Primordial Heavy Element Production

T. Rauscher ¹, F.-K. Thielemann ²

¹Institut für Kernchemie, Universität Mainz, D-55099 Mainz, Germany
²Institut für theoretische Physik, Universität Basel, CH-4046 Basel, Switzerland

Introduction

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 (Malaney and Mathews 1993). In this work we are not concerned with how the inhomogeneities were generated but we want to focus on 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 (Rauscher et al. 1994b). Preliminary results can be found in (Thielemann et al. 1991; Rauscher et al. 1994a).

Method

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. High density, proton rich, environments might produce some intermediate elements via the triple-alpha-reaction but will in no case be able to produce heavy elements beyond iron. However, we included the effects of the diffusion of neutrons into the proton rich zones. Using a similar approach as introduced in (Applegate 1988; Applegate et al. 1988), the neutron diffusive loss rate κ is given by

$$\kappa = \frac{4.2 \times 10^4}{(d/a)_{\text{cmMeV}}} T_9^{5/4}(1 + 0.716 T_9)^{1/2} \text{s}^{-1}$$

(1)

in the temperature range $0.2 < T_9 < 1$. We want to emphasize that this analytical treatment is comparable in accuracy to numerical methods using high
resolution grids. Thus, the only open parameter in the neutron loss due to diffusion is the comoving length scale of inhomogeneities \((d/a)\). Small separation lengths between high density zones make the neutron leakage out of the small low density zones most effective. Large separation lengths make it negligible. (For a detailed derivation of (1), see also Rauscher et al. 1994b).

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 (see also Cowan et al. 1983). 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. (For details of the included rates and new rate determinations see Rauscher et al. 1994b).

**Results and Discussion**

The most favorable condition for heavy element formation is an initial neutron abundance of \(X_n = 1\) (i.e. only neutrons) in the low density region, leading to a density ratio \(\rho_{\text{low}}/\rho_0 = 1/8\) (Rauscher et al. 1994b). This leaves as open parameters the baryon to photon ratio \(\eta = n_b/n_\gamma = 10^{-10}\eta_{10}\) and the comoving length scale \((d/a)\). Four sets of calculations have been performed, employing \(\eta_{10}\) values of 416, 104, 52, and 10.4. Using the relation (Börner 1988)

\[
\Omega_b h_{50}^2 = 1.54 \times 10^{-2}(T_{\gamma o}/2.78\text{K})^3\eta_{10}^{1/2},
\]

with the present temperature of the microwave background \(T_{\gamma o}\) and the Hubble constant \(H_o = h_{50} \times 50\text{km s}^{-1}\text{Mpc}^{-1}\), this corresponds to possible choices of \((h_{50}, \Omega_b)\) being \((2.5,1)\), \((1.3,1)\), \((1.0,8)\), and \((1.0,16)\). The range covered in \(\eta_{10}\) extends from roughly a factor of 2.2 below the lower limit to a factor of 13 above the upper limit for \(\eta\) in the standard big bang. For each of the \(\eta\)-values we considered four different cases of \(d/a\): (0) \(\infty\) (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 \(\infty\), 2700, 270, and 27 m, respectively, at the time of the quark-hadron phase transition).

An exponential increase in r-process abundances with increasing \(\eta\) 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 \(X_t = 2^n X_{\text{seed}}\), with \(X_{\text{seed}}\) denoting the initial mass fraction of heavy nuclei. The cycle number \(n\) is decreasing with decreasing neutron number density \(n_n\) (and increasing temperature \(T\)) because
the reaction flux experiences longer half-lives when the r-process path is moving closer to stability.

Since the formation of heavy elements beyond Fe and Kr is a very sensitive measure of \( \eta \) it can be used to provide an independent upper limit for the product \( \Omega_b H_0^2 \). Figure 1 shows observational (upper) limit on possible primordial heavy element abundances (Cowan et al. 1991; Beers et al. 1992; Mathews et al. 1992) compared to our results. Also shown are the limits for \( \Omega_b H_0^2 \) from comparison of observed (Meyer et al. 1991; Kurki-Suonio et al. 1990; Ryan et al. 1992; Duncan et al. 1992) and calculated light element abundances. The tightest constraints are given by the light elements including Li, Be, and B (however, see recent doubts on the primordial \(^7\)Li abundance in (Deliyannis et al. 1993)) 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 (Mao et al. 1994) seem to suggest that the rate used in our calculations (Rauscher et al. 1992) has to be increased by a factor of 3. Since the Li-rate is only affecting the seed abundances \( X_{\text{seed}} \), only a linear dependence of the resulting r-process abundances \( (X_r = 2^n X_{\text{seed}}) \) 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 (Beer et al. 1994). The total change in heavy element abundances by a factor of 30 is also shown in Fig. 1. 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 \( \eta_0 \) or \( \Omega_b H_0^2 \) 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.

Acknowledgement: TR is an Alexander von Humboldt fellow.

References

Applegate, J.H. (1988): Phys. Rep. 163 141
Applegate, J.H., Hogan, C.J., Scherrer, R.J. (1988): Ap. J. 329 572
Beer, H., Käppeler, F., Wiescher, M. (1994): in Capture Gamma-Ray Spectroscopy, ed. by J. Kern (IOP, Bristol), p. 756
Beers, T., Preston, G.W., Shectman, S.A. (1992): Astron. J. 103 1987
Börner, G. (1988): The Early Universe (Springer, New York)
Cowan, J.J., Cameron, A.G.W., Truran, J.W. (1983): Ap. J. 265 429
Cowan, J.J., Thielemann, F.-K., Truran, J.W. (1991): Phys. Rep. 208 267
Deliyannis, C.P., Pinsonneault, M.H., Duncan, D.K. (1993): Ap. J. 414 740
Duncan, D.K., Lambert, D.L., Lemke, D. (1992): Ap. J. 401 584
Kurki-Suonio, H., Matzner, R.A., Olive, K.A., Schramm, D.N. (1990): Ap. J. 353 406
Malaney, R.A., Mathews, G.J. (1993): Phys. Rep. 229 145
Mao, Z.Q., Vogelaar, R.B., Champagne, A.E., Blackmon, J.C., Das, R.K., Hahn, K.I., Yuan, J. (1994): Nucl. Phys. A567 125
Fig. 1. Limits on $\Omega_b h^2$ from light and heavy element abundances. Shown are the results for cases 0 (full sq.), 1 (crosses), 2 (open sq.), and case 0 with enhanced rates (dotted). (The lines are drawn to guide the eye). The limits resulting from the calculated values for the light elements are given by the vertical lines. (See text)