Contents lists available at ScienceDirect

Physics Letters B

www.elsevier.com/locate/physletb

PHYSICS LETTERS B

Possible capture of keV sterile neutrino dark matter on radioactive β-decaying nuclei

Y.F. Li [a], Zhi-zhong Xing [a,b,*]

[a] Institute of High Energy Physics, Chinese Academy of Science, Beijing 100049, China
[b] Institute of Advanced Studies, Nanyang Technological University, Singapore 639673, Singapore

ARTICLE INFO

ABSTRACT

There exists an observed "desert" spanning six orders of magnitude between $\mathcal{O}(0.5)$ eV and $\mathcal{O}(0.5)$ MeV in the fermion mass spectrum. We argue that it might accommodate one or more keV sterile neutrinos as a natural candidate for warm dark matter. To illustrate this point of view, we simply assume that there is one keV sterile neutrino ν_4 and its flavor eigenstate ν_s weakly mixes with three active neutrinos. We clarify different active–sterile neutrino mixing factors for the radiative decay of ν_4 and β decays in a self-consistent parametrization. A direct detection of this keV sterile neutrino dark matter in the laboratory is in principle possible since the ν_4 component of ν_e can leave a distinct imprint on the electron energy spectrum when it is captured on radioactive β-decaying nuclei. We carry out an analysis of its signatures in the capture reactions $\nu_e + {}^3\mathrm{H} \to {}^3\mathrm{He} + e^-$ and $\nu_e + {}^{106}\mathrm{Ru} \to {}^{106}\mathrm{Rh} + e^-$ against the β-decay backgrounds, and conclude that this experimental approach might not be hopeless in the long run.

1. The existence of dark matter (DM) in the Universe has been established, but its nature remains a fundamental puzzle in particle physics and cosmology. Within the standard model (SM) three active neutrinos and their antiparticles may constitute hot DM, which only has a tiny contribution to the total matter density of the Universe. A careful study of the structure formation indicates that most DM should be cold at the onset of the galaxy formation [1]. Possible candidates for cold DM include weakly interacting massive particles, axions and other exotic objects beyond the SM [2]. Between the hot and cold limits, warm DM is another possibility of accounting for the observed non-luminous and non-baryonic matter content in the Universe. Its presence may solve or soften several problems that one has so far encountered in the DM simulations [3] (e.g., damping the inhomogeneities on small scales by reducing the number of dwarf galaxies or smoothing the cusps in the DM halos). Sterile neutrinos are expected to be a good candidate for warm DM, if their masses are of $\mathcal{O}(1)$ keV and their lifetimes are much longer than the age of the Universe [4]. They could be produced in the early Universe in several ways (e.g., either via non-resonant active–sterile neutrino oscillations [5] or via resonant active–sterile neutrino oscillations in the presence of a non-negligible lepton number asymmetry [6]). DM in the form of keV sterile neutrinos may not only suppress the formation of dwarf

galaxies and other small-scale structures but also have impacts on the X-ray spectrum, the velocity distribution of pulsars and the formation of the first stars [7]. Hence their masses and mixing angles can get stringent constraints from the measurements of the X-ray fluxes and the Lyman-α forest [8].

Sterile neutrinos of $\mathcal{O}(1)$ keV are well motivated in some theoretical models. Two typical examples of this kind are the νMSM [9] and the *split seesaw* model [10], which can realize the seesaw and leptogenesis ideas and accommodate one keV sterile neutrino as the DM candidate. Other interesting scenarios have also been proposed [11]. Here we give a purely *phenomenological* and *model-independent* argument to support the conjecture of keV sterile neutrinos as warm DM. Note that there exists an apparent "desert" spanning six orders of magnitude between $\mathcal{O}(0.5)$ eV and $\mathcal{O}(0.5)$ MeV in the SM fermion mass spectrum as shown in Fig. 1. Such a puzzle is a part of the flavor problem in the SM, and it might be solved if there exist one or more keV sterile neutrinos in the desert as a natural candidate for warm DM [12].[1] For simplicity, we assume that only a single sterile neutrino ν_s hides in the desert and it weakly mixes with three active neutrinos. We also assume that its mass eigenstate ν_4 possesses a rest mass of

---

* Corresponding author.
E-mail addresses: liyufeng@ihep.ac.cn (Y.F. Li), xingzz@ihep.ac.cn (Z.-z. Xing).

[1] One of us (Z.z.X.) first put forward this simple point of view as a positive comment on Alexander Kusenko's talk entitled "The dark side of the light fermions" at the 16th Yukawa International Seminar (YKIS) Symposium on Particle Physics beyond the Standard Model, Kyoto, March 2009.
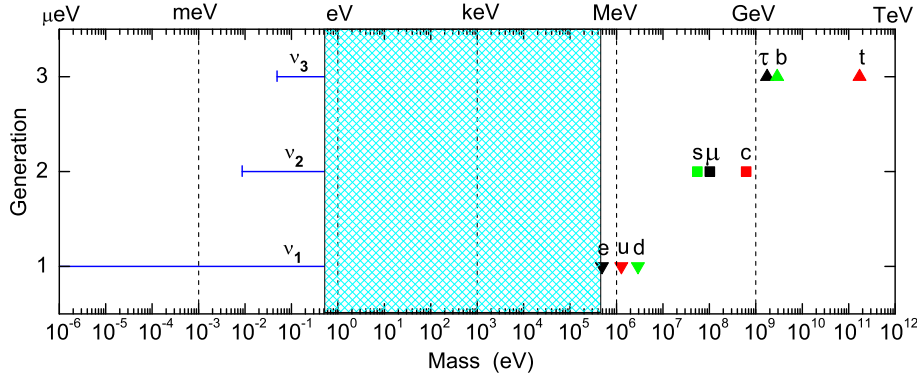
Fig. 1. A schematic illustration of the flavor "hierarchy" and "desert" problems in the SM fermion mass spectrum at the electroweak scale M_Z, where the allowed ranges of neutrino masses with a normal hierarchy are cited from Ref. [30], and the central values of charged-lepton and quark masses are quoted from Ref. [33].

$\mathcal{O}(1)$ keV and satisfies all the prerequisites of warm DM. We shall focus on how to directly detect this sterile neutrino DM in the laboratory.

Because ν_s mixes with ν_e, a careful study of the kinematics of different β decays is in principle possible to probe keV sterile neutrino DM [13]. A more promising method, which is quite analogous to the direct detection of active [14–17] and sterile [17] components of the cosmic neutrino background (CνB), is to investigate the capture of ν_4 on radioactive β-decaying nuclei [18]. The point is simply that the ν_4 component of ν_e can leave a distinct imprint on the electron energy spectrum when it is captured on a nucleus. We carry out an analysis of the signatures of this keV sterile neutrino DM in the capture reactions $\nu_e + {}^3\text{H} \to {}^3\text{He} + e^-$ and $\nu_e + {}^{106}\text{Ru} \to {}^{106}\text{Rh} + e^-$ against the β-decay backgrounds to illustrate the salient features of such a detection method. Our work is different from Ref. [18] in several aspects: (1) we are not subject to any specific neutrino mass models such as the νMSM; (2) we clarify different active–sterile neutrino mixing factors for the radiative decay of ν_4 and β decays, which correspond to the constraints from measurements of the X-ray spectrum and the ν_4 capture, in a self-consistent parametrization; (3) we take account of the finite energy resolution in detecting the electron energy spectrum to make this method more realistic; and (4) we take into account the finite lifetimes of ${}^3\text{H}$ and ${}^{106}\text{Ru}$ and find that the latter may have a non-negligible effect on the capture rate of ν_4 on ${}^{106}\text{Ru}$ nuclei.

2. For simplicity, we consider a SM-like electroweak theory in which there exists one sterile neutrino (ν_s) belonging to the isosinglets together with three charged leptons (e, μ, τ) and three active neutrinos (ν_e, ν_μ, ν_τ) belonging to the isodoublets. Without loss of generality, one may choose to identify the flavor eigenstates of charged leptons with their mass eigenstates. In this flavor basis the 3×4 lepton mixing matrix appearing in the Lagrangian of weak charged-current interactions links the neutrino flavor eigenstates ν_α (for $\alpha = e, \mu, \tau$) to the neutrino mass eigenstates ν_i (for $i = 1, 2, 3, 4$). Although ν_s does not directly participate in the standard weak interactions, it may oscillate with active neutrinos or interact with matter in an indirect way (i.e., via its mixing with ν_α). So we are concerned about the 4×4 active–sterile neutrino mixing matrix V whose explicit form reads

$$\begin{pmatrix} \nu_e \\ \nu_\mu \\ \nu_\tau \\ \nu_s \end{pmatrix} = \begin{pmatrix} V_{e1} & V_{e2} & V_{e3} & V_{e4} \\ V_{\mu 1} & V_{\mu 2} & V_{\mu 3} & V_{\mu 4} \\ V_{\tau 1} & V_{\tau 2} & V_{\tau 3} & V_{\tau 4} \\ V_{s1} & V_{s2} & V_{s3} & V_{s4} \end{pmatrix} \begin{pmatrix} \nu_1 \\ \nu_2 \\ \nu_3 \\ \nu_4 \end{pmatrix}, \quad (1)$$

where ν_4 denotes the mass eigenstate of ν_s. A generic parametrization of V needs six mixing angles θ_{ij} and three (Dirac) or six

(Majorana) CP-violating phases δ_{ij} (for $1 \leqslant i < j \leqslant 4$). In the assumption of $|\theta_{i4}| \ll 1$ (for $i = 1, 2, 3$), one may simplify the standard parametrization of V advocated in Ref. [19]. For instance, $V_{s1} \simeq \hat{s}_{14}^*$, $V_{s2} \simeq \hat{s}_{24}^*$, $V_{s3} \simeq \hat{s}_{34}^*$ and $V_{s4} \simeq 1$ for the matrix elements relevant to ν_s, where $\hat{s}_{ij} \equiv s_{ij}\, e^{i\delta_{ij}}$ and $s_{ij} \equiv \sin\theta_{ij}$ are defined. The dominant decay mode of ν_4 is $\nu_4 \to \nu_\alpha + \nu_\beta + \bar{\nu}_\beta$ (for $\alpha, \beta = e, \mu, \tau$) mediated by the Z^0 boson at the tree level, and its rate is given by

$$\sum_{\alpha=e}^{\tau} \sum_{\beta=e}^{\tau} \Gamma(\nu_4 \to \nu_\alpha + \nu_\beta + \bar{\nu}_\beta) = \frac{C_\nu G_\text{F}^2 m_4^5}{192\pi^3} \sum_{\alpha=e}^{\tau} |V_{\alpha 4}|^2$$

$$= \frac{C_\nu G_\text{F}^2 m_4^5}{192\pi^3} \sum_{i=1}^{3} |V_{si}|^2, \quad (2)$$

where $C_\nu = 1$ for the Dirac neutrinos or $C_\nu = 2$ for the Majorana neutrinos, m_4 denotes the mass of ν_4, and $m_4 \gg m_i$ (for $i = 1, 2, 3$) holds. The lifetime of ν_4 turns out to be

$$\tau_{\nu_4} \simeq \frac{2.88 \times 10^{27}}{C_\nu} \left(\frac{m_4}{1 \text{ keV}}\right)^{-5} \left(\frac{s_{14}^2 + s_{24}^2 + s_{34}^2}{10^{-8}}\right)^{-1} \text{s}, \quad (3)$$

which can be much larger than the age of the Universe ($\sim 10^{17}$ s). So keV sterile neutrinos may be a natural candidate for warm DM.

We are more interested in the subdominant decay channel of ν_4—its radiative decay at the one-loop level. Following Ref. [20] and taking $m_4 \gg m_i$ (for $i = 1, 2, 3$), we find

$$\sum_{i=1}^{3} \Gamma(\nu_4 \to \nu_i + \gamma) \simeq \frac{9\alpha_\text{em} C_\nu G_\text{F}^2 m_4^5}{512\pi^4} \sum_{i=1}^{3} \left|\sum_{\alpha=e}^{\tau} V_{\alpha 4} V_{\alpha i}^*\right|^2$$

$$= \frac{9\alpha_\text{em} C_\nu G_\text{F}^2 m_4^5}{512\pi^4} \sum_{i=1}^{3} |V_{s4} V_{si}^*|^2$$

$$\simeq \frac{9\alpha_\text{em} C_\nu G_\text{F}^2 m_4^5}{512\pi^4} (s_{14}^2 + s_{24}^2 + s_{34}^2), \quad (4)$$

where $\alpha_\text{em} \simeq 1/137$ denotes the electromagnetic fine-structure constant, and $C_\nu = 1$ (Dirac) or 2 (Majorana). A comparison of Eq. (4) with Eq. (2) yields $27\alpha_\text{em}/(8\pi) \simeq 1/128$ for the ratio of two decay rates [21]. A search for the X-ray flux arising from the radiative decay of ν_4 can set a model-independent bound on its mass and mixing angles [4]:

$$s_{14}^2 + s_{24}^2 + s_{34}^2 \lesssim 1.8 \times 10^{-5} \left(\frac{1 \text{ keV}}{m_4}\right)^5. \quad (5)$$

Another model-independent constraint on m_4 comes from the Tremaine–Gunn bound on DM particles [22]: $m_4 \gtrsim 0.4$ keV. More

stringent constraints on the mass and mixing parameters of keV sterile neutrinos can be achieved when their production mechanism and proper DM abundance are taken into account. In the non-resonant active–sterile neutrino oscillation scenario [5], for instance, one obtains 1.7 keV $< m_4 <$ 6.3 keV [8,23][2] together with [4]

$$s_{14}^2 + s_{24}^2 + s_{34}^2 \simeq 3.2 \times 10^{-9} \left(\frac{3 \text{ keV}}{m_4}\right)^{1.8} \qquad (6)$$

to fit the observed DM abundance (i.e., $\Omega_{\text{DM}} \simeq 0.21$ [1]) in the Universe at the present time.

Note that an analysis of recent observational data on the Willman 1 dwarf spheroidal galaxy in the Chandra X-ray Observatory shows evidence of a relic sterile neutrino with $m_4 \sim 5$ keV and $s_{14}^2 + s_{24}^2 + s_{34}^2 \sim 10^{-9}$ [26]. On the other hand, the excess of the intensity in the FeXXVI Lyman-γ line in the spectrum of the Galactic center observed recently by the Suzaku X-ray mission hints at the existence of a relic sterile neutrino with $m_4 \sim 17.4$ keV and $s_{14}^2 + s_{24}^2 + s_{34}^2 \sim 10^{-12}$ [27]. In either case the inferred number density of sterile neutrinos can account for a part or all of DM. Although the statistical significance of the above evidence for keV sterile neutrino DM is not sufficiently strong, it *does* motivate us to take the issue more seriously than before.

3. Now we look at how to directly detect keV sterile neutrino DM in the laboratory. We focus our attention on the capture of cosmic low-energy electron neutrinos on radioactive β-decaying nuclei (i.e., $\nu_e + N \rightarrow N' + e^-$), in which the ν_4 component of ν_e may leave a distinct imprint on the electron energy spectrum. This capture reaction can happen for any kinetic energy of the incident neutrino, because the corresponding β decay $N \rightarrow N' + e^- + \bar{\nu}_e$ always releases some energies ($Q_\beta = m_N - m_{N'} - m_e > 0$). So it has a unique advantage in detecting cosmic neutrinos with $m_i \ll Q_\beta$ and extremely low energies [14–17]. In the low-energy limit the product of the cross section of non-relativistic neutrinos σ_{ν_i} and the neutrino velocity v_{ν_i} converges to a constant value [15], and thus the capture rate for each ν_i reads

$$\mathcal{N}_{\nu_i} = N_T |V_{ei}|^2 \sigma_{\nu_i} v_{\nu_i} n_{\nu_i}, \qquad (7)$$

where n_{ν_i} denotes the number density of ν_i around the Earth or in our solar system, and N_T measures the average number of target nuclei for the duration of detection. The standard Big Bang model predicts $n_{\nu_i} = n_{\bar{\nu}_i} \simeq 56$ cm^{-3} (for $i = 1, 2, 3$) today for each species of active neutrinos. As for the keV sterile neutrinos, we assume that they were produced in the early Universe through active–sterile neutrino oscillations [5,6] and their number density could account for the total amount of DM. With the help of the average density of DM in our Galactic neighborhood (i.e., $\rho_{\text{DM}}^{\text{local}} \simeq 0.3$ GeV cm^{-3} [28]), one may estimate the number density of ν_4 to be $n_{\nu_4} \simeq 10^5$ (3 keV/m_4) cm^{-3}. The average number of target nuclei in the detecting time interval t can be calculated as follows:

$$N_T = \frac{1}{t} \int_0^t N(0) e^{-\lambda t'} dt' = \frac{N(0)}{\lambda t}\left(1 - e^{-\lambda t}\right), \qquad (8)$$

where $\lambda = \ln 2/t_{1/2}$ with $t_{1/2}$ being the half-life of each target nucleus, and $N(0)$ is the initial number of target nuclei. In the capture reaction each non-relativistic ν_i can in principle produce a mono-energetic electron with the kinetic energy $T_e^{(i)} = Q_\beta + E_{\nu_i} \simeq Q_\beta + m_i$. Because a realistic experiment must be subject to a finite energy resolution, we consider the Gaussian energy resolution function

$$R\left(T_e, T_e^{(i)}\right) = \frac{1}{\sqrt{2\pi}\sigma} \exp\left[-\frac{(T_e - T_e^{(i)})^2}{2\sigma^2}\right], \qquad (9)$$

which makes the ideally discrete energy lines of the electrons to spread and form a continuous energy spectrum. Then the overall neutrino capture rate (i.e., the energy spectrum of the detected electrons) is given by

$$\begin{aligned}
\mathcal{N}_\nu &= \sum_{i=1}^4 \mathcal{N}_{\nu_i} R\left(T_e, T_e^{(i)}\right) \\
&= \sum_{i=1}^4 N_T |V_{ei}|^2 \sigma_{\nu_i} v_{\nu_i} n_{\nu_i} R\left(T_e, T_e^{(i)}\right).
\end{aligned} \qquad (10)$$

It is worth emphasizing that $N_T \simeq N(0)$ is an excellent approximation for ^{3}H [17], but it will not be true for ^{106}Ru and some other heavy nuclei with $t_{1/2} \sim t$ or $t_{1/2} < t$.

The main background of a neutrino capture process is its corresponding β decay. The finite energy resolution may push the outgoing electron's ideal endpoint $Q_\beta - \min(m_i)$ towards a higher energy region, and hence it is possible to mimic the desired signal of the neutrino capture reaction. Given the same energy resolution as that in Eq. (9), we can describe the energy spectrum of a β decay as

$$\begin{aligned}
\frac{d\mathcal{N}_\beta}{dT_e} &= \int_0^{Q_\beta - \min(m_i)} dT_e' \Bigg\{ N_T \frac{G_F^2 \cos^2\theta_C}{2\pi^3} F(Z, E_e) |\mathcal{M}|^2 \\
&\quad \times \sqrt{E_e^2 - m_e^2} E_e (Q_\beta - T_e') \\
&\quad \times \sum_{i=1}^4 \Big[|V_{ei}|^2 \sqrt{(Q_\beta - T_e')^2 - m_i^2} \\
&\quad \times \Theta\left(Q_\beta - T_e' - m_i\right)\Big] R(T_e, T_e') \Bigg\},
\end{aligned} \qquad (11)$$

where $T_e' = E_e - m_e$ is the intrinsic kinetic energy of the outgoing electron, $F(Z, E_e)$ denotes the Fermi function, $|\mathcal{M}|^2$ stands for the dimensionless contribution of relevant nuclear matrix elements [29], and $\theta_C \simeq 13°$ is the Cabibbo angle.

Let us stress that the active–sterile neutrino mixing factor in Eq. (10) or Eq. (11) is very different from that in the radiative decay of ν_4 as given by Eq. (4). Taking account of $|\theta_{i4}| \ll 1$ (for $i = 1, 2, 3$), we have $|V_{e1}| \simeq c_{12}c_{13}$, $|V_{e2}| \simeq s_{12}c_{13}$ and $|V_{e3}| \simeq s_{13}$ to a good degree of accuracy in the standard parametrization of V [19]. Nevertheless,

$$\begin{aligned}
|V_{e4}|^2 &\simeq \left|c_{12}c_{13}\hat{s}_{14} + \hat{s}_{12}^* c_{13}\hat{s}_{24} + \hat{s}_{13}^* \hat{s}_{34}\right|^2 \\
&\simeq c_{12}^2 s_{14}^2 + s_{12}^2 s_{24}^2 + 2c_{12}s_{12}s_{14}s_{24}\cos(\delta_{24} - \delta_{12} - \delta_{14})
\end{aligned} \qquad (12)$$

holds for $s_{13} \ll 1$ and $c_{13} \simeq 1$. We see that the neutrino mixing parameters appearing in $\nu_e + N \rightarrow N' + e^-$ and $N \rightarrow N' + e^- + \bar{\nu}_e$ are mainly θ_{12}, θ_{14}, θ_{24} and $\delta_{24} - \delta_{12} - \delta_{14}$. While θ_{12} is already known from the solar neutrino oscillation experiments [1], the others are relevant to the sterile neutrino ν_4 and thus undetermined. In particular, the CP-violating phase $\delta_{24} - \delta_{12} - \delta_{14}$ contributes to the neutrino capture reactions and the corresponding β decays. In

---

[2] Here the upper bound on m_4 comes from the X-ray measurement [8], which is in contradiction with $m_4 > 8.0$ keV obtained from the Lyman-α forest [24]. But in the entropy dilution scenario the Lyman-α bound on m_4 can even be lowered to 1.6 keV [18,25].
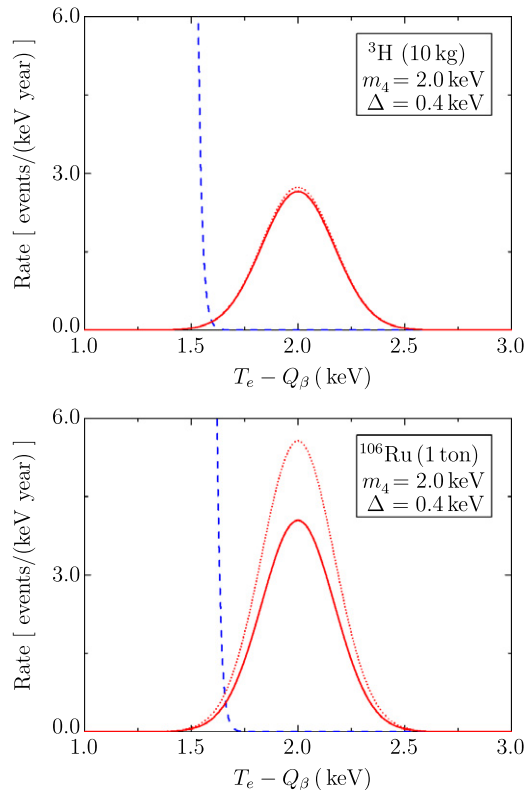
comparison, the rate of the radiative decay of ν_4 given in Eq. (4) has nothing to do with θ_{12} and $\delta_{24} - \delta_{12} - \delta_{14}$. This remarkable difference, which cannot be eliminated even if one makes use of another self-consistent parametrization of V, implies that both the X-ray measurement and the neutrino capture experiment are important in order to probe keV sterile neutrino DM and determine or constrain its full parameter space.

4. To illustrate, we consider the tritium (^{3}H) and ruthenium (^{106}Ru) nuclei as the targets to capture keV sterile neutrino DM. Their capture reactions have relatively large cross sections, as one can see from Table 2 in the paper by Cocco et al. [15]. The typical values of Q_β, $t_{1/2}$ and $\sigma_{\nu_i} v_{\nu_i}$ for these two kinds of nuclei are quoted as follows [15]: $Q_\beta = 18.59$ keV, $t_{1/2} = 3.8878 \times 10^8$ s and $\sigma_{\nu_i} v_{\nu_i}/c = 7.84 \times 10^{-45}$ cm^2 for ^{3}H; or $Q_\beta = 39.4$ keV, $t_{1/2} = 3.2278 \times 10^7$ s and $\sigma_{\nu_i} v_{\nu_i}/c = 5.88 \times 10^{-45}$ cm^2 for ^{106}Ru, where c is the speed of light. In addition, we adopt $|\mathcal{M}|^2 \simeq 5.55$ for both ^{3}H and ^{106}Ru [29]. Our numerical analysis shows that the relative values of $T_e - Q_\beta$ in the electron energy spectra of the neutrino capture reaction and the β decay are actually insensitive to the inputs of $|\mathcal{M}|^2$, although $d\mathcal{N}_\beta/dT_e$ itself is proportional to $|\mathcal{M}|^2$ and sensitive to its value.

We proceed to do a numerical calculation of $\mathcal{N}_\nu$ and $d\mathcal{N}_\beta/dT_e$ for ^{3}H and ^{106}Ru nuclei by using Eqs. (10) and (11). Because our main concern is the signature of keV sterile neutrino DM, we simply assume a normal mass ordering for three active neutrinos with $m_1 = 0$, $m_2 = \sqrt{\Delta m_{21}^2} \simeq 8.7 \times 10^{-3}$ eV and $m_3 = \sqrt{|\Delta m_{31}^2|} \simeq 4.9 \times 10^{-2}$ eV [30].[3] Moreover, we adopt the best-fit values $\theta_{12} \simeq 34.4°$, $\theta_{13} \simeq 5.6°$ and $\theta_{23} \simeq 42.9°$ for the mixing angles among ν_1, ν_2 and ν_3 [30] in the standard parametrization of V. To illustrate the signature and background of ν_4, we take two different mixing scenarios of sterile neutrinos as our typical examples: (1) scenario A with $m_4 = 2$ keV and $|V_{e4}|^2 \simeq 5 \times 10^{-7}$, compatible with the upper bound of $s_{14}^2 + s_{24}^2 + s_{34}^2$ given in Eq. (5) so as to reveal the most optimistic experimental prospect; (2) scenario B with $m_4 = 5$ keV and $|V_{e4}|^2 \simeq 1 \times 10^{-9}$, consistent with the preliminary evidence for keV sterile neutrino DM obtained recently in the Chandra X-ray Observatory [26].[4]

Our numerical results for the spectrum of the neutrino capture rate against the β-decay background are shown in Figs. 2 and 3, where a typical value of the finite energy resolution Δ ($= 2\sqrt{2\ln 2}\sigma \approx 2.35482\sigma$) has been chosen to distinguish the signal from the background. Furthermore, the half-life $t_{1/2}$ of target nuclei should be taken into account because their number has been decreasing during the experiment. We give a comparison between the result including the finite half-life effect and that in the assumption of a constant number of target nuclei for an experiment with the one-year exposure time ($t = 1$ year). To optimistically illustrate the signature of keV sterile neutrino DM in this detection method, we assume 10 kg ^{3}H and 1 ton ^{106}Ru as the isotope sources in our calculations.

Figs. 2 and 3 clearly show that the half-life effect is important for the source of ^{106}Ru nuclei but negligible for the source of ^{3}H nuclei. It may reduce about 30% of the neutrino capture rate on ^{106}Ru in the vicinity of $T_e - Q_\beta \simeq m_4$. Hence this effect must be included if the duration of such an experiment is

---

[3] A similar signature of ν_4 in the electron energy spectrum can be obtained for the inverted or nearly degenerate mass pattern of three active neutrinos, only if the input values of those parameters associated with ν_4 are unchanged.

[4] In this work we do not take into account the other preliminary evidence for sterile neutrino DM with $m_4 \sim 17.4$ keV and $s_{14}^2 + s_{24}^2 + s_{34}^2 \sim 10^{-12}$ [27], because it implies $|V_{e4}|^2 \sim 10^{-12}$ and leads to an extremely small capture rate of ν_4 on β-decaying nuclei.

Fig. 2. The capture rate of keV sterile neutrino DM as a function of the kinetic energy T_e of electrons, where $m_4 = 2$ keV and $|V_{e4}|^2 \simeq 5 \times 10^{-7}$ are typically input (scenario A). The solid (or dotted) curves denote the signals with (or without) the half-life effect of target nuclei. The dashed curve stands for the β-decay background.

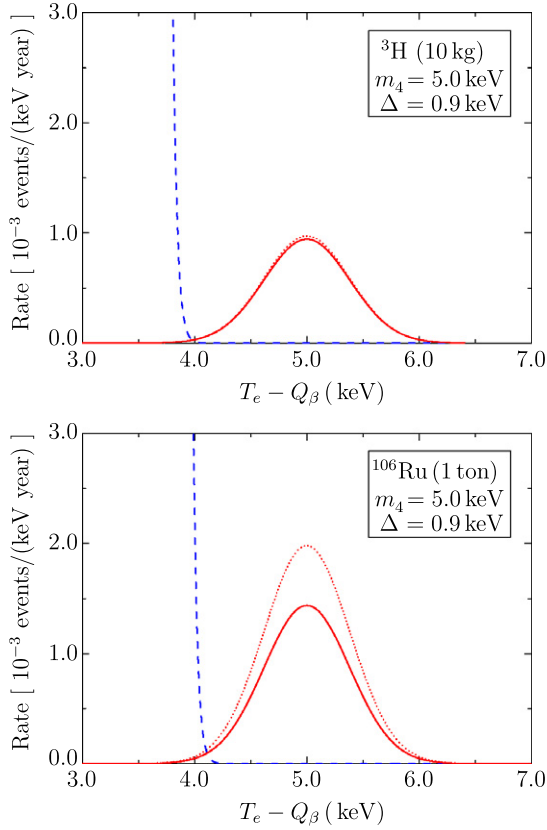comparable with the half-life of the source. We see that smaller m_4 requires a much better energy resolution (i.e., smaller Δ). The endpoint of the β-decay energy spectrum is sensitive to Δ, while the peak of the neutrino-capture energy spectrum is always located at $T_e \simeq Q_\beta + m_4$. So a comparison between Δ and m_4 can easily reveal the signal-to-background ratio. The required energy resolution to identify a signature of keV sterile neutrino DM is of $\mathcal{O}(0.1)$ keV, which can easily be reached in a realistic β-decay experiment (such as the KATRIN experiment with ^{3}H being the isotope source [29]). Note that the endpoint location of the tritium β-decay energy spectrum is slightly different from that of the ruthenium β-decay energy spectrum for a given Δ, simply because they have different values of Q_β. A large gap between the location of the signature of ν_4 and the β-decay endpoint in the electron recoil energy spectrum will in practice make the signature itself almost independent of the corresponding β-decay background.

The main problem which makes the observability of keV sterile neutrino DM rather dim and remote is the tiny active–sterile neutrino mixing angles. As one can see from Fig. 2 and Fig. 3, the capture rates of ν_4 on given β-decaying nuclei are of $\mathcal{O}(1)$ in scenario A but only of $\mathcal{O}(10^{-3})$ in scenario B. So a sizable capture rate requires a great enhancement of other parameters in Eq. (10), such as N_T, n_{ν_i} and $\sigma_{\nu_i} v_{\nu_i}$. The largeness of a combination of these factors may serve for a primary criterion for us to search for the most promising target candidates. In Ref. [15] some typical isotopes with sufficiently large values of $\sigma_{\nu_i} v_{\nu_i} t_{1/2}$ have been listed so as to pursue sufficiently large signal-to-noise ratios in the detection of the CνB. Here our selection criterion for the target nuclei is more or less the same. A re-analysis of all the isotope sources shown in Fig. 5 of Ref. [15] is desirable in order to optimize the detection of keV sterile neutrino DM.

Fig. 3. The capture rate of keV sterile neutrino DM as a function of the kinetic energy T_e of electrons, where $m_4 = 5$ keV and $|V_{e4}|^2 \simeq 1 \times 10^{-9}$ are typically input (scenario B). The solid (or dotted) curves denote the signals with (or without) the half-life effect of target nuclei. The dashed curve stands for the β-decay background.

Besides the β-decay background, two potential backgrounds relevant to the capture of keV sterile neutrino DM on radioactive β-decaying nuclei come from the capture of keV solar neutrinos and from the coherent scattering of sterile neutrinos off the electrons in the target nuclei (i.e., $\nu_s + e^- \rightarrow \nu_e + e^-$ or equivalently $\nu_4 + e^- \rightarrow \nu_i + e^-$ for $i = 1, 2, 3$). The standard solar model predicts the flux of solar neutrinos around $E_\nu \sim 10$ keV is about 10^7 cm^{-2} s^{-1} to 10^8 cm^{-2} s^{-1} [31], and thus the number density of such keV solar neutrinos (mainly pp neutrinos) is around 10^{-4} cm^{-3} to 10^{-3} cm^{-3}, far below the inferred number density of keV sterile neutrino DM $n_{\nu_4} \sim 10^5$ cm^{-3} in our Galactic neighborhood. The keV solar neutrino background is therefore negligible in the analysis of the capture of keV sterile neutrino DM.[5] On the other hand, the $\nu_4 + e^- \rightarrow \nu_i + e^-$ scattering background is not expected to contaminate the signatures of keV sterile neutrino DM in the capture reactions under discussion either. As pointed out in Ref. [32], the momentum transfer to the final-state e^- and ν_i is approximately equal to m_4. So the kinetic energy of the outgoing electron is given by $m_4^2/(2m_e) \simeq 1$ eV $(m_4/\text{keV})^2$, which is of $\mathcal{O}(10)$ eV for m_4 to be a few keV. If the electron energy spectrum resulting from this reaction is measured, it should sharply peak at $m_4^2/(2m_e)$ minus the atomic binding energy [32]. In comparison, the signature of keV sterile neutrino DM in a capture reaction will peak at $T_e \simeq Q_\beta + m_4 \gg m_4^2/(2m_e)$ as clearly shown in Figs. 2 and 3, far away from the peak of the ν_4-e^- scattering effect. Hence the latter is also negligible in the keV sterile neutrino DM cap-

ture on β-decaying nuclei, although it must exist for a neutrino detector. When ^{106}Ru is used as the target, however, one should take care of its metal property. Only the electrons produced on the surface of the ^{106}Ru target may assure the kinetic energy of the outgoing electron to be equal or close to $T_e \simeq Q_\beta + m_4$ in the presence of a keV ν_4. An electron emitted from the interior of a "thick" ^{106}Ru sample will have its energy altered by the interaction with the ruthenium lattice. This effect can affect the electron energy spectrum. Therefore, the actual line-like feature of the ν_4 signature can only be expected from a "thin" layer of ruthenium, which is likely to make the size of an 1 ton ^{106}Ru detector enormous.[6] How to build a realistic detector and how to do a feasible experiment are still open questions.

5. In summary, we have argued that there might exist one or more keV sterile neutrinos in the desert of the fermion mass spectrum. This kind of warm DM can in principle be captured by means of radioactive β-decaying nuclei, because the sterile component of ν_e may leave a distinct imprint on the electron energy spectrum of the capture reaction. For simplicity, only a single keV sterile neutrino ν_s or ν_4 is assumed in the present work. After clarifying different active–sterile neutrino mixing factors for the radiative decay of ν_4 and β decays in a self-consistent parametrization, we have carried out an analysis of the signatures of ν_4 in the capture reactions $\nu_e + {}^3\text{H} \rightarrow {}^3\text{He} + e^-$ and $\nu_e + {}^{106}\text{Ru} \rightarrow {}^{106}\text{Rh} + e^-$ against the β-decay backgrounds so as to reveal a few salient features of this detection method. We admit that it remains extremely difficult to detect keV sterile neutrino DM even if it really exists, but we conclude that the experimental approach under discussion should not be hopeless in the long run.

Acknowledgements

References

[1] Particle Data Group, K. Nakamura, et al., J. Phys. G 37 (2010) 075021.
[2] For a recent review with extensive references, see: J.L. Feng, arXiv:1003.0904.
[3] P. Bode, J.P. Ostriker, N. Turok, Astrophys. J. 556 (2001) 93.
[4] For reviews with extensive references, see: A. Kusenko, Phys. Rep. 481 (2009) 1;
A. Boyarsky, O. Ruchayskiy, M. Shaposhnikov, Ann. Rev. Nucl. Part. Sci. 59 (2009) 191.
[5] S. Dodelson, L.M. Widrow, Phys. Rev. Lett. 72 (1994) 17;
A.D. Dolgov, S.H. Hansen, Astropart. Phys. 16 (2002) 339.
[6] X.D. Shi, G.M. Fuller, Phys. Rev. Lett. 82 (1999) 2832;
M. Laine, M. Shaposhnikov, JCAP 0806 (2008) 31;
A. Boyarsky, J. Lesgourgues, O. Ruchayskiy, M. Viel, Phys. Rev. Lett. 102 (2009) 201304.
[7] See, e.g., A. Kusenko, G. Segre, Phys. Lett. B 396 (1997) 197;
G.M. Fuller, A. Kusenko, I. Mocioiu, S. Pascoli, Phys. Rev. D 68 (2003) 103002.
[8] See, e.g., K. Abazajian, S.M. Koushiappas, Phys. Rev. D 74 (2006) 023527;
M. Loewenstein, A. Kusenko, P.L. Biemann, Astrophys. J. 700 (2009) 426.
[9] T. Asaka, S. Blanchet, M. Shaposhnikov, Phys. Lett. B 631 (2005) 151;
M. Shaposhnikov, Nucl. Phys. B 763 (2007) 49.

---

[5] Even if this background were not negligibly small, it could be rejected if the experiment is able to distinguish between solar and anti-solar directions [32].

[6] We are grateful to the anonymous referee for calling our attention to the metal property of ^{106}Ru and its possible effect on the capture of keV sterile neutrino DM.

[10] A. Kusenko, F. Takahashi, T. Yanagida, Phys. Lett. B 693 (2010) 144.
[11] See, e.g., A. Kusenko, Phys. Rev. Lett. 97 (2006) 241301;
     K. Petraki, A. Kusenko, Phys. Rev. D 77 (2008) 065014;
     W.L. Guo, Phys. Rev. D 77 (2008) 033005.
[12] Z.Z. Xing, Invited plenary talk given at COSMO/CosPA 2010, September 2010, Tokyo.
[13] F. Bezrukov, M. Shaposhnikov, Phys. Rev. D 75 (2007) 053005;
     M. Shaposhnikov, arXiv:0706.1894.
[14] S. Weinberg, Phys. Rev. 128 (1962) 1457;
     J.M. Irvine, R. Humphreys, J. Phys. G 9 (1983) 847.
[15] A. Cocco, G. Mangano, M. Messina, JCAP 0706 (2007) 015;
     R. Lazauskas, P. Vogel, C. Volpe, J. Phys. G 35 (2008) 025001.
[16] M. Blennow, Phys. Rev. D 77 (2008) 113014;
     A. Kaboth, J.A. Formaggio, B. Monreal, Phys. Rev. D 82 (2010) 062001.
[17] Y.F. Li, Z.Z. Xing, S. Luo, Phys. Lett. B 692 (2010) 261.
[18] W. Liao, Phys. Rev. D 82 (2010) 073001.
[19] See, e.g., W.L. Guo, Z.Z. Xing, Phys. Rev. D 65 (2002) 073020;
     W.L. Guo, Z.Z. Xing, Phys. Rev. D 66 (2002) 097302;

[20] P.B. Pal, L. Wolfenstein, Phys. Rev. D 25 (1982) 766;
     R.E. Shrock, Nucl. Phys. B 206 (1982) 359.
[21] V. Barger, R.J.N. Phillips, S. Sarkar, Phys. Lett. B 352 (1995) 365.
[22] S. Tremaine, J.E. Gunn, Phys. Rev. Lett. 42 (1979) 407.
[23] A. Boyarsky, O. Ruchayskiy, D. Iakubovskyi, JCAP 0903 (2009) 005;
     A. Boyarsky, O. Ruchayskiy, arXiv:0811.2385.
[24] A. Boyarsky, J. Lesgourgues, O. Ruchayskiy, M. Viel, JCAP 0905 (2009) 012.
[25] F. Bezrukov, H. Hettmansperger, M. Lindner, Phys. Rev. D 81 (2010) 085032.
[26] M. Loewenstein, A. Kusenko, Astrophys. J. 714 (2010) 652.
[27] D.A. Prokhorov, J. Silk, arXiv:1001.0215.
[28] M. Kamionkowski, A. Kinkhabwala, Phys. Rev. D 57 (1998) 3256.
[29] E.W. Otten, C. Weinheimer, Rep. Prog. Phys. 71 (2008) 086201.
[30] M.C. Gonzalez-Garcia, M. Maltoni, J. Salvado, JHEP 1004 (2010) 056;
     M.C. Gonzalez-Garcia, M. Maltoni, J. Salvado, JHEP 1008 (2010) 117.
[31] J.N. Bahcall, Neutrino Astrophysics, Cambridge University Press, 1989.
[32] S. Ando, A. Kusenko, Phys. Rev. D 81 (2010) 113006.
[33] Z.Z. Xing, H. Zhang, S. Zhou, Phys. Rev. D 77 (2008) 113016.

Z.Z. Xing, Int. J. Mod. Phys. A 19 (2004) 1.