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Neutron Diffusion and Nucleosynthesis in the Inhomogeneous Universe

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Nucleosynthesis in the universe with isothermal density fluctuations is investigated. It is shown that neutrons in low-density regions diffuse back to high-density regions. Thus the abundances of light elements contradict with $\Omega_B=1$ if the scale of density fluctuations is as small as 10^4 cm at $T=1$ MeV.

It has been suggested that isothermal baryon density fluctuations are generated during the quark-hadron phase transitions.[1)~6)] These fluctuations significantly affect primordial nucleosynthesis through 2 effects: (1) The abundances of elements sensitively depend on the local baryon-photon ratio, and the final average abundances of the elements are much different from those in the uniform universe. (2) When the temperature falls down to ~1 MeV, the weak interactions among nucleons cannot catch up with cosmic expansion and decouple. Then the neutron diffusion length becomes significantly longer than the proton diffusion length and neutron-proton segregation occurs.[7)]

Recently, Applegate et al.,[7)] Alcock et al.[8)] and Fuller et al.[9)] investigated the nucleosynthesis in this model in detail and showed that the light element abundances are greatly modified in particular by the effect of (2): They showed that ^{4}He overproduction in the high-density region is suppressed by the escape of neutrons and also synthesized abundance of D is enhanced in the low-density region by neutrons which come from the high-density region. Their most important and interesting results is that in this scenario, $\Omega_B=1$ universe can be consistent with the observations of the abundances of light elements except ^{7}Li provided that the baryon density contrast between high and low density regions is sufficiently large. If the ^{7}Li problem is removed, the dark matter can be baryonic and no more speculative candidates, such as photinos, gravitinos, etc. are necessary. However they investigated nucleosynthesis in the simple 2-zone model, in which nucleosynthesis is calculated independently in the two regions and neutron diffusion is neglected during the period of nucleosynthesis, i.e., they assumed that neutron diffusion is switched off before nucleosynthesis begins.[7)~10)] However the assumption that neutron diffusion stops before the onset of nucleosynthesis is quite unnatural. Since neutron diffusion length keeps growing during nucleosynthesis,[7)] neutrons must diffuse out to be uniform in the density also during nucleosynthesis as long as the fluctuation scale is small enough for neutrons to diffuse out completely before nucleosynthesis. It is crucial whether neutron diffusion lasts after the onset of nucleosynthesis or not since nucleosynthesis in the high-density region proceeds faster than in the low-density region and neutrons may diffuse back to the high-density region from the low-density region. To examine this effect we calculate nucleosynthesis in the 2-zone model in which neutron diffusion begins at the decoupling time of the weak interaction among nucleons and lasts after the onset of nucleosynthesis.

The universe is assumed to consist of two regions; high-density region whose volume fraction is f_v and low-density region. The average baryon density is then,

$$\rho_B = f_v \rho_h + (1 - f_v)\rho_l , \tag{1}$$

where ρ_h and ρ_l are the baryon densities in the high and low density regions respectively. The ratio of ρ_h and ρ_l is kept constant before the onset of neutron diffusion,

$$R \equiv \frac{\rho_h{}^0}{\rho_l{}^0} . \tag{2}$$

The time scale of neutron diffusion ($\tau_{\rm diff}$) depends on the physical size of density fluctuation (d), the thermal velocity of neutrons ($v_{\rm th}$) and the mean free path of neutrons (l),

$$\tau_{\rm diff} \sim \frac{d^2}{v_{\rm th} l} . \tag{3}$$

In order to see the effect of neutron diffusion back to high-density region we consider scales of baryon density fluctuations such that the physical size of high-density regions is small enough for neutrons to diffuse out completely and the mean distance of the high-density regions is significantly shorter than the neutron diffusion length during nucleosynthesis, e.g., $d \ll 10^6$ cm at $T \sim 100$ keV. For simplicity, we assume that neutron diffusion between two regions is switched on instantaneously after the decoupling of the weak interactions ($T \sim 800$ keV) and neutron densities of the two region remain to be equal during the period of nucleosynthesis.

The background universe is assumed to be described by the Einstein equation for the uniform and isotropic Friedmann-Robertson-Walker model,

$$\left(\frac{1}{a}\frac{da}{dt}\right)^2 = \frac{8}{3}\pi G \rho , \tag{4}$$

where ρ is the total energy density of the universe and it is dominated by the radiation and neutrinos. Thus intrinsic parameters of the calculation are the average baryon density parameter Ω_B, the volume fraction of the high-density region f_v and the initial ratio of the baryon density of the 2 regions R. We take $\Omega_B = 1$($H_0 = 50$ kmMpc^{-1}sec^{-1}, $T_0 = 2.7$ K) to examine the compatibility of $\Omega_B = 1$ with nucleosynthesis in the universe with isothermal density fluctuations and calculate in the ranges; $0 \le f_v \le 1$, $1 \le R \le 1000$.

Our nucleosynthesis network is large enough including up to ^{32}S[11)] and thermonuclear reaction rates are taken from Refs. 12)~14) and some of them are updated[15)] according to the recent experimental results. The neutron lifetime and the number of neutrino species are taken $\tau_n = 898$ sec[16)] and $N_\nu = 3$ respectively.

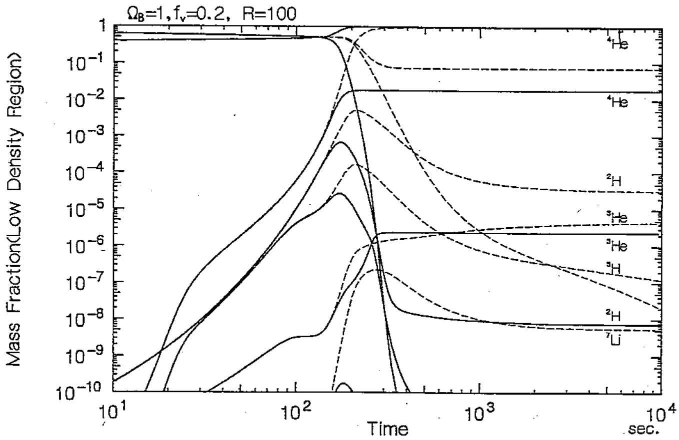


Fig. 1. Time evolution of the abundances of elements for $\Omega_B=1, f_v=0.2, R=100$ in the low-density neutron-rich region. Solid lines: diffusion lasting model. Broken lines: switched-off model. Note at the decrease in the neutron fraction $t\sim100$ sec due to the diffusing back to the high-density region in the diffusion lasting model.

In Fig. 1, we show an example of the time evolution of the element abundances for $\Omega_B=1, f_v=0.2, R=100$, in the low-density neutron-rich region in our diffusion-lasting model superposing with that in the model in which the neutron diffusion is switched off before nucleosynthesis (hereafter we call simply switched-off model). Although the ^{4}He abundance becomes almost 100% in the switched-off model, the abundances of all the elements are very small in the diffusion-lasting model. This is because neutrons in the low-density region diffuse back to the high-density region where nucleosynthesis proceeds faster than in the low-density region. Due to this effect, the baryon density in the high-density region rises at $t\sim100$ sec as shown in Fig. 2. Thus it is crucial whether neutron diffusion lasts till the onset of nucleosynthesis or not. As long as we assume such a status that a simple 2-zone model is valid, there is no reason that the neutron diffusion stops before nucleosynthesis. We find that most of neutrons in the low-density region diffuse back to the high-density region and neutron-rich nucleosynthesis does not take place for all the calculated ranges of the parameters.

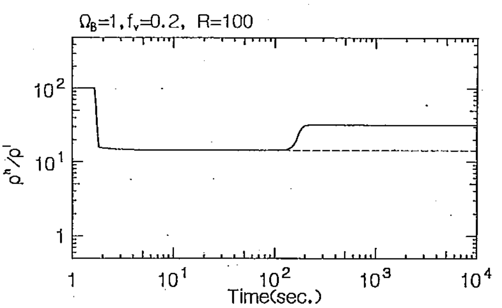
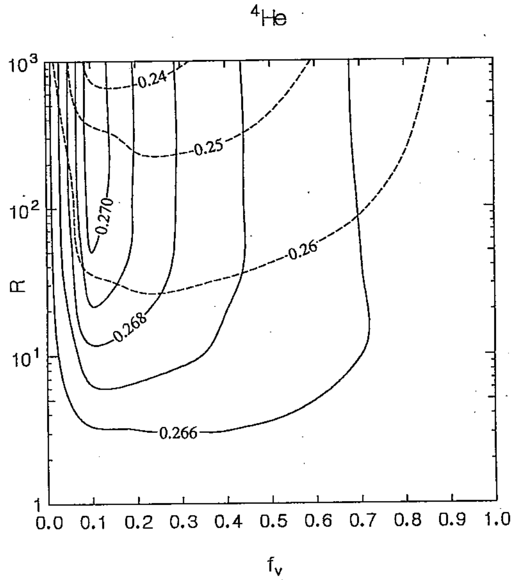
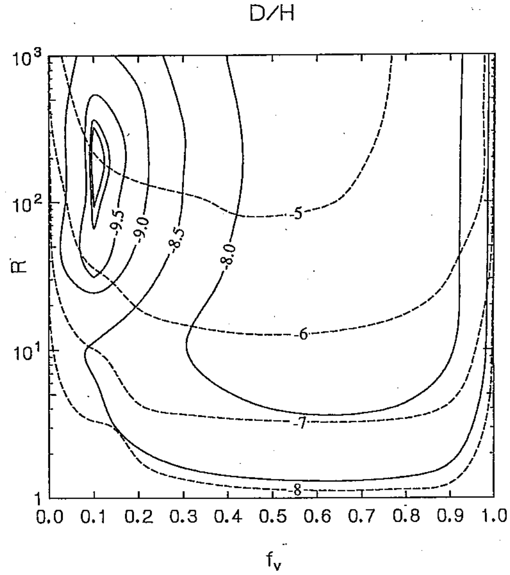


Fig. 2. The ratio of the baryon densities in the high-density region and the low-density region plotted against the cosmic time. The decrease at $t\sim2$ sec indicates that the neutron density became uniform due to diffusion. When nucleosynthesis in the high-density region begins at $t\sim100$ sec, neutrons diffuse back to the high-density region from the low-density region and the density contrast grows again in consequence.

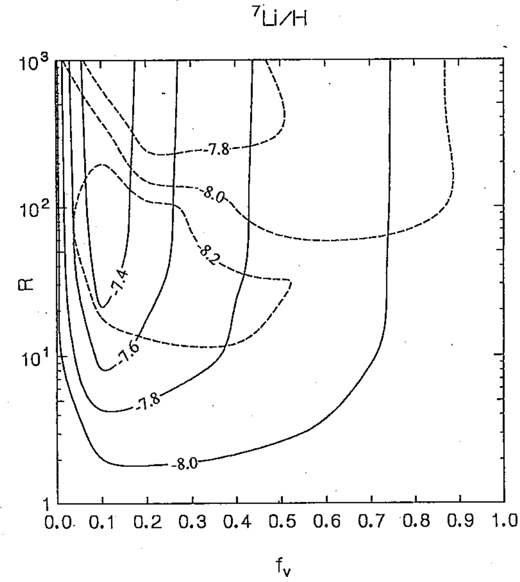
In Fig. 3 we show the average abundances of ^{4}He, D and ^{7}Li on the f_v-R plane. As shown in Fig. 3(a), the ^{4}He abundance increases with increasing R, but it is not different so much from the abundance in the uniform case ($R=1$). Hence even the ^{4}He abundance contradicts with the primordial abundance inferred from observations, $Y<0.26$.[17]



(a)



(b)



(c)

Fig. 3. The contour maps of the average abundances of ^{4}He, D and ^{7}Li on the f_v-R plane. Solid lines: diffusion lasting model. Broken lines: switched-off model. (a) The mass fraction of ^{4}He. (b) The D abundance. Contour levels are log(D/H). (c) The ^{7}Li abundance. Contour levels are log(^{7}Li/H).

The D abundance is, as shown in Fig. 3(b), too small to be consistent with the primordial abundance though it satisfies the constraints on the primordial abundance in the range $R \gtrsim 100$ in the switched-off model. Major contribution to the average D abundance comes from that in the low-density. However D is not produced much also in the low-density region since neutrons diffuse back to the high-density region.

Although ^{3}He abundance is small enough not to contradict with the constraints on its primordial abundance, ^{7}Li is overproduced similarly to the switched-off model (Fig. 3(c)).

Thus even the ^{4}He abundance and the D abundance are not consistent with their primordial abundances though they are consistent for the appropriate value of R in the switched-off model.[7)~10)] From this conflict, we may conclude that $\Omega_B=1$ universe is ruled out if the scale of the fluctuations is small enough for the diffusion time to be much smaller than the duration of nucleosynthesis. According to Applegate et al.[7)] the critical scale is of the order of 10^5 cm at the nucleosynthesis period ($T \sim 100$ keV), which corresponds to the scale smaller than 10^{-3} of the horizon size at the quark-hadron phase transition period. In order to clarify whether we can make the same conclusion for the larger scale, we need to calculate nucleosynthesis simultaneously with tracing the evolution of the density fluctuations and solving the diffusion process. Recently Matzner et al.[18] carried out this type of calculation and found that neutrons in the low-density region diffuse back into the high-density region. They, however, calculated only for three models, and their results should be taken preliminary, as they themselves noted, because of the very short nuclear chain which does not include ^{7}Li. We will show the results of detailed and systematic calculations for the wide range of the scale and the amplitude of density fluctuation in a forthcoming paper.[19]

Although we neglected proton diffusion, almost all the light elements except for D are synthesized in the high density zone and protons which diffuse out to the low density region do not affect the average abundance of light elements. In fact, we confirmed by the calculations which incorporated the proton diffusion effect that proton diffusion simply changes the fractions of other elements in each zone due to the increase or decrease of protons and does not affect the average abundances of elements if the scale of density fluctuations is small.[19]

We examined primordial nucleosynthesis in the universe with isothermal density fluctuations. We have shown that neutrons diffuse back to the high-density region from the low-density region and neutron-rich nucleosynthesis does not occur as far as the density fluctuations have a small enough scale, $d\sim 10^4$ cm at $T\sim 1$ MeV. Hence we cannot but conclude that the switched-off model studied so far (7)~10)) does not reflect any realistic status of the nucleosynthesis in the universe with density fluctuations.

Furthermore the density contrast, once leveled off, grows again by the neutron diffusion accompanying with nucleosynthesis as shown in Fig. 2. Hence nucleosynthesis itself affects the evolution of the density fluctuations.

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