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Hadronic decay of late-decaying particles and big-bang nucleosynthesis

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Abstract

We study the big-bang nucleosynthesis (BBN) scenario with late-decaying exotic particles with lifetime longer than ~ 1 s. With a late-decaying particle in the early universe, predictions of the standard BBN scenario can be significantly altered. Therefore, we derive constraints on its primordial abundance. We pay particular attention to hadronic decay modes of such particles. We see that the non-thermal production process of D, ^{3}He and ^{6}Li provides a stringent upper bound on the primordial abundance of late-decaying particles with hadronic branching ratio.

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It has long been recognized that the (standard) big-bang nucleosynthesis (BBN) provide a good probe for the early universe. With our current knowledges of nuclear reaction processes, we can precisely calculate abundances of the light elements (in particular, D, ^{3}He, ^{4}He, ^{6}Li, and ^{7}Li) as functions of the baryon-to-photon ratio $\eta \equiv n_B/n_\gamma$. Thus, comparing the theoretical predictions with the observations, we can obtain various informations about the evolution of the universe. Importantly, using the value of η suggested by the WMAP ($\eta = (6.1 \pm 0.3) \times 10^{-10}$ [1]), the theoretical predictions show relatively good agreement with the observations.[1]

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[1] The reduced χ^2 approximately ranges $\chi^2/3 = 0.6$–0.8 (or 1.4–1.7) for the observational value of Y_p of Izotov and Thuan [13] (Fields and Olive [12]), for the detail, see Ref. [9]. Therefore, the SBBN prediction fits the observational light element abundance well within 1σ (2σ) when we adopted Y_p of Izotov and Thuan (Fields and Olive).

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In cosmological scenarios in the frameworks of physics beyond the standard model, however, the BBN may not proceed in the standard way. This is because, if we assume physics beyond the standard model, there exist various exotic particles. Those exotic particles may cause non-standard processes and spoil the success of the standard BBN.

In particular, if the exotic particle (called X hereafter) decays radiatively and/or hadronically after the BBN starts, the primordial abundances of the light elements may be significantly affected. Indeed, energetic particles produced by the decay of X may scatter off and dissociate the background nuclei. If such processes occur with sizable rates, predictions of the standard BBN scenario are changed.

In various models of particle physics, there exist long-lived (but unstable) particles and hence their effects on the BBN should be studied. In particular, many of those particles interact very weakly and hence it is difficult to study their properties by collider experiments. Thus, in some case, the BBN provides useful and important informations about those weakly interacting particles. Probably the most famous example of such late-decaying particle is the gravitino in the supergravity theory. Gravitinos are produced in the very early universe by scattering processes of the particles in the thermal bath. Their interaction is suppressed by the inverse powers of the (reduced) Planck scale M_*, and hence the lifetime becomes very long. An order of magnitude estimate shows that, if the gravitino is lighter than ~ 10 TeV, its lifetime becomes longer than ~ 1 s. In this case, the thermally produced gravitinos decay after the BBN starts.

Effects of the radiative decay of such long-lived particles have been extensively studied (see, e.g., [2–5]). However, in many cases, hadronic branching ratio may not be negligible and hence, in studying the BBN with late-decaying particles, it is necessary to consider effects of the hadronic decay processes. Even if X dominantly decays into the photon (and something else), hadronic branching ratio is expected to be at least $10^{-(2\text{–}3)}$ since the emitted photon can be converted to a quark–antiquark pair. Of course, if X directly interacts with the colored particles, hadronic branching ratio may become larger.

In the past, the BBN with hadro-dissociation processes induced by hadronic decays of long-lived particles was studied in [6], which are effective for relatively long lifetime ($\gtrsim 10^2$ s).[2] The analysis in Ref. [6] contains, however, a lot of room to be improved since many of nuclear reactions that they used were not accurate enough or not available at that time. After the study of [6], however, there have been significant theoretical, experimental and observational progresses in the study of the BBN. First of all, new data for the hadron reactions have become available and their qualities have been improved very much. Moreover, the primordial abundances of the light elements have been precisely determined with various new observations. In addition, it has been recently known that some of the non-standard processes induced by the decay of late-decaying particle X, which were not taken into account in [6], may play important roles in the BBN. With these progresses, a new study of the late-decaying particles with hadronic branching ratio should be relevant.

Thus, in this Letter, we reconsider the BBN processes with long-lived exotic particle X paying particular attention to the effects of the hadronic decay modes. As a result, we will see that, with hadronic decay modes, the constraint on the primordial abundance of X becomes very severe compared to the case only with the radiative decay modes. In particular, we will see that non-thermal production of D, ^{3}He and ^{6}Li provides a stringent constraint.

We first introduce the framework of our study. Although we have several candidates of the late-decaying particles, we perform our analysis as model-independently as possible. Thus we parameterize the property of the late-decaying particle X using the following parameters: ϵ_X (released energy from the single decay of X) which is equal to its mass m_X unless specially stated, $E_{\rm jet}$ (energy of the primary parton from the decay of X), τ_X (lifetime), B_h (hadronic branching ratio), and the primordial abundance of X. We parameterize the primordial abundance by using the following "yield variable" $Y_X \equiv n_X/s$, which is defined at the cosmic time $t \ll \tau_X$. Here, n_X is the number density of X while s is the total entropy density. We assume that X decays only into the particle in

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[2] BBN constraints from the interconversion process between neutrons and protons by hadronic decays were studied in Refs. [7,8], which is effective for shorter lifetime ($\lesssim 10^2$ s).