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The rapid neutron capture process in an explosive astrophysical environment

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Abstract The rapid neutron capture process (*r*-process) is one of the major nucleosynthesis processes responsible for the production of heavy elements beyond iron Recent models of *r*-process nucleosynthesis rely on a neutrino-heated bubble developing at late times, which provides both the necessary conditions and the requisite amount of ejected mass for the *r*-process Meyer *et al* [1] showed that the hot bubble that forms outside the protoneutron star during a supernovae (SN) explosion may be a viable site for the *r*-process as long as the entropy per baryon can be made sufficiently high But in a very neutron rich environment such as a neutron star, the *r*-process could occur even at low entropy The high entropy wind is not the correct *r*-process site, owing to the inherent deficiencies in the abundance pattern below A=110 as well as the problems in obtaining the high entropies in SN II explosions required for producing the massive r-process nuclei up to A ~ 195 and beyond We have tried to associate the explosion entropies with the site-independent classical approach (n_n and T_9) and thereby compare the results of the two approaches from the abundances at different entropy conditions We find that an entropy of ≈ 300 with $Y_e \approx 0\ 45$ can lead to a successful r-process This is in agreement with the *r*-process abundance peaks at $n_n \approx 10^{32}$ cm^{-3} and $T_9 \approx 1\ 5$

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1. Introduction

The existence and distribution of chemical elements and their isotopes are a consequence of nuclear processes. To attempt to understand the sequence leading to the formation of elements, it is necessary to study the universal abundance curve. The first attempt to construct such an abundance curve was made by Goldschmidt in 1937. An improved curve was given by Brown in 1949 and then by Suess and Urey [2]. These curves are derived mainly from terrestrial, meteoritic and solar data and sometimes from mass

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spectroscopic data. All these tables along with the more recent one by Wapstra *et al* [3] form the basic data for our analysis

If we look at the abundance curve we see that H is the most abundant element followed by He; Li, Be, B are very rare. From C to O the abundance increases – then to Sc, there is a fairly regular downward trend which again increases up to Fe. Beyond Fe there is an almost uniform abundance of all other elements. Thus it is material to attempt to explain the interactions of nuclei of elements and their origin by a synthesis or build-up process starting with one or other or both of the building blocks. The synthesis from H to Fe can be explained by charged particle interactions. But this does not lead to significant nucleosynthesis beyond the iron group as the coulomb barrier becomes very high. So we attempt to study and present here the nucleosynthesis process chiefly the r-process responsible for the production of heavy elements beyond iron. We choose Supernovae as the site for the *r*-process because the Supernovae light curve shows the presence of $_{98}Cf^{254}$ found in nature.

Stars in the mass range 10-30 $M_{\odot}$ evolve to form iron cores of 1.3 to 1.6 $M_{\odot}$. These iron cores collapse according to well known instabilities, photodisintegration and electron capture. As the central density exceeds ~ 10^{10} gm cm^{-3}, electron capture on nucleons and nuclei becomes so fast that the collapse approaches free fall. The collapse is halted as the central density reaches about twice the nuclear –matter density. An outward bound shock wave then forms in the matter that is continuing to fall onto the nearly stationary core. After the shock wave has propagated out to several hundred kilometers, conditions behind the shock at 100 to 200 kms are suitable for neutrino heating. Matter that has fallen into 200 km has just internal energy to dissociate into free nucleons and so is relatively cool after being dissociated. This material can absorb the high energy neutrinos from the accreting core but does not efficiently reemit it since its temperature is low The neutrino heating blows a hot bubble above the proto-neutron star [4].

Meyer *et al.* [1] first calculated the *r*-process under conditions appropriate to a neutrino-heated bubble and found that the solar *r*-process abundances could be replicated. They showed that the hot bubble that forms outside the protoneutron star during a SN explosion may be a viable site for the *r*-process as long as the entropy per baryon can be made sufficiently high. A high entropy per baryon means that few nucleons reassemble beyond He^4. Those few α-particle that do reassemble into heavier nuclei, can capture many free neutrons, so an *r*-process can occur.

2. Nuclear physics considerations in the R-process path

Our method is aimed at comparing the net results of *r*-processing under the different astrophysical conditions of high and low entropies, but with necessarily the same nuclear data. For our purposes, such evolution occurs as the temperature falls from ~ 10^{10} to 10^9 K. Beginning at about 10^{10} K, nuclear statistical equilibrium favors the assemblage of nucleons into α-particles and heavy nuclei. As the temperature drops below about 5×10^9 K, the reactions responsible for converting α-particles back into heavy nuclei begin fall out of equilibrium. By 3×10^9 K, charged particle reactions freeze out. Below this temperature, the *r*-process occurs until the temperature reaches ~ (1-2) $\times10^9$ K, where the neutron reactions also cease as the neutrons are depleted [4]. From the considerations of neutron capture on neutron magic nucleus which is quite difficult, we find that the Q_n value is most likely somewhere between 2 to 4 MeV.

The condition for dynamical equilibrium between (n,γ) and (γ, n) reactions is expressed as

$$X(A, Z) + n \Leftrightarrow X(A+1, Z) + \gamma + Q_n(A, Z) \quad (1)$$

where $Q_n(A, Z)$ is the neutron binding to nucleus $X(A, Z)$.

Writing $n(A, Z)$ and n_n for the number densities of nuclei (A, Z) and neutrons respectively, the statistical balance in this reaction is expressed by

$$\log (n(A+1,Z)/n(A,Z)) = \log n_n - 34.07 - (3/2)\log T_9 + (5.04/T_9)Q_n \quad (2)$$

Using the condition that in equilibrium $n(A+1, Z) \approx n(A, Z)$ we obtain Q_n as

$$Q_n = (T_9/5.04)(34.07 + (3/2)\log T_9 - \log n_n). \quad (3)$$

The temperature and density conditions considered here range from

$$T = 1.0 - 2.0 \times 10^9 \text{ K and } n_n = 10^{20} - 10^{30} \text{ cm}^{-3}$$

Variation of Q_n values with respect to temperature and density

N_n	T_9	Q_n	N_n	T_9	Q_n	N_n	T_9	Q_n	N_n	T_9	Q_n
10^{24}	1.0	1 99	10^{26}	1 2	1 95	10^{28}	1 6	2.02	10^{30}	1 8	1 58
10^{24}	1.2	2 40	10^{26}	1 4	2.28	10^{28}	1 8	2 29	10^{30}	2 0	1 79
10^{24}	1.4	2 85	10^{26}	1 6	2 66	10^{28}	2 0	2 58	10^{30}	2 2	2 0
10^{24}	1.6	3.29	10^{26}	1 8	2.99	10^{30}	2 4	2 2	10^{30}	2 6	2 42
10^{24}	1 8	3.73	10^{26}	2.0	3.38	10^{28}	2 2	2 87	10^{30}	2 8	2 63
10^{24}	2 0	4 17	10^{26}	2.2	3.74	10^{28}	2 4	4 11			

In terms of temperature T_9 in units of 10^9 K and density ρ_5 in units of 10^5 gm cm^{-3} we introduce the entropy at this stage as

$$S = 3.34 \times T_9^3/\rho_5 .$$

We consider the determination of $Q_n(A, Z)$ on the basis of smooth Weizsacker atomic mass formula neglecting shell, pairing and quadruple deformation effects :

$$M(A, Z) = (A-Z)M_n + ZM_h - (1/c^2)\left[\alpha A - \beta(A-2Z)^2/A - \gamma A^{2/3} - \varepsilon Z(Z-1)/A^{1/3}\right] \quad (4)$$

M_n and M_h are masses of neutron and proton, α, β, γ and ε are constants in energy units which represent volume, isotopic, surface and coulomb energy parameters respectively.

With this we calculate the neutron binding energy as

$$Q_n\ (A, Z) = B_n(A+1, Z) = c^2 \left(M\ (A, Z) + M_n - M\ (A+1, Z\ )\right) \quad (5)$$

Based on the treatment of Burbidge *et al.* [5] we modify the above expression for $M\ (\ A,\ Z\ )$ as

$$M\ (\ \mathrm{A},\ \mathrm{Z}\ ) = M_w(\ A,\ Z\ ) - (1/c^2)\ (\ (\ f\ (\ N\ ) + g\ (\ N\ )\ ) \quad (6)$$

$M_w(A, Z\ )$ represents the Weizsacker expression given by equation (4).

We now obtain

$$Q_n = f\ (A,Z) + f'(\ A - Z), \text{ using}$$

$$f'(A-Z) = f'(N) = df(N)/dN = f\ (\ A+1,\ Z) - f\ (A,Z)$$

On simplification and on putting $Z = A - N$ we rewrite this equation as

$$Q_n\ (A,\ N) = f\ (A,\ N) + f'(N),$$

$f'(N)$ is the excess neutron binding energy to nuclei with a specified N over that given by the smooth Weizsacker mass formula normalized to zero at the beginning of the shell in which N lies. Using mass tables of Wapstra *et al.* [3] for various N, the resulting average values have been plotted against N. Another form of averaging is then affected by

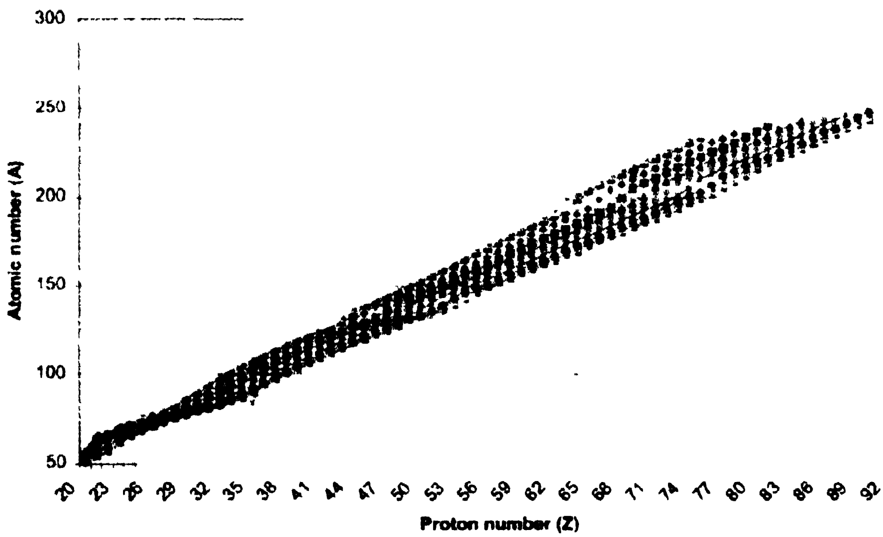

Figure 1. Average *r*-process path used in the calculation.

drawing a smooth curve through the points obtained in this way. By substituting Q_n for different values of T_9 and n_n and reading $f'(N)$ values from N and $f'(N)$ plot, we get equations relating to A and N.

3. Abundance calculation

The charge of the most stable isobar Z_A is given by

$$Z_A = (A/2)\left[1 + (\varepsilon/4\beta)A^{2/3}\right]^{-1}. \tag{7}$$

Then we determine a factor B_A using expression

$$B_A = \left(0.58\, A^{2/3} - 0.78\right)/\left[(A/2) - Z_A\right], \quad \text{for } A \le 150$$

$$B_A = (8\beta/A)\left[1 + (\varepsilon/4\beta)A^{2/3}\right] \quad \text{for A > 150.} \tag{8}$$

The fermi energy term given by Fermi [6] is

$$\delta_A = 67/A^{3/4}. \tag{9}$$

The effective β^- decay energy W_β expressed in MeV is then determined as

$$W_\beta = B_A(Z_A - Z - 2.5) + 0.5 \quad \begin{cases} +0 & \text{odd } A \\ -\delta_A/2 & \text{even } Z, \text{ even } A. \\ +\delta_A/2 & \text{odd } Z, \text{ even } A \end{cases} \tag{10}$$

Then the mean lifetime of a nucleus at the waiting point is calculated as

$$t_{\beta^-} = 10^4 / W_{\beta^-}^5 \tag{11}$$

under the assumption that in a steady state the abundances of elements in the neutron capture path are proportional to β^- decay lifetimes. The abundance of an element is then given by

$$n(A) = const.\left(\tau_{\beta^-}/\Delta A\right) \tag{12}$$

where ΔA is the number of neutrons added to a nucleus.

The computed abundances are then calculated with observed universal abundances taken from Suess and Urey [2] for different values of Q_n, and is shown in Figure 2.

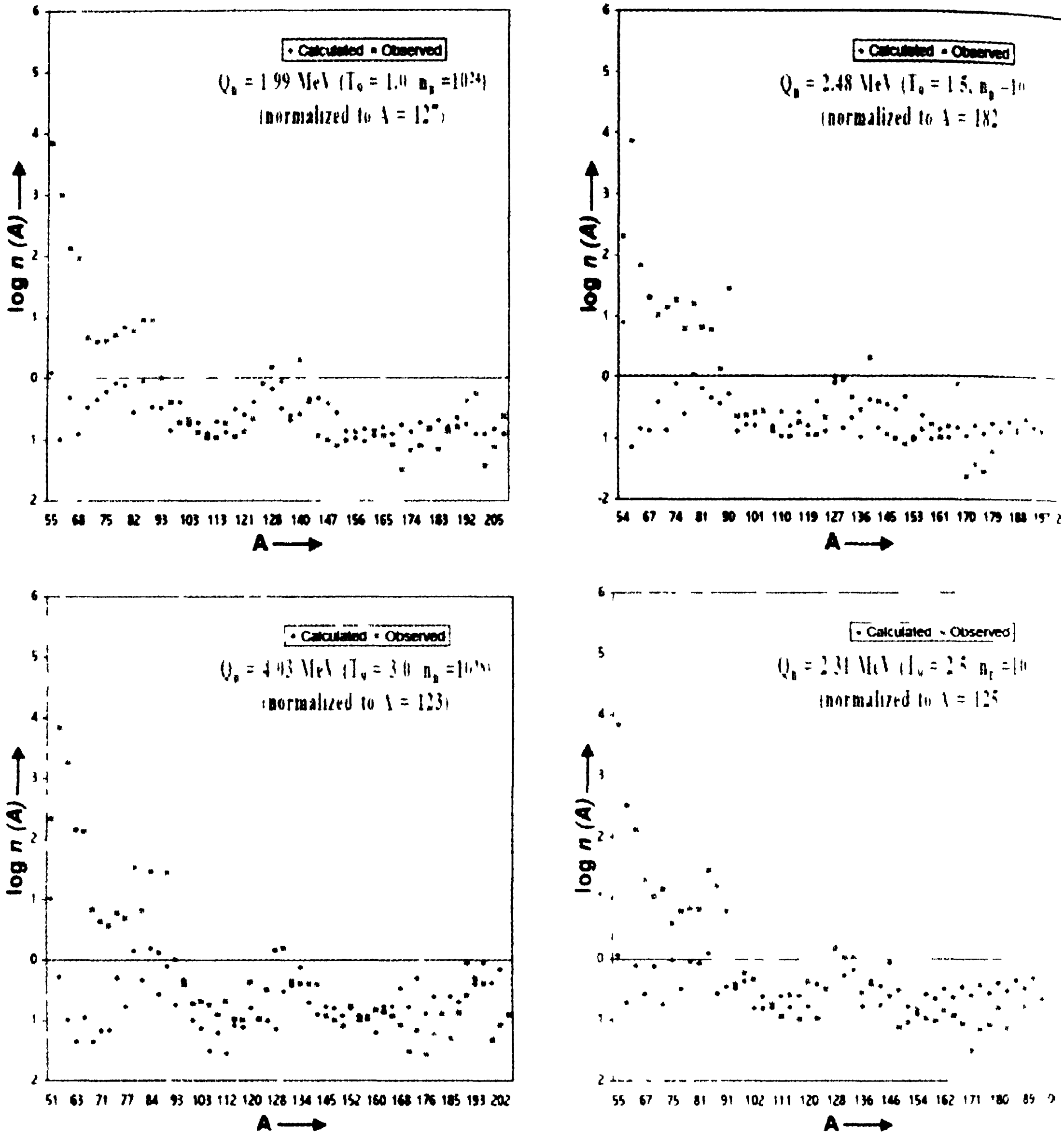

Figure 2. Abundances of nuclei produced in the rapid neutron capture process

4. Results and conclusion

We have studied the r-process isotopic abundances at various temperatures ranging from 1.0 to 2.2 × 10^9 K and neutron number densities ranging from 10^{20} to 10^{32} cm^{-3}. At all these ranges we get appreciable abundance curves comparable to the observed ones We mostly concentrate on our analysis at energies greater than 2 Mev as this is the condition prevailing in the Supernovae envelopes and neutron capture occurs during the later expanding stage. We start our calculation at A ~ 40 which is the possible product of the *p*-process. Most of our abundance curves were found to be significant by a normalization at A=126. We tried to analyze the abundance peaks at all the conditions considered. The calculated peaks were found to correspond the observed ones in most of the curves.

We see that at extreme densities during core collapse we get elements which are not seen in observation. At later expansion/cooling and low density state the elements are produced in the *r*-process chain which is also observed experimentally. We propose that, during iron cores' collapse according to well known instabilities, the elements that are formed instantly undergo photodisintegration and electron capture. Only in the later stage, they undergo neutron capture and correspondingly beta decay to produce the observable elements. For example at $n_n=10^{24}$ and T_9 = 2.0, the chain shows all the isotopes that are observed by Wapstra *et al.* [3]. We conclude that this is one process by which all the heavy elements have been produced. These elements were created during SN explosion and in the later expansion stages they were distributed all over the universe.

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