Hadronic decay of the gravitino in the early universe and its implications to inflation*

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Abstract

We discuss the effects of the gravitino on the big-bang nucleosynthesis (BBN), paying particular attention to the hadronic decay mode of the gravitino. We will see that the hadronic decay of the gravitino significantly affect the BBN and, for the case where the hadronic branching ratio is sizable, very stringent upper bound on the reheating temperature after inflation is obtained.

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1 Introduction

It has long been regarded that the gravitino, superpartner of the graviton in the supergravity theory, may cause serious problem in cosmology\cite{1, 2}. This is because the primordial gravitinos produced in the very early universe decay with vary long lifetime. In particular, if the gravitino mass $m_{3/2}$ is smaller than $\sim O(10 \text{ TeV})$, its lifetime is expected to become longer than 1 sec so the primordial gravitinos decay after the big-bang nucleosynthesis (BBN) starts. Even with the inflation, such a problem may not be solved; even if the gravitinos are diluted by the inflation, gravitinos are produced by the scattering processes of the thermal particles after the reheating. As we will discuss later, the gravitino abundance becomes larger as the reheating temperature becomes higher. Consequently, in order not to spoil the success of the BBN scenario, upper bound on the reheating temperature is obtained, and the primordial gravitinos provide stringent constraints on cosmological scenarios based on (local) supersymmetry.

Thus, the effects of the gravitinos on the BBN have been intensively studied in many studies. In particular, in the past, the BBN with hadrodissociation processes induced by hadronic decays of long-lived particles was studied in several articles\cite{3}. After those studies, however, there have been significant theoretical, experimental and observational progresses in the study of the BBN. Thus, we performed a new analysis taking account of those progresses, paying a special attention to the hadronic decay of the gravitino\cite{4}. The most important improvements compared to the old works are as follows. (i) We carefully take into account the energy loss processes for high-energy nuclei through the scattering with background photons or electrons. In particular, dependence on the cosmic temperature, the initial energies of nuclei, and the background $^4\text{He}$ abundance are considered. (ii) We adopt all the available data of cross sections and transferred energies of elastic and inelastic hadron-hadron scattering processes. (iii) The time evolution of the energy distribution functions of high-energy nuclei are computed with proper energy resolution. (iv) The JETSET 7.4 Monte Carlo event generator\cite{5} is used to obtain the initial spectrum of hadrons produced by the decay of gravitino. (v) The most resent data of observational light element abundances are adopted. (vi) We estimate uncertainties with Monte Carlo simulation which includes the experimental errors of the cross sections and transferred energies, and uncertainty of the baryon to photon ratio.

2 Outline of the Analysis

Let us briefly discuss the outline of our analysis. In our study, we first calculate the gravitino abundances as a function of the reheating temperature, which is defined as $T_R \equiv \left( \frac{10^{-3} M_\star^2 \Gamma_{\text{inf}}^2}{g_\star \pi^2} \right)^{1/4}$, where $\Gamma_{\text{inf}}$ is the decay rate of the inflaton, and $g_\star = 228.75$ is the effective number of the massless degrees of freedom in the MSSM. By numerically solving the Boltzmann equations governing the evolution of the number density of the gravitino, we found that the number density of the gravitino $n_{3/2}$ normalized by the entropy density
s is well approximated by
\[
\frac{n_{3/2}}{s} \simeq 1.9 \times 10^{-12} \times \left( \frac{T_R}{10^{10} \text{ GeV}} \right) \left[ 1 + 0.045 \ln \left( \frac{T_R}{10^{10} \text{ GeV}} \right) \right] \left[ 1 - 0.028 \ln \left( \frac{T_R}{10^{10} \text{ GeV}} \right) \right].
\] (2.1)
Thus, the number density of the primordial gravitino is approximately proportional to \( T_R \) and hence, with higher reheating temperature, effects on the BBN becomes more significant.

Once the primordial abundance of the gravitino is given, we consider the effects of the decay of the gravitino on the BBN. Importantly, the interaction of the gravitino is well constrained by the local supersymmetry and its lifetime is calculable. (For the detailed values, see the next section.) Here, we assume several reasonable values of the hadronic branching ratio \( B_h \) of the gravitino, and calculated the abundances of the light elements taking account of the effects of hadronic and electro-magnetic showers induced by the decay products of the unstable gravitino. Outline of our treatments of the hadronic and electro-magnetic processes is schematically shown in Fig. 1 and the details of our study are discussed in the full papers\cite{4, 6}. (Notice that there are other recent studies on the BBN scenario with late-decaying exotic particles\cite{7}.)

We compare the theoretically predicted values of the light-element abundances with the observations. As observational constraints on the light element abundances, we adopt the following values, \( \text{D/H} = (2.8 \pm 0.4) \times 10^{-5} \)\cite{8}, \( ^4\text{He} \) mass fraction \( Y_p = 0.238 \pm 0.002 \pm 0.005 \) by Fields and Olive (FO)\cite{9} and \( Y_p = 0.242 \pm 0.002(\pm 0.005)_{\text{syst}} \) by Izotov and Thuan (IT)\cite{10}, \( \log_{10}(7\text{Li/H}) = -9.66 \pm 0.056(\pm 0.3)_{\text{syst}} \)\cite{11}, \( ^6\text{Li}/^7\text{Li} < 0.07(2\sigma) \)\cite{12}, and \( ^3\text{He}/\text{D} < 1.13(2\sigma) \)\cite{13}. The above errors are at 1\( \sigma \) level unless otherwise stated. Then, we derive upper bound on the reheating temperature requiring that the theoretical predictions be consistent with the observations.

3 Results

Now, we show the results of our analysis. Here, we consider two typical case. The first case is that the gravitino dominantly decays into the gluino pair; in this case, the hadronic branching ratio is expected to be 1 and, in addition, the lifetime of the gravitino is estimated to be
\[
\tau_{3/2}(\psi_\mu \to g + \tilde{g}) \simeq 6 \times 10^7 \text{ sec} \times \left( \frac{m_{3/2}}{100 \text{ GeV}} \right)^{-3}.
\] (3.2)
The second case is that the gravitino decays into the photon and the lightest neutralino (which we assume to be the photino); then, the hadronic branching ratio is expected to be \( \sim O(10^{-2} - 10^{-3}) \) and the lifetime is given by
\[
\tau_{3/2}(\psi_\mu \to \gamma + \tilde{\gamma}) \simeq 4 \times 10^8 \text{ sec} \left( \frac{m_{3/2}}{100 \text{ GeV}} \right)^{-3}.
\] (3.3)
Figure 1: Outline of our analysis.
For these two cases, we have derived the upper bound on the reheating temperature.

In Fig. 2, upper bound on the reheating temperature after the inflation is plotted as a function of the gravitino mass. The results indicates that, as the hadronic branching ratio becomes larger, constraint on the reheating temperature becomes severer. For the case with $B_h = 1$, for example, behavior of the upper bound can be understood in the following way. For $m_{3/2} < \sim 200$ GeV, energetic neutron is likely to decay before scattering off the background nuclei. In this case, effects of the hadronic decay is not so significant while, in this case, effects of the photodissociation becomes comparable to or more significant than the hadrodissociation. Then, the strongest constraint is from the overproduction of $^3$He; For $200$ GeV $\lesssim m_{3/2} < \sim 7$ TeV, energetic hadrons (in particular, neutron) is hardly stopped by the electro-magnetic processes and hence the hadrodissociation processes become the most efficient. In particular, in this case, non-thermal productions of D and $^6$Li provide the most stringent constraint; For $7$ TeV $\lesssim m_{3/2} \lesssim 100$ TeV, the $p \leftrightarrow n$ conversion processes are efficient and significant amount of $p$ may be converted to $n$ resulting in the enhancement of $^4$He. In this case, the constraint from the overproduction of $^4$He is the most significant; For $m_{3/2} \gtrsim 100$ TeV, gravitino decays before the BBN starts. In this case, no upper bound is obtained on the reheating temperature.
4 Summary

In our study, we have studied the effects of the unstable gravitino on the BBN, paying particular attention to the hadronic decay modes. As we have emphasized, as the hadronic branching ratio becomes larger, constraints become more stringent.

Our results have significant implications. In particular, for the gravity-mediated supersymmetry breaking, gravitino mass is expected to be \( \sim O(100) \) GeV. In this case, even if the hadronic branching ratio is \( \sim O(10^{-3}) \), the reheating temperature is constrained to be smaller than \( 10^6 - 10^8 \) GeV. If the gravitino mass is much larger than \( \sim O(100) \) GeV, the constraint on \( T_R \) may be relaxed. With such gravitino, however, the hadronic branching ratio would be close to 1 since, in such a case, all the superpartners of the standard-model particles are expected to be lighter than the gravitino from the naturalness point of view. (Such a mass spectrum may be realized in the anomaly-mediated supersymmetry breaking scenario\[14\].) For \( m_{3/2} \sim O(10 - 100) \) TeV with \( B_h \sim 1 \), the upper bound is given by \( T_R \lesssim 10^7 - 10^{10} \) GeV. For the cosmology, since the reheating temperature is required to be very low when the gravitino mass is \( O(100 \text{ GeV} - 1 \text{ TeV}) \), baryogenesis should occur with very low reheating temperature. This fact imposes significant constraints on some of the scenarios of the baryogenesis, in particular for the leptogenesis scenario with right-handed neutrinos\[15\].

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