Cosmic Rays during BBN as Origin of Lithium Problem

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Abstract

There may be non-thermal cosmic rays during big-bang nucleosynthesis (BBN) epoch (dubbed as BBNCRs). This paper investigated whether such BBNCRs can be the origin of Lithium problem or not. It can be expected that BBNCRs flux will be small in order to keep the success of standard BBN (SBBN). With favorable assumptions on the BBNCR spectrum between 0.09 – 4 MeV, our numerical calculation showed that extra contributions from BBNCRs can account for the $^7$Li abundance successfully. However $^6$Li abundance is only lifted an order of magnitude, which is still much lower than the observed value. As the deuteron abundance is very sensitive to the spectrum choice of BBNCRs, the allowed parameter space for the spectrum is strictly constrained. We should emphasize that the acceleration mechanism for BBNCRs in the early universe is still an open question. For example, strong turbulent magnetic field is probably the solution to the problem. Whether such a mechanism can provide the required spectrum deserves further studies.

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1 Introduction

Big Bang cosmology is an excellent model to describe our Universe [1]. Al-beit its success there is still puzzling “Lithium problem” [2, 3] in its building block – big bang nucleosynthesis (BBN). Namely the theoretical predicted primordial $^7$Li abundance is higher than observation while the $^6$Li abundance is lower. Primordial $^7$Li abundance from measurements of metal-poor halo stars is $^7$Li/H = $(1 \sim 2) \times 10^{-10}$ [2]-[9], while prediction by the standard BBN (SBBN) model is three to five times higher: $^7$Li/H = $(5.24^{+0.71}_{-0.67}) \times 10^{-10}$ [10]. Meanwhile $^6$Li abundance from observation is $^6$Li/H $\approx 6 \times 10^{-12}$ [3], a factor of about 1000 higher than the SBBN model prediction [11].

Extensive investigations have focused on Lithium problem. The discrepancy could be due to astrophysical origin [12, 13, 14]. While it is also possible that the discrepancy is arising from Physics beyond the SBBN model. Investigations showed that Lithium abundance would change by varying the nucleon effective couplings as well as the mass parameters, namely the neutron lifetime, the neutron-proton mass difference and the deuteron binding energy etc. [15, 16, 17]. These parameters can be modified due to virtual effects of Physics beyond the Standard Model of particle physics. Another possibility of Physics beyond the SBBN could contain new particles/resonances. Such new particles/resonances participate in thermal nuclear reactions during BBN [18]-[28], as such Lithium abundance will depend on the detail assumptions about the new particles/resonances. Besides these two approaches, non-thermal electromagnetic [29] and hadronic [30]-[35] energy injection was also investigated. Non-thermal particles originate from the nuclear reactions before the final state particles are thermalized. The preliminary studies showed that the mono-energetic injection is hardly the origin of Lithium problem. In this paper we will extend, in some sense, such idea to include the non-thermal energy injection from cosmic rays during and/or shortly after the epoch of BBN.

In this paper, we propose a possible solution to the Lithium problem by not going far from the SBBN model, neither due to the astrophysical factors nor by introduction of new particles. In order to destroy $^7$Li $^1$, we include new contributions from non-thermal particles, namely the accelerated SBBN particles. As is known that the non-thermal particles accelerated in

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$^1$ Actually we need to destroy $^7$Be. The relic primordial $^7$Li mainly (about 90%) comes from the decay of $^7$Be.
astrophysical environment today are called cosmic rays, it is expected there is such cosmic rays even in the early stage of BBN. We expect that some kind of plasma wave or other mechanisms can feed energy to thermal ions [36], provided that there is strong enough turbulence before/during BBN epoch. As a consequence the particle energy spectrum deviates from thermal distribution. Exploring detailed mechanism on how to induce non-thermal component is beyond the scope of this paper and which will be the focus of the further work. However we propose a toy model to support our basic hypothesis in this paper.

The primordial magnetic fields might be created at some early stage of the evolution of the Universe, for example inflation, the electro-weak phase transition, quark-hadron phase transition and so on. As investigated by authors in ref. [37], after electro-weak phase transition the magnetic field build up and evolve with the expanding Universe. We can estimate the strength of induced electric field through \( E \approx \Delta B / \Delta t \times L \approx B H L \), where \( B \propto R^{-2} \) is the characteristic magnetic field, \( H \) is the expansion rate as inverse of the characteristic time, and \( L \) is the characteristic length of turbulence which is given by equations (47) and (49) of [37] (here \( L = l_0(R/R_0) \) which includes the effect of cosmic expansion). Using the same initial parameters as in ref. [37] and extrapolating to 0.01MeV, we get the induced electric field \( E \approx 30 \) V/m in plasma with temperature 0.01MeV. A charged particle like proton undergoing such electric field will gain energy \( \Delta E \approx \tau_{\text{ther}} v_\parallel q E \), where \( v_\parallel \) is the particle velocity parallel to the electric field, \( q \) is the electric charge of the particle, and \( \tau_{\text{ther}}(T) \) is the thermalization time of a high energy (of order MeV) nuclear in plasma of temperature \( T \). For O(MeV) protons in plasma of temperature 0.01MeV, \( \tau_{\text{ther}}(0.01) \approx 10^{-2} \) s [38], the possible energy gain of an accelerated thermal proton is of order 0.1 MeV. During one free time, a proton can travel a distance of \( L_{\text{free}} \approx 10^{-3} c \times 10^{-2} s \approx 3 \times 10^5 \) cm (\( c \) is the light velocity) which is just several percent of the characteristic length scale. Protons have the opportunity to be accelerated several times and thus to gain a couple of MeV energy, though the probability is low. Thus we can expect the energy spectrum of high energy particles will not be too hard.

This proposed toy model needs hydro-magnetic turbulence as the premise. We don’t know exactly how hydro-magnetic turbulence develops during the BBN. However according to ref. [39], helical hydromagnetic turbulence survives until 100 eV. We found that the correlation length and magnetic field will be larger if we adopt model in ref. [39] instead. Therefore there should be a considerable parameter space to support our hypothesis.
In this paper we will examine phenomenologically whether such scenario can account for Lithium problem. These non-thermal particles are dubbed as BBN cosmic rays (BBNCRs). In the SBBN conventional abundance calculation, the exothermic reactions are included. BBNCRs contributions to the exothermic SBBN reactions will be investigated. Most importantly, we have to include the endothermic reactions in order to destroy $^7\text{Be}$ by BBNCRs. In the SBBN, the endothermic reactions are thought not important.

This paper proceeds as following. In section 2 we describe the required characteristics of BBNCRs, namely the particle species, the energy range and energy spectrum and so on. There are many reactions involving BBNCRs so we need to select which reactions may be important, and detailed discussions on these are contained in this section. The necessary formulae for the abundance computation by including BBNCRs contributions are depicted in section 3. The numerical results are given in this section. Section 4 contains our conclusions and discussions. Some calculation details are given in Appendix A and B.

## 2 BBNCRs and Reactions

In order to estimate the effects of BBNCRs, we need to know the flux, the energy range and the energy spectrum of BBNCRs. They are maybe in evolution during its work time with the Universe expanding, so the following characters can be seen as an average. Obviously we don’t have any knowledge on BBNCRs, therefore we examine some constraints on BBNCRs.

Candidate for BBNCRs may be protons, neutrons, nuclei and electrons. Neutrons are hard to accelerate for electric neutrality, and electrons are out of consideration in SBBN computation, so we focus on nuclei. Because Helium loses energy more quickly through Coulomb scattering [38, 41, 42] due to the higher nuclear electric charge [43], we exclude $^3\text{He}$ and $^4\text{He}$ as the components of BBNCRs. We assume that BBNCRs consist of energetic hydrogens, namely protons, deuterons and tritones. In order not to violate the success of SBBN, the intensity of each kind of BBNCRs must be much lower than that of the corresponding SBBN particles. For simplicity we assume that the fraction of BBNCRs is fixed as one single free parameter $\epsilon$.

Next we examine the energy range of BBNCRs. In order not to change deuterium abundance significantly, we must avoid BBNCRs contributions from reaction $D(p,n)2H$. Note that the threshold energy and cross section
of this reaction are 3.337 MeV and $\approx 10^{-2}$ barn respectively. We examined the endothermic reactions with threshold energy [44] below 3.337 MeV. In order to destroy $^7$Be by proton, the most effective one is $^7$Be$(p, p\alpha)^3$He with threshold energy $E_{th} = 1.814$ MeV. Other endothermic reactions besides $^7$Be$(p, p\alpha)^3$He are summarized in table 1.

### Table 1: Endothermic reactions by energetic hydrogen with threshold energy below 3.337 MeV.

| Process                  | Threshold/MeV | Effect                                                                 |
|--------------------------|---------------|------------------------------------------------------------------------|
| $^7$Be$(d, ^3$He)$^6$Li  | 0.144         | destroy $^7$Be indeed, but less important than $^7$Be$(p, p\alpha)^3$He, for D is much less than p; produce $^6$Li |
| $^7$Li$(d, p)^8$Li       | 0.247         | destroy $^7$Li, not important, for we need to destroy $^7$Be             |
| $^7$Be$(d, 2p)^7$Li      | 0.747         | transformation between $^7$Li and $^7$Be, but less important than $^7$Li$(p, n)^7$Be |
| T$(p, n)^3$He            | 1.019         | transformation between T and $^3$He, and T and $^3$He abundances are assumed to change little |
| $^7$Li$(d, t)^6$Li       | 1.278         | destroy $^7$Li; produce $^6$Li                                        |
| $^6$Li$(p, p\alpha)$D   | 1.721         | destroy $^6$Li, negative, for we need to produce $^6$Li                 |
| $^7$Be$(p, p\alpha)^3$He| 1.814         | the most important process to destroy $^7$Be                           |
| $^6$Li$(n, p)^7$Li       | 1.850         | destroy $^6$Li                                                         |
| $^7$Li$(p, n)^7$Be       | 1.880         | transformation between $^7$Li and $^7$Be, important                    |
| $^6$Li$(d, \alpha)$D    | 1.967         | destroy $^6$Li                                                         |
| $^7$Be$(d, \alpha)^3$He | 2.041         | destroy $^7$Be, but less important                                     |
| $^6$Li$(t, \alpha)$T    | 2.213         | destroy $^6$Li                                                         |
| $^7$Be$(t, \alpha)^3$He | 2.268         | destroy $^7$Be, but less important                                     |
| $^3$He$(d, 2p)$T         | 2.436         | transformation between T and $^3$He                                    |
| $^7$Be$(d, n)^5$B        | 2.688         | destroy $^7$Be, but less important                                     |
| $^7$Li$(p, p\alpha)$T   | 2.821         | destroy $^7$Li                                                         |
| $^7$Li$(d, \alpha)$T    | 3.175         | destroy $^7$Li                                                         |

Now we switch to examine the energy spectrum of BBNCRs. In principle the BBNCR energy spectrum will be determined by acceleration mechanism
and we are lack of knowledge on this. In the realistic case, the energy of BBNCRs should exceed 1.8 MeV but the amount is required to decrease quickly, especially above 3.337 MeV, namely the energy threshold of \(D(p, n)\)\(^2\)H. Motivated by the power law of cosmic rays today, we assume the spectrum of BBNCRs obeys a power law with index 4 from 2 MeV to 4 MeV \(^2\). Below 2 MeV \(^3\), we choose the power index to be 2 or even in uniform distribution like white noise. Our choice of energy spectrum of BBNCRs is depicted in figure 1.

\[\alpha \text{ is the power index (see eq. (5) for detail).}\]

\(^2\) The energy range is so narrow that small variation of the power index will not change the results too much. It is obvious that the larger the power index is, the less important the higher energy particles are.

\(^3\) Exactly it is the energy range between 0.09 MeV and 2 MeV. In fact, BBNCRs come from SBBN particles, and the lower limit of the energy range of BBNCRs is near or a little above the temperature of SBBN particles. In the SBBN, \(^7\)Be is produced mainly during the epoch when the temperature is between 0.08 MeV and 0.04 MeV, so it seems reasonable that we take 0.09 MeV as the lower limit. Note that \(^7\)Be abundance is not sensitive to the change of the lower limit.
BBNCRs can affect element abundance via endothermic processes. Besides these BBNCRs will also involve into exothermic SBBN reactions. The exothermic processes are thought much less important than endothermic ones in the SBBN relatively. However via exothermic processes the non-thermal BBNCRs may have important influence upon the element abundances, especially through which D abundance may be decreased. Complete classification of exothermic processes is summarized in Appendix A. Reactions added in our numerical computation are as following:

1. Endothermic reactions, including the most important process to destroy $^7\text{Be} - ^7\text{Be}(p, p\alpha)^3\text{He}$ and a weighty origin of $^7\text{Be} - ^7\text{Li}(p, n)^7\text{Be}$;

2. Exothermic reactions, including the collisions between isotopes of hydrogen, especially destroying $D - D(p, \gamma)^3\text{He}$, $D(d, p)^3\text{T}$, $D(d, n)^3\text{He}$, and $T(d, n)^4\text{He}$, and the ones producing or destroying $^7\text{Li}$ by energetic hydrogen among the most relevant reactions for BBN [45] – $^4\text{He}(t, \gamma)^7\text{Li}$, and $^7\text{Li}(p, \alpha)^4\text{He}$;

3. The ones to produce and destroy $^6\text{Li}$, including exothermic reactions $^4\text{He}(d, \gamma)^6\text{Li}$ and $^6\text{Li}(p, \alpha)^3\text{He}$ and endothermic reactions $^7\text{Be}(d, ^3\text{He})^6\text{Li}$ and $^7\text{Li}(d, t)^6\text{Li}$. Note that the computation for $^6\text{Li}$ abundance is neither complete nor accurate and we will come back to this point in section 4.

The above reactions are listed in table 2:
Table 2: Additional reactions added in our element abundance computation.

| Process                  | Threshold/MeV | Cross Section |
|--------------------------|---------------|---------------|
| $D(p, \gamma)^3He$      | 0             | [46]          |
| $D(d, p)^4T$            | 0             | [47]          |
| $D(d, n)^3He$           | 0             | [48]          |
| $T(d, n)^4He$           | 0             | [49]          |
| $^4He(d, \gamma)^6Li$  | 0             | [50]          |
| $^4He(t, \gamma)^7Li$  | 0             | [51]          |
| $^6Li(p, \alpha)^3He$  | 0             | [52, 53]      |
| $^7Li(p, \alpha)^4He$  | 0             | [53, 54]      |
| $^7Li(p, n)^7Be$        | 1.880         | [55]          |
| $^7Be(p, p\alpha)^3He$ | 1.814         | [56]          |
| $^7Li(d, t)^6Li$        | 1.278         | [57]          |
| $^7Be(d, ^3He)^6Li$     | 0.144         | [58]          |

3 Element abundances after including BBN-CRs contributions

Now we turn to element abundance computation after including BBN-CRs contributions. Besides the standard contributions in SBBN, extra contributions come from the processes where the thermal particles collide with non-thermal BBN-CRs particles. According to the Boltzmann equation, variation of the abundance of nuclide $i$ is described as

$$\frac{dY_i}{dt} = -\sum_j Y_i Y_j [ij] + \sum_{k,l} Y_k Y_l [kl],$$

where $[ij]$ is the rate for destroying nuclide $i$ and $[kl]$ is the rate for creating $i$, $Y_i = X_i/A_i$ is the abundance of nuclide $i$ with $X_i$ the mass fraction and $A_i$ the mass number of nuclide $i$. The sum over $j$ goes through all reactions to destroy nuclide $i$ and the sum over $k, l$ goes through all reactions to produce nuclide $i$. The rate $[ij]$ is defined by

$$[ij] \equiv N_A \rho \langle ij \rangle,$$

where $N_A$ is the Avogadro’s number, $\rho$ is the baryon energy density, and $\langle ij \rangle \equiv \langle \sigma v \rangle_{ij}$. Here $\sigma$ is the cross section of the reaction $(ij \rightarrow kl)$, and $v$ is
the relative velocity between these two particles $i$ and $j$. The $\langle \rangle$ stands for the mean over different relative velocities [59]. In the SBBN, $\langle \rangle$ means the thermal average, while in the case with BBNCRs it can be computed as

$$
\langle \sigma v \rangle_{12}(T, \alpha) = \frac{1}{K_3} \int_{-1}^{1} d \cos \theta \frac{1}{K_1} \times \int_{-\infty}^{+\infty} f_1(E_1, T) dE_1 \times \frac{1}{K_2} \int_{0.09}^{4} f_2(E_2, \alpha) dE_2 \sigma(E_i) v(E_1, E_2, \cos \theta).
$$

(3)

Here distribution of SBBN particles $f_1(E_1, T)$ is the normalized Boltzmann distribution,

$$
f_1(E_1, T) = 2 \sqrt{\frac{E_1}{\pi kT}} e^{-E_1/kT},
$$

(4)

where $k$ is the Boltzmann’s constant, $T$ is the Universe temperature, and $E_1$ is the energy of the SBBN particle. Thus the normalization constant $K_1 = 1$ and the energy range is $(-\infty, +\infty)$. Distribution of BBNCRs is power law with index $\alpha$ (see figure 1),

$$
f_2(E_2, \alpha) \propto E_2^{-\alpha},
$$

(5)

$$
\alpha = \begin{cases} 
2 \text{ or } 0 & \text{for } 0.09 \text{ MeV} < E_2 < 2 \text{ MeV} \\
4 & \text{for } 2 \text{ MeV} < E_2 < 4 \text{ MeV}
\end{cases},
$$

(6)

where $E_2$ is the energy of the BBNCR particle, with $\alpha = 2$ for power law case and $\alpha = 0$ for uniform distribution case. We normalize the function $f_2$ from 2 MeV to 4 MeV,

$$
K_2 = \int_{2}^{4} f_2(E_2, \alpha) dE_2,
$$

(7)

and make $f_2$ continuous at 2 MeV point. When the mass of the SBBN particle is noted as $m_1$ and that of the BBNCR as $m_2$, we can compute the relative velocity with the angle of incidence $\theta$,

$$
v = |\vec{v}_1 - \vec{v}_2| = \sqrt{\frac{2E_1}{m_1} + \frac{2E_2}{m_2} - 4 \sqrt{\frac{E_1E_2}{m_1m_2}} \cos \theta},
$$

(8)
and incident energy $E_i$

$$E_i = \frac{1}{2} m_i v^2,$$

(9)

where $m_i$ is the mass of the incident particle. The normalization constant over $\theta$ is $K_3 = \int_{-1}^{1} \cos \theta \, d\cos \theta = 2$. The cross sections in eq. (3) are taken from experimental data source DataBase EXFOR [60] and ENDF[61]. As a result, the incident particle is not simply the energetic particle, but on the criterion from nuclear experiments. Taking $^4\text{He}(t,\gamma)^7\text{Li}$ for example, data of cross sections are obtained under the situation where $^4\text{He}$ is taken as the incident particle.

We calculate abundances utilizing the updated version [62, 63] of the Wagoner code [64] from [65] with appropriate modification in order to include new contributions from BBNCRs. The baryon-to-photon ratio is updated to $6.23 \times 10^{-10}$ [66]. The rates of endothermal and exothermic processes in table 2 where BBNCRs particles involve are multiplied by $\epsilon$. The new contributions are added to the code as new channels. Details of the cross sections we adopted can be found in Appendix B.

As the cross section of $^7\text{Be}(p,pa)^9\text{He}$ is unknown from experiments, we take D$(p,n)2\text{H}$ with a shift of the threshold energy as a substitute. If the difference is considerable, e.g., the D$(p,n)2\text{H}$ cross section is $x$ times the $^7\text{Be}(p,pa)^9\text{He}$ cross section, we need to replace $\epsilon$ as $x\epsilon$.

Now we turn to show our numerical results for element abundance after including new contributions from BBNCRs. Figure 2 and 3 show processing rates, which is defined as $\epsilon Y_i Y_j [ij]/H$ [67] ($H$ is the expansion rate), of producing and destroying $^7\text{Li}/^7\text{Be}$. From the figures we can clearly see contributions from non-thermal processes, especially in the low temperature regime.

$^7\text{Be}$ abundances under $\alpha = 2$ for $0.09 \text{ MeV} < E_2 < 2 \text{ MeV}$ and different values of $\epsilon$ are shown in figure 4, among which the red solid line stands for SBBN result ($\epsilon = 0$). We can see that $\epsilon = 7 \times 10^{-5}$ can destroy 70% $^7\text{Be}$. As a price, 5% D is destroyed (as a comparison, the number shifts to 1% for uniform distribution). From the figure we can see clearly that new contributions from BBNCRs can account for $^7\text{Li}$ abundance quite satisfactory. Note that for the processes whose reactants are both hydrogen, the effect on D abundance need to be doubled according to the symmetry.

In figure 5 and 6 shows abundances of $^7\text{Li}/^7\text{Be}$ and $^6\text{Li}$, as well as all elements as a function of temperature respectively. Here the solid lines stand for the SBBN results, and the dashed lines for results with BBNCRs under
\( \alpha = 2 \) for \( 0.09 \text{ MeV} < E_2 < 2 \text{ MeV} \) and \( \epsilon = 7 \times 10^{-5} \). While the BBNCRs can account for \(^7\text{Li} \) abundance, for the \(^6\text{Li} \) abundance, energetic BBNCRs can enhance \(^6\text{Li} \) one order of magnitude, but not enough compared to observations. From the curves we can also see that the shifts of other element abundances after including BBNCRs contributions are usually tiny.

For completeness we also show processing rates of producing and destroying \(^6\text{Li} \) in figure 7 and 8. It is not hard to see that non-thermal contributions are quite similar to the \(^7\text{Li} \) case. BBNCRs play important role mainly when the Universe temperature falls below 0.04 MeV.
Figure 3: Processing rate of destroying $^7$Li/$^7$Be as a function of temperature.
Figure 4: $^7$Be abundance as a function of temperature. Here $\epsilon$ is taken as 0, $5 \times 10^{-5}$, $7 \times 10^{-5}$ and $1 \times 10^{-4}$ respectively.
Figure 5: Abundances of $^7\text{Li}/^7\text{Be}$ and $^6\text{Li}$ as a function of temperature with $\epsilon = 7 \times 10^{-5}$. 
Figure 6: Abundances of all elements as a function of temperature with $\epsilon = 7 \times 10^{-5}$. 
Figure 7: Processing rate of producing $^6$Li as a function of temperature.
Figure 8: Processing rate of destroying $^6$Li as a function of temperature.
4 Conclusions and discussions

In this paper, we investigated whether cosmic rays in the BBN epoch (BBNCRs) can account for Lithium problem or not. In order to keep the success of SBBN, the flux, energy range and spectrum of BBNCRs are severely constrained. In the allowed parameter space, extra contributions from BBNCRs to $^7$Li abundance can fill the discrepancy between SBBN prediction and observations. However BBNCRs can lift $^6$Li abundance in the SBBN an order of magnitude, but still less than that of observations.

We need to point out some factors beyond investigations in the paper. First, measurements of cross sections of nuclear reactions, especially $^7$Be($p$, $p\alpha$)$^3$He is critical. Lack of knowledge on T($t$, $\gamma$)$^6$He ($^6$He will decay to $^6$Li in 0.8s) and $^3$He($t$, $\gamma$)$^6$Li cross sections brings uncertainty on $^6$Li results, too. If their cross section between 2 MeV and 4 MeV is about $O$(mb), the contributions to $^6$Li abundance is comparable to that of $^4$He($d$, $\gamma$)$^6$Li.

Second, we consider hydrogen as the only component of BBNCRs in this paper, however the possible $^3$He or $^4$He as BBNCRs particles will change our results. We can imagine that $^3$He and $^4$He are accelerated to the same energy and spectrum (in fact their energy should be lower and the spectrum be softer than hydrogen). In this case, effects of some reactions (e.g. $^4$He($d$, $\gamma$)$^6$Li and $^4$He($t$, $\gamma$)$^7$Li) will be doubled. At the same time, new reactions are triggered by energetic $^3$He and $^4$He (see table 3). The reaction $^7$Be($\alpha$, $p$)$^{10}$B will destroy $^7$Be and produce $^{10}$B.

In our analysis, it is important that the amount of BBNCRs should be very low above 3.337 MeV, namely the D($p$, $n$)2H threshold. In order to test the effect of the spectrum choice on the deuteron abundance, we tried different spectrums, and show some representative ones in figure 9. For each spectrum, we give the necessary fraction of BBNCRs, namely $\epsilon$, to destroy 70% $^7$Be, and the corresponding percentage of destructed deuterium. The results are shown in table 4. The upper limit of BBNCRs spectrum is taken to be 10 MeV. We find that BBNCRs above 3.337 MeV would destroy deuterium inevitably. Therefore, the main part of the realistic spectrum should lie between 1.814 MeV and 3.337 MeV, and a rapid drop below 1.814 MeV and above 3.337 MeV is favorable.

At last but not least, the critic issue for the BBNCRs is about acceleration mechanism during BBN and whether the required flux and energy range as

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4 We ignore endothermic reactions whose threshold is higher
Figure 9: Energy spectrum test.
Table 3: List of new reactions triggered by energetic $^3$He and $^4$He.

| Process | Threshold/MeV |
|---------|--------------|
| $^6$Li($^3$He, 2$p$)$^7$Li | 0.703 |
| $^7$Li($^3$He, $^t$)$^7$Be | 1.259 |
| $^7$Be($\alpha, p$)$^{10}$B | 1.800 |
| $^6$Li($^3$He, $d\alpha$)$^3$He | 2.213 |
| $^7$Be($^3$He, $\alpha$)$^2$He | 2.268 |
| $^6$Li($\alpha, d$)$^4$He | 2.455 |
| $^7$Be($\alpha, 2\alpha$)$^3$He | 2.491 |
| $^6$Li($\alpha, d$)$^8$Be | 2.608 |
| $^7$Be($\alpha, ^3$He)$^8$Be | 2.635 |
| $^6$Li($^3$He, $d$)$^8$B | 2.965 |
| $^6$Li($^3$He, $np$)$^7$Be | 3.171 |

Table 4: The effect of the spectrum choice on the deuteron abundance.

| Description of spectrum | Curves in figure 9 | $\epsilon$ fraction | D destroyed |
|------------------------|-------------------|--------------------|-------------|
| uniform distribution between 2 MeV and 4 MeV | black, solid | $2 \times 10^{-5}$ | 1.9% |
| uniform distribution between 0.09 MeV and 2 MeV, $E^{-4}$ between 2 MeV and 10 MeV | black, dashed | $3 \times 10^{-5}$ | 10.6% |
| $E^2e^{-E^2}$ between 0.09 MeV and 10 MeV | red, solid | $3 \times 10^{-4}$ | 15% |
| $E^7e^{-E^2}$ between 0.09 MeV and 10 MeV | orange, solid | $1.5 \times 10^{-4}$ | 1.8% |
| $E^4e^{-(E/1.814)^3}$ between 0.09 MeV and 10 MeV | blue, dashed | $1 \times 10^{-4}$ | 1.2% |

well as spectrum can be induced. Anyhow the energetic particles are thought to be easily thermalized by photons and nuclei around before they collide with other nuclei [41, 42].

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A Classification of Exothermic Reactions

Exothermic reactions where BBNCRs involve are listed in two tables. Table 5 shows SBBN reactions which are included in the Wagoner code and table 6 shows reactions besides those.
Table 5: Exothermic reactions – Part I

| Process           | Effect                                                                 |
|-------------------|------------------------------------------------------------------------|
| H(n,γ)D           | produce D, but not important, for n is too little                     |
| D(n,γ)T           | destroy D, but not important, for n is too little                     |
| D(p,γ)^3He        | destroy D, see table 2                                                 |
| D(d,n)^3He        | destroy D, see table 2                                                 |
| D(d,p)^3T         | destroy D, see table 2                                                 |
| T(p,γ)^4He        | destroy T^5                                                            |
| T(d,n)^4He        | destroy D, see table 2; destroy T, see the footnote                    |
| ^3He(d,p)^4He     | destroy D, but less important than D(p,γ)^3He;                         |
|                   | destroy ^3He, see the footnote                                         |
| ^4He(d,γ)^6Li     | produce ^6Li, see table 2                                              |
| ^4He(t,γ)^7Li     | produce ^7Li, see table 2                                              |
| ^6Li(p,γ)^7Be     | destroy ^6Li, but less important than ^6Li(p,α)^3He, for the electromagnetic cross section is smaller than the strong one |
| ^6Li(p,α)^3He     | destroy ^6Li, see table 2                                              |
| ^7Li(p,α)^4He     | destroy ^7Li, see table 2                                              |
| ^7Li(d,n)^2^4He   | destroy ^7Li, but less important than ^7Li(p,α)^4He                   |
| ^7Be(d,p)^2^4He   | destroy ^7Be, but less important                                      |
| ^7Be(p,γ)^8^B     | destroy ^7Be, but less important, for the electromagnetic cross section |

Table 6: Exothermic reactions – Part II

| Process           | Effect                                                                 |
|-------------------|------------------------------------------------------------------------|
| D(d,γ)^4He        | destroy D, but less important than D(d,p)^3T or                        |
|                   | D(d,n)^3He, for the electromagnetic cross section                      |
| T(t,2n)^4He       | destroy T, but change little compared to the SBBN situation           |
| T(t,γ)^6He        | produce ^6Li, see Section 4                                            |
| ^3He(t,γ)^6Li     | produce ^6Li, see Section 4                                            |
| ^3He(t,d)^4He     | produce D, but change little compared to the SBBN situation            |
| ^3He(t,np)^4He    | destroy T and ^3He, but change little compared to the SBBN situation  |

To be continued...
| Process          | Effect                                                                 |
|------------------|-------------------------------------------------------------------------|
| $^6\text{Li}(d,\alpha)^4\text{He}$ | destroy $^6\text{Li}$, but less important                               |
| $^6\text{Li}(d,p)^7\text{Li}$      | destroy $^6\text{Li}$, but less important                               |
| $^6\text{Li}(d,n)^7\text{Be}$      | destroy $^6\text{Li}$, but less important                               |
| $^6\text{Li}(d,pt)^4\text{He}$     | destroy $^6\text{Li}$, but less important                               |
| $^6\text{Li}(d,n^3\text{He})^4\text{He}$ | destroy $^6\text{Li}$, but less important                               |
| $^6\text{Li}(t,\gamma)^9\text{Be}$ | destroy $^6\text{Li}$, but less important; produce $^9\text{Be}$, but less important than $^7\text{Li}(t,n)^9\text{Be}$, for the electromagnetic cross section |
| $^6\text{Li}(t,n)^2^4\text{He}$    | destroy $^6\text{Li}$, but less important                               |
| $^6\text{Li}(t,d)^7\text{Li}$      | destroy $^6\text{Li}$, but less important                               |
| $^6\text{Li}(t,p)^8\text{Li}$      | destroy $^6\text{Li}$, but less important                               |
| $^7\text{Li}(d,\gamma)^9\text{Be}$ | produce $^9\text{Be}$, but less important than $^7\text{Li}(t,n)^9\text{Be}$, for the electromagnetic cross section |
| $^7\text{Li}(t,\gamma)^{10}\text{Be}$ | produce $^{10}\text{B}$, ($^{10}\text{Be}$ decays to $^{10}\text{B}$) but less important than $^7\text{Be}(\alpha,p)^{10}\text{B}$ |
| $^7\text{Li}(t,n)^9\text{Be}$      | produce $^9\text{Be}$, maybe important, constraints from observations$[69]$ |
| $^7\text{Li}(t,\alpha)^6\text{He}$ | produce $^6\text{Li}$, but less important than $^6\text{T}(t,\gamma)^6\text{He}$ or $^3\text{He}(t,\gamma)^6\text{Li}$ |
| $^7\text{Li}(t,2n)^2^4\text{He}$   | destroy $^7\text{Li}$, but less important                               |
| $^7\text{Be}(t,\gamma)^{10}\text{B}$ | produce $^{10}\text{B}$, but less important than $^7\text{Be}(\alpha,p)^{10}\text{B}$ |
| $^7\text{Be}(t,\alpha)^6\text{Li}$ | produce $^6\text{Li}$, but less important than $^6\text{T}(t,\gamma)^6\text{He}$ or $^3\text{He}(t,\gamma)^6\text{Li}$ |
| $^7\text{Be}(t,d)^2^4\text{He}$    | destroy $^7\text{Be}$, but less important                               |
| $^7\text{Be}(t,p)^9\text{Be}$      | produce $^9\text{Be}$, maybe important, constraints from observations$[69]$ |
| $^7\text{Be}(t,np)^2^4\text{He}$   | destroy $^7\text{Be}$, but less important                               |
| $^7\text{Be}(t,^3\text{He})^7\text{Li}$ | transformation between $^7\text{Li}$ and $^7\text{Be}$, but less important than $^7\text{Li}(p,n)^7\text{Be}$ |

B Cross Sections and Details of Computation Scheme

Cross sections of the reactions included in our computation are shown in figure 10-21. The possible errors here can be accommodated by changing the amount of BBNCRs, namely varying the free parameter $\epsilon$.

Cross sections below the first available point from the experiment is set to zero, and above the last available point the cross sections are set to be...
Among the experimental points, cross sections are interpolated simply linearly. However for \( D(p, \gamma)^3\text{He} \), \( ^7\text{Li}(p, \alpha)^4\text{He} \), \( ^6\text{Li}(p, \alpha)^3\text{He} \) and \( T(d, n)^4\text{He} \), the cross sections are interpolated double-logarithmic linearly, in order to make them more smooth.

The integral limit over thermal spectrum is not infinite. Instead we use \( 0.001T \) as the lower limit and \( 8T \) as the upper limit, where \( T \) is the Universe temperature. Integration is carried out in six-point Gaussian scheme.
Figure 10: Cross sections of D(p, γ)³He

Figure 11: Cross sections of D(d, p)T
Figure 12: Cross sections of D(d, n)^3He

Figure 13: Cross sections of T(d, n)^4He
Figure 14: Cross sections of $^4\text{He}(d, \gamma)^6\text{Li}$

Figure 15: Cross sections of $^4\text{He}(t, \gamma)^7\text{Li}$
Figure 16: Cross sections of $^6\text{Li}(p,\alpha)^3\text{He}$

Figure 17: Cross sections of $^7\text{Li}(p,\alpha)^4\text{He}$
Figure 18: Cross sections of $^7\text{Li}(p, n)^7\text{Be}$

Figure 19: Cross sections of D(p, n)2H
Figure 20: Cross sections of $^7\text{Li}(d,t)^6\text{Li}$

Figure 21: Cross sections of $^7\text{Be}(d,^3\text{He})^6\text{Li}$