Relic keV Sterile Neutrinos and Reionization

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A sterile neutrino with a mass of several keV can account for cosmological dark matter, as well as explain the observed velocities of pulsars. We show that x rays produced by the decays of these relic sterile neutrinos can boost the production of molecular hydrogen, which can speed up the cooling of gas and the early star formation, which can, in turn, lead to a reionization of the Universe at a high enough redshift to be consistent with the Wilkinson Microwave Anisotropy Probe results.

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There is ample evidence that most of the matter in the Universe is not ordinary atomic matter, but that it is made up of new, yet undiscovered particles. A seemingly unrelated astrophysical puzzle is the origin of the rapid motions of pulsars, whose velocities range in hundreds of km/s, while as many as 15% of pulsars have speeds in excess of 1000 km/s [1]. It is intriguing that these two puzzles may have a simultaneous solution if there exists a sterile neutrino with a mass of several keV and a small mixing with ordinary neutrinos. If such a particle exists, it would be produced in the early universe with the right abundance to be the dark matter [2–4], and it would have an important effect on the cosmological structure formation [5]. The same particle would be emitted from a supernova with a sufficient anisotropy to give the pulsar a kick velocity of the right magnitude [1,6,7]. The pulsar kick from an anisotropic emission of sterile neutrinos can enhance the convection during the first second of the supernova, which can increase the energy of the supernova shock and bring the supernova calculations in better agreement with observations [8]. Another hint at the existence of such a particle comes from the observations [9] of central galactic black holes with masses 3×10^6 to 3×10^9 solar masses at redshifts as high as 6.4. Dark matter in the form of sterile neutrinos could speed up the formation of supermassive black holes at high redshift [10]. Theoretical considerations lead one to believe that at least three sterile neutrinos should exist below the electroweak scale [11], in which case the neutrino oscillations can explain the baryon asymmetry of the Universe [12,13].

Structure formation and reionization of the Universe can be used to test some of the properties of dark-matter particles. Here we show that x-ray photons from the decays of the relic sterile neutrinos could help speed up the reionization of the intergalactic medium (IGM), in accordance with the Wilkinson Microwave Anisotropy Probe (WMAP) observations of the early ionization at redshift $z_r = 17 \pm 5$ [14,15].

If the IGM was reionized by stars (rather than some new physics [16]), the WMAP data imply a very early and efficient star formation. Sterile neutrinos with keV masses have a non-negligible free-streaming length, which could delay the small-scale structure formation [17], if it were not for the photons emitted in their decays. The width of the decay is extremely small, and the sterile neutrinos are stable on cosmological time scales. Nevertheless, some of them do decay, producing photons with keV energies. If the dark matter is made up of sterile neutrinos, the x-ray photons from their decay can catalyze the formation of molecular hydrogen in the amounts that can speed up the gas cooling and star formation, hence leading to an early reionization.

The decays of particles during "dark ages" and their impact on reionization were discussed in Refs. [18,19]. According to Mapelli and Ferrara [19], the electron fraction x_e remains between 0.001 and 0.01 at redshifts $10 < z < 100$. These values are too small to produce the appreciable Thompson optical depth, but they are considerably higher than the electron fraction in the absence of sterile neutrinos. Mapelli and Ferrara [19] concluded that the x-ray photons from sterile neutrino decays can play no role in reionization. However, even a small fraction of ions may be sufficient to catalyze the formation of H_2, which, in turn, can precipitate a rapid star formation. Then the early stars can reionize the IGM. We will show that the electron fraction as high as 10^{-3} can, in fact, boost the production of molecular hydrogen, H_2, to a value which is more than sufficient for a rapid star formation well before $z_r = 17 \pm 5$.

Let us consider a singlet neutrino that has a nonzero mixing with the electron neutrino, and let us ignore other mixings for simplicity. Then the mass eigenstates have a simple expression in terms of the weak eigenstates:

$$|\nu_1\rangle = \cos\theta|\nu_e\rangle - \sin\theta|\nu_s\rangle, \quad (1)$$

$$|\nu_2\rangle = \sin\theta|\nu_e\rangle + \cos\theta|\nu_s\rangle. \quad (2)$$

If the mixing angle θ is small, one of the mass eigenstates, ν_1, behaves very much like a pure ν_e, while the other, ν_2, is practically "sterile," which means it has weak

interactions suppressed by a factor ($\sin^2\theta$) in the cross section. The mixing enables the mass eigenstate ν_2 to decay into lighter neutrinos, as well as ν_1 and a photon. The inverse width of the $\nu_2 \to \nu_1\gamma$ decay is

$$\tau = 1.3 \times 10^{26}\,\mathrm{s}\left(\frac{7\ \mathrm{keV}}{m_s}\right)^5\left(\frac{0.8 \times 10^{-9}}{\sin^2\theta}\right). \quad (3)$$

The x-ray photon produced in this two-body decay has energy $E_\gamma = m_s/2$.

The mass range consistent with ν_2 being dark matter, with the pulsar kicks [1], and all the other constraints [3–5,10,19–21] is

$$2\ \mathrm{keV} < m_s < 8\ \mathrm{keV}.$$

The corresponding photon energies are

$$1\ \mathrm{keV} < E_\gamma < 4\ \mathrm{keV}.$$

This range is rather conservative. A broader range of parameters may be allowed, depending on cosmology [22].

The attenuation length λ for real absorption of such photons in hydrogen [23] is $0.12\ \mathrm{g/cm^2} < \lambda < 7.7\ \mathrm{g/cm^2}$. The dominant absorption process is the ionization edge of hydrogen [24]. Since the density of gas at redshift z is $\rho_{0,\mathrm{H}} = 4 \times 10^{-31}(1+z)^3\ \mathrm{g\,cm^{-3}}$, the energy attenuation length of a photons becomes smaller than the horizon size $H^{-1} = H_0^{-1}(1+z)^{-3/2}$ at redshift $z > z_{\mathrm{thick}} = 9$ for $E_\gamma = 1$ keV, and at $z > z_{\mathrm{thick}} = 148$ for $E_\gamma = 4$ keV. This includes a correction for the presence of helium. However, even at lower redshifts, $z < z_{\mathrm{thick}}$, the photons can ionize gas after they get redshifted. As the photon gets redshifted, the cross section goes up with $(1+z)^{-3}$ due to the ionization edge frequency behavior. The mean free path decreases as $(1+z)^{-3/2}$. Hence, the photons emitted at redshift z_a get all absorbed at some lower redshift z_b. For 4 keV photons, $7.7[(1+z_b)/(1+z_a)]^3 = 0.0043(1+z_b)^{3/2}$. Photons emitted at redshift 77 are all absorbed at redshift 40, implying a loss of about factor 2 in the energy available for ionization and heating. Lower redshifts of the emission yield even greater losses in energy that can be used for ionization. One can safely assume that all the photons produced at redshift greater than $z \gtrsim 40$ lose most of their energy to heating and ionization of the intergalactic medium within less than the Hubble time.

Interactions of 1–4 keV photons with gas start out by ionization which absorbs the photon and ejects an energetic electron, which heats and ionizes further. Compton scattering transfers only a small fraction of the photon energy to the electrons. A cascade started by a single photon can ionize a number of atoms. Photoionization and Compton ionization of atoms are the dominant energy loss processes [25]. The photon energy is divided between reionization, heating, and excitations, with about 30% of it going to ionization [26]. Hence the number of ionized atoms can be estimated as $\sim\eta(m_s/13.6\ \mathrm{eV})$ per x-ray photon, where $\eta \approx 0.3$.

The density of photons produced from the sterile neutrino decays at time t is the sterile neutrino density times $(t/\tau) = (t_0/\tau)(1+z)^{-3/2}$. Each of these photons then ionizes $\sim\eta(m_s/13.6\ \mathrm{eV})$ atoms. In the absence of other effects, at redshift $z \gtrsim 40$, the fraction of ionized atoms is

$$x_e^{(s)} \sim \frac{0.2}{(1+z)^{3/2}}\left(\frac{\eta}{0.3}\right)\left(\frac{m_s}{7\ \mathrm{keV}}\right)^5\left(\frac{\sin^2\theta}{0.8 \times 10^{-9}}\right). \quad (4)$$

Thus, the production of H^+ ions due to sterile neutrino decays occurs at a constant rate per atom,

$$A = 1.4 \times 10^{-16}\ \mathrm{s}^{-1}\left(\frac{m_s}{7\ \mathrm{keV}}\right)^5\left(\frac{\sin^2\theta}{0.8 \times 10^{-9}}\right). \quad (5)$$

The free electrons are consumed in the reaction $\mathrm{H}^+e^- \to \mathrm{H}\gamma$ with the rate $k_1 \approx 1.88 \times 10^{-10}(T_K)^{-0.64}\ \mathrm{cm^3\,s^{-1}}$, where T_K is the gas temperature in degrees Kelvin. Hence, the electron fraction is described by the equation

$$\dot{x_e} = A - k_1 n_{\mathrm{H}} x_e^2 = A - B\left(\frac{t_0}{t}\right)^{1.6} x_e^2, \quad (6)$$

where $n_{\mathrm{H}} = n_{0,\mathrm{H}}(1+z)^3$, $n_{0,\mathrm{H}} = 2 \times 10^{-7}\ \mathrm{cm^{-3}}$, and $B = k_1 n_{0,\mathrm{H}} = 2 \times 10^{-17}\ \mathrm{s^{-1}}$.

The star formation depends on cooling, which becomes very efficient when molecular hydrogen is produced. The critical H_2 fraction needed for a rapid star formation is $f_c \approx 5 \times 10^{-4}$ [27].

In the presence of ions, the molecular hydrogen can form in several reactions. One channel involves H^-,

$$\mathrm{H} + e^- \to \mathrm{H}^- + \gamma, \quad (7)$$

$$\mathrm{H}^- + \mathrm{H} \to \mathrm{H}_2 + e^-, \quad (8)$$

and proceeds at a high rate for $z \ll 200$. However, since H^- is quickly destroyed at high temperature by the interactions with the cosmic microwave background photons, this channel is closed at higher redshifts. At $z \gg 200$, the main reactions are

$$\mathrm{H}^+ + \mathrm{H} \to \mathrm{H}_2^+ + \gamma, \quad (9)$$

$$\mathrm{H}_2^+ + \mathrm{H} \to \mathrm{H}_2 + \mathrm{H}^+. \quad (10)$$

Both channels depend on the presence of ions and free electrons, and, hence, on the value of x_e. The fraction of molecular hydrogen can be found from the following equation:

$$\begin{aligned}\dot{f} &= k_m(t)n_{\mathrm{H}}(t)x_e(t)(1 - x_e(t) - 2f(t)) \\ &\approx k_m(t)n_{\mathrm{H}}(t)x_e(t),\end{aligned} \quad (11)$$

where k_m is a function defined in Ref. [27]. The behavior of k_m as a function of redshift is shown in Fig. 1. It reaches a maximum $k_{m,\max} \approx 2 \times 10^{-16}\ \mathrm{cm^3\,s^{-1}}$ at $z \approx 80$. In the

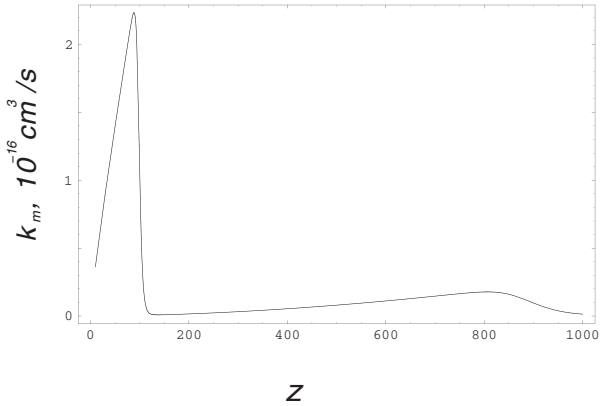

FIG. 1. The rate k_m of molecular hydrogen production as a function of redshift. For illustrative purposes, the gas temperature is assumed to be close to that of the CMBR (which is a good assumption, at least, for $z > 150$).

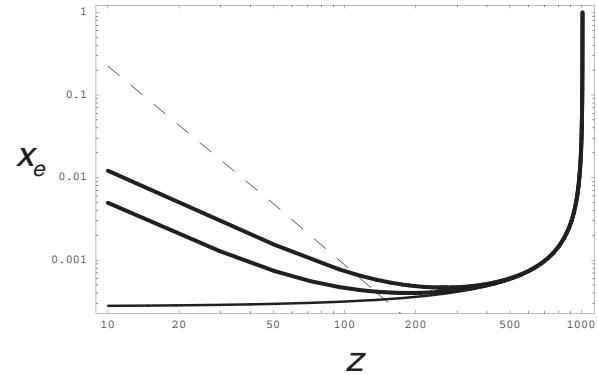

FIG. 2. The fraction of ions, x_e, in the absence of sterile neutrinos (thin line), and for the dark-matter sterile neutrinos with masses 4 and 7 keV (lower and upper thick lines, respectively). Also shown is the limit of baryon decoupling from CMBR (dashed line). Below the dashed line, gas cooling is unaffected by the CMBR.

relevant range of parameters, the molecular hydrogen is not destroyed [28], and the right-hand side of Eq. (11) remains positive.

Shortly after recombination, the ionization fraction $x_e \sim 1$, and some molecular hydrogen is produced. However, in the absence of sterile neutrinos, x_e falls below 10^{-3} by redshift $z = 400$, at which point further production of molecular hydrogen is stymied by the deficit of free electrons. In our case, the free electrons are continuously supplied by the decays of ν_s at the rate given by Eq. (5).

We can now integrate Eq. (6) with the initial condition $x_e = 1$ at recombination. The result can be used to obtain $f(t)$ from Eq. (11). Figure 2 shows the solution of Eq. (6) for three values of A corresponding to dark-matter sterile neutrino masses 4 and 7 keV, as well as for $A = 0$.

Let us now estimate the fraction of molecular hydrogen. Since H_2 is produced and not destroyed for $z \ll 10^3$, the value of $f(z)$ is always greater than the fraction produced at any earlier time. In particular, $f(z)$ is greater than the fraction of hydrogen generated during one Hubble time at redshift z_1, as long as $z_1 > z$. In other words,

$$f(z) > \Delta_z f(t_1) \approx \frac{df}{dt} t_1 \approx k_m(z_1) n_{\rm H}(z_1) x_e(z_1) \frac{t_0}{(1+z_1)^{3/2}}. \tag{12}$$

Let us consider a gas cloud that has virialized at some redshift $z_{\rm vir}$. The evolution of this cloud takes place as usual [27], as long as the electron fraction is not high enough to maintain the thermal equilibrium between the gas and the cosmic microwave background radiation (CMBR) at redshift close to $z_{\rm vir}$. However, if the gas interacts strongly with the CMBR, the Compton scattering keeps its temperature close to that of the CMBR, and the analyses of Ref. [27] do not apply. Compton cooling is described by the following equation:

$$\frac{dT}{dt} = (T_\gamma - T) k_{\rm compt} x_e, \tag{13}$$

where $k_{\rm compt} = 2.6 \times 10^{-20}(1+z)^4\ {\rm s}^{-1}$. To check the efficiency of the Compton cooling, one must compare the cooling rate with the expansion rate of the Universe. This gives a limit on the fraction of ions. The Compton cooling is inefficient (and can be neglected) as long as

$$x_e < 0.9 \times 10^{-3} \left(\frac{100}{1+z}\right)^{5/2}. \tag{14}$$

This limit is shown in Fig. 2 as a dashed line. As one can see, for the parameters of interest, the decoupling of gas from the CMBR occurs at $z > 100$. For smaller redshifts, one can use the semianalytical results from Ref. [27], making a correction for a higher electron fraction.

One should also check that the gas temperature is not raised significantly by the presence of keV photons. If the gas temperature reaches 3000 K, the molecular hydrogen is destroyed. The total energy released in photons from the sterile neutrino decays is

$$\begin{aligned} L &= n_{\nu_s}(m_s/2)\tau^{-1} \\ &= 8 \times 10^{-30} \frac{\rm erg}{{\rm cm}^3\,{\rm s}} \left(\frac{1+z}{100}\right)^3 \times \left(\frac{m_s}{7\ {\rm keV}}\right)^5 \left(\frac{\sin^2\theta}{0.8 \times 10^{-9}}\right). \end{aligned} \tag{15}$$

One can compare this heating process with the cooling processes discussed in Ref. [27]. For the relevant range of parameters, the heat deposited by sterile neutrinos can be neglected.

Let us now consider a gas cloud collapsing and virializing at some redshift $z_{\rm vir}$. The density in a recently virialized cloud is about a factor $18\pi^2$ higher than the mean hydrogen density [27]:

$$n_{\rm vir} = 23\ {\rm cm}^{-3}\left(\frac{1+z}{100}\right)^3.$$

Let us consider $z_{\rm vir} = 100$. The fraction of molecular hydrogen produced at this redshift, according to Eq. (12), is

$$f > \Delta_{100} f = 9 \times 10^{-4}\left(\frac{k_m}{10^{-16}\ {\rm cm}^3\ {\rm s}^{-1}}\right)\left(\frac{x}{10^{-3}}\right) \times \left(\frac{n_{\rm vir}}{20\ {\rm cm}^{-3}}\right). \quad (16)$$

This lower bound on the molecular hydrogen fraction is higher than the critical value $f_c \approx 5 \times 10^{-4}$ derived by Tegmark *et al.* for a successful collapse, especially near the maximum of k_m. This maximum is achieved at $z = 80$, as shown in Fig. 1, and one expects the most efficient production of H_2 for $z_{\rm vir} \sim 10^2$. In the absence of sterile neutrinos, the electron fraction is around 3×10^{-4}, for which f drops below f_c.

In conclusion, if sterile neutrinos with masses of several keV constitute the dark matter, their decays produce enough photons to boost the production of molecular hydrogen in clouds collapsing at redshifts as high as $z \sim 100$. The presence of molecular hydrogen facilitates rapid cooling and the early star formation. At the same time, the sterile neutrinos can have a non-negligible free-streaming length, which can affect the early halo collapse [2,5]. The full analysis must combine the enhanced production of molecular hydrogen with simulations of dark-matter halo formation. Such detailed analysis is beyond the scope of this Letter; it will be presented elsewhere.

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