Towards the detection of cosmological relic neutrino with neutrino capture on a beta decaying nuclei

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on behalf of
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Abstract

In this paper we report on recent results in the field of the phenomenology of very low energy neutrino interactions. We briefly describe the cross section calculation for Neutrino Capture on Beta decay nuclei (NCB). We show that the resulting cross section open the possibility to detect the cosmological relic neutrinos. With this achievement, the relic neutrino detection has been downscaled from a principle problem to a technological challenge. We also summarise the state of the art about possible detection techniques.

1 Introduction

Several methods have been proposed [3] to detect the Cosmological Relic Neutrinos (CRN). Among the most relevant there is the idea that Extremely Energetic Cosmic neutrinos ($> \ 10^{22} eV$) annihilate with the relic neutrinos forming a Z^0 state. A different approach for CRN detection is based on the acceleration of target nuclei to very high energy ($E_{beam} > 10^7 \ TeV$) to increase the energy available in the center of mass reference frame increase the interaction rate. Furthermore, a method based on the measurement of macroscopic forces due to coherent scattering of the neutrinos and anti-neutrinos on a torsion balance installed in the galactic space was proposed.

All these methods rely on experimental parameters that are not really realisable. In this paper we propose a much simpler technique where the CRN detection is based on a reaction without energy threshold. For details we refer to [1, 2]. The interaction of electron (anti)neutrinos with a nucleus N ($\nu_e + N \to e + N^{'}$) that undergoes beta decay to a nucleus $N^{'}$ does not require an energy threshold for the incoming neutrino. The interesting feature of the reaction mentioned is due to the fact that the $Q_\beta = M(N) - M(N^{'}) > 0$. This implies that the neutrino contributes to the Neutrino Capture on Beta decaying nuclei (NCB) only via its quantum numbers. Therefore any neutrino of vanishing energy can stimulate the NCB process. Since the neutrinos do have a mass different from zero, the energy of the electron due to NCB process has an energy of $Q_\beta + m_\nu$, while the most energetic electron from the corresponding beta decay has an energy of $Q_\beta - m_\nu$. Consequently, the gap of $2m_\nu$ between the end point of the beta decay energy distribution and the energy of the electron from NCB allows for a better signal and background separation in case the necessary energy resolution is reached. As will be shown in the next paragraphs, if m_ν is in eV range, future NCB experiments could represent an almost unique way to detect cosmological neutrinos.

2 Cross section calculation for the NCB process

The NCB and the corresponding beta decay process are very similar if we consider the crossing symmetry of the invariant amplitude. In order to calculate the NCB cross section we use the beta decay formalism amply discussed in [4]. According to this formalism, with a spin averaged initial state and unobserved polarization we have that the cross section for a neutrino (electron) of momentum p_ν (p_e) and energy $E_\nu(E_e)$ of

$$\sigma_{\rm NCB} v_\nu = \frac{G_\beta^2}{\pi} p_e E_e F(Z, E_e) C(E_e, p_\nu)_\nu \, , . \tag{1}$$

Here $F(Z, E_e)$ is the Fermi function and $E_e = E_\nu + Q_\beta + m_e = E_\nu + m_\nu + W_0$ with W_0 the corresponding beta decay end point ($W_o = Q_\beta - m_\nu$), the nuclear shape factor $C(E_e, p_\nu)_\nu$ is the transition amplitude for the nuclear state averaged over the angular momentum. Details about this expression can be found in [4]. If we assume an isotropic neutrino flux, the integrated rate of the NCB processes is

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

where $f(p_\nu)$ is the neutrino momentum distribution. Furthermore, the relation $C(E_e, p_\nu)_\nu = C(E_e, -p_\nu)_\beta$ holds between the NCB and the beta decay nuclear shape functions, though the variables have different kinematical domains.

The beta decay rate can be expressed in terms of $\overline{C}_\beta$ which depends on the measurable quantities W_o and the half-life $t_{1/2}$ by means of the expression: $ft_{1/2} = 2\pi^3 ln/(G_\beta^2 \overline{C}_\beta)$, where f is the integrated Fermi function. Thus, the cross section can be written as:

$$\sigma_{\rm NCB} v_\nu = 2\pi^2 \ln 2 \, p_e E_e F(Z, E_e) \frac{C(E_e, p_\nu)_\nu}{ft_{1/2} \, \overline{C}_\beta} \,, \tag{3}$$

and the two factors $C(E_e, p_\nu)_\nu$ and $\overline{C}_\beta$ depend on the same nuclear transition amplitudes. It is worth mentioning that the ratio of the two shape factors ($C/\overline{C}$)helps to reduce the theoretical uncertainties present in the nuclear shape factors calculation. For this reason it is useful to express the cross section by means of a factor

$$\mathcal{A} = \frac{f \, \overline{C}_\beta}{p_e E_e F(Z, E_e) C(E_e, p_\nu)_\nu} \,, \tag{4}$$

that contains the ratio of the NCB and the beta decay shape factors. Given Q_β and Z, $\mathcal{A}$ depend on E_ν only. Thus, by using the function $\mathcal{A}$ the NCB cross section times the neutrino velocity can be written as

$$\sigma_{\rm NCB} v_\nu = \frac{2\pi^2 \ln 2}{\mathcal{A} \cdot t_{1/2}}. \tag{5}$$

In some cases the evaluation of $\mathcal{A}$ is particularly simple such that (5) can be evaluated analytically and, as previously underlined it allows to reduce the systematic uncertainties present in the calculation of the cross section. More details about the nuclear shape factors calculation at different order in perturbation theory for various beta transitions can be found in [1].

In Fig. 1 the cross sections for several NCB processes are shown. All cross sections reach a plateau at low neutrino energy and the plateau value of the cross section depends on the nuclear spin transition of the corresponding beta decay process and on the Q_β value.

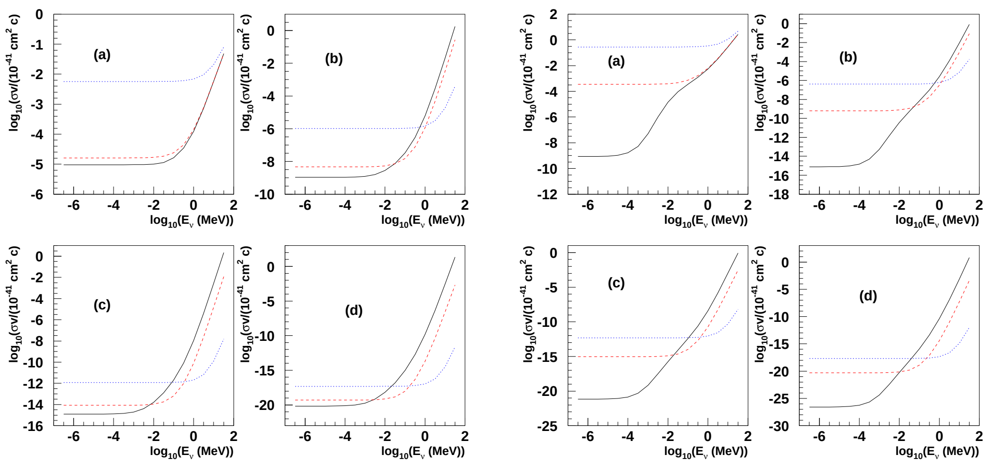

Fig. 1: The product $\sigma_{\rm NCB} v_\nu$ for β^- (left) and β^+ (right) decaying nuclei versus neutrino energy are shown for several decay processes. Typical values [5] for $\log(ft)$ have been assumed as follows: (a) nuclear spin transition equal to 0 and $\log(ft_{1/2}) = 5.5$, (b) nuclear spin transition equal to 1, and $\log(ft_{1/2}) = 9.5$, (c) nuclear spin transition equal to 2 and $\log(ft_{1/2}) = 15.6$, (d) nuclear spin transition equal to 3 and $\log(ft_{1/2}) = 21.1$. The three curves refer to different Q_β-values, solid line for $Q_\beta = 10^{-3}$ MeV, dashed line for $Q_\beta = 10^{-1}$ MeV, dotted line for $Q_\beta = 10$ MeV.

3 Detection issues and possible experimental approach

The detection of the cosmological relic neutrinos represents one of the most ambitious challenges in modern cosmology. In order to discuss this experimental issue two intertwined points should be addressed, the signal and background rates and the energy resolution. First of all, as it has been stressed the NCB process has no energy threshold, secondarily, the ratio of NCB and the corresponding beta decay event rate is typically very small as shown in [1].

In the case of ^{3}H the this ratio takes the value $\lambda_\nu(^3{\rm H})/\lambda_\beta(^3{\rm H}) = 0.66 \cdot 10^{-23}$. This is obtained assuming a standard and homogeneous relic neutrino background of about $\sim 50\nu/cm^3$. However, the neutrino density could be locally larger because of gravitational clustering in the case of massive neutrinos. This effect, in a Cold Dark Matter Halo, could be relevant for order of eV neutrino masses. For a comprehensive explanation about this topic see [8].

Despite of this disappointing result, at least in principle, the experimental signature of NCB events is unambiguous as the electron (positron) in the final state has a kinetic energy of at least $2m_\nu$ above the beta decay endpoint energy, if the neutrino mass is $m_\nu \neq 0$. In the optimistic scenario where values of neutrino masses and experimental energy resolution are comparable, the situation could be much more promising. As an example, we consider a future experiment reaching an energy resolution Δ, and neutrino masses in the eV range. The ratio of the event rate $\lambda_\beta(\Delta)$ for the last beta decay electron energy bin $W_o - \Delta < E_e < W_o$, compared to the total NCB event rate can be calculated as

$$\frac{\lambda_\nu}{\lambda_\beta(\Delta)} = \frac{9}{2}\zeta(3)\left(\frac{T_\nu}{\Delta}\right)^3 \frac{1}{(1+2m_\nu/\Delta)^{3/2}}\,, \qquad (6)$$

where we have used that $n_\nu = 3\zeta(3)T_\nu^3/(4\pi^2)$ and that $Q_\beta >> \Delta$. This results for example in a ratio, $\lambda_\nu/\lambda_\beta(\Delta) \sim 2.2 \cdot 10^{-10}$ for $\Delta = 0.2$ eV and $m_\nu = 0.5$ eV.

Let us now make some experimental considerations. Firstly for an experiment based on the NCB process, the $\sigma \cdot v_\nu$ has to be as large as possible as well as the energy resolution too. The first request is met with ^3H and ^{187}Re. These two elements are already used in existing experimental set-ups: electrostatic spectrometers as used in the ultimate direct neutrino mass search by mean of Tritium beta decay (KATRIN collaboration [6]) and bolometer detectors (MARE collaboration [7]) searching for evidence of neutrino mass with Renium beta decay. With both technique there are some issues. In the case of KATRIN, the detector does not contain enough Tritum target to be able to detect any relic neutrino interaction in a reasonable time. Any attempt to increase the mass of Tritium target will end up in spoiling the envisaged detector resolution ($\sim 0.2\ eV$). Furthermore, the bolometers allow in principle to have enough Renium mass to increase the sensitivity to the relic neutrinos, but this would end up with a huge number of read out channels (10^{10}). So, we need a detector capable to exploit the cross section of the Tritum, the resolution of the ultimate bolometer ($0.4 - 1\ eV$) and with the possibility to select only interesting events as done with detector of KATRIN collaboration. Such a goal can be, in principle, accomplished with a bolometer where enough Tritium is embedded in the absorber and a read out with a super-conductive temperature nano-sensor. The nano-sensors have the important feature [9] of allowing to set a window of the energy released in the absorber, with unprecedented precision and, consequently, a temperature variation in the nano-sensor. The current-voltage characteristics is such that only energy values above a certain threshold provide a signals. Furthermore, the threshold, can be optimised according to the experimental request. Although the assumptions we made need to be proven, no show-stopper were found so far preventing this idea to be a viable experimental solution. We believe that with a dedicated research and development program interesting results can be achieved on this detector option.

4 Conclusions

The fact that neutrino has a non zero mass has renewed the interest on Neutrino Capture on Beta decaying nuclei as a unique tool to detect very low energy neutrinos. Driven by this renewed interest in the neutrino field we performed a detailed study of NCB cross section for a large sample of known beta decays. The main result is that even for neutrinos of vanishing kinetic energy the cross section times the neutrino velocity might be as large as $10^{-45} cm^2 \cdot c$ for some elements. With such a value o the cross section the relic neutrino detection is not anymore completely out of reach but in a near future might be accomplished.

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