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Kinetic Analysis of Nonthermal Nuclear Processes in the Early Universe Plasma
初期宇宙プラズマにおける非熱的核反応過程の運動論的解析

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A plasma-kinetic model capable of properly describing the behavior of neutrons in the primordial plasma during the epoch of big bang nucleosynthesis (BBN) is formulated in order to exactly analyze the nonthermal reactions induced by these neutrons. After calculating the realistic neutron energy distribution, the nonthermal influence on individual reactions is examined on the example of the threshold $\mathrm{D}(n,2n)p$, $^{7}\mathrm{Li}(n,nt)^{4}\mathrm{He}$, and reverse $^{3}\mathrm{He}(n,d)\mathrm{D}$ processes. It is shown that at plasma temperatures $T_9 \leq 1.2$ the nonthermal neutrons strongly maintain these reactions, increasing their rate parameters by orders of magnitude as compared with the respective Maxwellian estimates.

1. Introduction

In the standard model of BBN, the nuclear reaction network is operated with thermal reaction rates in Maxwellian plasma [1]. In the primordial plasma, however, a number of nonthermal processes triggered by various energetic particles can occur. The sources producing such particles are exoergic reactions in the plasma and up-scattering of thermal background species by non-thermalized products of these reactions. All these energetic particles form several groups of non-Maxwellian plasma species ($n, p, t, {}^{3}\mathrm{He}, {}^{4}\mathrm{He}$) which can undergo nonthermal reactions. The most abundant and important nonthermal species are neutrons generated in the D-T and D-D fusion reactions [2].

Most part of the present paper is based on our recent studies [3] and focused on examining the rate parameters of nonthermal reactions induced by these neutrons. A rigorous plasma-kinetic approach is adopted to obtain realistic neutron distribution function.

2. Plasma-Kinetic Model

In the primordial plasma, fast neutrons slow down due to nuclear and electromagnetic scattering processes. The dominant mechanism is nuclear elastic scattering off bulk protons; the next contribution comes from elastic collisions with bulk α-particles [2].

Our model starts from an equation of evolution for the velocity distribution function of fast neutrons $f_{n,\,\mathrm{fast}}(\mathbf{v}_n, t)$:

$$\frac{\partial}{\partial t} f_{n,\mathrm{fast}}(\mathbf{v}_n, t) = \left(\frac{\partial f_{n,\mathrm{fast}}}{\partial t}\right)_C - L(\mathbf{v}_n, t) + S(\mathbf{v}_n, t), \quad (1)$$

where $(\partial f_{n,\,\mathrm{fast}}/\partial t)_C$ represents the scattering collision term, $L(\mathbf{v}_n, t)$ is the loss rate due to nuclear reactions, and $S(\mathbf{v}_n, t)$ is the source at an arbitrary time t. The main sources of fast neutrons are fusion reactions and close scattering collisions between bulk thermal neutrons and some energetic particles.

Because of the homogeneity and isotropy of the Universe, velocity distributions of neutrons and other species can be assumed isotropic. This enables us to use the neutron energy E_n instead of $\mathbf{v}_n$ as an independent variable and adopt the fast neutron flux defined by $\Psi = v_n f_{n,\,\mathrm{fast}}(E_n, t)$, where $f_{n,\,\mathrm{fast}}(E_n, t)$ is the energy distribution function of fast neutrons. Then, Eq. (1) is reduced to its final form:

$$\frac{1}{v_n}\frac{\partial \Psi}{\partial t} + \sum_j n_j(t)\sigma_{tj}^{\mathrm{eff}}(E_n)\Psi(E_n, t) = \sum_j \int n_j(t)\sigma_{Sj}^{\mathrm{eff}}(E_n' \to E_n)\Psi(E_n', t)dE_n' + S(E_n, t). \quad (2)$$

where n_j is the number density of background species j; $\sigma_{tj}^{\,eff}(E_n)$ and $\sigma_{Sj}^{\,eff}(E'_n \to E_n)$ are the total (scattering + absorption) and differential scattering cross sections, respectively, averaged over the energy distributions of background species j.

Equation (2) retains the time variable t. In most cases, however, the neutron thermalization time is much shorter than a typical time scale of plasma evolution in the BBN epoch. This implies that the plasma temperature and density can be assumed to ‘freeze out’ during the time needed for the slowing down and thermalization of fast neutrons. In such a case, we can make ‘steady-state’ calculations to obtain the neutron distribution function at each time step t_n of plasma evolution. For a full detail, see [3].

3. Numerical Results and Discussions

The realistic neutron distribution function $f_n(E_n)$ at a cosmic time t can be reasonably defined as $f_n(E_n) = f_{n,\,\text{fast}}(E_n) + f_{n,\,\text{bulk}}(E_n)$, where $f_{n,\,\text{bulk}}$ is the thermal distribution of bulk neutrons populating the primordial plasma at that time.

Figure 1 presents, as an example, the neutron energy distribution at a plasma temperature $T_9 = 0.7$. The solid curve shows the realistic distribution function allowing for the fast neutron component. For comparison, the Maxwellian distribution is indicated by the dashed curve. It is clearly seen that the high-energy tail of realistic distribution is appreciably enhanced and deviates from the Maxwellian function.

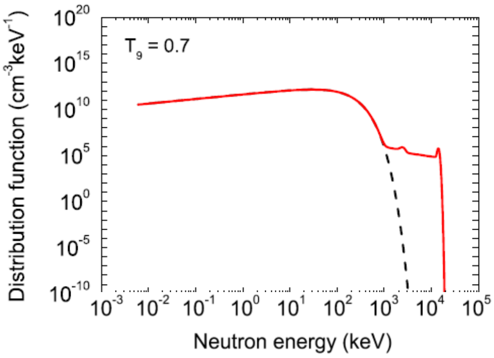

Fig.1. Neutron distribution function at $T_9 = 0.7$.

From the realistic distributions, the fraction of nonthermal neutrons η'_n in the total neutron component is evaluated to be at a level of 10^{-2}～10^{-3}%, while their effective temperature T'_n reaches several MeV and exceeds the plasma temperature in the BBN epoch by about a factor of 10^2.

The values of η'_n and T'_n can be used to simplify a computational procedure by using a two-temperature Maxwellian model for the neutron distribution.

Now we examine how the non-Maxwellian tail of the realistic neutron distribution affects the rate parameters of individual n-induced reactions. Here we consider the $n + X$ breakup (X = D, ^{7}Li) and reverse ^{3}He (n, d) D reactions which might have influences on some primordial element abundances. Figure 2 shows the astrophysical rate coefficients $N_A\langle\sigma v\rangle$ for these reactions. The solid curves show the rate coefficients obtained for the realistic neutron energy distribution. These realistic rate coefficients are compared with the Maxwellian ones given by the dashed curves. As seen, the nonthermal neutrons strongly support the breakup reactions as the Universe cools down. The enhancement factor obtained here is a few orders of magnitude.

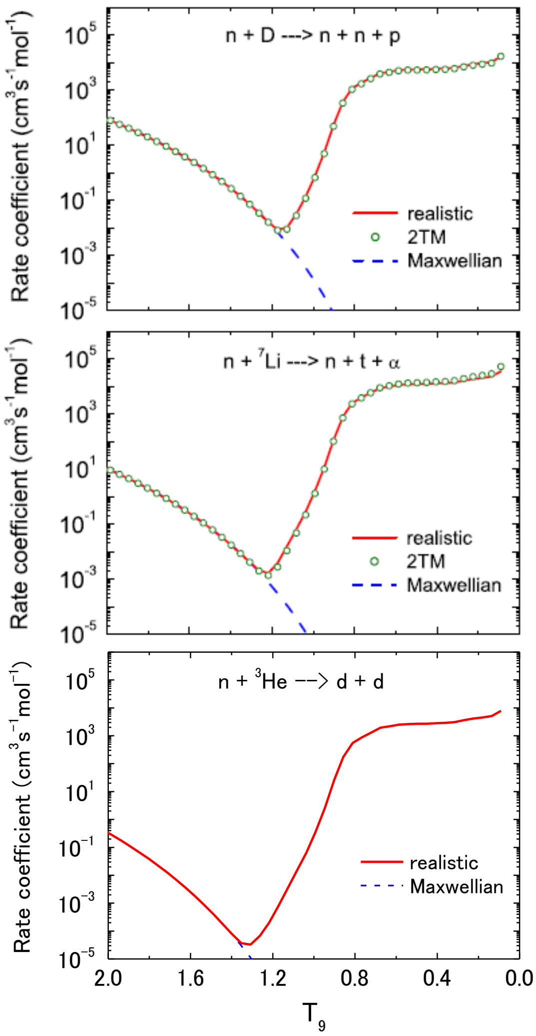

Fig.2. Astrophysical rate coefficients as a function of the Universe temperature.

4. Concluding Remarks

Based on the rigorous kinetic calculations, we have demonstrated that nonthermal neutrons can appreciably enhance rate parameters of endoergic processes, such as D, ^{7}Li breakup and reverse ^{3}He (n, d) D reactions.

An important question still remains—to what extent the nonthermal neutrons could affect the reaction kinetics in the early Universe and change the predictions of standard BBN. To this end, a number of nonthermal forward as well as reverse reactions should be incorporated in the BBN network. We address this in a future publication.

References

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