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^{163}Ho as a target for cosmic antineutrinos

M. Vignati and M. Lusignoli

Sapienza Università di Roma and Sezione INFN di Roma, P.le A. Moro 2, Roma I-00185, Italy

E-mail: marco.vignati@roma1.infn.it

Abstract. The electron capture decay of the isotope ^{163}Ho has been proposed since a long time as a candidate for measuring the electron neutrino mass and recently the interest on this idea has been renewed. A direct observation of the cosmic antineutrino background could be made using a target made of this isotope. We discuss the requirements for an experiment aiming to obtain this result, comparing it with experiments using tritium as target.

1. Introduction

The detection of neutrinos relic from the Big Bang is one of the most challenging researches of our days. We know that the average number density is $n_\nu = 55/\text{cm}^3$ for each flavor of neutrinos and antineutrinos, and that their momentum is around $p = 10^{-4}$ eV/c, implying an extremely low energy which is not detectable with present experimental techniques. The only practicable way seems to capture them with β decaying nuclei, as suggested by Weinberg years ago [1] and recently revisited [2]. Indeed, the process $\nu + (A, Z) \rightarrow (A, Z + 1) + e^-$ has no energy threshold and does not depend on the energy of relic neutrinos. The experimental signature is distinctive: while the energy spectrum of electrons emitted from the decay decreases up to the endpoint, the electron emitted in this process is monochromatic with energy equal to the endpoint plus two neutrino masses.

The obvious candidate nucleus is tritium, because its low Q-value favors a relatively large rate of decays at the endpoint. Nevertheless sensitivities of present or proposed β decay experiments are ridiculous, mainly because the quantity of target nuclei required is enormous. A higher quantity of neutrinos will soften the requirements, even though the foreseen over density [3] is not large enough [4].

The electron neutrino mass can also be measured via electron capture (EC) decaying nuclei, and recently there is growing interest in making experiments with the isotope ^{163}Ho . We show that the capture of relic (anti)neutrinos from EC decaying nuclei, $\bar{\nu} + (A, Z) \rightarrow (A, Z - 1) + \text{Energy}$, is possible and has the same signature of the capture from β ones [5]. We observe that experiments looking at the neutrino mass via EC and β decays have essentially the same sensitivity to relic neutrinos, provided that their sensitivity to the neutrino mass and the energy resolution are the same.

2. Capture from β decaying nuclei

The differential rate of electrons emitted in β decays as a function of the electron energy E is:

$$\frac{d\lambda_\beta}{dE} = F(Z, E)S(E) p_e (E + m_e) \cdot \left[(Q - E) \sqrt{(Q - E)^2 - m_\nu^2} \right] \quad (1)$$

where $F(Z, E)$ is the Fermi function, $S(E)$ is the nuclear shape factor of the transition and Q is the mass difference between the parent and daughter atoms. The neutrino phase space, highlighted with square brackets, is sensitive to the neutrino mass and determines the shape of the spectrum in proximity of the endpoint Q . To measure the neutrino mass, only the events falling in a small energy region Δ close to the endpoint are interesting. Their fraction over the total number of decays is known as “factor of merit” of the nucleus,

$$F_{\beta}(\Delta, m_{\nu}, Q) = \frac{1}{\lambda_{\beta}} \int_{Q-\Delta-m_{\nu}}^{Q-m_{\nu}} \frac{d\lambda_{\beta}}{dE} dE \propto \left(\frac{\Delta}{Q}\right)^3 \quad (2)$$

and indicates that nuclei with low Q -value have to be chosen. Tritium is the best candidate isotope, because of its short half-life and small Q -value (Tab. 1). It is used by the leading experiment of the field, *Katrin* [6], a β spectrometer which aims to reach a sensitivity on m_{ν} of 0.2 eV. Other proposed experiments are *Project8* [7], which also uses tritium, and *MARE* [8], which looks at the decay of ^{187}Re with bolometers.

As said before these experiments are in principle sensitive to relic neutrinos. The number of captured neutrinos can be expressed in terms of the number of events at the endpoint [2]:

$$\frac{N_{\nu\beta}}{N_{\beta}^{\text{endpoint}}} = \frac{\lambda_{\nu\beta}}{F_{\beta}(\Delta, m_{\nu}, Q) \lambda_{\beta}} \simeq \left[6 \pi^2 \frac{n_{\nu}}{\Delta^3} \left(1 + \frac{2m_{\nu}}{\Delta}\right)^{-\frac{3}{2}} \right]. \quad (3)$$

The above expression does not depend on the Q -value or on the half-life of the nucleus, and indicates that the fraction of events due to relic neutrino capture over the number of β decays at the endpoint is the same for all target nuclei.

3. Capture from EC decaying nuclei

The energy E emitted in EC decays is given by a series of lines, corresponding to the binding energy E_i of the electron hole in the final atom:

$$\frac{d\lambda_{EC}}{dE} = \frac{G_{\beta}^2}{4\pi^2} \left[(Q - E) \sqrt{(Q - E)^2 - m_{\nu}^2} \right] \cdot \sum_i n_i C_i \beta_i^2 B_i \rho(E - E_i). \quad (4)$$

In the above expression n_i is the occupancy of the i -th atomic shell, C_i is the nuclear shape factor, β_i is the Coulomb amplitude of the electron radial wave function, B_i is the electrons exchange and overlap correction and ρ is the density of final states.

It may appear that there is no sensitivity to the neutrino mass, because ρ can be considered as a δ -function and because it is very unlikely that some of the E_i is equal to Q , turning on the shaping effect of the neutrino phase space. However, years ago, it has been remarked that the lines have a natural width and therefore are represented by a Breit-Wigner shape [9]: $\rho = \Gamma_i/2\pi[(E - E_i)^2 + \Gamma_i^2/4]^{-1}$. If a line is close to the endpoint, the tail of the Breit-Wigner can be high enough to make the spectrum sensitive to the neutrino mass. From this point of view, the best isotope seems the ^{163}Ho , which decays via EC into ^{163}Dy :



^{163}Ho has relatively small half-life (4570 y) and a record low Q -value, between 2.2 and 2.8 keV (but still not known with precision). From the calculated de-excitation spectrum shown in the left panel of Fig. 1 one can see that the M1 line ($E_{\text{M1}} = 2047$ eV, $\Gamma_{\text{M1}} = 13$ eV) is close enough to the endpoint and makes the spectrum sensitive to the neutrino mass (right panel of Fig. 1).

The factor of merit (Eq. 2), whose exact value depends on the value of Q , is better than tritium, and partially compensates for the longer half-life of ^{163}Ho (Tab. 1). Since the

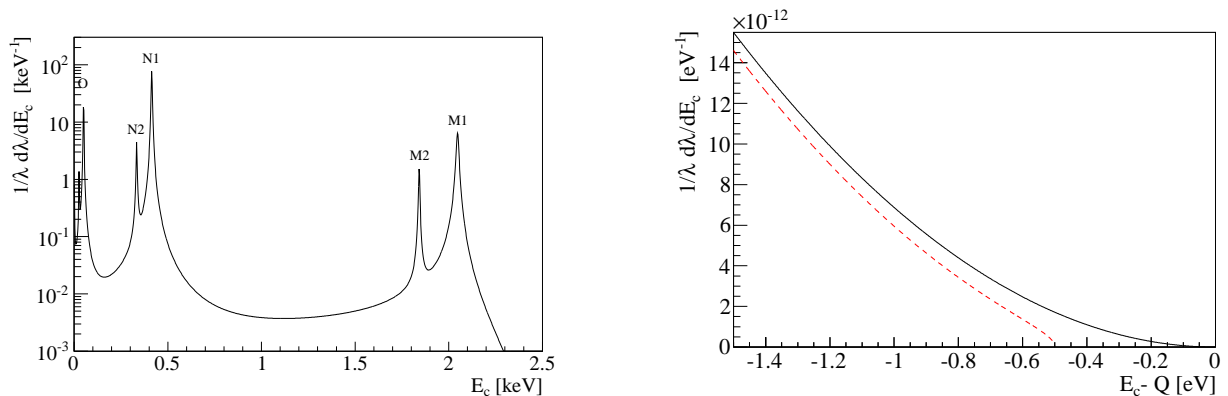


Figure 1. Left: calculated de-excitation spectrum of the ^{163}Ho EC decay into ^{163}Dy using $Q = 2.5$ keV. Right: zoom of the endpoint with neutrino mass equal to zero (solid black) and equal to 0.5 eV (red dashed).

de-excitation can proceed through different channels (X-ray cascades and Auger electrons) bolometric detectors must be used to detect the decay because of their capability to measure the entire energy released.

The capture of a relic anti-neutrino at first sight might seem not possible, because it is a process in which three bodies (the neutrino itself, the nucleus and an atomic electron) transform into only one body (the daughter atom with an electron hole). The tiny phase space available, however, is as low as in the capture from β -decaying nuclei, where the energies of daughter atom and emitted electron are constrained to match the Q -value. The expression of the capture rate is [5] :

$$\lambda_{\nu\text{EC}} = n_{\nu} \frac{G_{\beta}^2}{2} \sum_i n_i C_i \beta_i^2 B_i \frac{\Gamma_i}{2\pi} \frac{1}{(Q + m_{\nu} - E_i)^2 + \Gamma_i^2/4} \quad (6)$$

where the sum runs over all lines, even though the dominant term comes from the M1 line.

The ratio of captured anti-neutrinos over the number of decays at the endpoint turns out to be equal to that computed for β decaying nuclei (Eq. 3):

$$\frac{N_{\nu\text{EC}}}{N_{\text{EC}}^{\text{endpoint}}} = \frac{\lambda_{\nu\text{EC}}}{F_{\text{EC}}(\Delta, m_{\nu}, Q) \lambda_{\text{EC}}} \simeq \left[6\pi^2 \frac{n_{\nu}}{\Delta^3} \left(1 + \frac{2m_{\nu}}{\Delta} \right)^{-\frac{3}{2}} \right], \quad (7)$$

showing that EC decaying nuclei are in principle equally good to detect relic neutrinos.

4. Sensitivity

In this section we quantify the sensitivity to the relic neutrino signal of a ^{163}Ho -based experiment and compare the requirements with a ^3H -based experiment.

The number of signal events is: $N_S = \lambda_{\nu} N_A n_{\text{mol}} t$, where N_A is Avogadro's number, n_{mol} the number of mols and t the exposure time. To have a reasonable number of signal events, say $N_S = 10$, one needs about 307 kg.y of ^{163}Ho for $Q = 2.5$ keV (see other values in Tab. 1), to be compared with 137 g.y of ^3H . The intrinsic background depends on the energy resolution of the detector, which smears the endpoint contaminating the signal region:

$$N_B(\Delta, m_{\nu}, Q) = N_A n_{\text{mol}} t \frac{1}{\sqrt{2\pi}\Delta} \times \int_{Q+m_{\nu}-\Delta_{\text{FWHM}}/2}^{Q+m_{\nu}+\Delta_{\text{FWHM}}/2} dE' \int_0^{Q-m_{\nu}} dE \frac{d\lambda_{\text{EC}}}{dE}(E) e^{-\frac{(E-E')^2}{2\Delta^2}} \quad (8)$$

where $\Delta_{\text{FWHM}} = 2.35 \Delta$ is the usual definition for the detector resolution. Figure 2 (left) shows an example of signal and background distributions for $\Delta_{\text{FWHM}} = 0.33$ eV, $m_{\nu} = 0.5$ eV,

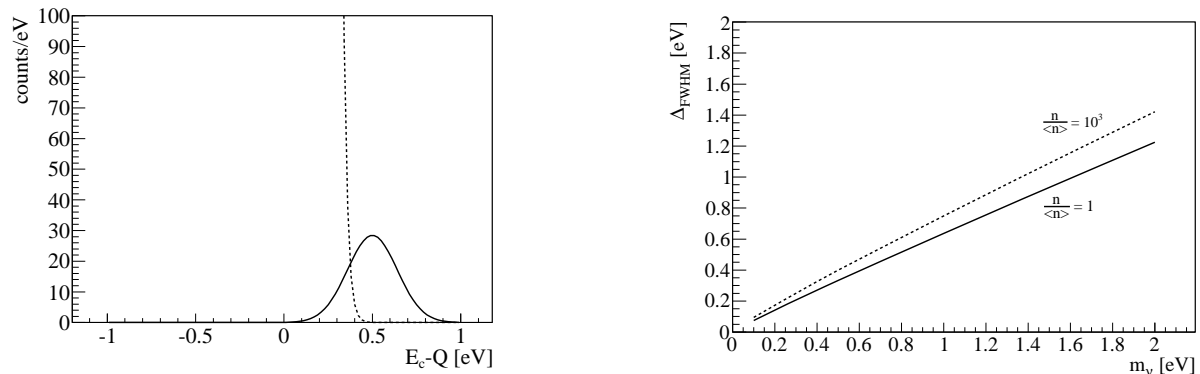


Figure 2. Left panel: relic neutrino signal (solid) and EC intrinsic background (dashed) for $Mt = 307 \text{ kg y}$ and $\Delta_{\text{FWHM}} = 0.33 \text{ eV}$. Right panel: energy resolution needed to make a discovery with 5σ significance, as a function of the neutrino mass, for normal density and density larger by a factor 10^3 .

$Q = 2.5 \text{ keV}$ and $Mt = 307 \text{ kg} \cdot \text{y}$. Figure 2 (right) shows the energy resolution needed to make a discovery with significance $N_S/\sqrt{N_B} = 5$, as a function of the neutrino mass. While a local over density of neutrinos clearly reduces linearly the needed exposure, the requirements on the energy resolution are found to be almost unchanged, as the figure shows.

The energy resolutions foreseen for upcoming or future experiments are about 1 eV , not too far from the needed ones. The amount of mass needed, however, is orders of magnitude higher, considering that ${}^3\text{H}$ and ${}^{163}\text{Ho}$ experiments will use a target mass of the order of micrograms or tens of micrograms. The hunt remains challenging, but possibly the experimental ingenuity will be stimulated by the new capture method we introduced.

Table 1. Q -value and half-life of ${}^{163}\text{Ho}$ and ${}^3\text{H}$; factor of merit F and relic neutrino capture rate over decay rate (total and at the endpoint) calculated using $m_\nu = 0.5 \text{ eV}$ and $\Delta = 0.2 \text{ eV}$; exposure needed to obtain 10 events of neutrino capture Mt_{10} .

	${}^{163}\text{Ho}$			${}^3\text{H}$
Q [keV]	2.2	2.5	2.8	18.6
$T_{1/2}$ [y]		4570		12.5
F	$3.6 \cdot 10^{-12}$	$2.7 \cdot 10^{-13}$	$6.5 \cdot 10^{-14}$	$3 \cdot 10^{-14}$
$N_\nu/N_{\text{decay}}^{\text{total}}$	$7.7 \cdot 10^{-22}$	$5.8 \cdot 10^{-23}$	$1.4 \cdot 10^{-23}$	$6.6 \cdot 10^{-24}$
$N_\nu/N_{\text{decay}}^{\text{endpoint}}$		$2.2 \cdot 10^{-10}$		$2.2 \cdot 10^{-10}$
Mt_{10} [kg · y]	23.2	307	1274	0.137

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