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Reply to "Comment on 'Heavy element production in inhomogeneous big bang nucleosynthesis'"

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This is a reply to Rauscher [Phys. Rev. D **75**, 068301 (2007)]. We studied heavy element production in the high baryon density region in the early universe [Phys. Rev. D **72**, 123505 (2005)]. However, it is claimed by Rauscher [Phys. Rev. D **75**, 068301 (2007)] that a small scale but high baryon density region contradicts observations for the light element abundance or, in order not to contradict the observations, the high density region must be so small that it cannot affect the present heavy element abundance. In this paper, we study big bang nucleosynthesis in the high baryon density region and show that in certain parameter spaces it is possible to produce enough of the heavy element without contradiction to cosmic microwave background and light element observations.

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I. INTRODUCTION

In a standard scenario, big bang nucleosynthesis (BBN) can produce only light elements, up to ^{7}Li, and all heavy elements have been synthesized in stars. However, many phase transitions in the early universe could have printed their trace in a nonstandard way. For example, some baryogenesis models [1] predict very high baryon density islands in ordinary low-density backgrounds.

In the previous paper [2], we studied heavy element production in inhomogeneous BBN from this point of view. However, we limited ourselves to the heavy element abundance and did not discuss the light element abundance and consistency with observations. This is because we assumed that the high baryon density region is very local and does not affect the global light element abundance. In [3], Rauscher pointed out that, in order not to contradict observations, the high baryon density region must be very small and cannot affect the present heavy element abundance. In this paper, we show that there is a parameter region in which the heavy element can be produced enough to affect the observation while keeping the light element abundance consistent with observations. We consider that the disagreement between Rauscher's opinion and our opinion comes from two points. One is that we are looking at some parameter regions in which neutrons in the high baryon density do not diffuse so much as to cause a disaster in standard BBN. We would like to emphasize this point. The other is that the relevant quantity is not the spatial size of the high baryon density region but the amount of baryon in high density regions.

We will discuss the following issues: In Sec. II, we discuss the light element abundance in the homogeneous high baryon density region and after mixing the high and the low baryon density region. In Sec. III, we study the heavy element (Ru, Mo) abundance in high and averaged baryon density and show that heavy elements can be produced without contradicting the light element observation. In Sec. IV, we briefly comment on the diffusion scale of the high baryon density region.

II. LIGHT ELEMENT ABUNDANCE

A. Homogeneous BBN

We calculate homogeneous BBN with various values of η (baryon photon ratio). In Tables I and II, we show the numerical result of the mass fraction and the number

TABLE I. The mass and the number fractions of light elements for the homogeneous BBN with $\eta = 10^{-3}$.

$\eta = 10^{-3}$ Name	Mass fraction	Number fraction
H	5.814×10^{-1}	8.475×10^{-1}
^{4}He	4.185×10^{-1}	1.525×10^{-1}
^{3}He	4.842×10^{-13}	1.614×10^{-13}
^{7}Li + ^{7}Be	1.559×10^{-12}	2.227×10^{-13}
D	1.577×10^{-22}	7.883×10^{-23}

TABLE II. The mass and the number fractions of light elements for the homogeneous BBN with $\eta = 3.162 \times 10^{-10}$.

$\eta = 3.162 \times 10^{-10}$ Name	Mass fraction	Number fraction
H	7.58×10^{-1}	9.26×10^{-1}
^{4}He	2.419×10^{-1}	7.39×10^{-2}
^{3}He	4.299×10^{-5}	1.433×10^{-5}
^{7}Li + ^{7}Be	8.239×10^{-10}	1.177×10^{-10}
D	1.345×10^{-4}	6.723×10^{-5}

fraction of each light element for $\eta = 10^{-3}$ and 3.162×10^{-10}.

As baryon density becomes higher, more protons and neutrons are bounded to form ^{4}He. At $\eta = 10^{-3}$, most of the final product of ^{7}Li comes from ^{7}Be, which decays to ^{7}Li after BBN. Details on light element production for various η can also be found in [4]. In this paper, we almost concentrate on a case in which high baryon density region has $\eta = 10^{-3}$. We expect that, compared to $\eta \geq 10^{-3}$, the profile of the abundance for $\eta = 10^{-3}$ is more different from standard BBN because most of the light element abundances change monotonically with respect to η and, if this case does not contradict to observations, other cases would also be consistent. Briefly, the amount of H decreases and ^{4}He increases monotonically as η becomes larger. The number fraction of D is less than 10^{-20} for η greater than 10^{-7}. For ^{3}He, the number fraction drastically decreases around $\eta = 10^{-4}$ down to $\mathcal{O}(10^{-13})$, and for ^{7}Li the number fraction increases until $\eta = 10^{-6}$ and drastically decreases for a larger value of η. In the following sections, we will see that this nonstandard setup does not strongly contradict the observations. For simplicity, we ignore the diffusion effect before and during BBN, and after BBN both high and low baryon density regions are completely mixed. Detailed analysis, such as the case in which the high baryon density region is not completely mixed, or taking into account diffusion effects, is left for future work.

B. Parameters and basic equations

In this section, we summarize the relations among parameters.

Notations: n, n^H, n^L are averaged, high, and low baryon number density. f^H, f^L are the volume fractions of the high and the low baryon density region. y_i, y_i^H, y_i^L are the mass fractions of each element (i) in averaged-, high-, and low-density regions. The basic relations are

$$f^H + f^L = 1 \tag{1}$$

$$f^H n^H + f^L n^L = n \tag{2}$$

$$y_i^H f^H n^H + y_i^L f^L n^L = y_i n. \tag{3}$$

Under the assumption that the temperature of the universe is homogeneous, the above equation can be written as

$$f^H \eta^H + f^L \eta^L = \eta \tag{4}$$

$$y_i^H f^H \eta^H + y_i^L f^L \eta^L = y_i \eta, \tag{5}$$

where $\eta = \frac{n}{n_\gamma}$, $\eta^{H,L} = \frac{n^{H,L}}{n_\gamma}$. Conventional parameters for inhomogeneous BBN are η, f, and density ratio $R = \frac{n^H}{n^L}$. Here we use a different combination of parameters. Relevant values for the abundance analysis are products $f^{H,L} \times \eta^{H,L}$ and $\eta^{H,L}$. $f_v^{H,L} \times \eta^{H,L}$ determines the amount of baryon from high- and low-density regions. $\eta^{H,L}$ determines the mass fraction of each species of nuclei. For convenience, we write the ratio of baryon number contribution from the high density region as a, i.e., $f^H\eta^H : f^L\eta^L = a:(1-a)$. There are 5 parameters ($n^{H,L}$, n, and $f^{H,L}$) and 2 constraints [Eqs. (1) and (2)]. We calculate the light element abundance for various values of $\eta^{H,L}$. η can also take any value, but in order not to contradict observational constraints, we choose η from 3.162×10^{-10} to 10^{-9}. a is determined by Eq. (4). The aim of the analysis in this section is not to find parameter regions which precisely agree with the observational light element abundance and η from cosmic microwave background (CMB). Our model is too simple to determine the constraints to parameters. For example, we completely ignore the diffusion effect before and during BBN. Instead we see that at least our analysis in the previous paper is physically reasonable.

C. Theoretical predictions and observations of light elements

We consider the cases of $\eta^H = 10^{-3}$ and $\eta^L = 3.162 \times 10^{-10}$. The mass fractions of H and ^{3}He in the high density region are 0.5814 and 4.842×10^{-13}, respectively, while those in the low-density region are 0.758 and 4.299×10^{-5}. From Eq. (5), we have

$$f^H \eta^H y^H_{^3\mathrm{He}} + f^L \eta^L y^L_{^3\mathrm{He}} = \eta y_{^3\mathrm{He}} \tag{6}$$

$$4.842 \times 10^{-13} \times a + 4.299 \times 10^{-5} \times (1-a) = y_{^3\mathrm{He}} \tag{7}$$

$$f^H \eta^H y^H_{\mathrm{H}} + f^L \eta^L y^L_{\mathrm{H}} = \eta y_{\mathrm{H}} \tag{8}$$

$$0.5814 \times a + 0.758 \times (1-a) = y_{\mathrm{H}}. \tag{9}$$

We can calculate an averaged value of the abundance ratio of ^{3}He to H as

$$\left(\frac{^3\mathrm{He}}{\mathrm{H}}\right) = \frac{1}{3}\frac{4.842 \times 10^{-13} \times a + 4.299 \times 10^{-5} \times (1-a)}{0.5814 \times a + 0.758 \times (1-a)}, \tag{10}$$

where a is related to η as

$$a = \frac{\eta^H}{\eta}\frac{\eta - \eta^L}{\eta^H - \eta^L} \tag{11}$$

$$= \frac{10^{-3}}{\eta}\frac{\eta - 3.162 \times 10^{-10}}{10^{-3} - 3.162 \times 10^{-10}} \tag{12}$$

$$\sim \frac{\eta - 3.162 \times 10^{-10}}{\eta}. \tag{13}$$

Here a varies from 0 to 0.9 for reasonable values of η, or 3.162×10^{-10}–10^{-9}. Similarly, for $\eta^H = 10^{-3}$ the number fractions are

$$\left(\frac{\mathrm{D}}{\mathrm{H}}\right) = \frac{1}{2}\frac{1.577 \times 10^{-22} \times a + 1.345 \times 10^{-4} \times (1 - a)}{0.5814 \times a + 0.758 \times (1 - a)} \tag{14}$$

$$\left(\frac{{}^{7}\mathrm{Li}}{\mathrm{H}}\right) = \frac{1}{7}\frac{1.559 \times 10^{-12} \times a + 8.239 \times 10^{-10} \times (1 - a)}{0.5814 \times a + 0.758 \times (1 - a)}. \tag{15}$$

Figures 1–3 represent the averaged abundance ratios (D/H), (^{3}He/H), and (^{7}Li/H), respectively.

We can see that the light element abundance is the same order around $\eta \sim 5 \times 10^{-10}$–$10^{-9}$ as observations [5–12].

$$\left(\frac{\mathrm{D}}{\mathrm{H}}\right)_{\mathrm{obs}} = (1.5\text{–}6.7) \times 10^{-5} \tag{16}$$

$$\left(\frac{{}^{7}\mathrm{Li}}{\mathrm{H}}\right)_{\mathrm{obs}} = (0.59\text{–}4.1) \times 10^{-10}. \tag{17}$$

We do not discuss diffusion in detail here. At least, the above result suggests that our analysis is not beside the point.

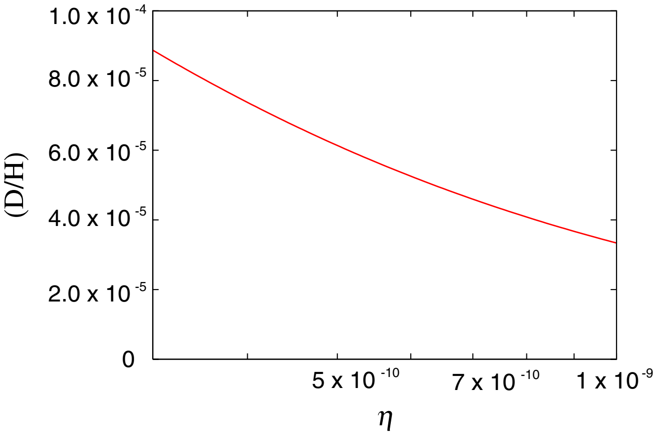

FIG. 1 (color online). Averaged ratio of D to H (D/H) vs η.

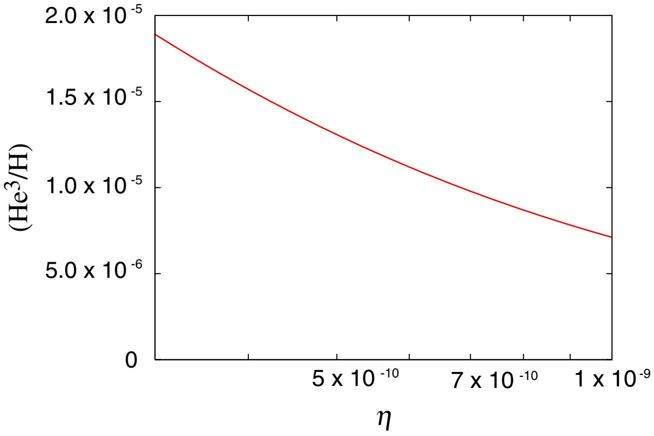

FIG. 2 (color online). Same as Fig. 1 but for (^{3}He/H).

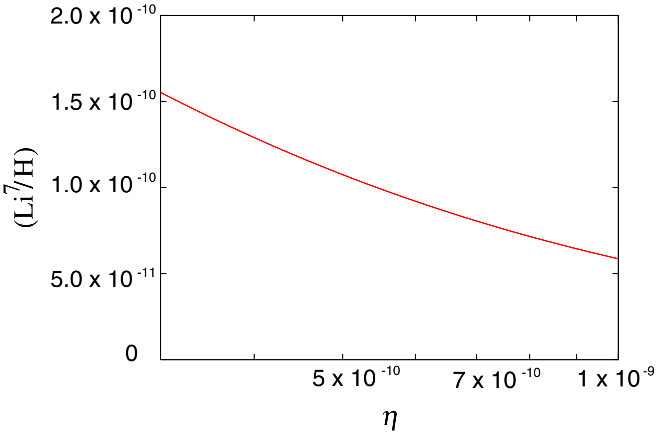

FIG. 3 (color online). Same as Fig. 1 but for (^{7}Li/H).

III. THEORETICAL PREDICTIONS AND OBSERVATIONS OF HEAVY ELEMENTS (^{92,94}Mo, ^{96,98}Ru)

The same analysis can be applied for heavy elements such as ^{92}Mo, ^{94}Mo, ^{96}Ru, and ^{98}Ru. We are interested in these elements because, in many models of supernovae nucleosynthesis, these p-nuclei are less produced. We will see that some amount of these heavy elements can be synthesized in BBN.

From Table III, we can derive the expected value of these elements:

$$\left(\frac{{}^{92}\mathrm{Mo}}{\mathrm{H}}\right) = \frac{1}{92}\frac{1.835 \times 10^{-5} \times a}{0.5814 \times a + 0.758 \times (1 - a)} \tag{18}$$

$$\left(\frac{{}^{94}\mathrm{Mo}}{\mathrm{H}}\right) = \frac{1}{94}\frac{4.1145 \times 10^{-6} \times a}{0.5814 \times a + 0.758 \times (1 - a)} \tag{19}$$

$$\left(\frac{{}^{96}\mathrm{Ru}}{\mathrm{H}}\right) = \frac{1}{96}\frac{1.0789 \times 10^{-5} \times a}{0.5814 \times a + 0.758 \times (1 - a)} \tag{20}$$

TABLE III. The mass fractions of nuclei for homogeneous BBN with $\eta = 10^{-3}$.

$\eta = 10^{-3}$ Name	Mass fraction
H	5.814×10^{-1}
^{4}He	4.185×10^{-1}
^{92}Mo	1.835×10^{-5}
^{94}Mo	4.1145×10^{-6}
^{96}Ru	1.0789×10^{-5}
^{98}Ru	1.0362×10^{-5}

$$\left(\frac{^{98}\mathrm{Ru}}{\mathrm{H}}\right) = \frac{1}{98}\,\frac{1.0362 \times 10^{-5} \times a}{0.5814 \times a + 0.758 \times (1 - a)}. \tag{21}$$

We plot the expected value of these quantities in Fig. 4.

These values should be compared with the solar abundance (Table IV) [13].

Comparing those observational values with Fig. 4, it is clear that the heavy element produced in BBN can affect the solar abundance heavy element. Some of them are produced too much. But this is not a problem of the previous work [2], because we assumed that high density regions are very small and do not disturb standard BBN. The analysis here suggests that, even if we assume the density fluctuations are completely mixed, the heavy element can have enough affect on the solar abundance.

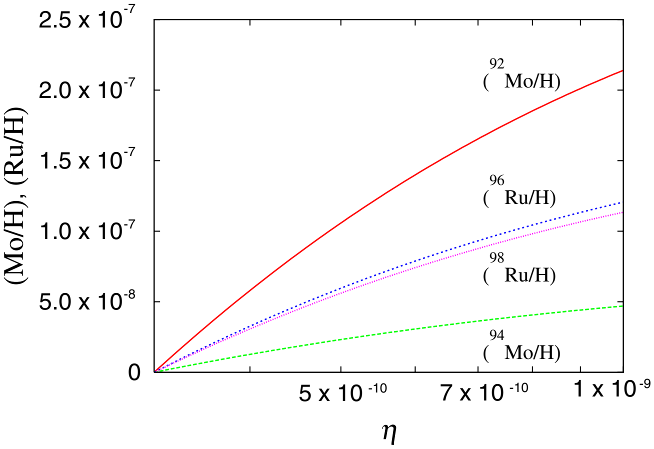

FIG. 4 (color online). ^{92}Mo/H, ^{94}Mo/H, ^{96}Ru/H and ^{98}Ru/H vs η. Red, green, blue, and pink lines represent the ratios ^{92}Mo/H, ^{94}Mo/H, ^{96}Ru/H, ^{98}Ru/H, respectively.

TABLE IV. The abundances of ^{92,94}Mo and ^{96,98}Ru in the solar system [13].

Name	Number fraction	Ratio to H
H	$7.057\,280 \times 10^{-1}$	1
^{92}Mo	$8.796\,560 \times 10^{-10}$	1.2465×10^{-9}
^{94}Mo	$5.611\,420 \times 10^{-10}$	7.9512×10^{-10}
^{96}Ru	$2.501\,160 \times 10^{-10}$	3.5441×10^{-10}
^{98}Ru	$8.676\,150 \times 10^{-11}$	1.2294×10^{-10}

TABLE V. Relation between temperature and scale.

Temperature and scale Temperature	Scale
1.1×10^{9} K (BBN)	d
3000 K (decouple)	$3.7 \times 10^{6} \times d$
2.725 K (now)	$4.0 \times 10^{8} \times d$

IV. DIFFUSION DURING BBN

In the previous analysis, we assumed that the diffusion effect can be ignored during BBN and both high density regions and low-density regions are completely mixed after BBN. In this section, we determine the scale of the high baryon density island in which the diffusion effect during BBN is small enough and our assumption is valid. We do not discuss the diffusion after BBN here.

A detailed analysis of the comoving diffusion distance of the baryon, the neutron, and the proton is in [14]. From Fig. 1 in [14], in order to safely ignore the diffusion effect, it is necessary for the high baryon density island to be much larger than 10^{5} cm at $T = 0.1$ MeV$(1.1 \times 10^{9}$ K). Notice that $T \propto \frac{1}{A}$, where A is a scale factor. For scale d now corresponds to $d/(4.0 \times 10^{8})$ at the BBN epoch. The present galaxy scale is $\mathcal{O}(10^{20})$ cm, which corresponds to $\mathcal{O}(10^{12})$ cm $\gg 10^{5}$ cm at the BBN epoch.

The maximum angular resolution of CMB is $l_{\max} \sim 2000$. The size of the universe is $\sim$5000 Mpc. In order not to contradict to CMB observation, the fluctuation of the baryon density must be less than $\sim$16 Mpc now. This corresponds to 10^{17} cm at BBN.

Since the density fluctuation size in Dolgov and Silk's model [1] is a free parameter, the above brief estimation suggests that we can take the island size large enough to ignore the diffusion effect without contradicting the observations, i.e., the reasonable size of 10^{5} cm–10^{17} cm at the BBN epoch. We can choose distances between high density islands so that we obtain a suitable value of f.

V. SUMMARY

In this paper, we studied the relation between the heavy element production in high baryon density regions during BBN and the light element observation. By averaging the light element abundances in the high- and the low-density regions, we showed that it is possible to produce a relevant amount of heavy element without contradicting observations. However, we should stress that in this paper we restricted ourselves to some parameter regions where neutrons in high baryon density regions do not destroy the standard BBN. So our setup is different from the conventional inhomogeneous BBN studies. We also studied the size of the density fluctuation to show that there is a parameter region in which the neutron diffusion is negligible and which is much smaller than CMB observation scale. It is worthwhile to investigate further how the produced heavy elements can be related to the detailed observations.

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