

## Decaying Particles and the Reionization History of the Universe

Elena Pierpaoli\*

*Physics Department and Astronomy Department, Princeton University, Princeton, New Jersey 08544, USA*  
(Received 13 September 2003; revised manuscript received 13 November 2003; published 22 January 2004)

We investigate the possibility that the Universe is significantly reionized by the decay products of heavy particles. The ionization produced by decaying particles implies a high optical depth even if the maximum level of ionization ever produced is low ( $10^{-2}$ ). As a consequence, a high ionization fraction ( $x \approx 0.5$ ) at high redshifts ( $z \approx 20$ ) fails to fit the cosmic microwave background (CMB) spectra at  $l \geq 30$ . Recent CMB data limit the primordial abundance of the decaying particles, favoring long decay times. Other significant sources of reionization are still needed at  $z \approx 13$ . The decay process heats up the medium, bringing the expected  $y$  distortion to unobservable levels.

DOI: 10.1103/PhysRevLett.92.031301

PACS numbers: 98.80.Cq, 95.35.+d, 98.70.Vc

*Introduction.*—The recent results of the Wilkinson Microwave Anisotropy Probe (WMAP) satellite [1] have shown that the Universe presents a higher optical depth than previously anticipated from the observation of absorption lines toward quasars at redshift  $z \approx 6$ . The data suggest that the Universe is highly ionized at redshifts as high as  $z \approx 20$ . Since this discovery, scientists have investigated different possibilities for producing this high-redshift reionization. In the standard reionization scenario where the first stars are fully responsible for reionization, the WMAP result would imply great difficulties for a number of models, namely, the ones in which the matter power spectrum at small scale is suppressed. Among these are, for example, the warm dark matter (WDM) model of structure formation [2,3] and the cold dark matter (CDM) model with a running spectral index. These models would not provide the sufficient amount of small scale power to produce the needed amount of bound objects at the appropriate (high) redshifts [4]. The issue is particularly important because the WMAP team data analysis seems to favor a running spectral index, when no link between reionization redshift and value of the running spectral index is assumed.

This difficulty may be overcome if the recombination/reionization history is altered by some nonstandard process, such as black hole evaporation or the decay of heavy particles, and theorists have started to develop specific models to this aim [5]. Bean *et al.* [6] analyzed the impact of the recombination history implied by the [5] models. As for decaying particles, their analysis is limited to fairly long-lived specific supermassive dark matter particles. In a recent paper, Hansen and Haiman [7] (hereafter HH) have proposed a model in which the products of heavy sterile neutrino decay would significantly reionize the Universe at redshift  $z \approx 20$ . Different from the previous models, these neutrinos may have a shorter lifetime and an inferred abundance linked to a different physics.

Given the apparent variety of decaying particle models, we take here a general approach and ask whether current data already put constraints on the reionization

history implied by the decay and, in turn, on the particle physics model involved. We revisit the reionization history implied by decaying particles and compare the implied cosmic microwave background (CMB) and large scale structure spectra with current data. We initially perform our calculations in the HH model, which we then generalize to the case of unspecified decay time and particle abundance. We work in a flat Universe with  $\Omega_m = 0.3$ ,  $\Omega_\Lambda = 0.7$ ,  $\Omega_b = 0.05$ , and  $H_0 = 70$  km/s Mpc $^{-1}$ .

*The decaying particle model for reionization.*—We consider here particles with a decay time  $t_{\text{dec}}$  of the order of  $10^{15}$  s (and define  $\tau_{15} \equiv t_{\text{dec}}/10^{15}$  s). The typical decay redshift for such particles would be  $z_{\text{dec}} \leq 20$ . For clarity, we refer here to the model presented by HH, in which a massive neutrino with mass  $m_x$  of a few hundred MeV decays into an electron plus a pion. The main mechanism of reionization in this case is the following: The relativistic electrons produced by the decay process inverse Compton scatter the CMB photons, which then reionize the hydrogen atoms. Each electron would be able to cause the reionization of a number of photons, according to its energy  $E_e = (M - 1)m_\pi/2$ , where  $M \equiv m_x/m_\pi > 1$ . Typical electron energies are of the order of 1–100 MeV; each electron is therefore expected to result in about  $10^6$  ionizations, with an efficiency of about 1/3. The sterile neutrino comoving number density is (HH):  $n_x \approx 5.5 \times 10^{-7} [1/\tau_{15}(M^2 - 1)] \text{ m}^{-3}$ , which would imply an abundance at the present time of  $\Omega_x \approx 7 \times 10^{-9} [M/\tau_{15}(M^2 - 1)]$ , irrelevant for determining the expansion at any time [8].

The decay process produces an additional ionization source which should be added to the standard rate in the ionization equation:

$$\left(\frac{dn}{dt}\right)_{\text{dec}} = \Gamma_x(E_e/I_H)\epsilon = \Gamma_x \frac{E_e}{\Delta E}, \quad (1)$$

where  $\Gamma_x = dn_x/dt$  in comoving coordinates,

$I_H = 13.6$  eV, and the efficiency  $\epsilon$  is approximately  $1/3$ , leading to an energy per reionization  $\Delta E \approx 50$  eV.

Because only a fraction of the electron energy is used to produce ionization, the remaining part is assumed to heat the intergalactic medium. The additional term in the equation for the matter temperature  $T_m$  therefore reads

$$(dT_m/dt)_{\text{dec}} = \frac{2\Gamma_x E_e}{3nk_B} \left(1 - \frac{I_H + 3/2k_B T_m}{(I_H/\epsilon)}\right). \quad (2)$$

We modified the RECFAST code [9] by adding the terms in Eqs. (1) and (2). Figure 1 shows the reionization/recombination rates for this ionization prescription. We have chosen as reference parameters  $m_x = 200$  MeV and  $\tau_{15} = 4$ , which would imply that most particles have decayed by  $z \approx 20$ . The presence of the extra-ionization source boosts the recombination rate at redshift  $z \leq 800$  (Fig. 1). This means that most of the atoms reionized by the decay process would quickly recombine. As a result, the maximum ionization fraction produced with this reionization prescription never exceeds 0.03 (Fig. 2), in contrast with that claimed in HH, who predict a 50% ionization fraction  $x$  at  $z = 20$ . Within the sterile neutrino model, it is impossible to reach such a level of reionization just changing the parameters. A  $\tau_{15}$  increase only shifts the maximum value of  $x$  toward lower redshifts, while altering the mass of the particle causes the neutrino number density and electron energy to have compensating effects on the ionization fraction.

In order to obtain 50% of reionization at  $z = 20$  as a consequence of the decay process, the number density of the neutrinos must be artificially increased by a factor of

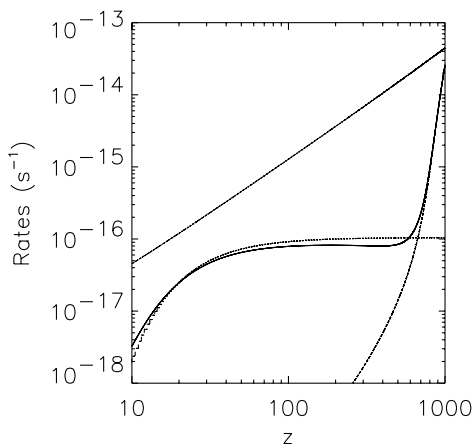


FIG. 1. Different rates are plotted as a function of redshift. Within the “standard” decaying particle model ( $m_x = 200$  MeV,  $\tau_{15} = 4$ ), the solid line is the recombination rate in the decaying particle model, the dotted line is the ionization rate due to the decaying particles, and the straight line is the expansion rate  $H(z)$ . The higher ionization produced by the decay particle implies a higher recombination rate at redshift  $z \approx 10$ –600 with respect to the standard reionization one (dashed line).

order 300 (see Fig. 2). This is not feasible in the sterile neutrino model, but it may be conceivable that other particle physics candidates would produce such abundance. It is therefore sensible to ask which is the maximum level of reionization that can be produced by decaying particles without violating the actual CMB constraints. If these particles produce yields which then cause the Universe to reionize, the reionization process is likely to be similar to the one described above. In order to investigate to what extent such reionization process is allowed, in the following we take as a reference model the  $m_x = 200$  MeV and  $\tau_{15} = 4$  sterile neutrino case to compute a reference abundance and decay yield energy. We then analyze the consequences of an hypothetical particle with abundance  $f_x$  times the one of the reference case ( $\Omega_x = 2.34 \times 10^{-9}$ ). We consider decay times in the range  $1 \leq \tau_{15} \leq 20$ .

*Implications on the CMB power spectrum.*—In this section, we examine the impact of the modified reionization history on the CMB power spectrum. It is well known that reionization has different effects on the temperature (TT) power spectrum and on the temperature polarization cross correlation (TE). In both cases, an increased optical depth  $\tau$  causes a damping of the spectra that is progressively more pronounced for higher  $l$ . The TE spectrum, however, is boosted at low  $l$  if significant reionization occurs at low redshift. The earlier reionization occurs, the greater the  $l$  where the effect appears in the TE spectrum. While the overall optical depth is to a large extent degenerate with other parameters, the low- $l$  bump in the spectra is a quite unique signature of reionization, and is precisely what has been observed by

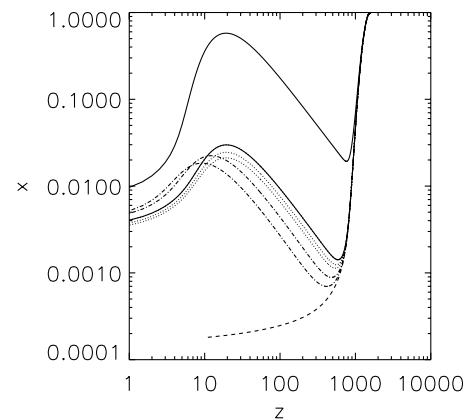


FIG. 2. Ionization histories with and without a decay model. The dashed line corresponds to standard recombination with no reionization. The solid line refers to the standard decay model adopted here ( $m_x = 200$  MeV,  $\tau_{15} = 4$ ); note that the maximum reionization implied is  $x \approx 0.03$ . The dot-dashed lines correspond to a decay model with the same particle mass but  $\tau_{15} = 8$ –12, while the dotted lines correspond to the same  $\tau_{15} = 4$  and  $m_x = 350$ –500 MeV. The three-dot-dashed line is obtained by the reference model by increasing the number density of the decaying particle by a factor 300.

WMAP. Assuming instantaneous and complete reionization occurring at some low redshift  $z_{re}$ , the WMAP team has found  $\tau \approx 0.17$ , corresponding to  $z_{re} \approx 17$  [10].

In the neutrino decay reference model, the decay process implies an alteration of the reionization history already at high redshift ( $z \leq 800$ ). Despite the fact that the ionization fraction  $x$  never reaches 0.1, it remains significantly higher than in the standard recombination case for an extended period of time, during which the number density of baryons is also high. This causes the optical depth to  $z \approx 1000$  to be high even if the ionization fraction never reaches high values. For the neutrino decay model with  $m_\nu = 200$  MeV and  $\tau_{15} = 4$ , we find that the optical depth in the range  $20 \leq z \leq 800$  is  $\tau = 0.11$ . These models therefore provide a way of fitting the TT power spectrum at high  $l$  without significantly altering the current accepted ranges for other parameters (see Fig. 3). Note, however, that a significant level of reionization at  $z \approx 10$ – $15$  is needed in order to match the WMAP low- $l$  result of the TE power spectrum, and sudden reionization at  $z = 6$  would fall too short in fitting the low- $l$  TE spectrum even if the adequate total optical depth was mainly provided by the decaying particles (Fig. 4). For these reasons, we still have to invoke an early star reionization.

Can decaying particles produce a reionization fraction of 0.5 at  $z \approx 20$ ? As shown in Fig. 2, in such a reionization scenario the ionization fraction would always be  $x \geq 0.02$ . The total optical depth would then be extremely high, causing an excessive damping of the TT and TE power spectra at high  $l$ . Moreover, the reionization signature in the TE power spectrum would appear at too

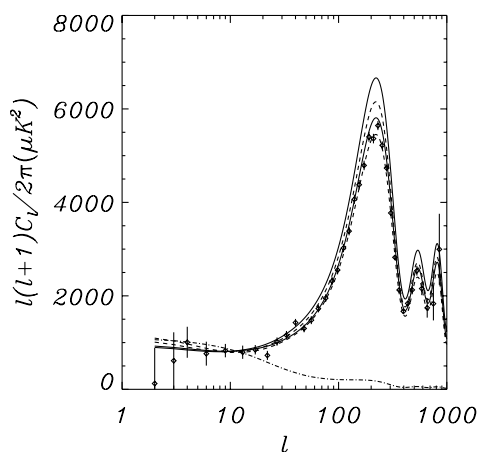


FIG. 3. Temperature power spectra of the CMB. The solid line is the model with no reionization. The dashed line is a model with sudden reionization at  $z \approx 17$  (implying the WMAP best fit value  $\tau = 0.17$ ). The three-dot-dashed line is the standard neutrino decaying model from HH, and the dot-dashed line is the decaying model where the abundance of the particles have been increased by a factor 300 in order to have  $x \approx 0.5$  at  $z = 20$ .

high  $l$  values ( $l \approx 30$ ) contradicting the data. We conclude that it is not possible to reionize the Universe to high levels at  $z \approx 15$  with a process that is powered by dark matter particle decay.

*Cosmological and astrophysical constraints.*—We want to determine to what extent current cosmological data allow a particle decay process with a decay time shorter than or equal to the age of the Universe to trigger reionization. We performed a multiparameter fit to the most recent radiation and matter power spectra data. We allowed for particle decay reionization with time scales  $1 \leq \tau_{15} \leq 140$  and arbitrary abundance (parametrized by  $f_x$ ). In addition, we allowed for instantaneous reionization at a redshift  $z_{re}$ . We kept the spectral index  $n_s$  and the amplitude of the matter power spectrum  $A_s$  as free parameters. The results were obtained with a modified version of the CosmoMC package [11] which uses the WMAP likelihood [12,13].

The results are shown in Fig. 5. The abundance of decaying particles is limited by  $f_x \leq 51$  at 95% C.L., and there is no evidence in the data that such decay-induced reionization models fit the spectra better than the standard reionization scenario. Longer-lived particles are preferred to short-lived ones. The data naturally constrain the reionization rate in the early Universe, which is proportional to  $f_x/\tau_{15}$ . Its 95% C.L. upper limit is  $f_x/\tau_{15} \leq 0.48$ . The reason why long-lived particles are favored resides precisely in the fact that there is a broad range of possible abundances for which the reionization history is little affected. On the contrary, short-lived particles imply a higher reionization rate, therefore constraining  $f_x$  more.

The marginalized likelihoods show a peak at a slightly lower reionization redshift ( $z_{re} = 13$ ) and a smaller optical depth with respect to the standard reionization case

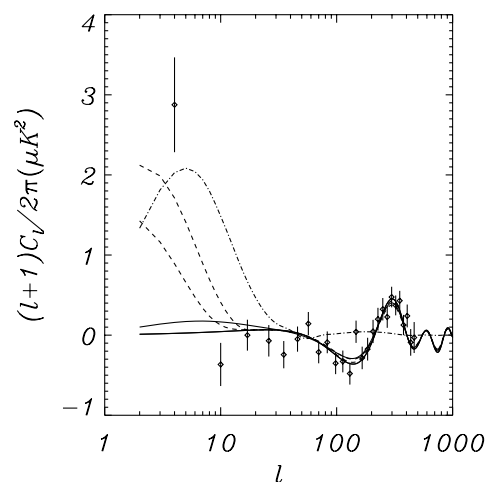


FIG. 4. Temperature-polarization correlation for the models of Fig. 3. The lower dashed curve is a model with sudden reionization at  $z = 6$ , which falls short in fitting the low  $l$  power spectrum.

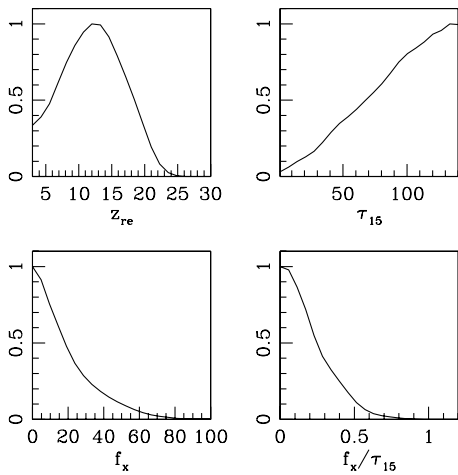


FIG. 5. Marginalized likelihoods for the decay model of reionization parameters.

investigated by the WMAP team, but the likelihoods are still wide. The spectral index is not significantly affected.

As for other astrophysical constraints, it has been argued (HH) that decay-induced reionization may produce a specific distortion in the cosmic microwave background. We computed the evolution of matter temperature with the extra term in Eq. (2). In the decay particle scenario, the additional ionization causes the matter temperature to follow the radiation one for a longer time. The derived  $y$  parameter, which depends on the difference between matter and radiation temperatures in the past, is therefore very small. For the reference neutrino model, it is  $|y| \leq 3 \times 10^{-10}$ , and increasing the decay particle abundance by a factor 300 we have  $|y| \leq 4 \times 10^{-10}$ ; still too small to be detected.

*Conclusions.*—In this Letter, we analyzed to which extent decaying particles may contribute to produce the high ionization rate observed at high redshift by the WMAP experiment.

We showed that if decay yields had to produce a significant reionization at redshifts  $z \approx 20$ , they would alter the reionization history already at redshift  $z \approx 800$ , significantly modifying the reionization/recombination rate and the derived ionization fraction at all redshifts. The implied optical depth would be too high to match the one derived from recent CMB observations. Therefore the decay mechanism cannot be invoked to produce a significant ionization fraction at high redshift.

As a consequence, a standard reionization mechanism (e.g., starlight) acting at fairly high redshifts ( $z_{re} \approx 13$ ) must still be invoked in order to fit the polarization data. These findings suggest that having some reionization produced by decaying particles would not ease the constraints put on a small scale matter power spectrum by

the requirement of having enough collapsed structure at high redshifts to produce small scale objects. Decaying particles do not alleviate the challenge that current data impose to models of structure formation such as WDM or CDM with a running spectral index.

We showed that the current CMB and large scale structure data constrain the abundance of the decaying dark matter particles to  $\Omega_x \leq 1.3 \times 10^{-7} (1+z)^3$  at 95% C.L., when the decay time is in the range  $1-140 \times 10^{15}$  s. Within this range, the data tend to prefer long-lived particles. This result translates into a limit on the fraction of electrons reionized per unit time in the early Universe:  $2 \times 10^{-16} \text{ s}^{-1}$ . There is no evidence that this altered reionization prescription produces a better fit to the data than the instantaneous reionization one. We evaluated the  $|y|$  distortion that would be expected from this reionization mechanism, and found it to be below  $10^{-9}$ , therefore too small to be observed.

E. P. is supported by NASA Grant No. NAG5-11489. She wishes to thank Bruce Draine for several helpful discussions, the Aspen Center for Physics, and the University of Cagliari (Italy) for hospitality during the preparation of this work.

---

\*Electronic address: epierpao@princeton.edu

- [1] C. L. Bennett *et al.*, *Astrophys. J. Suppl. Ser.* **148**, 1 (2003).
- [2] E. Pierpaoli, S. Borgani, A. Masiero, and M. Yamaguchi, *Phys. Rev. D* **57**, 2089 (1998).
- [3] S. Colombi, S. Dodelson, and L. M. Widrow, *Astrophys. J.* **458**, 1 (1996).
- [4] R. Barkana, Z. Haiman, and J. P. Ostriker, *Astrophys. J.* **558**, 482 (2001).
- [5] A. G. Doroshkevich, I. P. Naselsky, P. D. Naselsky, and I. D. Novikov, *Astrophys. J.* **586**, 709 (2003).
- [6] R. Bean, A. Melchiorri, and J. Silk, *Phys. Rev. D* **68**, 083501 (2003).
- [7] S. Hansen and Z. Haiman, astro-ph/0305126.
- [8] The sterile neutrinos are produced in the early Universe when  $T \approx 7$  GeV through neutrino oscillations. Their number density depends upon their mass and mixing angle. Because their decay time also depends on mass and mixing angle, it is possible to express  $\Omega_x$  as a function of  $M$  and  $\tau_{15}$ .
- [9] S. Seager, D. D. Sasselov, and D. Scott, *Astrophys. J.* **128**, 407 (2000).
- [10] D. N. Spergel *et al.*, *Astrophys. J. Suppl. Ser.* **148**, 175 (2003).
- [11] A. Lewis and S. Bridle, *Phys. Rev. D* **66**, 103511 (2002).
- [12] L. Verde *et al.*, *Astrophys. J. Suppl. Ser.* **148**, 195 (2003).
- [13] G. Hinshaw *et al.*, *Astrophys. J. Suppl. Ser.* **148**, 135 (2003).