Title
Solving the Crisis in Big-Bang Nucleosynthesis by the Radiative Decay of an Exotic Particle

Permalink
https://escholarship.org/uc/item/82j9f69t

Journal
Physical Review Letters, 77(18)

Author
Holtmann, E.

Publication Date
1996-03-01
Solving the Crisis in Big-Bang Nucleosynthesis by the Radiative Decay of an Exotic Particle

E. Holtmann, M. Kawasaki, and T. Moroi

March 1996
DISCLAIMER

This document was prepared as an account of work sponsored by the United States Government. While this document is believed to contain correct information, neither the United States Government nor any agency thereof, nor the Regents of the University of California, nor any of their employees, makes any warranty, express or implied, or assumes any legal responsibility for the accuracy, completeness, or usefulness of any information, apparatus, product, or process disclosed, or represents that its use would not infringe privately owned rights. Reference herein to any specific commercial product, process, or service by its trade name, trademark, manufacturer, or otherwise, does not necessarily constitute or imply its endorsement, recommendation, or favoring by the United States Government or any agency thereof, or the Regents of the University of California. The views and opinions of authors expressed herein do not necessarily state or reflect those of the United States Government or any agency thereof or the Regents of the University of California.
Solving the Crisis in Big-Bang Nucleosynthesis by the Radiative Decay of an Exotic Particle

Erich Holtmann\textsuperscript{a,b}, Masahiro Kawasaki\textsuperscript{c} and Takeo Moroi\textsuperscript{b}

\textsuperscript{a}Department of Physics, University of California, Berkeley, CA 94720, U.S.A.
\textsuperscript{b}Theoretical Physics Group, Lawrence Berkeley National Laboratory
University of California, Berkeley, CA 94720, U.S.A.
\textsuperscript{c}Institute for Cosmic Ray Research, University of Tokyo, Tokyo 188, Japan

Abstract

A new mechanism which can solve the crisis in the standard big-bang nucleosynthesis scenario is discussed. If we assume an unstable particle $X$ with a long lifetime ($10^4 \text{sec} \lesssim \tau_X \lesssim 10^6 \text{sec}$) which decays into photon(s), then cascade photons induced by the radiative decay of $X$ can destroy significant amounts of D and $^3\text{He}$ without affecting $^4\text{He}$, resulting in a better agreement between the theoretical and observational values of the primordial abundances of D, $^3\text{He}$, and $^4\text{He}$. We numerically investigate this process and derive a constraint on the properties of $X$ in order to make the big-bang nucleosynthesis scenario viable. We also present some candidates for the unstable particle $X$.

\textsuperscript{*This work was supported in part by the Director, Office of Energy Research, Office of High Energy and Nuclear Physics, Division of High Energy Physics of the U.S. Department of Energy under Contract DE-AC03-76SF00098 and in part by the National Science Foundation under grant PHY-90-21139.
The big-bang nucleosynthesis (BBN) scenario provides a crucial test of the big-bang universe, since it precisely predicts the primordial (i.e., before stellar processing) abundances of the light elements such as D, $^3$He, $^4$He, and $^7$Li [1]. In the past, improvements in the theoretical and observational estimates of the light elements seemed to give us a better confirmation of the standard BBN scenario.

Recently, however, observations seem to conflict with the theoretical predictions of the standard BBN scenario, i.e. if we determine the baryon-to-photon ratio $\eta$ by using the observed abundances of $^4$He, then the primordial abundances of D and $^3$He predicted from the standard BBN calculation become too large. In other words, the BBN prediction for $^4$He is too large if we take an $\eta$ that is consistent with $^3$He and D observations. In particular, based on a statistical argument, Hata et al. claimed that the standard BBN scenario is inconsistent with observations at a very high confidence level [2]. This is a serious problem since BBN, together with the Hubble expansion of the universe and the homogeneity of the cosmic microwave background radiation (CMBR), is one of the most important tests of the big-bang cosmology.

Some modification of the standard scenario may solve this difficulty. One way to modify standard BBN is to adopt a non-standard neutrino to decrease the amount of $^4$He. If a neutrino with mass about 1 MeV and lifetime about 1 sec decays into invisible particles, then the predicted $^4$He abundance decreases [3]. It is also possible to reduce $^4$He abundance by allowing degenerate electron neutrinos [4].

Another way to solve the BBN crisis is to reduce the predicted $^3$He and D abundances. In particular, if some exotic particle $X$ decays into photons with a long lifetime, then the predictions of the standard BBN scenario can be modified. That is, if the high energy cascade photons induced by the radiative decay of $X$ can destroy significant amounts of D and $^3$He without affecting $^4$He, then we can have a consistent scenario of nucleosynthesis. In fact, we can find several candidates for the unstable particle $X$ in realistic particle physics models, as will be noted below.

Therefore, in this letter, we assume the existence of an exotic particle $X$ which decays into a pair of photons, and we derive a constraint on the properties of $X$ which makes the BBN scenario viable. We also present some candidates for $X$ based on realistic particle physics models.

First of all, we would like to briefly review the effects of the radiative decay of $X$. Once a high energy photon is emitted into the thermal bath, cascade processes are induced. The high energy photon, electron, and positron spectra are formed accordingly. Cascade photons then induce photodissociation of the light elements. The Boltzmann equation for
a light nuclide N (= D, \(3\text{He}, \, 4\text{He}, \cdots\)) is

\[
\frac{dn_N}{dt} + 3Hn_N = -n_N \sum_i \int_{Q_i}^\infty d\epsilon_\gamma \sigma^i_{N \rightarrow N'}(\epsilon_\gamma)f_\gamma(\epsilon_\gamma)
+ \sum_i n_{N'} \int_{Q_i}^\infty d\epsilon_\gamma \sigma^i_{N' \rightarrow N}(\epsilon_\gamma)f_\gamma(\epsilon_\gamma),
\]

(1)

where \(n_N\) is the number density of the light nuclide N, \(Q_i\) and \(\sigma^i_{N \rightarrow N'}\) are the threshold energy and the cross section for the photodissociation process \(i\) (\(N + \gamma \rightarrow N' + \cdots\)), respectively, and \(f_\gamma(\epsilon_\gamma)\) represents the distribution function of the high energy photons. Then, as can be understood from Eq. (1), if the radiative decay of \(X\) induces a large number of cascade photons at the time \(t\) after BBN starts \((t \gtrsim 1\text{sec})\), then the prediction of standard BBN can be modified.

Before we show our result, it would be helpful to discuss here the typical behavior of the high energy photon spectrum. In the thermal bath with temperature \(T\), high energy photons and electrons lose their energy through the following processes: double photon pair creation \((\gamma + \gamma_{BG} \rightarrow e^+ + e^-)\), photon-photon scattering \((\gamma + \gamma_{BG} \rightarrow \gamma + \gamma)\), pair creation in nuclei \((\gamma + N_{BG} \rightarrow e^+ + e^- + N)\), Compton scattering \((\gamma + e_{BG}^- \rightarrow \gamma + e^-)\), and inverse Compton scattering \((e^\pm + \gamma_{BG} \rightarrow e^\pm + \gamma)\). (The subscript "BG" indicates particles in the thermal background.) One important point is that the typical event rate for double photon pair creation is much larger than those of other processes, since the number of targets or the cross section for this process is much larger than those of the other processes. However, there is a threshold energy \(\epsilon_{thr}\) for this process: the event rate for photons with energy smaller than \(\epsilon_{thr} \sim O(m_e^2/22T)\) is kinematically suppressed [5, 6, 7]. (Here, \(m_e\) is the electron mass.) Therefore, the mean free time of photons with \(\epsilon_\gamma \gtrsim \epsilon_{thr}\) is much shorter than that of photons with \(\epsilon_\gamma \lesssim \epsilon_{thr}\), resulting in \(f_\gamma(\epsilon_\gamma \gtrsim \epsilon_{thr}) \ll f_\gamma(\epsilon_\gamma \lesssim \epsilon_{thr})\). In fact, in usual cases, \(f_\gamma(\epsilon_\gamma \gtrsim \epsilon_{thr})\) is so suppressed that the photodissociation rates for the processes \(i\) with \(Q_i \gtrsim \epsilon_{thr}\) becomes negligibly small. For example, photodissociation of \(4\text{He}\), whose binding energy is about 20MeV, can be effective only for \(T \lesssim 500\text{eV}\), i.e. for \(t \gtrsim O(10^{6-7}\text{sec})\).

The effects of the radiative decay of \(X\) essentially depend on the following parameters: the lifetime \(\tau_X\) of \(X\), the number density of \(X\), and the energy \(\epsilon_{\gamma 0}\) of the photons emitted in \(X\) decay. In this letter, for simplicity, we assume that \(X\) decays only into a pair of photons, i.e. \(BR(X \rightarrow \gamma + \gamma) = 100\%\). Then, \(\epsilon_{\gamma 0} = m_X/2\). In order to parameterize the abundance of \(X\), we use the yield variable \(Y_X\), which is the ratio of the number density of \(X\) to that of photons: \(Y_X = n_X/n_\gamma\). The yield variable is essentially the number of \(X\) in a comoving volume, and it evolves with time as \(Y_X = Y_{X0}e^{-t/\tau_X}\). Therefore, once \(\tau_X\), \(Y_{X0}\),
\( e_{70} \) and \( \eta \) are fixed, we can calculate the primordial abundances of the light elements.

The procedure used in this letter is as follows. We first solve the Boltzmann equations for the distribution functions of the high energy photons and electrons in order to determine the abundance of cascade photons. Then, combining the derived cascade spectrum with the modified Kawano code [8] in which effects of the photodissociation are taken into account, we calculate the primordial abundances of the light elements, i.e. \( y_{2p} \), \( y_{3p} \), and \( Y_p \), where \( y_{2p} \) and \( y_{3p} \) are the primordial number fraction of D and \(^3\)He relative to hydrogen H, respectively, and \( Y_p \) is the primordial mass fraction of \(^4\)He. (For details, see Refs. [6, 7].)

These theoretical predictions should be compared with the constraints obtained from observations. First, let us discuss the constraints on D and \(^3\)He. Since D is only destroyed after BBN, the mass fraction of D decreases with time, and hence [9]

\[
y_{2, \text{ism}} \leq y_{2p} R_X, \\
y_{2\odot} \leq y_{2p} R_X,
\]

where \( R_X = X_{H, p}/X_{H, \text{now}} \), \( y_2 \) is the number fraction of D relative to H, \( X_H \) is the mass fraction of H, and the subscripts “ism”, “\( \odot \)”, and “now” denote the abundances in interstellar matter, those in the solar system, and those in the present universe, respectively. Furthermore, taking into account the chemical evolution of D and \(^3\)He, we obtain a third constraint [9]:

\[
\left\{-y_{2p} + \left( \frac{1}{g_3} - 1 \right) y_{3p} \right\} y_{2\odot} - \frac{1}{g_3} y_{2p} y_{3\odot} + \left( y_{2p}^2 + y_{2p} y_{3p} \right) R_X \leq 0,
\]

where \( y_3 \) is the number fraction of \(^3\)He relative to H, and \( g_3 \) is the survival fraction of \(^3\)He in stellar processes. Usually, \( g_3 \) is estimated to be 0.25 – 0.5 [10].

From observation, the present abundances of the light elements (with 1-\( \sigma \) error) are known to be [11]

\[
y_{2, \text{ism}} = (1.6 \pm 0.2) \times 10^{-5}, \\
y_{2\odot} = (2.57 \pm 0.92) \times 10^{-5}, \\
y_{3\odot} = (1.52 \pm 0.34) \times 10^{-5}, \\
R_X = 1.1 \pm 0.04.
\]

Here, we briefly comment on the detection of D in the primordial H\(_1\) cloud. The absorbed line observed in Ref. [12] suggests \( y_2 \simeq 2.5 \times 10^{-4} \), which is much larger than the value
given in (5) and (6). However, it is claimed that the observed absorption line may be due to a Doppler-shifted hydrogen line [13]. Therefore, in this paper, we do not adopt the D abundance obtained in Ref. [12].

For fixed values of $y_{2p}$, $y_{3p}$, and $g_3$, by regarding $y_{2,ism}$, $y_{2,0}$, $y_{3,0}$, and $R_X$ as statistical variables which obey Gaussian distributions, we can calculate the probability $P(y_{2p}, y_{3p}; g_3)$ that the conditions (2) – (4) are satisfied simultaneously:

$$P(y_{2p}, y_{3p}; g_3) = \int_V dy_{2,ism} dy_{2,0} dy_{3,0} dR_X f(y_{2,ism}; \bar{y}_{2,ism}, \sigma^2_{y_{2,ism}}) f(y_{2,0}; \bar{y}_{2,0}, \sigma^2_{y_{2,0}}) \times f(y_{3,0}; \bar{y}_{3,0}, \sigma^2_{y_{3,0}}) f(R_X; \bar{R}_X, \sigma^2_{R_X}).$$

(9)

In Eq.(9), the integration is performed in the volume $V$ in which all the constraints (2) – (4) are satisfied, and $f(\cdot; \bar{\cdot}, \sigma^2)$ is the Gaussian distribution function for $\cdot$ with mean $\bar{\cdot}$ and variance $\sigma^2$.

By using the probability $P(y_{2p}, y_{3p}; g_3)$, we can obtain a constraint on the primordial abundance of D and 3He. In this letter, for a fixed value of $g_3$, we exclude the parameter set $(y_{2p}, y_{3p})$ if $P(y_{2p}, y_{3p}; g_3) < 0.05$. Here, we note the fact that our $P(y_{2p}, y_{3p}; g_3) = 0.05$ contour with $g_3 = 0.25$ is almost the same as the 95% C.L. constraint given in Ref. [2]. That is, comparing two constraints on $y_{3p}$ for a fixed value of $y_{2p}$, we checked that the discrepancy between the two approaches is at most $(10 - 20)%$, and hence we conclude that they are consistent.

Next, let us show the constraint on $^4$He. The primordial abundance of $^4$He, as estimated from the low-metallicity H II regions, is given by [14]

$$Y_p = 0.232 \pm 0.003\text{(stat)} \pm 0.005\text{(syst)}.$$  

(10)

Now, we are ready to show our numerical results. In our analysis, we compare the constraint on the baryon-to-photon ratio $\eta$ derived from (2) – (4) with that required from the primordial abundance of $^4$He. In Fig. 1 and Fig. 2, we show the contour for the 5% probability constraints in the $\eta$ vs. $m_XY_X$ plane for several values of $\tau_X$. Here, the mass of $X$ is taken to be $m_X = 20\text{MeV}$ (Fig. 1) and $m_X = 1\text{TeV}$ (Fig. 2), and we adopt a neutron lifetime of 887.0sec [15]. Furthermore, for both cases, we use two different values of $g_3$, 0.25 and 0.5.

The typical behavior of the constraint can be understood in the following way. If $\epsilon_{-\nu}Y_X$ is too small, then the abundance of cascade photons is so suppressed that the standard BBN scenario is almost unchanged. In this case, constraints from D and 3He prefer $\eta$ to be $(3 - 7) \times 10^{-10}$, which is too large to be consistent with the $^4$He constraint. However,
if $c_\gamma Y_X$ has the correct value, then sufficient amounts of D and $^3$He are destroyed by cascade photons, and a smaller value of $\eta$ is allowed. (Remember that, in the standard BBN scenario, smaller values of $\eta$ give larger values of $y_{2p}$ and $y_{3p}$.) In particular, adopting $g_3 = 0.25, Y_p = 0.232$ may be consistent with the constraints from D and $^3$He. Furthermore, even for $g_3 = 0.5, Y_p = 0.235$ is acceptable if $c_\gamma \sim 10\text{MeV}$. Thus, if there is an exotic particle, we can have a better agreement between the theoretical prediction and observation. If $c_\gamma Y_X$ is too large, then too much D and $^3$He are destroyed; hence such a parameter region is excluded. Notice that the distribution function of cascade photons depends primarily on the total amount of injected energy [7] when the mass of $X$ is much larger than the $^4$He destruction threshold. In this case, our results are almost independent of $m_X$ for fixed $m_X Y_X$.

Let us now discuss the constraints on $\tau_X$. First of all, the spectrum of CMBR observed by COBE [16] gives us a severe constraint on particles with lifetime longer than $\sim 10^6\text{sec}$ [17]; viz., the spectrum of CMBR observed by COBE is well-fitted by a blackbody distribution, so the spectrum constrains the energy release after the double Compton process ($\gamma + e^- \rightarrow \gamma + \gamma + e^-$) freezes out at $t \sim 10^6\text{sec}$. In particular, for $c_\gamma Y_X \sim 10^{-9}\text{GeV}$, $\tau_X \gtrsim 10^6\text{sec}$ is forbidden [17]. Furthermore, if $\tau_X \gtrsim 10^6\text{sec}$ and $c_\gamma \gtrsim 20\text{GeV}$, then cascade photons destroy $^4$He effectively, which may result in the overproduction of D and $^3$He. Thus, we have an upper bound on $\tau_X$ of $\sim 10^6\text{sec}$. On the other hand, as $\tau_X$ decreases, the threshold for double photon pair creation becomes low, and the number of photons contributing to D and $^3$He photodissociation decreases, for a fixed value of $c_\gamma Y_X$. In this case, a larger value of $m_X Y_X$ is required in order to destroy sufficient amounts of D and $^3$He, as can be seen in Fig. 1 and Fig. 2. However, if the initial mass density of $X$ increases, it speeds up the expansion of the universe, and $^4$He may be overproduced. These arguments exclude $\tau_X$ shorter than $\sim 10^4\text{sec}$. As a result, in order to make our scenario viable, we have to adopt $10^4\text{sec} \lesssim \tau_X \lesssim 10^6\text{sec}$. The allowed values of $m_X Y_X$ are shown as a function of $\tau_X$ in Fig. 3.

Finally, we would like to suggest several candidates for the unstable particle $X$, especially within the framework of models based on supergravity [18]. In such models, there may be several particles which have a long lifetime ($10^4\text{sec} \lesssim \tau_X \lesssim 10^6\text{sec}$). Probably the most famous such particle is the gravitino, whose cosmological implications have been well investigated [19, 6]. As we will see below, the gravitino may have the required properties to solve the crisis in BBN, although in the past it has been regarded as a source of cosmological difficulties (viz. the so-called gravitino problem). We can quantitatively check whether the gravitino can solve the difficulty in BBN, since its interaction is almost
unambiguously determined [18]. If the gravitino decays only into a photon and photino pair, then its lifetime is estimated as

\[ \tau_X \simeq 4 \times 10^5 \text{ sec} \times (1\text{TeV}/m_{3/2})^3, \]  

(11)

where \( m_{3/2} \) is the gravitino mass. Thus, if the gravitino mass is about 1 TeV, its lifetime is about \( 10^{5-6} \text{sec} \), which is appropriate for our purpose. Notice that the photino produced by the gravitino decay interacts very weakly with the particles in the thermal background. Thus, our results can be applied to the case of the gravitino if we rescale the \( m_X Y_{X_0} \)-axis by a factor of \( \sim 0.5 \). Furthermore, assuming an inflationary universe, the gravitino abundance is determined just after the reheating period. In this case, \( Y_{X_0} \) depends only on the reheating temperature \( T_R \) after inflation, and is given by [6]

\[ Y_{X_0} \simeq 2 \times 10^{-11} (T_R/10^{10}\text{GeV}). \]  

(12)

For \( m_{3/2} \sim 1\text{TeV}, \ T_R \sim 10^{8-9}\text{GeV} \) gives \( \epsilon_{X_0} Y_{X_0} \sim 10^{-(9-10)}\text{GeV} \). We note here that \( T_R \sim 10^9\text{GeV} \) may be realized in the chaotic inflation model [20] if the inflaton field decays though gravitational interactions.

If the gravitino is the lightest superparticle, then we can construct another scenario. In this case, the next-to-the lightest superparticle (NLSP), which we assume to be the photino, decays into a gravitino and a photon. By a loose tuning of the parameters, the NLSP can be identified with an unstable particle \( X \) which solves the difficulty in BBN. Thus, in a model based on supergravity, we have several candidates for the unstable particle \( X \) which can make the BBN scenario viable.

In summary, an exotic particle with lifetime \( \tau_X \sim 10^{4-6}\text{sec} \) can solve the crisis in BBN if \( m_X Y_{X_0} \) is tuned within a factor of 2 - 3. Candidates for \( X \) include the gravitino and the photino, both of which naturally appear in models based on supergravity. Of course, even in other types of models, one may be able to find a candidate for the radiatively decaying particle \( X \).

The authors thank N. Hata and D. Thomas for useful discussions and comments on the statistical analysis of the primordial abundances. This work was supported in part by the Director, Office of Energy Research, Office of High Energy and Nuclear Physics, Division of High Energy Physics of the U.S. Department of Energy under Contract DE-AC03-76SF00098 and in part by the National Science Foundation under grant PHY-90-21139.
References


Figure captions

Figure 1: Constraints on the $\eta$ vs. $m_X Y_{X_0}$ plane for $m_X = 20\text{MeV}$. The numbers on the figure represent the lifetime of $X$ in units of sec. Here, $g_3$ is taken to be 0.25 (solid line) and 0.5 (dotted line). The dashed lines are the contours for $Y_p = 0.232, 0.235, \text{and } 0.240$ (from left to right) for $\tau_X = 3 \times 10^3\text{sec}$.

Figure 2: Same as Fig. 1 except that $m_X = 1\text{TeV}$.

Figure 3: The contour for $P(y_{2p}, y_{3p}; g_3) = 0.05$ with $m_X = 1\text{TeV}$, $\eta = 2 \times 10^{-9}$, and $g_3 = 0.25$. 
Fig. 1
Fig. 2