Proc. 15th Int. Symp. Origin of Matter and Evolution of Galaxies (OMEG15)
JPS Conf. Proc. **31**, 011035 (2020)
https://doi.org/10.7566/JPSCP.31.011035

Big Bang Nucleosynthesis with Time-dependent Quark Mass

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(Received August 10, 2019)

Big bang nucleosynthesis (BBN) has been used as a tool to explore non-standard physics in the early Universe. Previous works have shown that BBN is sensitive to the quark mass, because their variations affect the Q-value of each reaction. However, the effect of resonances in the ^{7}Be(n,p)^{7}Li reaction has been ignored in the previous studies. We find that, if the quark mass in the BBN epoch is smaller than the present value, the resonance energies of the ^{7}Be(n,p)^{7}Li reaction decrease and lead to significantly large reaction rates. Although a smaller quark mass leads to an even larger Li abundance than standard BBN, the smaller abundance of ^{7}Li leads to a smaller increase in the abundance of ^{7}Li than that reported. If the quark mass is larger than the present value, the ^{7}Li abundance can be decreased significantly, although the results can lead to enhanced D/H depending upon the nuclear models.

KEYWORDS: cosmology, early Universe, primordial nucleosynthesis

1. Introduction

The standard model (SM) of particle physics is a successful theory to describe the fundamental nature of the Universe for now [1]. However, the SM is not the ultimate theory because it cannot unify gravitation. Physics beyond the SM has been therefore searched for many years using astrophysical processes that occur on a cosmological timescale [2, 3].

Big bang nucleosynthesis (BBN) produced hydrogen, helium and lithium in $\sim$ 10 minutes after the big bang. The abundances of hydrogen and helium agree with astronomical observations, so the framework of standard BBN is widely accepted. Therefore, BBN can be used as a probe of beyond-standard-model physics in the early Universe. Nevertheless, the abundance of ^{7}Li predicted by standard BBN exceeds the observed abundance. Beyond-standard-model physics may provide a solution to this problem.

The roles of time-dependent quark mass in BBN have been discussed by several authors [4–6]. It has been shown that time-dependent quark mass changes the Q-value of each reaction [7]. Hence the final abundances are significantly affected. However, resonances of the ^{7}Be(n,p)^{7}Li reaction have been ignored. In this study, we investigate the effects of the resonances on BBN with a time-dependent quark mass [8].

In addition to the theoretical aspects, another motivation is from recent observations which estimated the primodial deuterium abundance very precisely [9]. The new observational abundance slightly deviates from the prediction of standard BBN. We explore the possibility to explain this deviation with non-standard-model physics [8].

2. Model

The sensitivity of the binding energy to quark mass is calculated by Ref. [7]. The treatment of non-resonant reactions are described in detail in Refs. [4, 5, 8]. The cross sections for resonant reactions are written by the Breit-Wigner formula

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

where $\lambda\!\!\!^{-}$ is the de Broglie wave length, ω is the spin factor, Γ_{i} and Γ_{f} are the partial widths, E_{r} is the resonance energy, and Γ_{r} is the total width. The reaction rates with quark mass variations for narrow resonances are therefore given by

$$N_{\mathrm{A}}\langle \sigma v \rangle = [N_{\mathrm{A}}\langle \sigma v \rangle]_0 \left[1 + \frac{1}{2} \left(1 + \sqrt{\frac{E_{\mathrm{G}}}{Q}} \right) \frac{\delta Q}{Q} \right] \left\{ \frac{1 + [(E_0 - E_{\mathrm{r}}^0)/(\Gamma_{\mathrm{r}}/2)]^2}{1 + [(E_0 - E_{\mathrm{r}})/(\Gamma_{\mathrm{r}}/2)]^2} \right\}, \tag{2}$$

where $[N_{\mathrm{A}}\langle \sigma v \rangle]_0$ is the reaction rates without the quark mass variations, E_{G} is the Gamow energy, δQ is the change in the Q-value, and E_{r}^0 is the resonance energy without the quark mass variations. We note that Eq. (2) cannot be applied to the ^{7}Be(n,p)^{7}Li reaction because the equation assumes narrow resonances. In this case, one must integrate Eq. (1) numerically to calculate $N_{\mathrm{A}}\langle \sigma v \rangle$.

The sensitivity of the resonance energy to quark mass is not shown in Ref. [7]. Therefore, we consider the following three cases.

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

There are three resonant reactions which are important in BBN: ^{3}He(d,p), ^{3}H(d,n) and ^{7}Be(n,p). If these reactions are considered independently, we should consider 27 cases. However, the compound nuclei ^{5}Li and ^{5}He are mirror conjugates, so they are expected to behave in a similar way. Hence we adopt the same Cases for ^{3}He(d,p) and ^{3}H(d,n). This assumption reduces the number of cases to nine. In the Section 3, we will see that the cross sections of ^{7}Be(n,p) do not change as a function of quark mass in Case B, so Case B and Case C can be integrated for this reaction. Finally, the number of Cases is reduced to six. The Cases considered in this study are summarized in Table I.

Table I. The Cases considered in this study.

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

3. Results

Figure 1 shows the cross sections of the ^{7}Be(n,p)^{7}Li reaction in Case A. The red solid line shows the standard cross sections, and the others are the cross sections with different quark masses. The ^{7}Be(n,p)^{7}Li reaction is dominated by three resonances: a 2^- state at $E_{\mathrm{r}} = 0.00267$ MeV and two 3^+

states at $E_\mathrm{r} = 0.33$ MeV and 2.66 MeV [10]. The resonances shift to higher energies as the quark mass becomes larger. Especially, if the quark mass is smaller by $\sim 1\%$ than the present value, the 3^+ resonance at $E_\mathrm{r} = 0.33$ MeV shifts to ~ 1 MeV, which is important at the temperatures of BBN. As a result, the reaction rates at $T \sim 10^9$ K become $\sim 26\%$ higher than the standard rates.

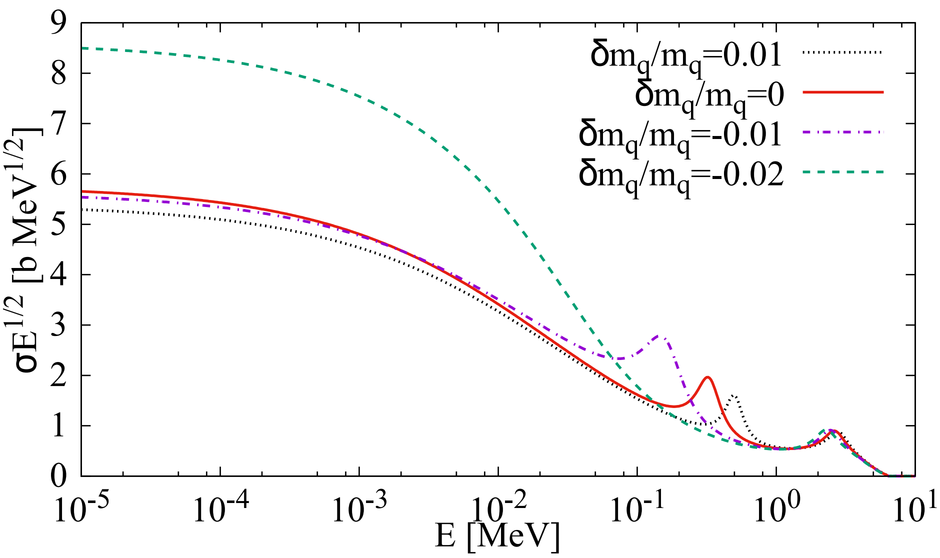

Fig. 1. The cross sections of the ^{7}Be(n,p)^{7}Li reaction in Case A. The solid line shows the standard cross sections, and the other lines show the cross sections with variations of quark mass. This figure is reprinted from Ref. [8].

On the other hand, the change in the cross sections in Case B is negligibly small because the effects from changes in the binding energies of ^{7}Li and ^{7}Be almost cancel out.

Figure 2 shows the results of a BBN calculation. The gray region indicates the observed abundances from astronomical observations [9, 11]. The upper panel shows the ^{7} Li abundance. It is seen that, if the quark mass change δm_q is negative and the resonance shift of the ^{7}Be(n,p)^{7}Li reaction is included, the ^{7}Li production decreases compared to cases without the resonance shift.

The lower panel of Figure 2 shows the D abundance. We can see that the positive quark mass change of $0 \lesssim \delta m_q/m_q \lesssim 0.5\%$ is favored in terms of agreement between the model and the observation, although model uncertainties including statistical and systematic errors in nuclear reaction rates should be evaluated to make a conclusion. Interestingly, the ^{7}Li problem is mitigated with $0 \lesssim \delta m_q/m_q \lesssim 0.5\%$ in Cases V and VI. It is also notable that the model ^{7}Li abundances coincides with the observational value when $\delta m_q/m_q \sim 1.5\%$ in Cases V and VI, although in this case the D abundance exceeds the observational value.

Acknowledgments

This work is supported by NSFC Research Fund for International Young Scientists (11850410441) and JSPS KAKENHI Grant Number JP19J12892.

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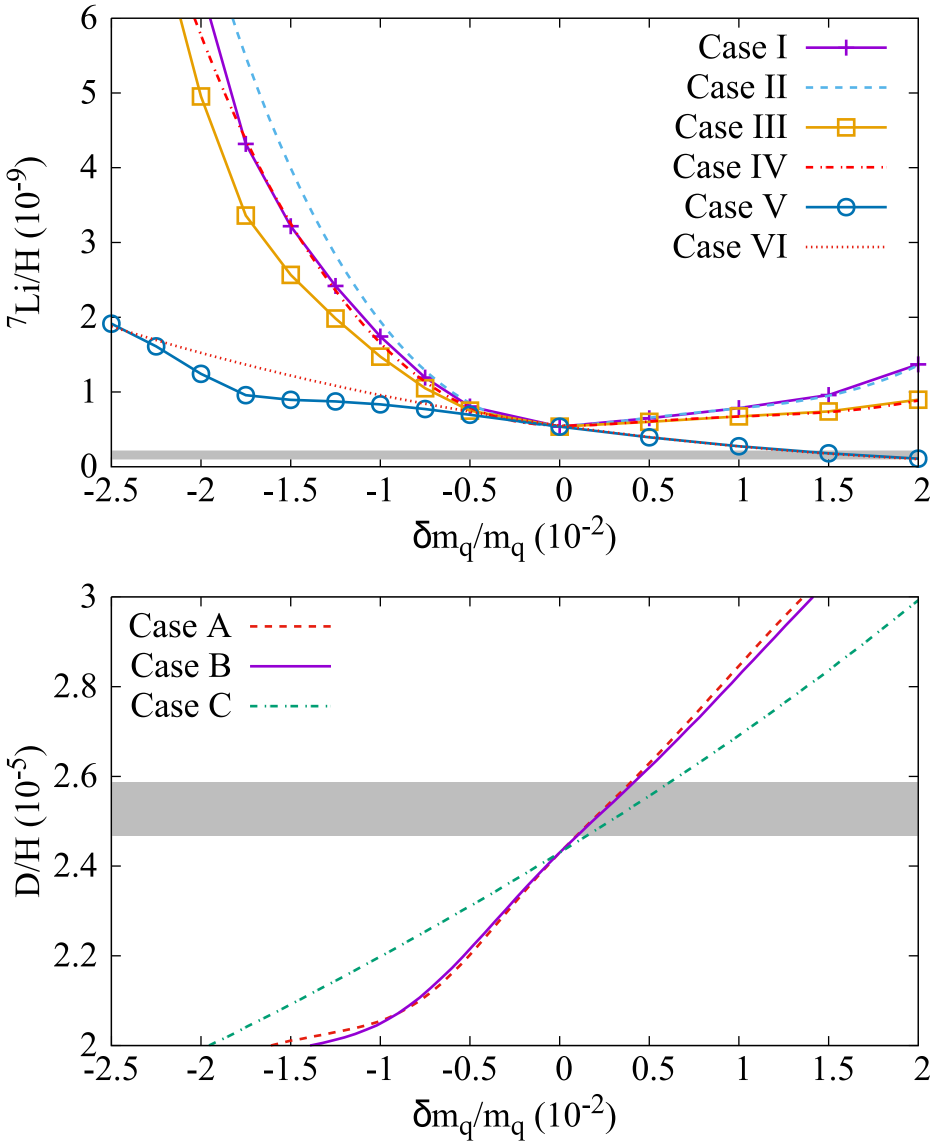

Fig. 2. The results of the BBN calculations. The upper panel shows the ^{7}Li abundances and the lower panel shows the D abundances. The gray region is the 2σ-level observed abundances from astronomical observations [9, 11]. This figure is reprinted from Ref. [8].

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