Direct detection of hot dark matter including light sterile neutrinos

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Abstract. Both active and sterile sub-eV neutrinos can serve for hot dark matter (DM) in the Universe. We consider the beta-decaying (e.g., $^3$H) and EC-decaying (e.g., $^{163}$Ho) nuclei as the most promising targets to capture hot DM in the laboratory. We calculate the capture rates of relic electron neutrinos and antineutrinos against the corresponding beta decay or electron capture (EC) decay backgrounds in different flavor mixing schemes. We stress that such direct measurements of hot DM might not be hopeless in the long term.

1. Introduction
Although the existence of dark matter (DM) in the Universe has been established, what it is made of remains a fundamental puzzle [1]. Within the standard model (SM) three kinds of active neutrinos and their antiparticles, whose masses lie in the sub-eV range, may constitute hot DM. Beyond the SM one or more species of sterile neutrinos and antineutrinos at a similar mass scale may also form hot DM, if they were thermalized in the early Universe as their active counterparts. Such light sterile particles are hypothetical, but their existence is more or less implied by current experimental and cosmological data [2, 3]. We are therefore open-minded to conjecture that hot DM might in general consist of both active and sterile components.

How to detect hot DM is a great challenge to the present experimental techniques. Among several possible ways [4], the most promising one is the relic neutrino capture experiment by means of radioactive beta-decaying nuclei [5]–[10]. The signal of this method is measured by the monoenergetic electron’s kinetic energy for each neutrino mass eigenstate, well beyond that of the corresponding beta-decay background. A measurement of the gap between the capture and decay processes will directly probe hot DM neutrinos and determine or constrain their masses and mixing angles. However, this method does not directly apply to the capture of hot DM antineutrinos, simply because it is $\nu_e$ (instead of $\bar{\nu}_e$) that is involved in the capture reaction. A possible way out for relic antineutrino detection is to make use of some radioactive nuclei which can decay via electron capture (EC) [11]–[13].

2. Relic neutrino captures
In the presence of $3 + N_s$ species of active and sterile neutrinos, the flavor eigenstates of three active neutrinos can be written as [1]

$$|\nu_\alpha\rangle = \sum_i V_{\alpha i}^* |\nu_i\rangle,$$  \hspace{1cm} (1)
where $\alpha$ runs over $e, \mu$ and $\tau, \nu_i$ is a mass eigenstate of active (for $1 \leq i \leq 3$) or sterile (for $4 \leq i \leq 3 + N_s$) neutrinos, and $V_{\alpha i}$ stands for an element of the $3 \times (3 + N_s)$ lepton flavor mixing matrix $V$ in the weak charged-current interactions.

The relic neutrino capture on radioactive beta-decaying nuclei (i.e., $\nu_e + N \rightarrow N' + e^-$) can happen for any kinetic energy of the incident neutrino, because the corresponding beta decay $N \rightarrow N' + e^- + \nu_e$ always releases some energies ($Q_\beta = m_N - m_N' - m_e > 0$). So it has a unique advantage in detecting the cosmic neutrino background with both $m_i \ll Q_\beta$ and extremely low energies [5]–[10]. In the low-energy limit, the differential neutrino capture rate reads [7]

$$\frac{d\lambda_\nu}{dT_e} = \sum_i |V_{\alpha i}|^2 \sigma_{\nu_i} n_{\nu_i} R(T_e, T_e^i),$$  \hspace{1cm} (2)

where $n_{\nu_i}$ denotes the number density of relic $\nu_i$ neutrinos around the Earth. The standard Big Bang model predicts $\langle n_{\nu_i} \rangle \approx 10^{-3}$ today for each species of active neutrinos and antineutrinos [1], and this prediction is also expected to hold for each species of light sterile neutrinos and antineutrinos if they could be completely thermalized in the early Universe. The number density of hot neutrino and antineutrino DM around the Earth may be more or less enhanced by the gravitational clustering effect when $m_i$ is larger than 0.1 eV [14]. In Eq. (2), $R(T_e, T_e^i)$ is a Gaussian energy resolution function defined by [9]

$$R(T_e, T_e^i) = \frac{1}{\sqrt{2\pi} \sigma} \exp \left[ -\frac{(T_e - T_e^i)^2}{2\sigma^2} \right],$$  \hspace{1cm} (3)

in which $T_e$ is the overall kinetic energy of the electrons detected in the experiment, and $T_e^i = Q_\beta + E_{\nu_i}$ is the kinetic energy of the outgoing electron for each incoming mass eigenstate $\nu_i$. Using $\Delta$ to denote the experimental energy resolution, we have $\Delta = 2\sqrt{2\ln 2} \approx 2.35482 \sigma$.

The main background of a neutrino capture process is its corresponding beta decay. The energy spectrum (i.e., $d\lambda_\beta/dT_e$) of a beta decay can be found in [15] and be convolved with the same energy resolution in Eq. (3). Note that the numerical results of $\lambda_\nu$ and $\lambda_\beta$ can be properly normalized by using the half-life of the mother nucleus via the relation $(\lambda_\beta T_{1/2}^\beta = \ln 2)$. Then the distributions of the numbers of signal and background events are expressed, respectively, as

$$\frac{dN_S}{dT_e} = \frac{1}{\lambda_\beta} \cdot \frac{d\lambda_\nu}{dT_e} \cdot \frac{\ln 2}{T_{1/2}^\beta} N_T t,$$

$$\frac{dN_B}{dT_e} = \frac{1}{\lambda_\beta} \cdot \frac{d\lambda_\beta}{dT_e} \cdot \frac{\ln 2}{T_{1/2}^\beta} N_T t$$  \hspace{1cm} (4)

for a given target factor $N_T$ (i.e., the number of target atoms) and for a given exposure time $t$ in the experiment.

3. Numerical illustration

We illustrate the relic neutrino capture signals against the beta-decay backgrounds by considering two neutrino mixing schemes: (a) the standard scheme with three sub-eV active neutrinos; (b) the $(3 + 2)$ scheme with three sub-eV active neutrinos and two sub-eV sterile neutrinos. In our numerical calculations we typically take 100 g $^3$H as the target.

In the standard scheme we shall use $\Delta m_{21}^2 \approx 7.6 \times 10^{-5}$ eV$^2$ and $|\Delta m_{31}^2| \approx 2.4 \times 10^{-3}$ eV$^2$ together with $\theta_{13} \approx 34^\circ$ and $\theta_{12} \approx 10^\circ$ as typical inputs in our numerical estimates and only take the case of $\Delta m_{31}^2 > 0$ for illustration. Fig. 1 shows the relic neutrino capture rate as a function of the kinetic energy $T_e$ of electrons for different values of $m_1$. The finite energy resolution $\Delta$
is taken in such a way that only one single peak can be observed beyond the background. As the smallest neutrino mass $m_1$ increases from 0 to 0.1 eV, the capture signal moves towards the larger $T_e - Q_e$ region. In comparison, the shift of the corresponding background is less obvious because $m_1$ and $\Delta$ have the opposite effects on the location of the spectral endpoint of the beta decay. Hence the distance between the peak of the signal and the background becomes larger for a larger value of $m_1$, and accordingly the required energy resolution $\Delta$ becomes less stringent.

Next we consider the $(3 + 2)$ neutrino mixing scheme with two sub-eV sterile neutrinos. In view of the preliminary hints of sub-eV sterile neutrinos [2, 3], we simply assume $m_4 = 0.2$ eV and $m_5 = 0.4$ eV together with $|V_{e4}| \approx 0.792$, $|V_{e5}| \approx 0.534$, $|V_{e3}| \approx 0.168$, $|V_{e4}| \approx 0.171$ and $|V_{e5}| \approx 0.174$ in our numerical estimates. We calculate the relic neutrino capture rate as a function of the kinetic energy $T_e$ of electrons against the corresponding background for both $\Delta m_{31}^2 > 0$ and $\Delta m_{31}^2 < 0$ cases in Fig 2, where $m_1 = 0$ or $m_3 = 0$ is taken for simplicity. To illustrate possible gravitational clustering effects, we assume $\zeta_1 = \zeta_2 = \zeta_3 = 1$ (without clustering effects for three active neutrinos because their maximal mass is only about 0.05 eV in the scenario under discussion) and $\zeta_5 = 2 \zeta_4 = 10$ (with mild clustering effects for two sterile neutrinos because their masses are 0.2 eV and 0.4 eV, respectively). As shown in Fig. 2, the signals of two sterile neutrinos are obviously enhanced due to $\zeta_4 > 1$ and $\zeta_5 > 1$. If the gravitational clustering of non-relativistic neutrinos is very significant around the Earth, it will be very helpful for us to detect the cosmic neutrino background.

As mentioned in section 1, the beta-decaying nuclei can only be used as the targets of relic neutrino captures and one should employ the EC-decaying nuclei to detect relic antineutrinos. The rather stable isotope $^{163}$Ho [11] is expected to be one of the most promising targets for relic antineutrino detection. We stress that the fine structure near the spectral endpoint of the EC decay of $^{163}$Ho nuclei could be used to study the lepton flavor effects in a similar manner as that of the beta decays, and the properties of the antineutrino capture rate against its background are more or less the same as those discussed above. More discussions can be found in [12, 13].

4. Conclusion

To pin down what DM is really made of has been one of the most important and most challenging problems in particle physics and cosmology. Both the active and sterile species of sub-eV neutrinos and antineutrinos might be a part of hot DM. Here we have addressed ourselves to the direct laboratory detection of relic neutrinos and antineutrinos. The beta-decaying (e.g., $^3$H) and EC-decaying (e.g., $^{163}$Ho) nuclei have been considered as the most promising targets to
Figure 2. The relic neutrino capture rate as a function of the kinetic energy of electrons in the (3 + 2) neutrino mixing scheme with $\Delta m^2_{31} > 0$ (left panel) or $\Delta m^2_{31} < 0$ (right panel). The gravitational clustering of relic sterile neutrinos around the Earth is illustrated by taking $\zeta_1 = \zeta_2 = \zeta_3 = 1$ and $\zeta_5 = 2\zeta_4 = 10$ for example.

capture such extremely low energy objects. Although the present experimental techniques are unable to lead us to a guaranteed measurement of hot DM in the foreseeable future, we might have a chance to make a success of this great exploration in the long term.

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