

Comment on “Heavy element production in inhomogeneous big bang nucleosynthesis”

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(Received 23 February 2006; published 15 March 2007)

The work of Matsuura *et al.* [Phys. Rev. D **72**, 123505 (2005)] claims that heavy nuclei could have been produced in a combined p - and r -process in very high baryon density regions of an inhomogeneous big bang. However, they do not account for observational constraints and previous studies which show that such high baryon density regions did not significantly contribute to big bang abundances.

DOI: [10.1103/PhysRevD.75.068301](https://doi.org/10.1103/PhysRevD.75.068301)

PACS numbers: 26.35.+c, 13.60.Rj, 98.80.Ft

The recent paper by Matsuura, Fujimoto, Nishimura, Hashimoto, and Sato [1] (hereafter referred to as MFNHS) presents reaction network calculations of big bang nucleosynthesis (BBN) for baryon-to-photon ratios $\eta = n_b/n_\gamma \leq 10^{-2}$, far exceeding the commonly adopted value of $\eta \approx 6 \times 10^{-10}$. They argue that their study can be motivated by supersymmetric models which may allow the creation of bubbles with very high baryon density, approaching $\eta = 1$. They find that heavy elements, including p -nuclei, are synthesized in such scenarios with high η .

In their studies, MFNHS neglect baryon diffusion. They motivate this by stating that their aim is to study BBN in the high-density regions created by supersymmetric baryogenesis and not to make a precise adjustment between BBN and the measured Cosmic Microwave Background Radiation (CMBR). Furthermore, they state that they just assume that the high-density bubbles are large enough to neglect diffusion but not so large as to contradict CMBR observations.

In MFNHS it is claimed that, in order to compare the results with observations, model-dependent dynamical mixing has to be invoked. However, it is possible to make a first check of the feasibility of the BBN model by a simple back-of-the-envelope calculation. Even without considering details in the shape of the bubbles, a simple estimate on the required properties of the bubbles can easily be made by using the volume fraction f_v occupied by the high-density bubbles and the density contrast $R = n_b^{\text{hi}}/n_b^{\text{lo}}$ between regions of high and low density. The volume fraction f_v can only assume values in the range $0 \leq f_v \leq 1$. When computing the BBN yields, one has to average both density regions, leading to

$$\bar{X}_i \propto f_v R X_i^{\text{hi}} + (1 - f_v) X_i^{\text{lo}}, \quad (1)$$

with X_i being the produced mass fraction of nucleus i . This approach was already introduced and used in [2–4].

Assuming a given value of the Hubble parameter, the η values can be translated into a ratio of the baryon density ρ_b to the critical density ρ_c , $\Omega_b = \rho_b/\rho_c$. The following relations are obtained immediately:

$$\Omega_b = \bar{\Omega}_b = f_v \Omega_b^{\text{hi}} + (1 - f_v) \Omega_b^{\text{lo}}, \quad (2)$$

$$\Omega_b^{\text{hi}} = \frac{R \Omega_b}{f_v (R - 1) + 1}, \quad (3)$$

$$\Omega_b^{\text{lo}} = \frac{\Omega_b^{\text{hi}}}{R}. \quad (4)$$

The dependence of the density contrast R on the volume fractions f_v

$$R(f_v) = \frac{\Omega_b^{\text{hi}}(1 - f_v)}{\Omega_b - \Omega_b^{\text{hi}} f_v} \quad (5)$$

can easily be derived from the above, yielding positive values of R only for

$$\Omega_b^{\text{hi}} f_v < \Omega_b. \quad (6)$$

Table I shows Ω_b^{hi} , the upper limit of the volume fraction f_v^{max} , and the lower limit of the density contrast R^{min} for several values of η used in MFNHS. The value of Ω_b^{hi} was computed assuming that $\eta = 6 \times 10^{-10}$ corresponds to the standard BBN value of $\Omega_b \approx 0.05$. It is immediately obvious that the high-density regions can only occupy a tiny fraction $0 < f_v < f_v^{\text{max}}$ of the available space when requiring the average Ω_b to remain close to the standard BBN value. From Eq. (5) it can be seen that the corresponding density ratio range is $R^{\text{min}} = \Omega_b^{\text{hi}}/\Omega_b \approx 20 \Omega_b^{\text{hi}} < R < \infty$. It has to be noted that, although the values shown in Table I were derived assuming the standard value of $\Omega_b = 0.05$, the numbers will not change significantly even when, e.g., using the permitted maximal value $\Omega_b = 0.3$ (this would imply, of course, that there is no dark matter component in the Universe).

TABLE I. Upper limits of the volume fraction f_v^{max} and lower limits for the density contrast R^{min} for several values of η and Ω_b^{hi} , respectively, (see text for details).

η	Ω_b^{hi}	f_v^{max} ($R = \infty$)	R^{min} ($f_v = 0$)
10^{-6}	83.3	6×10^{-4}	1.67×10^3
10^{-4}	8333.3	6×10^{-6}	1.67×10^5
10^{-3}	83333.3	6×10^{-7}	1.67×10^6

Two conclusions can be drawn from this simple estimate. First, the fact that the volume fraction of the high-density regions is so tiny renders the assumption untenable that diffusion effects can be neglected. Second, it becomes doubtful whether the observed light element abundances can be reproduced in such a model. Since no values for the light element abundances are given in MFNHS, one has to resort to previous works. Fuller, Mathews, and Alcock [3] have studied the BBN of light elements in detail as a function of f_v and R in proton- as well as neutron-rich zones. They find the best agreement with primordial light element abundances for $f_v R \approx 10$ and moderate values of f_v and R . For example, it can be seen in Fig. 10 of [3] that the abundances resulting for $f_v < 0.2$ strongly deviate from the observed primordial abundances. Both $f_v R = 10$ and $f_v > 0.2$ cannot be achieved simultaneously in the high-density scenarios of MFNHS.

Furthermore, Fig. 12 of [3] shows the limits on the R - Ω_b parameter space, due to the observed abundances of ${}^7\text{Li}$ and ${}^2\text{H}$. It can be seen that $\Omega_b \gtrsim 0.1$ and $R \gtrsim 8$ are ruled out. These limits do not change significantly when using more modern observational constraints. Similar conclusions were found in Ref. [4]. Contrary to what is stated in MFNHS, nucleosynthesis in both proton-rich zones and neutron-rich zones (created by diffusion) were studied in the latter work. Although the main idea was to produce heavy elements in the neutron-rich regions, it turned out that this could not be achieved because of the limitation on η from the light element nucleosynthesis in the high-

density, proton-rich bubbles when compared to observation, even when trying to establish $\Omega_b = 1$. Similar limitations on η should apply for the calculations of MFNHS.

In order to compare to observational constraints, the nucleosynthesis products of the high- and low-density regions have to be mixed according to Eq. (1). The only indication as to how the light element abundances relate to the heavy element ones can be found in Fig. 7 of MFNHS. Trying to find a mix reproducing the heavy element abundances on the level of the ones found in metal-poor stars or old galaxies will invariably lead to a destruction of any agreement in the light element abundances because the incompatible light element production in the high-density regions will dominate the total abundances \bar{X}_i . On the other hand, attempting to find light element abundances compatible with observational constraints will lead to the result that the contribution of the high-density bubbles is negligible [$f_v R \ll (1 - f_v)$]. A more quantitative statement is not possible because the calculated light element abundances are not quoted in MFNHS.

Finally, it should be noted that there are models of very heavy population III stars which can account for early reionization and abundance patterns in extremely metal-poor stars without the need of a modified BBN, e.g. [5–7].

Summarizing, while it is still possible that density fluctuations are introduced into the Early Universe by some mechanism, it has already been shown in the past that such fluctuations can, if any, only have very limited impact on BBN. Similar constraints apply to the work of MFNHS.

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