β⁺ nuclei



Beta decaying nuclei having BR(β±) > 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}

Super-allowed $0^+ \rightarrow 0^+$ decays
used for CVC hypothesis 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
$\sigma_{\rm NCB}\, t_{1/2}$

Relic Neutrino Detection

The cosmological relic neutrino capture rate is given by

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

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

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

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

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 (I)

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

the assumption $m_\nu = 0$.

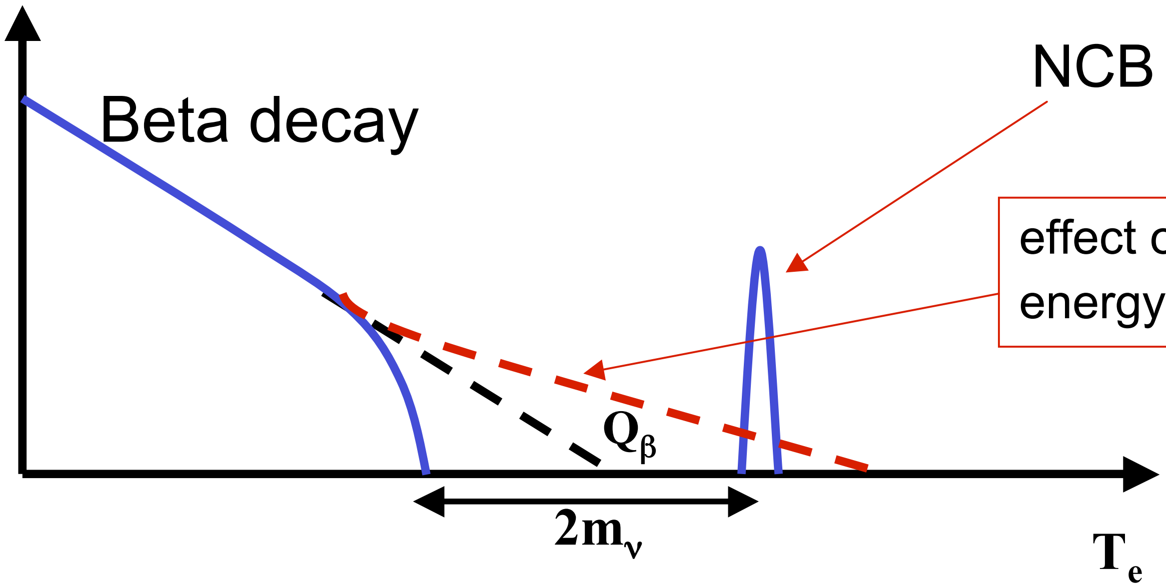
Relic Neutrino Detection (II)

signal to background ratio

As a general result for a given experimental resolution Δ the signal (λ_ν) to background (λ_β) 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.

A larger interaction rate is obtained in case of ν gravitational clustering. **A.Ringwald and Y.Y.Wong, JCAP 12(2004)005**

m_ν(eV)	FD (events/yr)	NFW (events/yr)	MW (events/yr)
0.6	7.5	90	150
0.3	7.5	23	33
0.15	7.5	10	12

Conclusions

- The fact that neutrino has a nonzero mass has renewed the interest on Neutrino Capture on Beta decaying nuclei as a unique tool to detect very low energy neutrino

- A detailed study of NCB cross section has been performed for a large sample of known beta decays and a method to reduce the uncertainty due to nuclear matrix elements evaluation has been found.

- The relatively high NCB cross section when considered in a favourable scenario could bring cosmological relic neutrino detection within reach in a near future if:
  - neutrino mass is in the eV range
  - an electron energy resolution of 0.1 – 0.2 eV is achieved