Astrophysical conditions for an r-process in the high-entropy bubble scenario

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A brief summary of the high-entropy bubble scenario is as follows. During the final stages of the evolution of a massive ($8-25\,M_\odot$) star, an "iron" core forms in its central region and subsequently undergoes gravitational collapse. When the central density reaches nuclear matter density, the collapse stops abruptly to cause a "core bounce". A shock wave is created and starts to propagate outward. According to hydrodynamical calculations [1], this shock wave loses its entire kinetic energy within a few milliseconds to stall well inside the outer edge of the initial iron core, and no immediate disruption (a "prompt" explosion) of the star occurs. On a timescale from several tens of milliseconds to about half a second, the neutrinos streaming out from the new-born neutron star can deposit energy behind the standing accretion shock at a rate high enough to revive its outward motion and initiate the final explosion of the star. This is the neutrino-driven "delayed" explosion mechanism originally suggested by Wilson [2].

We have started our network calculations after the total photodisintegration of the matter above the nascent neutron star at $9\,T_9$ with protons (p) and neutrons (n). The $n-$to$-p$-ratio is $Y_e = X_p = 1 - X_n$ with X_p and X_n being the mass fractions of protons and neutrons. Using the charged particle network of F.-K. Thielemann and the r-process code of C. Freiburghaus, combined with recent β-decay and neutron-capture rates, we were able to perform a detailed study of the α-process and of the subsequent r-process. Using the three parameters V_{exp} (expansion speed of the shock wave), S (entropy of the bubble) and Y_e, we could show that the above parameters have to fulfill specific conditions in order to make a subsequent r-process. According to hydrodynamical simulations the most realistic value for V_{exp} is 4500 Km/s, and $0.40 \leq Y_e \leq 0.43$. The calculated entropies are represented in the following table:

V_{exp} (km/s)	Y_e	Entropy (k_B/Baryon)	$\frac{Y_n}{Y_{seed}}$
4500	0.43	$80 \leq S \leq 335$	$1 \leq \ldots \leq 162$
	0.41	$60 \leq S \leq 320$	$1 \leq \ldots \leq 168$
	0.39	$30 \leq S \leq 305$	$1 \leq \ldots \leq 174$

Considering a large grid of expansion speeds between 4500 km/s and 50000 km/s, we find that in fact there is a relation between the three parameters wich can be written as: $\frac{Y_n}{Y_{seed}} = k_{SN} V_{exp} \left(\frac{S}{Y_e}\right)^3, \quad k_{SN} \approx 8,05835 \times 10^{-11}$.

With this simple formula we can determine the strength of an r-process only by knowing the three parameters. We can determine, for example, for any V_{exp} and Y_e the entropy ranges which can build the A=130 or A=190 solar r-abundance ($N_{r,\odot}$) peaks, etc. Another interesting result is, that for the seed nuclei after an α-rich freezeout one always obtains a very similar shape, and only the amount of the respective nuclei varies with entropy.

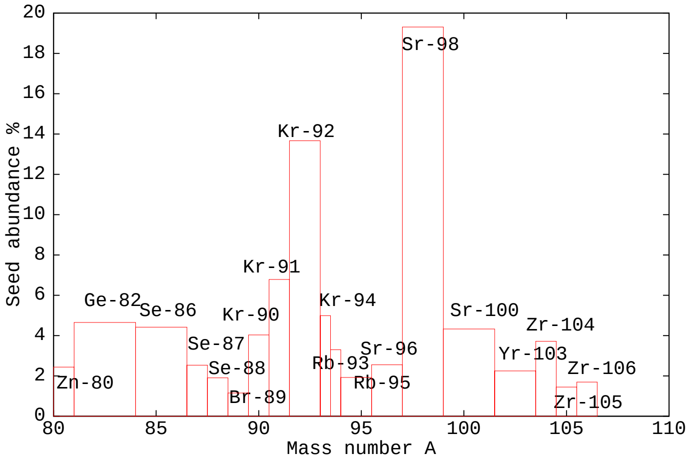

Figure 1: Typical seed nuclei distribution after an α-rich freezeout for $S \approx 200$

With this kind of seed, we were able to run a full r-process for a time duration $\tau = 180\,ms$ with a maximum entropy of 285 $k_B/Baryon$. This is in fact a very "fast" r-process because the seed composition lies already beyond N=50, thus avoiding this bottleneck.

As a first result of a fit to the total $N_{r,\odot}$ distribution, in Fig. 2 we show a superposition of the resulting abundances from only two entropies, using the fit function [3] [4]: $g(S_i) = X_1 e^{X_2 S_i}, \quad i = 1, 2.$

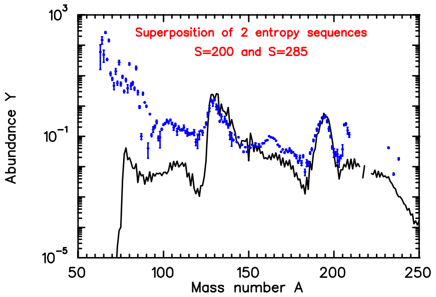

Figure 2: Superposition of abundances from 2 entropies, $S = 200$ and $S = 285$, to reproduce the solar r-abundances beyond $A \simeq 120$

References

[1] Myra & Bludman, 1989, ApJ 340, 384
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[3] Janka et al., 1994, A&A 286, 857
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