Early reionization by decaying particles and cosmic microwave background radiation

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(Dated: September, 2004)

We study the reionization scenario in which ionizing UV photons emitted from decaying particle, in addition to usual contributions from stars and quasars, ionize the universe. It is found that the scenario is consistent with both the first year data of the Wilkinson Microwave Anisotropy Probe and the fact that the universe is not fully ionized until \(z \sim 6\) as observed by Sloan Digital Sky Survey. Likelihood analysis revealed that rather broad parameter space can be chosen. This scenario will be discriminated by future observations, especially by the EE polarization power spectrum of cosmic microwave background radiation.

I. INTRODUCTION

The dark age between recombination and today has begun to be revealed to be very complicated by recent observations. The first witness is the Gunn-Peterson trough observed by Sloan Digital Sky Survey (SDSS), which implies that the universe was not fully reionized until \(z \sim 6\) \cite{1}. The second shed light on the beginning of reionization history, which may have started as early as \(z \sim 20\), by the spectrum of cosmic microwave background (CMB) radiation observed by Wilkinson Microwave Anisotropy Probe (WMAP) \cite{2}.

Conventionally the reionization is thought to be caused by the UV photons emitted from the early forming stars, where the ionization fraction of the universe is approximated by a step function \cite{3}. In fact, the early reionization may be possible with large efficiency for star formation at high redshifts \((z \sim 20)\) \cite{4, 5, 6}. (See also \cite{7}.) However, it makes the ionization fraction unity well before \(z \sim 6\) if it should explain large optical depth \(\tau_{\text{op}} \sim 0.17\) suggested by WMAP. On the contrary, the Compton optical depth for reionization is not large enough if one considers UV photons from forming stars to be consistent with the data by SDSS \cite{2, 8}.

In order to avoid such difficulties, one should think more complicated reionization scenarios. For example, with the use of unconventional initial mass function and different photon emission processes between Population II and III stars, one can obtain the complicated ionization history which has a period of partial reionization before \(z \sim 6\). In particular, some authors \cite{8, 9, 10} showed that the reionization occurs twice.

Here we focus on another possibility. The idea is that the additional UV photons from decaying particles can explain the earlier reionization, while contributions from conventional stars and quasars make the ionization fraction unity at \(z \sim 6\) \cite{12, 13, 14}. Although the existence of such particles may be suspicious, the ionization history is very realistic once we admit it. The photons from the particle decay are characterized by three parameters: mass, abundance, and lifetime. In this paper, we concentrate on the case that the mass is 30 eV\textsuperscript{1}, which emits two 15 eV photons to ionize the universe. For the difference between larger mass and this case, see \cite{12}. We will see the decaying particle scenario is consistent with WMAP and SDSS observations.

The structure of this paper is as follows. In the next section, we review how we obtain ionization history due to photons emitted from stars, quasars, and decaying particles. Temperature (TT) and temperature-polarization (TE) power spectra of CMB observed by WMAP are used to evaluate the significance of this scenario in sect.III. Section IV is for our conclusions.

II. IONIZATION HISTORY

In our scenario, the sources for ionizing UV photons are decaying particles, quasars and stars. Stars (and quasars) are indeed responsible for the full reionization at \(z \sim 6\). On the other hand, contribution of UV photons from the decaying particles keeps ionization fraction much smaller before \(z \sim 6\) for a long period.

We follow the thermal history from \(z > 10^3\) including recombination epoch, calculating the ionization fractions of hydrogen (HI) and helium (He\text{II} and He\text{III}), and the electron temperature, based on the argument of Fukugita and Kawasaki \cite{15}, where the hierarchical clustering scheme of the cold dark matter scenario is used. In addition, we include the sources of ionizing UV photons from decaying particles \cite{12}. Some different treatments of stars and QSOs from \cite{15} can also be found in \cite{12}.

We assume that the particle \(\phi\) emits two photons with monochromatic energy of half mass of that particle, i.e., \(E_\gamma = m_\phi/2\). The number density of \(\phi\)-particle is written as

\begin{equation}
 n_\phi = n_\phi(0)(1+z)^3e^{-\frac{z}{\Gamma_\phi}},
\end{equation}

\textsuperscript{1} Here we consider this decaying particle as a part of cold dark matter (CDM). It can be regarded as CDM in such a way that a scalar condensate is coherently oscillating.
where \( \tau_\phi \) is the lifetime of \( \phi \)-particle. Notice that those emitted photons with \( E_\gamma > 13.6 \text{ eV} \) can ionize hydrogen atoms. Then one can write a source term for the decaying particle as

\[
\left( \frac{dn_e}{dt} \right)_\phi = \frac{n_\phi(t)}{\tau_\phi}.
\]

In order to calculate how many photons are emitted, the abundance, mass, and the lifetime of the particle should be fixed. As mentioned above, we choose \( E_\gamma = 15 \text{ eV} \), since this case represents important features of decaying particle scenario. We calculate ionization histories with \( \tau_\phi = 10^{14} - 10^{16} \text{ sec} \) (and \( 10^{17} \text{ sec} \) for some cases), adjusting the abundance \( \Omega_\phi \) to get the desired value of optical depth \( \tau_{op} \), whose range we explored is \( \tau_{op} = 0.1 - 0.4 \). It is defined by

\[
\tau_{op} = \int_0^\infty dz \sigma_T \left( \frac{dt}{dz} \right) [n_e - n_e]_{\text{sr}},
\]

where \( \sigma_T \) is the Thomson cross section and \( n_e \) is the electron number density for standard recombination. We subtract this term in order to estimate only the effect of reionization.

Typical ionizing histories are shown in Fig. 1. Here ionization fraction is defined as

\[
\chi = \frac{n_e}{n_e + n_H},
\]

and \( n_e \) and \( n_H \) are the number densities of electron and hydrogen atom, respectively.

As we will see later, cosmological parameters such as Hubble parameter, \( H_0 \), matter density, \( \Omega_m \), baryon density, \( \Omega_b \), and the spectral index of primordial power spectrum, \( n_s \), are varied such that they give the minimum \( \chi^2 \) for fitting both TT and TE spectrum observed by WMAP in the flat LCDM cosmology.

As we can see in Fig. 1, ionization due to decaying particles endures for a long period, and the ionization fraction remains very small (\( 10^{-3} \lesssim \chi_e \lesssim 10^{-1} \)) until \( z \sim 6 \). Even in these cases, the optical depth becomes very large.

![FIG. 1: Evolution of ionization fraction. \( \tau_\phi = 10^{14} \text{ sec} \) (red), \( 10^{15} \text{ sec} \) (green), and \( 10^{16} \text{ sec} \) (blue) are plotted. For each lifetime, both \( \tau_{op} = 0.1 \) (solid) and 0.4 (dashed) are shown.](image1)

![FIG. 2: Likelihood contour of the decaying particle scenario.](image2)

### III. COSMIC MICROWAVE BACKGROUND

Now we look for how these ionization histories are consistent with CMB observation by WMAP. To this end, we calculate the power spectrum with obtained evolution of the ionization fraction and matter temperature as inputs to the code modified from CMBFAST [16], and evaluate \( \chi^2 \) using the code provided by WMAP [17]. We search for the range \( 10^{14} - 10^{16} \text{ sec} \), for the lifetime of the decaying particle, and \( \tau_{op} = 0.1 - 0.4 \). For fixed lifetime and optical depth, the \( \chi^2 \) minimum is estimated adjusting \( \Omega_b, \Omega_m, H_0, n_s \), and the amplitude of the spectrum. As an indicator for the likelihood, we use \( \Delta \chi^2 = \chi^2 - \chi^2_{\text{best}} \) to make the contour of likelihood with grid-based analysis. Here we take \( \chi^2_{\text{best}} = 1428.6 \) as the six-parameter \( \chi^2 \) minimum for LCDM model with WMAP-only data.

The likelihood contours are shown in Fig. 2. (See also the Table I below.) Here, we converted \( \Delta \chi^2 \) into the confidence level for two degrees of freedom. One can see the ionization history with \( \tau_{op} \lesssim 0.2 \text{ and } \tau_\phi = 10^{14} - 10^{16} \text{ sec} \) is consistent with WMAP data. In general, there is little dependence on the lifetime of decaying particle. For larger optical depth, \( \tau_\phi \sim 10^{15} \text{ sec} \) seems more preferable a bit, although its probability is very small because \( \chi^2 = 1434.7 \) and 1441.2 for \( \tau_{op} \approx 0.3 \) and 0.4, respectively. We omit the lifetime longer than \( 10^{17} \text{ sec} \) from the figure, because the ionization fraction becomes unity before \( z \sim 6 \) for \( \tau_{op} \gtrsim 0.3 \) even if there is no contributions of stars and quasars. Of course, if \( \tau_{op} \lesssim 0.2 \), it is consistent with observations as well. For example, \( \chi^2 = 1432.6 \) and 1430.5 for \( \tau_{op} = 0.2 \) and 0.1, respectively. Notice that, for fixed optical depth, ionization histories with lifetime longer than \( 10^{17} \text{ sec} \) are identical to \( 10^{17} \text{ sec} \) case, since it is the value of \( n_\phi/\tau_\phi \) that concerns with the amount of emitted photons; i.e., the abundance should be ten times larger for the ten times longer lifetime. This relation holds until the abundance reaches \( \Omega_\phi \approx \Omega_m \).

We should mention that \( \chi^2 \) itself is smaller if reionization takes place instantaneously for the same optical
depth. As we have mentioned several times, however, such instantaneous reionization histories do not respect the Gunn-Peterson trough at $z \sim 6$ observed by SDSS. On the other hand, optical depth becomes $\sim 0.04$ if the ionization fraction at $z \sim 6$ is suppressed enough to meet SDSS data. (When using our code without contribution of decaying particle, we get $\tau_{op} \sim 0.05$.)

Table I: Cosmological parameters which make $\chi^2$ minimum for typical optical depth and lifetime of decaying particle. We also show the contributions to the total $\chi^2$ from TT and TE spectra. Lifetime is measured in unit of sec. Baryon abundance, $\Omega_b$, present Hubble parameter, $H_0$, and matter abundance, $\Omega_m$ are shown the ratios to best fit values for WMAP-only data: $\Omega_b = 0.047$, $H_0 = 72 \text{ km/sec/Mpc}$, and $\Omega_m = 0.29$.

| $\tau_0$ | $\tau_{op}$ | $\chi^2$ | TT | TE | $\tau_s$ | $\Omega_b$ | $H_0$ | $\Omega_m$ |
|----------|-------------|----------|----|----|---------|-----------|--------|-----------|
| $10^{-4}$ | 0.417       | 1450.1   | 978.9 | 471.2 | 1.20 | 1.11 | 1.02 | 0.99 |
| $10^{-4}$ | 0.316       | 1438.9   | 976.7 | 462.1 | 1.13 | 1.07 | 1.01 | 0.99 |
| $10^{-4}$ | 0.203       | 1431.7   | 974.7 | 456.9 | 1.05 | 1.03 | 0.99 | 0.98 |
| $10^{-4}$ | 0.098       | 1429.8   | 974.7 | 455.1 | 0.99 | 1.00 | 0.98 | 1.00 |
| $10^{-5}$ | 0.405       | 1438.8   | 979.7 | 459.1 | 1.12 | 1.08 | 1.01 | 1.00 |
| $10^{-5}$ | 0.314       | 1434.7   | 978.8 | 455.9 | 1.07 | 1.06 | 1.00 | 0.99 |
| $10^{-5}$ | 0.202       | 1431.5   | 976.5 | 455.0 | 1.02 | 1.04 | 0.98 | 1.02 |
| $10^{-5}$ | 0.097       | 1430.4   | 975.5 | 454.9 | 0.97 | 1.01 | 0.96 | 1.03 |
| $10^{-6}$ | 0.407       | 1443.7   | 986.0 | 457.7 | 1.05 | 1.05 | 0.99 | 1.00 |
| $10^{-6}$ | 0.307       | 1437.0   | 981.6 | 455.4 | 1.02 | 1.02 | 0.99 | 0.97 |
| $10^{-6}$ | 0.201       | 1432.4   | 978.1 | 454.3 | 0.99 | 1.02 | 0.97 | 1.01 |
| $10^{-6}$ | 0.098       | 1431.4   | 975.8 | 454.9 | 0.98 | 1.00 | 0.98 | 1.00 |
| $10^{-7}$ | 0.199       | 1432.6   | 978.6 | 454.1 | 0.98 | 1.03 | 0.96 | 1.03 |
| $10^{-7}$ | 0.099       | 1430.5   | 976.0 | 454.6 | 0.96 | 1.02 | 0.95 | 1.05 |

Now let us see the CMB spectra in detail. We show TT, TE, and EE power spectra of CMB in Figs. 3 and 4. For TT and TE spectra, we also plot the WMAP data. One can see from Fig. 3 that all the models look almost identical for $\ell \gtrsim 100$. The biggest differences can be seen in low multipole region. This happens because large optical depth reduces height of the acoustic peaks, which results in larger power in low multipoles ($\ell \lesssim 100$) when the height of the first acoustic peak is fixed. In addition to this, the spectrum should be more tilted to the blue side for larger optical depth in order to fit the data, i.e., the well-known $\tau_{op} \sim \tau_s$ degeneracy, which lowers the plateau. Thus the outputs are made by competition between the two opposite effects.

Important point at present is that TE power spectrum does not have much ability of determining ionization histories using the first year WMAP data. The errors are still large, and even though those histories do not seem to fit the TE data well have small $\chi^2$ (see Fig. 4) and Table I if the fit to TT data is good enough. This may lead to the fact that there is little dependence of the $\chi^2$ on the lifetime especially for small optical depth region. Reversely, we could distinguish among different histories with various optical depth so long as the errors diminish.

Although one may discriminate among the models using TE spectrum, EE spectrum seems the most promising tool for that purpose. Most different feature of decaying particle scenario is the larger power at $\ell \sim (a \text{ few}) \times 10$ due
to enduring UV photon emission. Moreover, we may distinguish even the lifetime of decaying particle depending on whether there is a dip around $\ell \sim 10$ and the steepness of the slope below $\ell \sim 100$. Therefore, EE spectrum expected to be seen by Planck satellite or even WMAP should (dis)prove the photons from decaying particles in the near future.

IV. CONCLUSION

We have sought for a natural reionization history which respects both WMAP and SDSS observations. Decaying particles provide UV photons which reionize the universe from rather early period as suggested by WMAP, but keeps the ionization fraction very small until usually considered UV sources such as stars and quasars bring up the fraction to unity abruptly at $z \sim 6$ as observed by SDSS. The central concern is how well such scenario goes on. To this end, we have calculated TT and TE power spectra of CMB, and done the likelihood analysis. We have found decaying particle scenario is consistent with both observations in rather broad parameter space. Even particles with lifetime $10^{14}$ sec, corresponding to the redshift $z \sim 280$, which have the abundance to give $\tau_\phi \lesssim 0.3$, seems good as well.

Looking into the detail, it is the TT power spectrum that determines the value of $\chi^2$ dominantly. This is the reason why the reionization history, whose TE spectrum does not seem to fit the data so well, can have small $\chi^2$, such as 1429.8 for $\tau_\phi \simeq 0.1$ and $\tau_\phi = 10^{14}$ sec, for example. When the quality of TE data improves, then one may be able to tell which reionization history is preferable. As for the ability of discriminating each history, EE spectrum may be the best tool. Decaying particle scenario has a peculiar feature that there is much more excess of the power in the range $20 \lesssim \ell \lesssim 100$ compared with instantaneous reionization case. Moreover, it may be possible to observe even the lifetime of the decaying particle.

Finally, we comment on a maybe serious problem if one regards early forming stars as the whole source of ionization photons because of the less powers on smaller scales observed by, say, 2dFGRS and SDSS. Since the decaying particle scenario does not owe to early forming stars as the UV source, it is completely free from such a problem. We have checked that our model works also for the running spectral index suggested by WMAP. Since all the astrophysical UV sources may suffer this problem, the decaying particle could be the better source of ionizing UV photons.

Acknowledgments

SK is grateful to K. Ichikawa for useful discussions. MK is supported by Japanese Grant-in-Aid for Science Research Fund of the Ministry of Education, No.14540245 and No.14102004.

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