Low Energy Antineutrino Detection Using Neutrino Capture on EC Decaying Nuclei

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In this paper we present a study of the interaction of low energy electron antineutrino on nuclei that undergo electron capture. We show that the two corresponding crossed reactions have a sizeable cross section and are both suitable for detection of low energy antineutrino. However, only in case of antineutrino captured on nuclei having a mass difference between the parent and daughter neutral nuclei as interesting candidates for very low energy antineutrino detection. Indeed, the crossed reaction with an incoming (anti) neutrino has no energy threshold and the product of the corresponding cross section times velocity goes to a finite constant value at low neutrino velocities. Furthermore, the fact that neutrinos have a non zero mass has important consequences on the kinematics of the capture process and leads to the possibility, at least in principle, to unambiguously detect the very low energy Cosmological Neutrino Background (CνB) [2].

In this paper we address the closely related case of nuclei that decay through the electron capture (EC) process, where the nucleus of a neutral atom A captures one bound electron and produces a daughter atom B and an electron neutrino

\[ e^- + A^+ \rightarrow B^* + \nu_e \rightarrow B + \nu_e + n \gamma \]  \hspace{1cm} (1)

The atom B, initially in an excited state with a missing electron in an inner atomic shell, decays electromagnetically and releases a total energy \( E_I \). By simple considerations it turns out that \( E_I \) is the captured electron binding energy in the field of the daughter nucleus. The nucleus of atom B can be produced in an excited nuclear state as well. As we will see in details in the following, the behavior of reaction (1) depends on the value of the mass difference between the parent and daughter neutral atoms \( Q_{EC} = M(A) - M(B) \), the value of \( E_I \) and the value of the neutrino mass.

Electron capture processes are suitable to detect electron antineutrino via the two crossed reactions

\[ \bar{\nu}_e + A \rightarrow B^- + e^+ \]  \hspace{1cm} (2)

and

\[ \bar{\nu}_e + e^- + A^+ \rightarrow B \]  \hspace{1cm} (3)

In the following we will analyze in detail both these processes and give an estimate of the antineutrino cross section that in most cases does not require the evaluation of nuclear matrix elements. We will also show under which circumstances the two processes could be used to measure very low energy antineutrinos and estimate the amount of the background due to competing processes.

II. KINEMATICS OF ANTINEUTRINO CAPTURE ON EC DECAYING NUCLEI

The behavior of reaction (2) as a function of the \( Q \)-value can be divided in three categories. In case \( Q_{EC} > 2m_e - m_\nu \) the neutrino capture process has no energy threshold since the \( Q \)-value is large enough to allow the creation of a positron in the final state even without the contribution of the electron mass in the initial state of the EC decay. On the other hand, if the \( Q \)-value satisfies the relation \( Q_{EC} < 2m_e + m_\nu \), the \( \beta^+ \) decay becomes energetically allowed. This case is described in details in [1] and will not be treated here. There is therefore, a range of values of \( Q \) that is \( 2m_\nu \) wide and that would allow the detection of antineutrino with an arbitrarily small energy. Transitions falling in this category would have the remarkable property of a unique signature, since the positron in the final state of reaction (2) can be used to tag the antineutrino capture interaction with respect to the spontaneously occurring reaction (1). Finally, in the case of antineutrino captured on nuclei having \( Q_{EC} < 2m_e - m_\nu \), reaction (2) has a threshold on the energy of the incoming antineutrino given by

\[ E^{thr}_\nu = 2m_e - Q_{EC} \]  \hspace{1cm} (4)

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and the energy of the outgoing positron in this case reads $E_e = E_\nu + Q_{EC} - m_e$. Though this threshold prevents in the case the use of this reaction to detect low energy antineutrino, nevertheless, atoms undergoing EC decays in which $Q_{EC} > 2m_e$ could still be used for that purpose.

As far as reaction (4) is concerned, the Q-value plays a crucial role as well. For $Q_{EC} - E_l \geq -m_\nu$, reaction (4) has no energy threshold and moreover, the nucleus A is stable since the corresponding EC decay become energetically allowed only if $Q_{EC} - E_l \geq m_\nu$. Once again, there is a range of Q-values that is $2m_e$ wide and in which reaction (4) has no threshold on the energy of the incoming antineutrino. The process is also background free since the EC decay is energetically forbidden. Unfortunately, reaction (4), as it is, is forbidden by the lack of a suitable final state. Using the Fermi golden rule \((\omega = 2\pi/\hbar |\mathcal{M}|^2 \rho_f(E))\) one gets that the cross section depends on the number of available final states per unit energy $\rho_f(E) = \delta(E_\nu + (Q_{EC} - E_l))$, which in case of an incoming antineutrino at rest has only one possible solution, $Q_{EC} - E_l = -m_\nu$. Despite of this, we can still envisage at least two cases where the process might be allowed:

i) there exists an excited state B' having energy \(M(B) + E_\nu + Q_{EC} - E_l\); in this case the background reaction (EC decay through the same channel) would be forbidden due to energy conservation even in the limit of $E_\nu \rightarrow m_\nu > 0$

ii) the captured electron is “off-mass shell” with an effective mass given by $m_{\text{eff}} = m_e - Q_{EC} + E_l - E_\nu$; this could happen for example in a metal when the nucleus captures an electron in the valence band, being in this case $E_l$ the mean binding energy of valence electrons.

In the case of $Q_{EC} - E_l < -m_\nu$, reaction (4) could be still triggered by antineutrinos with energy greater than $E_{\nu}^{\text{thr}} = -Q_{EC} + E_l$. As an example, we recall the process pointed out in [3], where high energy reactor antineutrino and the electron are captured by a stable nucleus B and produces a $\beta$–unstable nucleus A.

III. ANTEINEUTRINO CAPTURE CROSS SECTION

The electron capture process has been studied in details in [4]. The corresponding rate is given by

$$\lambda_{EC} = \frac{G_F^2}{2\pi^3} \sum_x n_x C_x(q_\nu) f_x \; ,$$ \hspace{1cm} (5)

where the sum is over all atomic shells from which an electron can be captured, $n_x$ is the relative occupation number of that shell and $C_x(q_\nu)$ is the nuclear shape factor relative to the given transition. The index $x$ labels the orbital electron wave-function via the variable $\kappa_x$ given by the spherical waves decomposition, as described in [4]. To give an example, nuclear transitions with no change in angular momentum can be coupled only by $\kappa_x = \pm 1$ wave-functions, namely $K, L_1, L_2, M_1, M_2...$ shells. Finally, the function $f_x$ is the analogous of the integrated Fermi function of the $\beta$ decay and is given by the following expression

$$f_x = \frac{\pi}{2} x^2 \beta_x B_x \; ,$$ \hspace{1cm} (6)

where $q_x = (Q_{EC} - E_l)/m_e$ is the neutrino energy, $\beta_x$ is the Coulomb amplitude of the bound-state electron radial wave-function and $B_x$ is the associated electron exchange and overlap correction.

In full analogy with the procedure used in [1], the antineutrino capture cross section for reaction (2), $\sigma_{(2)}$, (in the following the cross section index will refer to the corresponding process, as introduced in Eqs. [2] and [3]) can be written as

$$\sigma_{(2)} = \frac{G_F^2}{\pi} p_e E_e F(Z, E_e) C_\nu(p_e, p_\nu) \; ,$$ \hspace{1cm} (7)

where $C_\nu(p_e, p_\nu)$ is the shape factor of the antineutrino capture interaction and should be evaluated using prescription given in [3], while $F(Z, E_e)$ is the Fermi function for the outgoing positron. It is worth noticing here that $C_\nu(p_e, p_\nu)$ and $C_\nu(q_\nu)$ contain the same nuclear form factors. Moreover, $C_\nu(p_e, p_\nu)$ can be expressed as a weighted sum of the $C_\nu(q_\nu)$ provided the correct superposition of free-particle and bound state electron wave-functions are evaluated for each specific case. We will show that in most of the cases $C_\nu(p_e, p_\nu)$ can be obtained to a very good approximation using leading order $C_\nu(q_\nu)$ terms.

Using Eq. (5), it is possible to rewrite the cross section (7) in the following way

$$\sigma_{(2)} = 2\pi^2 \ln 2 p_e E_e F(Z, E_e) C_\nu(p_e, p_\nu) \sum_x n_x C_x(q_\nu) f_x \; .$$ \hspace{1cm} (8)

According to the procedure used in [1] we define a shape factor ratio $A$ as

$$A = \frac{\sum_x n_x C_x(q_\nu) f_x}{p_e E_e F(Z, E_e) C_\nu(p_e, p_\nu)} \; ,$$ \hspace{1cm} (9)

where $q_\nu$ is the energy of the outgoing neutrino in the EC decay (reaction (1)) and the subscript (e) refers to the positron in the final state of reaction (2). The antineutrino cross section can then be written as

$$\sigma_{(2)} = \frac{2\pi^2 \ln 2}{A} p_e E_e F(Z, E_e) C_\nu(p_e, p_\nu) \; .$$ \hspace{1cm} (10)

In case of reaction (6) it is easy to show that the antineutrino cross section, $\sigma_{(3)}$ up to a numerical factor which depends upon initial and final angular momentum multiplicity of the considered process, is given by

$$\sigma_{(3)} = \frac{G_F^2}{\pi} \sum_x n_x C_x(p_\nu) g_x \rho_x (E_\nu) \; ,$$ \hspace{1cm} (11)
where $\rho_x(E_x)$ is the number of available final states per unit energy for an electron captured on the shell $x$ and

$$g_x = \frac{\pi}{2} \beta_x^2 B_x,$$

is the analogous of (11). As both energies in the initial and final states are given, $\rho_x(E_x)$ is a Dirac delta function $\delta(E_x + Q_{EC} - E_{(x)})$. Therefore, incoming neutrinos are captured only if their energy is compatible with the mass difference between initial and final states.

For reaction (3) the shape factor ratio is given by

$$A' = \frac{\sum_x n_x C_x(q_x)f_x}{\sum_x n_x C_x(p_x)g_x\rho_x(E_x)},$$

where the variable $q_x$ refers to the neutrino energy in the final state of the EC process while $p_x(E_x)$ is the momentum (energy) of the incoming neutrino in reaction (3). Also in this case the cross section can be written according to Eq. (10).

We will now show that the shape factor ratios $A$ and $A'$ can be evaluated to a very good approximation for allowed decays and in an exact way for superallowed and forbidden unique decays.

A. Superallowed transitions

In case of superallowed transitions the shape factor involved in the neutrino capture process is given by

$$C_{EC}(p_e, p_e) = |A F_{101}^{(0)}|^2.$$

On the other hand, the electron capture proceeds only via capture from $K, L_1, L_2, M_1, M_2...$ shells, being contributions involving electron orbital momentum forbidden. This means that

$$C_x(q_x) = |A F_{101}^{(0)}|^2 \kappa_x = \pm 1$$

and that the shape factor ratios can be easily written as

$$A = \frac{\sum_x n_x f_x}{p_e E_x F(Z, E_x)}, \quad A' = \frac{\sum_x n_x f_x}{\sum_x n_x g_x \rho_x(E_x)},$$

where both expressions do not depend anymore on nuclear matrix elements evaluation. We notice here that $A'$ can be seen as the squared neutrino energy mean weighted with the electron capture probability of each shell. This is of course strictly true only in the limit of incoming neutrino having an energy greater than the K-capture threshold.

B. Allowed transitions

Using the same arguments of (11) it is easy to show that in case of allowed transitions and neglecting the (small) contribution of nuclear transitions with a large angular momentum transfer, the electronic capture shape factors reduce to a single term, hereafter denoted by $C_0$, that describes the lowest order transition and is independent of the outgoing neutrino energy. We have

$$\sum_x C_x n_x f_x \simeq C_0 \sum_x n_x f_x \quad C_0 \simeq C_{EC}.$$

Up to a very good approximation, the antineutrino capture shape factor ratio is given in this case by (14).

C. Unique K-th forbidden transitions

In case of K-th unique forbidden transitions and taking again only dominant terms

$$C_x = |A F_{L,-11}^{(0)}|^2 B_L^3 (p_x R)^{2(k_x-1)}(q_x R)^{2(L-k_x)},$$

where $L > k_x$ and numerical coefficients, here and in the following, can be evaluated using prescriptions given in (3). In case of capture from $s$-shells ($k_x = \pm 1$) we obtain the simple form

$$C_x = |A F_{L,-11}^{(0)}|^2 \frac{(q_x R)^{2(L-1)}}{(2 L - 1)!!},$$

and the shape factor ratio can be written as

$$C_x C_0 = \frac{((2 L - 1)!!)^{-1}(q_x R)^{2(L-1)}}{\sum_{n=1}^L B_L^3 \lambda_n(p_x R)^{2(n-1)}(p_x R)^{2(L-n)}}$$

again with no dependence on the nuclear form factors. The ratio $A'$ is again given by (14). In Fig. 1 we show the value of the ratio $Q_{EC}/A$ in case of superallowed and unique forbidden EC transitions for a specific case.

IV. ESTIMATING ANTINEUTRINO CAPTURE CROSS SECTION

The cross section for reaction (2) can be evaluated using (10) and following the procedure illustrated in Section (11). Numerical values for the constants appearing in Eq. (6) and (10) can be found in (4), while a description of the algorithm used to compute the Fermi function is given in (3). We report in Table II the value of $\sigma(2)$ for nuclei having the largest product of cross section times lifetime for a specific value of the incoming neutrino energy.

Antineutrino capture cross section behavior as a function of the incoming antineutrino energy is shown in Fig. 2 for a specific case. As an example, we consider the case of $^7$Be, which decays with a half-life of $t_{1/2}^{EC} = 53.22$ days [6] with $Q_{EC} = 861.815 \pm 0.018$ keV [6]. The difference in the electron binding energy between $^7$Be and its daughter $^7$Li is of $E_1 = 54.8$ eV [7], and can be neglected with respect to the decay $Q$-value. The energy threshold,
TABLE I: Pure EC decaying nuclei with the largest \(\sigma(2) \cdot t_r^{EC}\) value for neutrino capture processes of Eq. (2). Cross section is evaluated for incoming antineutrino energy of 1 MeV above reaction threshold and in case of K shell capture. Allowed transitions (top) and forbidden unique (bottom) are shown.

According to (14), is of 160.24 keV. Assuming an incoming antineutrino with energy of 100 eV above the energy threshold we have that

\[
\sigma(2) = 2.0 \cdot 10^{-48} \text{ cm}^2 ,
\]

in case of the \(3/2^- \rightarrow 3/2^-\) transition.

Similarly, the antineutrino cross section for reaction (3) can be easily written using (14). For an electron captured from the K-shell we can write (we recall that \(q_s\) is the outgoing neutrino in the EC process)

\[
\sigma(3) \approx 2\pi^2 \ln \frac{2}{q_s^2} \frac{\rho_k(E_{\nu})}{\nu},
\]

with \(t_r^{EC}\) the half-life of the nucleus EC decay.

V. ANTINEUTRINO CAPTURE VERSUS EC DECAY RATE

Using Eqs. (9) and (13), the ratio between antineutrino capture (2) and EC decay rates can be written as

\[
\frac{\lambda_\nu}{\lambda_{EC}} = \frac{2\pi^2}{A^{1/3}} n_\nu ,
\]

where \(n_\nu\) is the antineutrino density at the nucleus. As an example, in case of reaction (2) and superallowed transitions we have that

\[
\frac{\lambda_\nu}{\lambda_{EC}} = \frac{4\pi}{3} \frac{n_\nu}{B_x} \frac{p_k E_\nu F(Z, E_\nu)}{q_s^2} ,
\]

while for (3) and considering only K-shell capture in superallowed and K-th unique transitions

\[
\frac{\lambda_\nu}{\lambda_{EC}} = 2\pi^2 \frac{n_\nu \rho_k(E_\nu)}{q_s^2} .
\]

FIG. 1: Values of \(Q_{EC}^2/A\) for EC decaying nuclei at \(E_\nu = 2m_e\). The four curves represent from bottom to top superallowed, first unique forbidden, second unique forbidden and third unique forbidden transitions, respectively. Curves are shown for \(Z = 20\) and the sharp cutoff at 3.6 keV is due to the electron binding energy \(E_i\) of the K shell electron capture.

It is possible to get an order of magnitude estimate for the rate ratio using a simple argument. For reaction (2), the corresponding EC decay rate is related to the electron density at the nucleus and to the electron neutrino phase space

\[
\frac{\lambda_\nu}{\lambda_{EC}} \approx \frac{n_\nu}{|\psi_\nu(0)|^2} \frac{p_k E_\nu F(Z, E_\nu)}{q_s^2} .
\]

where \(\psi_\nu(\vec{x})\) is the captured electron wave-function and \(E_\nu = (E_\nu + Q_{EC}) - m_e\) is the outgoing positron energy in the antineutrino capture process. The expected antineutrino capture cross section is therefore, given by

\[
\sigma(2) \approx \frac{\lambda_{EC}}{|\psi_\nu(0)|^2} \frac{p_k E_\nu F(Z, E_\nu)}{q_s^2} ,
\]

which depends only upon the experimental decay rate \(\lambda_{EC}\) and on the electron wave-function at the nucleus. To test this result, we re-evaluate the antineutrino capture cross section on \(^7\)Be and compare the result with what we found in the previous section. Assuming antineutrino having an energy of 100 eV above threshold for the \(3/2^- \rightarrow 3/2^-\) reaction and using expression (24) we obtain \(\sigma(2) = 2.88 \cdot 10^{-48} \text{ cm}^2\) (compare with Eq. (14)) where a plain single particle hydrogen-like wave-function has been used to describe K-shell electrons in the \(^7\)Be atom.
VI. COSMOLOGICAL ANTINEUTRINO BACKGROUND DETECTION

Recently, the possibility to detect the CvB using beta unstable nuclei has received a great interest \[1, 8, 9\]. In particular, this is strictly related to the now well established experimental evidence for neutrino mass from oscillation experiments. Though a direct measure of the neutrino mass scale is still missing, results from Large Scale Structure power spectrum and Cosmic Microwave Background suggest an upper limit for the sum of the three eigenstate masses at the 0.5 - 1 eV level (a lower value is obtained if data from Lyman α clouds are included in the analysis), see e.g. \[10\] for a review. In case neutrino masses saturate this bound, Cosmological Neutrino Background could be really within the experimental reach in the near future. For an overview on perspectives for direct measurements of the CvB see e.g. \[11\].

The detection of very low energy antineutrino using reaction (2) is of course problematic due to the presence of the energy threshold in expression (4). A possible solution could be using the CvB as a target for accelerated nuclei. In this case the threshold energy is provided by the energy of the accelerated nucleus in the CvB comoving frame. From simple kinematical considerations, the minimal value of the γ factor (for a non-relativistic CvB electron neutrino) reads

$$\gamma_{\text{min}} = \frac{E_{\nu}^{\text{thr}}}{m_{\nu}}.$$  \hspace{1cm} (26)

It is worthwhile noticing here that EC decaying atoms show the remarkable property of having a Q-value that depends on the ionization degree of the parent atom. This is simply due to the fact that the difference between the electron binding energies of the parent and the daughter atoms depends on the total number of electrons in the atom before and after the decay. This result is well known and has been used for example, to evaluate the age of the Universe using the Os-Re transition in case of fully ionized atoms \[12\]. In order to evaluate the change of the Q-value as a function of the decaying nucleus we recall here that nuclear masses are related to the atomic ones by the relation

$$M_N(A, Z) = M_A(A, Z) - Z \times m_e + B_e(Z),$$  \hspace{1cm} (27)

where \(B_e(Z)\) is the total binding energy of all removed electrons. Values of this quantity can be found in \[14\], while an useful parametrization is reported in \[15\].

$$B_e(Z) = 14.4381 \, Z^2 + 1.55468 \times 10^{-6} \times Z^{5.35} \, \text{eV}.$$  \hspace{1cm} (28)

In case of fully ionized atoms the effective Q-value is given by

$$Q_{\text{eff}} = Q_{EC} - m_e + [B_e(Z) - B_e(Z - 1)].$$  \hspace{1cm} (29)

A completely ionized EC decaying atom whose Q-value is smaller than 2\(m_e\) represents the best low energy antineutrino detector one could achieve, since there are no competing backgrounds. The process of Eq. (2) only occurs in presence of an electron antineutrino having an energy greater than \(E_{\nu}^{\text{thr}}\).

As the relic antineutrino capture rate per nucleus can be expressed as (we notice that \(t_{1/2}^{EC}\) is the half-life in the nucleus rest frame)

$$\lambda_\nu = \frac{n_\nu \, 2 \pi^2 \ln 2}{A \cdot t_{1/2}^{EC}},$$  \hspace{1cm} (30)

the total rate is obtained by multiplying this expression by the total number of accelerated nuclei \(N\), where realistic values for present storage rings are \(N = 10^{13}\) and \(\gamma = 100\). Assuming a transition having a value of \(Q_{\text{eff}}\) of the order of the electronvolt this would lead to an interaction rate in case of allowed transitions of the order of \(\lambda_\nu \simeq 10^{-18} \, \text{s}^{-1}\), too slow to be effectively detected even in absence of background due to the EC decay of the nucleus (in case of a fully ionized beam).

The CvB detection using reaction (3) appears even more difficult since for neutrinos having very small energy the number of final states per unit energy \(\rho_\nu(E_\nu)\) is basically unknown. The atom in the final state has to have an excess energy \(Q_{EC} - E_l - m_\nu\) and this can only happen if this energy can be radiated out via electromagnetic or phonon emission, if the decaying atom is bounded in a solid. Photons emission can be due either to atomic electrons or to nuclear level transitions; in

![Graph showing the product σν vs. Eν](attachment:image.png)

FIG. 2: The product σ\(\nu\) for EC decaying nuclei versus neutrino energy for reaction (2). Typical values for log(\(\lambda\)) values have been assumed \[15\] from top to bottom as follows: allowed (5.5), first unique forbidden (9.5), second unique forbidden (15.6) and third unique forbidden (21.1). The curves refer to \(Q_{EC} = 1 \, \text{MeV}\), \(Z = 20\) and nuclear radius given by \(R = 1.24 \, \text{fm}\), where \(A = 2.5Z\).
the first case the typical energy lies in the eV-keV region and, being \( E_l \) in the same energy range, this implies that only nuclei with a very small \( Q \)-value could be suitable for this detection. In the second case, there should exist a nuclear level that matches the energy difference. Furthermore, to avoid the possibility that spontaneous EC decay are also allowed, these levels must be \( m_\nu \) above the transition \( Q \)-value by the fine–tuned value \( m_\nu \). Notice that in this latter case (EC decay forbidden) there is a priori no easy way to evaluate the cross section for reaction (3).

VII. CONCLUSIONS

In this paper we have considered the interaction of low energy electron antineutrino on nuclei that undergo electron capture spontaneously. Depending on the \( Q \)-value, crossed processes where a neutrino is in the initial state, could be in principle exploited to measure low energy incoming neutrino fluxes from astrophysical or cosmological sources. Using a method already applied to neutrino captures on beta decaying nuclei in [1] to relate the nuclear shape factors of crossed reaction, we have computed the expected neutrino-nucleus cross section versus neutrino energy. The results shows that these processes seem quite difficult to be used as a way to measure the \( \nu_B \), whose detection might be more promisingly pursued in the future using beta decaying nuclei for sufficiently massive neutrinos. Nevertheless, EC decaying nuclei could be an interesting perspective for higher energy neutrino fluxes, if very specific conditions on the \( Q \)-value of the decay are met or significant improvements on the performances of ion storage rings are achieved.

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