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Big Bang nucleosynthesis with time-dependent quark mass

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Abstract. The primordial Li problem is a mystery in the big bang theory. A class of possible solutions take into account beyond-standard physics. In this study we investigate the effects of time-dependent quark mass on big bang nucleosynthesis. Previous studies on time-dependent quark mass ignore the resonance effect of the ^{7}Be(n, p)^{7}Li reaction, which plays important roles in destruction of ^{7}Be. It is found that the ^{7}Be(n, p)^{7}Li cross sections can be significantly enhanced when the quark mass is smaller than the present value. This makes the ^{7}Li abundance smaller than that shown in the previous works.

Key words. Cosmology: theory – Cosmology: early universe – Cosmology: primordial nucleosynthesis – elementary particles – nuclear reactions, nucleosynthesis, abundances

1. Introduction

Big bang nucleosynthesis (BBN) is one of the most strong evidences that support standard cosmology. Theoretical prediction of the standard BBN scenario agrees with the observed primordial abundances of D and ^{4}He. In the current era of precision cosmology, it is getting more and more important to include detailed corrections to the BBN theory and compare abundances with the observations (Pitrou et al. 2018).

The last obvious flaw in the standard BBN scenario is the primordial Li problem(Fields 2011). The predicted ^{7}Li abundance is $\sim$ 3 times larger than the observed abundance (Ryan et al. 2000; Bonifacio et al. 2007; Shi et al. 2007; Aoki et al. 2009; González Hernández et al. 2009; Matsuno et al. 2017).

Proposed solutions can be classified into three categories. First, the cross sections of related nuclear reactions have been measured to decrease uncertainties of the BBN theory. Second, because the Li abundance is estimated from the so-called Spite plateau (Spite & Spite 1982) of metal-poor stars, something may be missing in our understanding of stellar physics. Finally, beyond-standard physics in the early Universe may be responsible for the Li overproduction. In this study, we focus on the last possibility.

The standard model of particle physics is characterized by the fundamental constants, whose values cannot be deduced from the

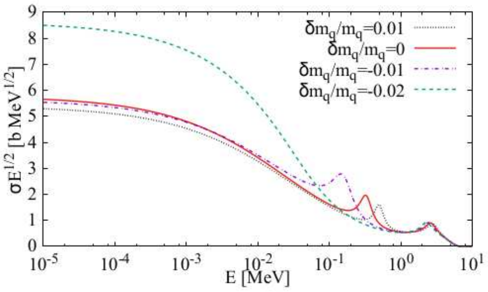

Fig. 1. The ^{7}Be$(n, p)^7$Li cross sections in Case A. The solid curve shows the standard cross sections and the others show the cross sections with the quark mass variation. This figure is reprinted from Mori & Kusakabe (2019)

model itself. Some of beyond-standard theories (e.g. the Kaluza-Klein theory and the superstring theory) permit the idea of time-dependent fundamental constants (Uzan 2011). If the fundamental constants vary with time, it will affect BBN. Therefore BBN can be used to probe the time-dependent fundamental constants. In addition, the variations of the constants may affect the Li abundance to mitigate the Li problem.

In this study, we focus on time-dependent quark mass. If the quark mass in the BBN epoch was different from the present value, it should have changed the cross sections of each reaction and therefore prediction of the primordial abundances. The time-dependent quark mass has been studied by several authors (Berengut et al. 2010; Cheoun et al. 2011; Bedaque et al. 2011), but they ignore the effect of ^{7}Be$(n, p)^7$Li resonances, which play important roles in the Li production. We include the resonance effect to make more accurate prediction.

2. Method

This section describes how we calculate nuclear reaction rates from the quark mass variation. The details are shown in Mori & Kusakabe (2019) and Cheoun et al. (2011), and here we summarize our treatment. The quark mass variations δm_{q} change the nuclear binding energies. Flambaum & Wiringa (2007) solves the Dyson-Schwinger equation to calculate the binding energies as a function of δm_{q}, and we adopt their results. We can easily calculate the Q-values and cross sections of non-resonant reactions with the varied binding energies.

It is not so straightforward to calculate cross sections of resonant reactions, namely ^{3}He$(d, p)^4$He, ^{3}H$(d, n)^4$He, and ^{7}Be$(n, p)^7$Li, because we have to consider the energy change of excited states of compound nuclei. Flambaum & Wiringa (2007) does not show results for the excited states, and we make the following assumption to include the resonance effects:

- Case A: The energy of each excited state changes in the same way as its ground state does.
- Case B: The resonance energy of the inverse reaction does not change.
- Case C: The resonance energy of the forward reaction does not change.

If we adopt one of the Cases as an assumption, we can calculate the resonance energies E_{r} of the resonant reactions. The resonant cross sections are given by the Breit-Wigner formula

$$\sigma(E) = \pi\lambda\!\!\!^{-}(E)^2 \frac{\omega\Gamma_{\mathrm{i}}(E)\Gamma_{\mathrm{f}}(E)}{(E - E_{\mathrm{r}})^2 + [\Gamma_{\mathrm{r}}(E)/2]^2}, \quad (1)$$

where $\lambda\!\!\!^{-}(E)$ is the de Broglie length, ω is the spin factor, $\Gamma_{\mathrm{i,f}}(E)$ is the partial widths and $\Gamma_{\mathrm{r}}(E) = \Gamma_{\mathrm{i}}(E) + \Gamma_{\mathrm{f}}(E)$ is the total width. The reaction rates are calculated by integrating Eq. (1):

$$N_{\mathrm{A}}\langle\sigma v\rangle = \sqrt{\frac{8}{\pi\mu}} \frac{N_{\mathrm{A}}}{(k_{\mathrm{B}}T)^{\frac{3}{2}}} \int_0^\infty EdE\ \sigma(E)\mathrm{e}^{-E/k_{\mathrm{B}}T} \quad (2)$$

Here μ is the reduced mass and k_{B} is the Boltzmann constant.

3. Results

Fig. 1 shows the ^{7}Be$(n, p)^7$Li cross sections defined by Eq. (1). Here Case A is adopted because the cross sections do not change as a function of δm_{q} in Case B and C. It is seen that the energy of the resonance at $E = 0.33$

Table 1. The six cases considered in this work. The ^{7}Be$(n, p)^{7}$Li reaction is treated separately from the other resonant reactions, because the structure of its compound nucleus is different from the others.

^{7}Be(n, p) \ ^{3}He(d, p), ^{3}H(d, n)	A	B	C
A	I	III	V
B/C	II	IV	VI

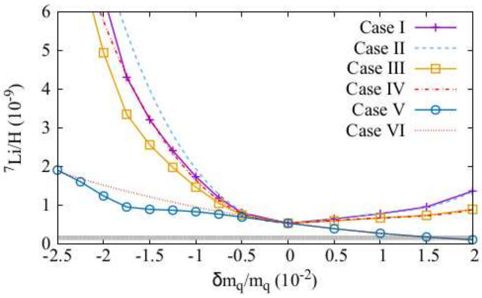

Fig. 2. The ^{7}Li abundances as a function of the quark mass variation. The Cases I-VI are defined in Table 1. The grey band is the observed ^{7}Li abundance (Sbordone et al. 2010). This figure is reprinted from Mori & Kusakabe (2019)

MeV becomes lower when the quark mass is smaller. Especially the resonance energy becomes $\sim$ 0.1 MeV when the quark mass is $\sim$ 1 % smaller than the present value. The Li and Be production and destruction are activated when $T \sim 0.1$ MeV during BBN, so that this resonance effect decreases the Li production.

Fig. 2 shows the Li abundance as a function of the quark mass variation. In order to consider ^{7}Be$(n, p)^{7}$Li and the other resonant reactions separately, we adopt six Cases (Table 1). It is seen that the Li abundance becomes consistent with the observed value when either Case V or VI is adopted and $\delta m_{\mathrm{q}}/m_{\mathrm{q}} \sim 0.015$. However the D abundance becomes higher than the observations in this case, so this cannot be a solution of the Li problem.

In Cases I, III and V, the ^{7}Be$(n, p)^{7}$Li cross sections are increased by the quark mass variation. Since ^{7}Be decays to ^{7}Li, the enhancement of the ^{7}Be$(n, p)^{7}$Li reaction rates leads to smaller ^{7}Li abundances. Therefore the ^{7}Li abundances in Cases I, III, and V become smaller than those in Cases II, IV and VI, respectively.

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