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

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Abstract. In this paper we investigate the possibility to detect Cosmological Relic Neutrinos, the oldest (after the Cosmological Microwave Background) particles produced after the Big Bang. In this paper we make a short overview of the methods proposed so far and we propose a new method that allows the CRN detection based on beta decaying target nuclei. The most important features of this process is that it does not require any minimum energy in order the neutrino interacts with nucleus. A detailed calculation of the cross section of the neutrino interaction on beta decaying nuclei is shown. The quoted value of the cross section times the neutrino velocity is of the order of $10^{-42} cm^2 \cdot c$.

1. Introduction

So far, neutrinos with energy from zero up to few keV are still undetected. Several methods have been proposed by several authors [1] aiming to detect the Cosmological Relic Neutrinos (CRN). The most relevants are the one based on the existence of Extremely Energetic Cosmic neutrino ($> 10^{22} eV$) which might annihilate with the relic neutrinos forming a Z_0 state. This process affects the primary spectrum of the cosmic neutrinos which would show a change of the slope at an energy above $10^{22} eV$. A different approach for the CRN detection is the one based on the acceleration of target nuclei at very high energy ($E_{beam} > 10^7 TeV$) to increase the energy available in the center of mass reference frame and to allow the relic neutrinos to do charged current interactions with accelerated nuclei. In this case a terrestrial accelerator as long as the terrestrial circumference is needed. The last and not the least methods we mention is the one based on the measurement of macroscopical forces due to coherent scattering of the neutrino and anti-neutrino on the torsion balance target material [2]. This method requires a strong asimmetry of the neutrino and anti-neutrino distribution function or neutrinos and target polarization.

All the methods proposed so far are based on unrealistic assumptions of some experimental parameters. In this paper we propose a much simpler technique where the CRN detection is based on a reaction without energy threshold. In fact, the interaction of the electron (anti)neutrino with a nucleus N ($\nu_e + N \rightarrow e + N^{'}$) that naturally undergo beta decay to nucleus $N^{'}$ has the property of having no energy threshold for the incoming neutrino. The interesting feature of the reaction mentioned is due to the fact that the $Q_\beta = M(N) - M(N^{'})$ ($M(N), M(N^{'})$ are the mass of the neutral atoms) is greater than zero, this implies that the neutrino contributes

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to the Neutrino Capture on Beta decaying nuclei (NCB) only via its quantum number. So any neutrino of vanishing energy can stimulate the NCB process. In the case of mass-less neutrino the out-coming electron of the NCB reaction will have an energy value as large as the maximal energy allowed to the electron of the beta decay of the parent nucleus N. Furthermore, the fact that the neutrino has a mass today is fully accepted. In this case we must consider that the electron due to NCB process has an energy of $Q_\beta + m_\nu$ where the most energetic electron from the corresponding beta decay has an energy of $Q_\beta - m_\nu$. So the gap of $2m_\nu$ between the end point of the beta decay distribution and the energy of the electron from NCB will allow a better signal and background separation in case the necessary energy resolution is reached.

Presently, the oscillation experiment data provide a lower limit to the value of one neutrino mass eigenstate of order of $0.05eV$[3], while ^3H decay experiments give a direct limit on $m_\nu < 2eV$ [4, 5]. An independent bound on the sum of neutrino mass eigenvalues are provided by cosmological data in the range of $0.3 \div 2\ eV$, see e.g. [6]. 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 NCB process

The NCB and the corresponding beta decay process are almost the same process 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 [7].

According to such formalism, with a spin averaged initial state and unobserved polarization we have that the cross section for a neutrino of momentum p_ν and velocity v_ν is

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

where $F(Z, E_e)$ 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 ($W_o = Q_\beta - m_\nu$), $C(E_e, p_\nu)_\nu$ the nuclear shape factor that is the transition amplitude nuclear state averaged on the angular momentum. Detailed expression can be found in [7]. 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. The rate of the NCB and of the beta decay are strongly related given that the relation $C(E_e, p_\nu)_\nu = C(E_e, -p_\nu)_\beta$ holds, 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:

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

and the two factors $C(E_e, p_\nu)_\nu$ and $\overline{C}_\beta$ depend on the same nuclear shape factors. It is worth mentioning that the ration of the two shape factors 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 the factor $\mathcal{A}$ defined as

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

that contains the ratio of the of the NCB and the beta decay shape factors. Given the value of Q_β and Z, $\mathcal{A}$ depends on E_ν only. Then the NCB cross section times the neutrino velocity can be easily 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 so that (5) can be evaluated exactly and, as previously underlined the (5) 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 for different beta transition can be found in [8].

3. Estimating the cross section

NCB cross section has been calculated for several nuclei decaying β^- and β^+ by using parametrization of the Fermi function and of the shape factor as in [7] and [11]. In Figure. 1 the cross section curves for several NCB processes are shown. All the curves reach a plateau at low neutrino energy and the scale value of the cross section strongly depends on the nuclear spin transition of the corresponding beta decay process and on the Q_β. The NCB corss section has been calculated for almost all the decay processes listed in ENSDF database [9] and we restricted our attention to the β^+ and of the β^- decay processes having a beta decay branching ratio of at least 5%.

Any use the the NCB process to detect the low energy neutrino is crucially releted to the issue of the background event rejection due to the corresponding beta decay process. In fact, given an incident neutrino flux the ratio of the NCB to decay events is proportional to $\sigma_{\rm NCB} \cdot t_{1/2}$, so the nuclei with highest value of this combination might give a chance to reveal the very low energy neutrinos in a future experiment.

4. Comparison between the NCB and beta decay rate in the case of cosmological relic neutrinos.

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 discussed, i.e. the event to background rate and the energy resolution. First of all, even if it has been stressed several times the NCB process is with no energy threshold, nevertheless, the ratio of NCB and of the corresponding beta decay events rate is typically very small and as shown in [8] it is

$$\lambda_\nu / \lambda_\beta = 2\pi^2 n_\nu / \mathcal{A} \tag{6}$$

In (6) we exploited that relic neutrinos have a very small mean momentum of order T_ν with a spread of the same order of magnitude, and the that the product of NCB cross section times neutrino velocity gets an asymptotic constant value for small neutrino energies, see Figure 1. In the case of ^{3}H we get $\lambda_\nu(^3\mathrm{H}) = 0.66 \cdot 10^{-23} \lambda_\beta(^3\mathrm{H})$.

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 at least $2m_\nu$ above the beta decay endpoint energy. However, the finite energy resolution of any experimental apparatus and the extremely low cross section make relic neutrino detection via NCB a real challenge due to the large background events. In particular, for low neutrino masses, smaller than the typical experimental energy resolution, it is really impossible to disentangle few expected NCB events from the large background of standard beta events. In this case NCB processes are of no use.

On the other hand, in more optimistic scenario with comparable values of neutrino masses and experimental energy resolution, the situation could be much more promising. As an example, we consider a future experiment reaching an energy resolution Δ, and neutrino masses in

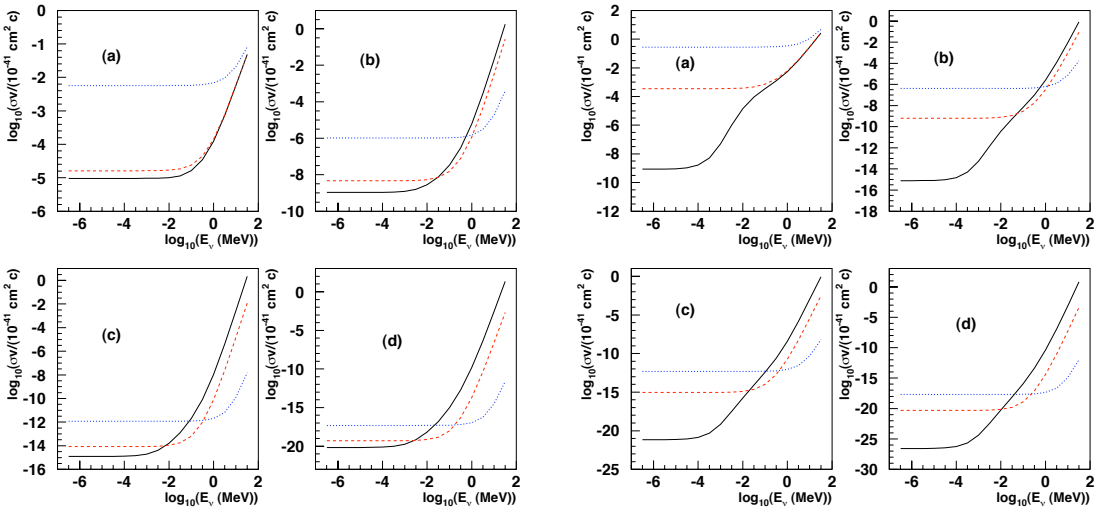


Figure 1. The product $\sigma_{\rm NCB} v_\nu$ for β^- decaying nuclei versus neutrino energy. Typical values for $\log(ft)$ values have been assumed [10] as follows: (a) nuclear spin transition equal to 0, $\log(ft_{1/2}) = 5.5$, (b) nuclear spin transition equal to 1, $\log(ft_{1/2}) = 9.5$, (c) nuclear spin transition equal to 2, $\log(ft_{1/2}) = 15.6$, (d) nuclear spin transition equal to 3, $\log(ft_{1/2}) = 21.1$. 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. Curves are for $Z = 21$ and nuclear radius given by $R = 1.2A^{1/3}$ fm, where $A = 2.5Z$

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 with the total NCB event rate can be easily calculated, giving

$$\frac{\lambda_\nu}{\lambda_\beta(\Delta)} = \frac{9}{2}\zeta(3)\left(\frac{T_\nu}{\Delta}\right)^3 \frac{1}{(1+2m_\nu/\Delta)^{3/2}}\,, \tag{7}$$

where we have used that $n_\nu = 3\zeta(3)T_\nu^3/(4\pi^2)$ and that $Q_\beta >> \Delta$. We have checked that this expression is accurate at percent level for most of the decays with endpoint energy in the range $10^{-3} < Q_\beta < 10$ MeV. This gives for example, the value $\lambda_\nu/\lambda_\beta(\Delta) \sim 2.2 \cdot 10^{-10}$ for $\Delta = 0.2$ eV and $m_\nu = 0.5$ eV.

A signal to noise ratio of order 3 is for example obtained if $\Delta = 0.2$ eV for $m_\nu = 0.7$ eV, while a smaller neutrino mass of 0.3 eV requires $\Delta = 0.1$ eV. In these cases a total event number of order 10 is needed to get a 5-σ *discovery* claim. Presently, this energy resolution seems very hard to get. Nevertheless, if a large neutrino mass will be found by ongoing beta decay experiments such as KATRIN, it is not inconceivable that a future generation of experiments might reach energy resolution as low as 0.1 eV.

Finally, we estimate the order of magnitude of the mass of detector required to see neutrino events from the cosmological background using NCB. For a mass M[g] expressed in grams, the expected total event rate is

$$\lambda_\nu \frac{N_A\ M[\mathrm{g}]}{A}\,, \tag{8}$$

where N_A is the Avogadro number and A is the atomic number of the decaying nucleus. Inserting

numerical values we get the following molar rate

$$2.85 \cdot 10^{-2} \, \frac{\sigma_{\rm NCB} v_\nu / c}{10^{-45} {\rm cm}^2} \, {\rm yr}^{-1} \, {\rm mol}^{-1} \, . \tag{9}$$

As an interesting example, we consider the case of ^{3}H. From (9) and quoting the results reported in [8], we estimate 7.5 events per year of data taking for a mass of 100 g.

We conclude this Section by observing that our results are obtained assuming a standard and homogeneous relic neutrino background. However, massive neutrino density could be locally larger because of gravitational clustering. 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 [13, 14].

5. 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 neutrino. 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 and we developed a method that allows to reduce the uncertainty due to nuclear matrix elements calculation. The result is that even for neutrinos of vanishing kinetic energy the cross section times the neutrino velocity might be as large as $10^{-42} cm^2 \cdot c$ for some elements. This value can span in a range of several order of magnitude if we consider beta decaying elements with different nuclear spin transition or Q_β value. For example, we found that with 100 gr of ^3H we expect of order of 10 events per year due to the scattering of cosmological relic neutrinos.

The real possibility to detect the relic neutrino is strongly dependent on the experimental capability to separate the signal from the background. If we consider the recent results obtained by experiments which measure neutrino mass directly, in agreement with cosmological observation the neutrino mass of the order of $2\ eV$ is acceptable. In this case if we consider the $2m_\nu$ energy gap between beta decay electrons and electrons due to the NCB and a resolution of $0.1 - 0.3\ eV$ the NCB signal can be fully well separated from its background.

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