Proton-Induced Nonthermal Nuclear Effects in the Early Universe Plasma

Victor T. VORONCHEV[1)], Yasuyuki NAKAO[2)] and Makoto NAKAMURA[3)]

[1)]*Institute of Nuclear Physics, Moscow State University, Moscow 119991, Russia*

[2)]*Department of Applied Quantum Physics and Nuclear Engineering, Kyushu University, Fukuoka 819-0395, Japan*

[3)]*Central Research Institute of Electrical Power Industry, Tokyo 201-8511, Japan*

(Received: 4 August 2008 / Accepted: 29 December 2008)

Nonthermal effects in big bang nucleosynthesis (BBN), which are triggered by MeV protons produced in the primordial plasma via D(d, p)T and ^{3}He(d, p)^{4}He fusions, are examined using the formalism of in-flight reaction probability. We particularly focus on p-induced breakups of loosely bound D, ^{7}Li, ^{7}Be nuclei – the processes heretofore omitted in the standard scenario of BBN. It is found that at plasma temperatures below 70 keV, the in-flight reactions enhance the breakups by orders of magnitude, so that Maxwellian-based estimates of their reactivities involve appreciable errors. However, the revised breakup rates prove to be insufficiently high to affect the prediction of light element abundances. The two-temperature Maxwellian model for particle distribution functions is used to determine the fraction η'_p of hot protons needed to obtain a signature of suprathermal protonic reactions in the plasma. It is shown that the influence on elements abundances of the hot proton component appears at $\eta'_p \simeq 10^{-6}$ and becomes significant at $\eta'_p \simeq 10^{-4}$, essentially improving the prediction for primordial ^{7}Li. An important question however remains what mechanism(s) could provide such high percentage of hot protons in the plasma.

Keywords: early universe plasma, energetic protons, in-flight nuclear reactions, light element abundance

1. Introduction

Big bang nucleosynthesis (BBN) has been recognized to offer a unique probe of the early universe physics. A key point in the theory of BBN is realistic description of nuclear reaction kinetics in the primordial plasma. In the standard scenario of BBN, the reaction kinetics is treated within the Maxwellian approximation, which is a conventional tool for studying equilibrium plasmas or plasmas under conditions close to thermal equilibrium. At the same time, however, particle distributions in the hot primordial plasma are not purely Maxwellian due to a number of reasons. First of all, products of nuclear reactions are naturally non-Maxwellian; they slow down in the plasma and form groups of species with Maxwellian-like distributions having pronounced high-energy tails. Besides that, the energetic products can undergo close collisions with thermal particles, accelerate them and thereby pump the population of high-energy tails of the respective particle distributions. As a result, a deviation of the particle distributions from the Maxwellian form appears.

Since these non-Maxwellian perturbations induce suprathermal processes in the plasma, a natural question arises whether they can influence the chain reaction kinetics and modify the picture of nucleosynthesis. Such question seems particulary interesting in view of recent findings [1, 2, 3] showing that similar nonthermal effects can appreciably enhance the rates of some reactions in laboratory plasmas. Furthermore, the influence of nonthermal effects on nuclear reaction yields has also been considered in astrophysical plasmas. In [4, 5, 6], for example, non-Maxwellian distortions of particle velocity distributions were discussed in the context of the solar neutrino problem. In particular, a deviation from Maxwellian distribution (a possible depletion of its high-energy tail) suspected in [5] was shown to result in reducing the neutrino counting rate. The significance of nonthermal effects in the primordial plasma was demonstrated in unconventional BBN scenarios (see, e.g., [7, 8, 9, 10]). In these works, nonthermal reactions are assumed to be triggered due to decays of hypothetical relic unstable particles.

Table 1 The breakup reactions considered.

Reaction	E_{thr} (MeV)
$p + \mathrm{D} \to p + p + n$	2.22
$p + {}^7\mathrm{Li} \to p + t + \alpha$	2.47
$\to t + {}^5\mathrm{Li} \to p + t + \alpha$	4.43
$\to p + {}^7\mathrm{Li}^* \to p + t + \alpha$	4.65
$p + {}^7\mathrm{Be} \to p + {}^3\mathrm{He} + \alpha$	1.59
$\to {}^3\mathrm{He} + {}^5\mathrm{Li} \to p + {}^3\mathrm{He} + \alpha$	3.55
$\to p + {}^7\mathrm{Be}^* \to p + {}^3\mathrm{He} + \alpha$	4.57

An objective of the present paper is to examine nonthermal nuclear effects induced by energetic protons in standard BBN. We will particularly focus on breakups of loosely bound nuclei D, ^{7}Li, ^{7}Be – the processes omitted in the standard BBN reaction network. They are listed in Table 1. The p+^{7}Li and p+^{7}Be reactions can proceed via three channels with different threshold energies E_{thr}. It is worth emphasizing here that the above threshold processes, being suppressed at low energies, should be sensitive to the

author's e-mail: voronchev@srd.sinp.msu.ru, nakao@nucl.kyushu-u.ac.jp and makoto-n@criepi.denken.or.jp

Table 2 A list of reactions in the primordial plasma.

No.	Reaction		Q-value (MeV)
1	n-decay	t, e	0.78
2	H(n,γ)D	t, a	2.22
3	D$(p,\gamma)^3$He	t, a	5.49
4	D(d,p)T	t, e	4.03
5	D$(d,n)^3$He	t	3.27
6	T$(d,n)^4$He	t	17.59
7	^{3}He(n,p)T	t, e	0.76
8	^{3}He$(d,p)^4$He	t, e	18.35
9	T$(\alpha,\gamma)^7$Li	t	2.47
10	^{3}He$(\alpha,\gamma)^7$Be	t	1.59
11	^{7}Li$(p,\alpha)^4$He	t, a	1.59
12	^{7}Be$(n,p)^7$Li	t, e	1.64
13	^{3}He(^{3}He,2p)^{4}He	e	12.86
14	^{3}H$(p,\gamma)^4$He	a	19.81
15	^{6}Li$(p,\gamma)^7$Be	a	5.61
16	^{6}Li$(p,\alpha)^3$He	a	4.02

presence of fast protons in the plasma.

2. Energetic protons in the plasma

The standard BBN network [11] includes about 90 reactions responsible for synthesis of 26 nuclides. However, only a part of these reactions can efficiently contribute to the production of light elements, such as D, ^{3}He, ^{4}He, ^{7}Li. The top 12 reactions controlling the abundances of these elements are given in Table 2 and marked by symbol (t). It is essential that a half of these reactions also touch on protonic events in the plasma, performing the role of protons emitters (e) or absorbers (a). Table 2 is completed with other reactions between protons and light nuclei with mass number $A \leq 7$ incorporated in the standard BBN network.

To examine nonthermal p-induced reactions in the plasma, one needs to evaluate the flux of energetic protons in the early universe. The emission rate of a proton in a reaction i+j is $R_p = N_p \times R_{ij}$, where N_p is the number of protons produced per pair of (ij), and R_{ij} is the reaction rate of the form

$$R_{ij} = \alpha_{ij} n_i n_j \langle\sigma v\rangle_{ij}. \tag{1}$$

In Eq. (1), α_{ij} equals 1/2 or 1 for identical or different colliding nuclei i and j, respectively, n_k is the number density of plasma species k, $\langle\sigma v\rangle_{ij}$ is the i+j reaction rate parameter. The n_k values have been computed for the BBN scenario with the WMAP's baryon density [12]. We used the code [11] updated so as to incorporate revised estimates of $\langle\sigma v\rangle$ [13, 14], as well as the neutron lifetime τ_n and the Newton's constant G_N recommended by the Particle Data Group (2006) [15]. The number densities of various plasma species as a function of plasma temperature (and universe age) are shown in Fig. 1. The data on electron-positron pairs displayed in Fig. 2(b) are taken from [8].

The emission rate of fast protons R_p via individual reactions listed in Table 2 is shown in Fig. 2. As seen, the plasma is strongly irradiated by 0.57-MeV protons born in the ^{3}He(n,p) reaction. Although this reaction itself is a dominant source of suprathermal protons, the proton energy is insufficient to induce the D, ^{7}Li, ^{7}Be breakups. Therefore, we exclude the ^{3}He(n,p) process from the present analysis. We also neglect the contributions of the ^{3}He(^{3}He,2p) and ^{7}Be(n,p) reactions because their emission rates are essentially suppressed. Thus, we will consider the D(d,p) and ^{3}He(d,p) fusions generating an appreciable flux of energetic protons with birth energies E_0 = 3.02 MeV and 14.68 MeV, respectively. This flux is seen to be peaked around temperatures $T \simeq 70$ keV.

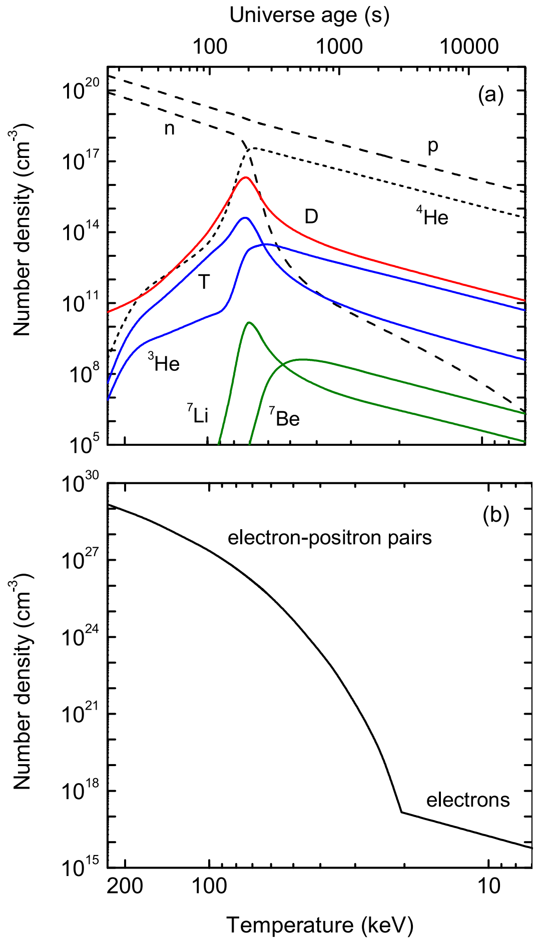

Fig. 1 The number densities of nuclei (a), electrons and positrons (b) in the primordial plasma. Nucleons and ^{4}He are shown by the dashed and dotted curves, respectively. The solid curves present the other plasma species.

3. Proton-induced nonthermal reactions

While slowing in the plasma from the birth energy E_0 down to the thermal energy $E_{th} = 3T/2$, fast DD and D^{3}He protons can undergo a number of suprathermal reactions. We will describe these nuclear events using a formalism of in-flight reaction probability. The probability F_{pX} for a nonrelativistic proton to undergo an in-flight p+X reaction

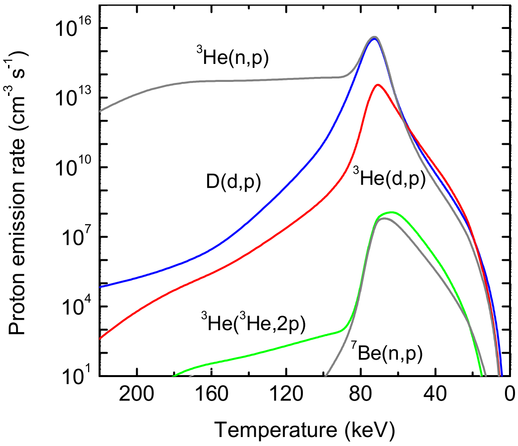

Fig. 2 The proton emission rates in the early universe plasma.

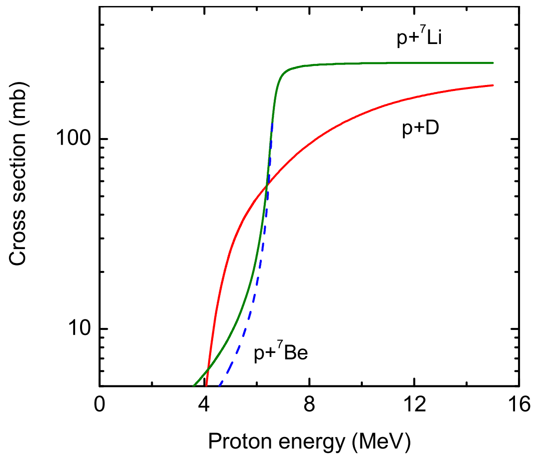

Fig. 3 The breakup reaction cross sections.

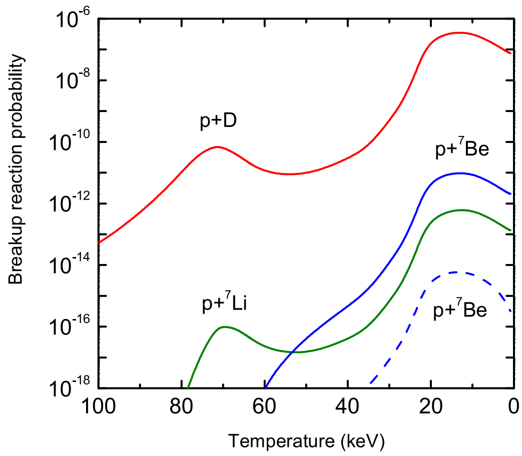

Fig. 4 The breakup reaction probabilities.

can be expressed as

$$F_{p\mathrm{X}}(E_0 \to E_{th}) = 1 - \exp\left[\int_{E_{th}}^{E_0} \left(\frac{2E_p}{m_p}\right)^{1/2} \frac{n_\mathrm{X}\sigma(E_p)}{\left\langle dE_p/dt\right\rangle} dE_p\right]. \quad (2)$$

In Eq. (2), E_p is the proton energy in the laboratory frame, n_X is the number density of target species X, $\sigma(E_p)$ is the p+X reaction cross section. The term $\left\langle dE_p/dt\right\rangle$ represents the average energy loss rate of fast proton. In the primordial plasma, the proton losses its energy via Coulomb scattering off background electrons and positrons (e), ions (i), and via inverse Compton scattering off thermal photons (γ). Accordingly, the energy loss rate in Eq. (2) is given by

$$\left\langle\frac{dE_p}{dt}\right\rangle = \left\langle\frac{dE_p}{dt}\right\rangle_{(p-e)} + \left\langle\frac{dE_p}{dt}\right\rangle_{(p-i)} + \left\langle\frac{dE_p}{dt}\right\rangle_{(p-\gamma)}. \quad (3)$$

It is found that the majority of $\left\langle dE_p/dt\right\rangle$ comes from the (p-e) scattering process described in the conventional binary-collision model with Debye cut-off [16]. Details of the formalism accepted, as well as explicit expressions for all the terms in Eq. (3) are given in [17].

The breakup reaction cross sections are shown in Fig. 3. The p+D and p+^{7}Li data are taken from [18] and [19], respectively. The p+^{7}Be cross section at energies $E_p > 6$ MeV (i.e., above Coulomb barriers in the entrance and exit reaction channels) is assumed to be close to that for p+^{7}Li. As for lower energies, the cross section has been derived using the p+^{7}Li data, which were modified so as to incorporate Coulomb suppression peculiar to the p+^{7}Be exit channels (see Table 1).

Figure 4 shows the calculated probabilities $F_{p\mathrm{X}}(E_0 \to E_{th})$ of the breakup reactions induced by D^{3}He (solid) and DD (dashed) protons. These probabilities are related to the in-flight reaction rates as $R_{p\mathrm{X}} = R_p \times F_{p\mathrm{X}}$, where R_p is the proton emission rate in DD or D^{3}He fusions. The rates can be rewritten in the form of Eq. (1)

$$R_{p\mathrm{X}} = \alpha_{p\mathrm{X}} n_p n_\mathrm{X} \langle\sigma v\rangle_{p\mathrm{X,\,in\text{-}fl}}, \quad (4)$$

$$\langle\sigma v\rangle_{p\mathrm{X,\,in\text{-}fl}} = \begin{cases} n_\mathrm{D}^2\langle\sigma v\rangle_\mathrm{DD} F_{p\mathrm{X}}/(2n_p n_\mathrm{X}) & \mathrm{DD\ p} \\ n_\mathrm{D} n_{^3\mathrm{He}}\langle\sigma v\rangle_{\mathrm{D}^3\mathrm{He}} F_{p\mathrm{X}}/(n_p n_\mathrm{X}) & \mathrm{D^3He\ p.} \end{cases} \quad (5)$$

Although the quantity $\langle\sigma v\rangle_\mathrm{in\text{-}fl}$ is not a conventional rate parameter, it reasonably indicates reaction "strength" and, therefore, can be considered as the effective rate parameter of in-flight reaction. The comparison of the nonthermal and thermal breakup reactivities is presented in Fig. 5 on the example of the p+D reaction. Shown are the in-flight and Maxwellian rate coefficients $N_A\langle\sigma v\rangle$, where $N_A = 6.0221 \times 10^{23}$ mol^{-1} is the Avogadro's number. It is seen that the in-flight channel can significantly support the reaction as the plasma cools down. The thermal contribu-

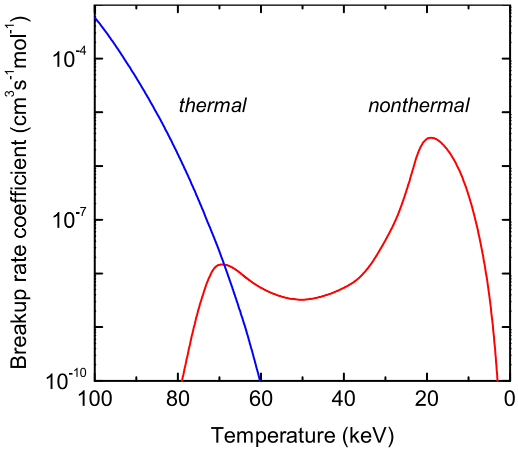

Fig. 5 The p+D breakup rate coefficients.

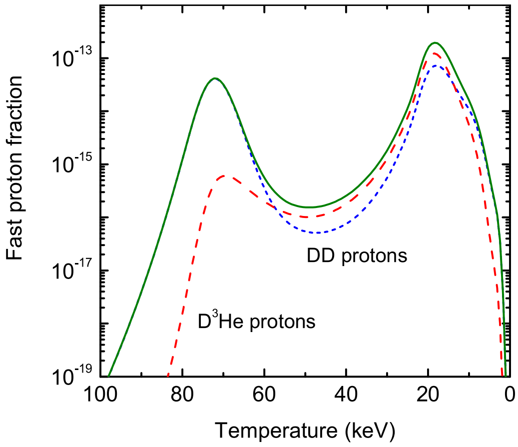

Fig. 6 The fractions of fast DD (dotted) and D^{3}He (dashed) protons in the plasma. The solid curve shows the total fraction of these energetic protons.

tion even becomes imperceptible at $T < 70$ keV, so that the p+D reaction takes the form of a suprathermal process.

An important question is whether the breakup processes can affect reaction kinetics in the primordial plasma. To examine this, the rate equation for abundance change dY_i/dt [11] has been generalized so as to incorporate thermal and in-flight channels of the p+X reactions (X = D, ^{7}Li, ^{7}Be). Our simulation of BBN with the extended reaction network has not revealed changes in light element abundances as compared with Maxwellian-based predictions. The respective results found with the WMAP's baryon density are shown in the second column of Table 3. Thus, although the in-flight reactions can appreciably enhance the breakup reactivities, their levels remain insufficient to affect the picture of BBN.

One can explain this by a lack of fast DD and D^{3}He protons in the early universe plasma. The density of these protons can approximately be estimated as $n'_p = R_p \times \tau_{th}$, where R_p and τ_{th} are the proton emission rate and slowing-down time, respectively. The latter is defined as

Table 3 The primordial abundances of light elements.

Element	Prediction: thermal	Prediction: 2TM model 0.6–2.1 MeV$^{a)}$	Observation Ref. [15]
D/H (10^{-5})	2.54	2.54–2.55$^{b)}$	2.78±0.29
		2.55–2.90$^{c)}$	
^{3}He/H (10^{-5})	1.00	1.00–1.01$^{b)}$	–
		1.01–1.59$^{c)}$	
^{4}He (10^{-1})	2.46	2.46$^{b)}$	2.49±0.09
		2.46$^{c)}$	
^{7}Li/H (10^{-10})	4.44	4.44–4.42$^{b)}$	1.70±0.02
		4.41–2.66$^{c)}$	
		2.69$^{c_1)}$	
		2.73$^{c_2)}$	
		4.30$^{c_3)}$	

$^{a)}$ the coefficient $T'_{\max}$ in Eq. (9)
$^{b)}$ $\eta'_{\max} = 10^{-6}$; $^{c)}$ $\eta'_{\max} = 10^{-4}$
$^{c_1)}$ without p+D; $^{c_2)}$ without p+^{7}Li; $^{c_3)}$ without p+^{7}Be

$$\tau_{th} = \int_{E_{th}}^{E_0} -dE_p / \left\langle dE_p/dt \right\rangle \tag{6}$$

The fractions $\eta'_p = n'_p/n_p$ of fast DD and D^{3}He protons in the plasma, as well as their sum (solid), are shown in Fig. 6. The maximum value of η'_p is only about 10^{-13}.

It would be useful to determine what amount of fast protons is needed to obtain a signature of nonthermal protonic effects in the plasma. Another interesting point is whether these effects would have a positive or negative impact on the prediction of light element abundances. In the present work, we examine this in a semi-qualitative approach based on the two-temperature Maxwellian (2TM) model [2]. According to it, the distribution function of primordial hydrogen $f_{\rm H}$ is expressed as superposition of two Maxwellian functions: $f_{\rm H} = f_p(\boldsymbol{v_p}) + f'_p(\boldsymbol{v'_p})$. The function f_p describes the behavior of bulk protons with density n_p and temperature T, while f'_p is introduced to model the whole ensemble of hot protons (of various origins) with some density $n'_p < n_p$ and temperature $T' > T$. Then, the rate of a H+j reaction can be expresses as

$$R_{{\rm H}j} = R_{pj}(n_p, T)\left[1 + \lambda(n_p, n'_p, T, T')\right], \tag{7}$$

where R_{pj} is the reaction rate associated with bulk protons, while λ introduces the correction caused by the hot proton component f'_p. The density n'_p and the temperature T' of hot protons are accepted to have the following forms

$$n'_p = \eta'_p \times n_p = \eta'_{\max}\, \phi'_p(T(t)) \times n_p, \tag{8}$$

$$T' = T'_{\max}\, \varphi'_p(T(t)). \tag{9}$$

In Eqs. (8)-(9), the functions ϕ'_p and φ'_p reproduce the time dependences (temporal evolutions) of hot proton fraction

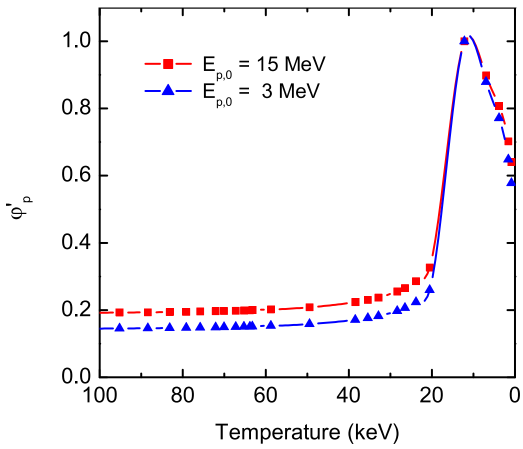

Fig. 7 The temporal evolution of hot proton temperature in the plasma.

and temperature during the universe expansion. The both functions are dimensionless, being normalized to unity at their maxima. The coefficient $\eta'_{\rm max}$ is declared to be a free parameter. To estimate the hot proton temperature T', we employ an "equivalent Maxwellian approximation" proposed in [20]. According to it, an equivalent Maxwellian temperature of an ensemble of suprathermal species in a plasma, which is formed by some source of monoenergetic particles k with an initial energy $E_{k,0} \gg E_{th}$ and has a slowing-down distribution function, can be presented as

$$T' = \epsilon(v_c/v_{k,0})E_{k,0}. \qquad (10)$$

In Eq. (10), v_c is the so-called crossover velocity, $v_{k,0}$ is the initial speed of particles k, and the function ϵ can be expressed in an analytical form [20]. Figure 7 shows the calculated temporal evolution (function φ'_p) of the hot proton temperature T' as the universe expands. These results are found for fast protons with initial energies $E_{p,0}$ in the 3–15 MeV range. The function φ'_p proves to be nearly invariant with respect to the initial (proton) energy: φ'_p varies within less than 30 % when $E_{p,0}$ changes by 5 times at T = 20–100 keV. However, the temperature T' itself changes significantly as the universe expands. It is found that the coefficient $T'_{\rm max}$ in Eq. (9) equals to 2.1 MeV (for D^{3}He proton source) and 0.6 MeV (for D^{3}He proton source), and accordingly T' ranges within 0.4–2.1 MeV and 0.1–0.6 MeV, respectively.

The results of BBN simulations, which allow for nonthermal protonic effects described in the 2TM model, are given in the third column of Table 3. Here, we take into account 14 different suprathermal reactions: the 3 breakup reactions from Table 1 and the 11 (forward and reverse) proton-induced reactions listed in Table 2. In this work, we assume that the hot proton fraction $\eta'_p = n'_p/n_p$ has the double-peaked form displayed in Fig. 6 (solid). The results in Table 3 indicate that the nonthermal reaction contribution appears at $\eta'_{\rm max} = 10^{-6}$ and becomes essential at $\eta'_{\rm max} = 10^{-4}$. One should emphasize that the nonthermal protonic effects have positive impacts *simultaneously* on D and ^{7}Li abundances. Particularly, the hot proton component can improve the prediction for primordial ^{7}Li. As seen from Table 3, the p-induced breakup of ^{7}Be plays the key role in reducing the ^{7}Li abundance.

4. Concluding Remarks

In the present paper we examined nonthermal protonic nuclear effects in the early universe plasma. The processes of our particular interest were reactions omitted in the standard BBN scenario – the breakups of D, ^{7}Li, ^{7}Be nuclei induced by MeV protons generated in D(d,p)T and ^{3}He$(d,p)^4$He fusions. It has been demonstrated that the in-flight reaction modes can enhance the breakup reactivities by several orders of magnitude. However, the revised breakup rates have proven to be insufficiently high to affect chain reaction kinetics in the plasma. The amount of fast protons in the plasma needed to obtain an influence on light element abundances was determined in the semi-qualitative approach based on the two-temperature Maxwellian model for hydrogen distribution function. It has been shown that if the fraction of hot protons would reach ∼ 0.01%, the prediction for the ^{7}Li primordial abundance could be essentially improved. However, an important question remains what mechanisms could provide such percentage of hot protons in the plasma.

[1] M. Nakamura *et al.*, J. Phys. Soc. Jpn. **75**, 024801 (2006).
[2] M. Nakamura *et al.*, Phys. Lett. A **359**, 663 (2006).
[3] M. Nakamura *et al.*, Nucl. Instr. Meth. A **580**, 1502 (2007).
[4] J.N. Bahcall, *Neutrino Astrophysics* (Cambridge Univ. Press, 1989).
[5] D.D. Clayton *et al*, Astrophys. J. **199**, 494 (1975).
[6] G.E. Kocharov, Ioffe Phys.-Tech. Inst. Report No. 298 (Leningrad, USSR, 1972).
[7] M.H. Reno and D. Seckel, Phys. Rev. D **37**, 3441(1988).
[8] M. Kawasaki *et al.*, Phys. Rev. D **71**, 083502 (2005).
[9] K. Jedamzik, Phys. Rev. D **74**, 103509 (2006).
[10] D. Cumberbatch *et al.*, Phys. Rev. D **76**, 123005 (2007).
[11] L. Kawano, *Let's go: early universe II* (Preprint Fermilab-Pub-92/04-A, 1992).
[12] D.N. Spergel *et al.*, Astrophys. J. Supp. **148**, 175 (2003).
[13] R.H. Cyburt, Phys. Rev. D **70** 023505, (2004).
[14] P. Descouvemont *et al.*, At. Data Nucl. Data Tables **88**, 203 (2004).
[15] W.M. Yao *et al.* (Particle Data Group), J. Phys. G **33** 1, (2006).
[16] D.V. Sivukhin, Rev. Plasma Phys. **4** 93, (1966).
[17] V.T. Voronchev *et al.*, J. Cosmol. Astropart. Phys. **05**, 010 (2008).
[18] S.N. Abramovich *et al.*, Nuclear-Physics Constants of Thermonuclear Fusion (TSINIIatominform Publ., Moscow, 1998).
[19] N.A. Vlasov and A.A. Ogloblin, Proc. Soviet Conf. on Nuclear Reactions at Low and Medium Energies (Moscow, USSR) p. 24 (1958).
[20] C. Estrada-Mila *et al.*, Phys. Plasmas **13**, 112303 (2006).