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Revisiting big-bang nucleosynthesis constraints on dark-matter annihilation

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ABSTRACT

We study the effects of dark-matter annihilation during the epoch of big-bang nucleosynthesis on the primordial abundances of light elements. We improve the calculation of the light-element abundances by taking into account the effects of anti-nucleons emitted by the annihilation of dark matter and the interconversion reactions of neutron and proton at inelastic scatterings of energetic nucleons. Comparing the theoretical prediction of the primordial light-element abundances with the latest observational constraints, we derive upper bounds on the dark-matter pair-annihilation cross section. Implication to some of particle-physics models are also discussed.

Recent cosmological and astrophysical observations have revealed that about 26% of the mass density of the present universe is occupied by dark matter [1]. This fact suggests that there exists a stable (or very long-lived) particle or field which behaves as a non-relativistic object in the present universe. However, the particle-physics nature of dark matter is almost unknown yet, and it is an important task to acquire information about it.

From particle-physics point of view, a stable particle has attracted much attention as a candidate for dark matter; in our analysis, we assume that some stable particle plays the role of dark matter and denote it as X. In order for an efficient production of the dark-matter particle in the early universe, it is often the case that X has interactions with some of the standard-model particles. In such a case, we may derive constraints on the properties of dark matter by studying the effects of dark-matter pair annihilation into standard-model particles in the early universe.

One of the important effects of dark-matter pair-annihilation is on the big-bang nucleosynthesis (BBN). If dark matter pair-annihilates into charged particles during or after the BBN, they induce photodissociation processes of light elements synthesized via the BBN reactions. In addition, energetic hadrons are often produced as a consequence of the pair-annihilation; if so, hadrodissociation of the light elements are induced. Because the standard BBN scenario predicts the light-element abundances which are more-or-less consistent with observations, too large pair annihilation cross section is excluded. Indeed, such a constraint has been intensively discussed in literatures [2–8].[1]

Recently, there has been progress in the observational determination of the primordial abundances of the light elements. In particular, uncertainty in the primordial deuterium (D) abundance has been significantly reduced. Such a progress has a large impact on the BBN bounds on the dark-matter properties.

In this letter, we revisit the BBN constraint on the annihilation cross section of dark matter, taking into account the recent progresses in the observation of the light-element abundances. For a reliable calculation of the light-element abundances, we improve the treatment of hadrodissociation; in particular, we have newly included the effects of anti-nucleons emitted by the annihilation of dark matter as well as the effects of interconversion between neutron and proton at inelastic scatterings of energetic nucleons. Then, comparing the theoretical predictions with observational constraints on the light-element abundances, we derive upper bounds on the annihilation cross section of dark matter.

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[1] Besides photodissociation and hadrodissociation, annihilation of light dark matter ($m_X \lesssim O(10)$ MeV) affects the BBN by changing the temperature ratio between neutrinos and photons, from which constraints are obtained [9].

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We first summarize the current status of the observational constraints on the primordial abundances of light elements. The primordial abundance of D is inferred from D absorption in damped Lyα systems (DLAs). Recently Cooke et al. [10] observed a DLA toward QSO SDSS J1358+6522 and performed very precise measurement of D. They also reanalyzed other four previously known DLAs and, using the total five DLA samples, obtained the primordial D abundance as

$$(\mathrm{D/H})_p = (2.53 \pm 0.04) \times 10^{-5}, \quad (1)$$

where (A/B) denotes the ratio of number densities of light elements A and B, and p indicates the primordial value. Notice that the error is smaller by a factor of 5 than that adopted in our previous study [6]. This progress in the measurement of D leads to more stringent constraints on dark-matter annihilation as seen later.

As for the primordial mass fraction, Y_p, of helium 4 (^{4}He), a new determination with the use of the infrared as well as visible ^{4}He emission lines in 45 extragalactic HII regions was reported in Ref. [11], where $Y_p = 0.2551 \pm 0.0022$ is obtained. More recently, Aver, Olive and Skillman [12] reanalyzed the data of Ref. [11] and estimated the ^{4}He abundance using Markov chain Monte-Carlo analysis. They obtained

$$Y_p = 0.2449 \pm 0.0040, \quad (2)$$

which we adopt in this letter.

We also use a constraint on ^{3}He/D which is derived from D and ^{3}He abundances observed in protosolar clouds [13]; taking into account that the ratio ^{3}He/D increases monotonically in time, we adopt

$$(^3\mathrm{He/D})_p < 0.83 + 0.27. \quad (3)$$

This observational constraint is the same adopted in Ref. [6].

In the previous studies, constraint based on the lithium 7 (^{7}Li) abundance was also discussed. However, the situation of the ^{7}Li observation is now confusing. The observed ^{7}Li abundances in metal-poor halo stars showed almost a constant value ($\log_{10}(^7\mathrm{Li/H}) \simeq -9.8$) called Spite plateau which was considered as primordial. However, the recent observation found much smaller ^{7}Li abundances ($\log_{10}(^7\mathrm{Li/H}) < -10$) for more metal-poor stars [14]. Since we do not know any mechanism to explain such small abundances, we do not use ^{7}Li to constrain the properties of dark matter in this letter. We do not use ^{6}Li either because ^{6}Li abundance is observed as the ratio to the number density of ^{7}Li.

In order to derive constraints on the dark-matter properties, we calculate the primordial abundances of the light elements, taking into account the effects of dark-matter annihilation. Our calculation of the light-element abundances is based on Refs. [15,16] with the modifications explained below. The Boltzmann equations for the evolution of the light-element abundances have the following form:

$$\frac{dn_A}{dt} + 3Hn_A = \left[\frac{dn_A}{dt}\right]_{\mathrm{SBBN}} + \left[\frac{dn_A}{dt}\right]_{\mathrm{photodis}} + \left[\frac{dn_A}{dt}\right]_{\mathrm{hadrodis}} + \left[\frac{dn_A}{dt}\right]_{p\leftrightarrow n}, \quad (4)$$

where n_A denotes the number density of the light element A, and H is the expansion rate of the universe. Here, $[dn_A/dt]_{\mathrm{SBBN}}$ denotes the effects of the standard BBN reactions while the other terms in the right-hand side are the effects of dark-matter annihilation, i.e., those of photodissociation, hadrodissociation, and $p \leftrightarrow n$ conversion. The reaction rates due to the dark-matter annihilation are proportional to the annihilation rate of dark matter which is given by[2]

$$\Gamma_{\mathrm{annihilation}} = n_X \langle \sigma v \rangle, \quad (5)$$

where n_X is the number density of dark matter. In addition, $\langle \sigma v \rangle$ is the annihilation cross section, with which the Boltzmann equation for the evolution of the number density of dark matter is given by

$$\frac{dn_X}{dt} + 3Hn_X = \langle \sigma v \rangle \left(n_{X,\mathrm{eq}}^2 - n_X^2\right), \quad (6)$$

where $n_{X,\mathrm{eq}}$ is the equilibrium value of the number density of dark matter. We assume that the dark-matter annihilation occurs through an s-wave process so that $\langle \sigma v \rangle$ is independent of the relative velocity of dark-matter particles in the non-relativistic limit. The effects of the pair annihilation do not change n_X significantly during and after the BBN epoch because those epochs are long after the freeze-out time of dark matter. Then we use the following time-evolution of n_X:

$$n_X(t) = \frac{3M_{\mathrm{Pl}}^2 H_0^2 \Omega_X}{m_X} \left(\frac{a(t)}{a_0}\right)^3, \quad (7)$$

where $M_{\mathrm{Pl}} \simeq 2.4 \times 10^{18}$ GeV is the reduced Planck scale, H_0 is the Hubble constant, Ω_X and m_X are the density parameter and the mass of dark matter, respectively, and $a(t)$ and a_0 are the scale factor at the cosmic time t and at present, respectively. (In our numerical calculation, we use $H_0 = 68$ km/sec/Mpc and $\Omega_X h^2 = 0.12$.) $[dn_A/dt]_{\mathrm{photodis}}$, $[dn_A/dt]_{\mathrm{hadrodis}}$, and $[dn_A/dt]_{p\leftrightarrow n}$ are proportional to $n_X^2 \langle \sigma v \rangle$, and the effects of the dark-matter annihilation become more efficient as the annihilation cross section $\langle \sigma v \rangle$ increases. In order not to affect the light-element abundances too much, $\langle \sigma v \rangle$ is bounded from above.

Next, we summarize the new points in the calculation of the light element abundances compared to Refs. [15,16]: revision of the SBBN reaction rates and the treatment of the hadrodissociations. In the present study, we renewed reaction rates by adopting the results of Ref. [17].[3] In order to take into account the uncertainties in the reaction rates, we use the Monte-Carlo simulation to estimate the errors of the light element abundances by assuming that the errors of the reaction rates obey Gaussian distributions.

As for the hadrodissociations, we have improved the treatment of the hadronic showers initiated by injections of energetic hadrons into the thermal plasma, including the following effects[4]:

1. Effects of anti-nucleons emitted from dark-matter annihilation.
2. Effects of interconversion reactions between (anti-) neutron and (anti-) proton, with which injected and secondary-produced beam nucleons, as well as target nucleons, change their charges at the time of the inelastic scattering.

Concerning the effects of anti-nucleons, we have considered scatterings of anti-nucleons off the background protons and ^{4}He's.

[2] In a series of papers [15,16], the effects of decaying particles had been studied. The Boltzmann equations used in the present analysis can be obtained from those in Refs. [15,16] by replacing $\Gamma_{\mathrm{decay}} \to \Gamma_{\mathrm{annihilation}}$, where Γ_{decay} is the decay rate defined in Refs. [15,16], with properly rescaling the numbers of final-state particles produced by the pair annihilation of dark matter using the fact that two dark matters participate in the pair-annihilation process (instead of one for the decay process).

[3] For another recent study of nuclear reaction rates, see also Ref. [18], which we do not use in our analysis because there is a technical difficulty in implementing the errors given in Ref. [18] into our Monte-Carlo analysis.

[4] For more details, see Ref. [19].