Primordial Heavy Element Production

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A number of possible mechanisms have been suggested to generate density inhomogeneities in the early Universe which could survive until the onset of primordial nucleosynthesis [1]. We studied the effect of such inhomogeneities on primordial nucleosynthesis. One of the proposed signatures of inhomogeneity, the synthesis of very heavy elements by neutron capture, was analyzed for varying baryon to photon ratios η and length scales L. A detailed discussion is published in [2].

After weak decoupling the vastly different mean free paths of protons and neutrons create a very proton rich environment in the initially high density regions, whereas the low density regions are almost entirely filled with diffused neutrons. Since the aim of the present investigation was to explore the production of heavy elements we considered only the neutron rich low density zones. However, we included the effects of the diffusion of neutrons into the proton rich zones, using an analytical treatment comparable in accuracy to numerical methods using high resolution grids. The only open parameter in the neutron loss due to diffusion is the comoving length scale L of the inhomogeneities. Small separation lengths between high density zones make the neutron leakage out of the small low density zones most effective.

Our reaction network consists of two parts, one part for light and intermediate nuclei ($Z \leq 36$), being a general nuclear network of 655 nuclei. The second part is an r-process code (including fission) extending up to $Z = 114$ and containing all (6033) nuclei from the line of stability to the neutron-drip line. These two networks were coupled together such that they both ran simultaneously at each time step, and the number of neutrons produced and captured was transmitted back and forth between them.

Four sets of calculations have been performed, employing $\eta_{10} = 10^{10}\eta$ values of 416, 104, 52, and 10.4, corresponding to possible choices of (h_{50}, Ω_b) being (2.5,1), (1.3,1), (1,0.8), and (1,0.16). For each of the η-values we considered four different cases of L: (0) ∞ (negligible neutron back diffusion), (1) $10^{7.5}$ cm MeV, (2) $10^{6.5}$ cm MeV, and (3) $10^{5.5}$ cm MeV. (This corresponds to distances between nucleation sites of ∞, 2700, 270, and 27 m, respectively, at the time of the quark-hadron phase transition).

An exponential increase in r-process abundances with increasing η was found. This is due to "fission cycling", whereby each of the fission fragments can form a fissionable nucleus again by neutron captures. This is of particular importance in environments with a long duration of high neutron densities. In an r-process with fission cycling the production of heavy nuclei is not limited to the r-process flow coming from light nuclei but requires only a small amount of fissionable nuclei to be produced initially. The total mass fraction of heavy nuclei is doubled with each fission cycle and can thus be written as $X_r = 2^n X_{seed}$, with the total number of cycles $n = n(\eta)$, and X_{seed} denoting the initial mass fraction of heavy nuclei.

Since the formation of heavy elements beyond Fe and Kr is a very sensitive measure of η it can be used to provide an independent upper limit for the product $\Omega_b H_0^2$. However, it was found that the tightest constraints are still given by the light elements including Li, Be, and B, for which the conditions cannot differ much from the standard big bang.

To study the influence of uncertainties in the reaction rates some test calculations were performed with a variation of the ^{8}Li$(\alpha,n)^{11}$B rate. Recent experiments [3] seem to suggest that the rate used in our calculations [4] has to be increased by a factor of 3. Since the Li-rate is only affecting the seed abundances X_{seed}, only a linear dependence of the resulting r-process abundances was found. The same is true for the ^{18}O$(n,\gamma)^{19}$O rate which was changed by a factor of 10 in a recent investigation [5]. The total change in heavy element abundances is a factor of 30. However, this underlines that not all reactions of importance are fully explored, yet, and future changes can be expected.

Provided that density fluctuations exist with large length scales compared to the neutron diffusion length, the limits for η_{10} or $\Omega_b h_{50}^2$ change to 104 and 1.6, respectively, at which heavy element abundances are produced in inhomogeneous big bang models at a level comparable to the ones seen at lowest observable metallicities. This reduces the difference between the constraints from light and heavy elements, although the light element constraint is still tighter.

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References

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