R-PROCESS NUCLEOSYNTHESIS IN HIGH ENTROPY ENVIRONMENT IN EXPLOSION OF SUPERNOVA TYPE II AND NEUTRON STAR FORMATION

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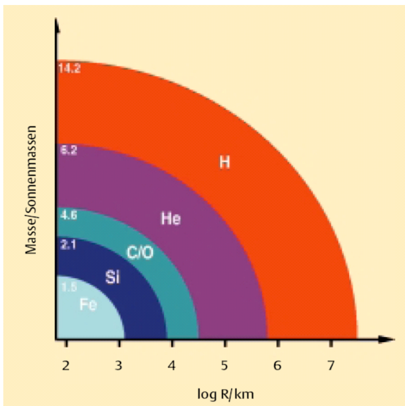
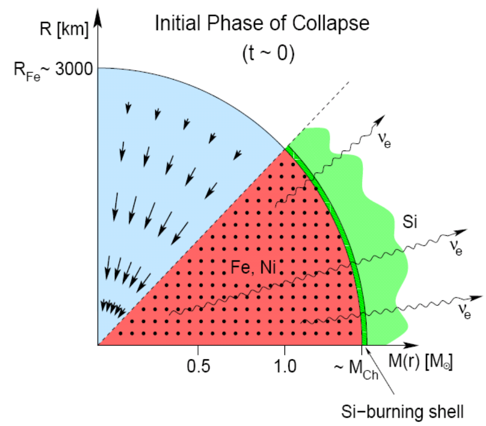
Stars in the mass range 10-30 $M_\odot$ evolve to form iron cores of 1.3 to 1.6 $M_\odot$. These iron cores collapse according to well known instabilities , photodisintegration and electron capture . As the central density exceeds ~ 10^{10} gm cm^{-3} , electron capture on nucleons and nuclei becomes 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. In the neutrino-driven explosion, only a small amount of matter is heated to the requisite high specific energy and entropy.

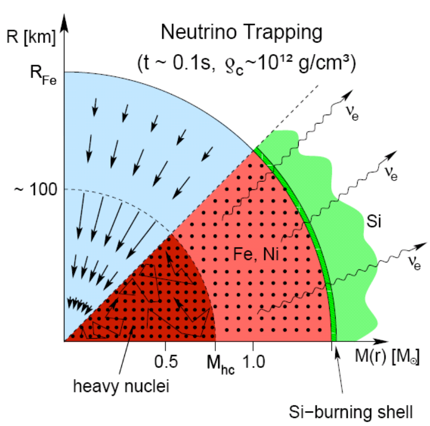
Core collapse mechanism

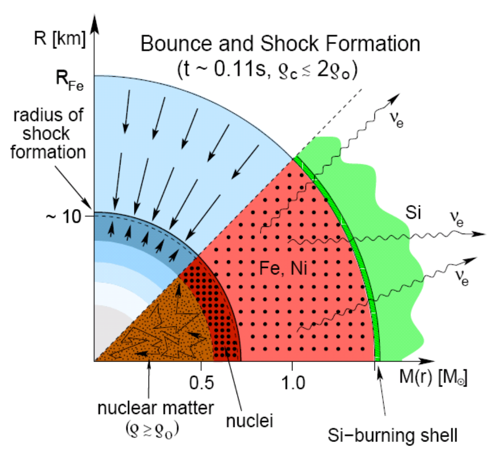
- The beginning of collapse

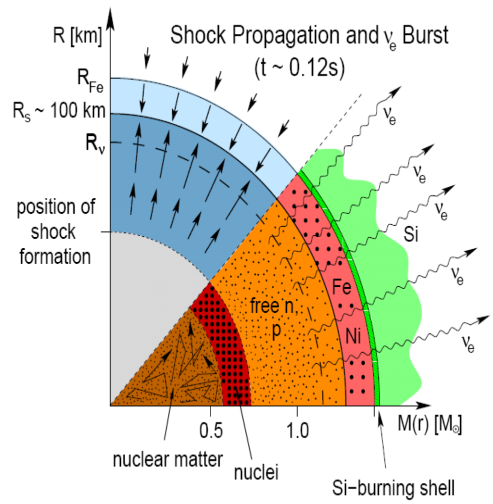


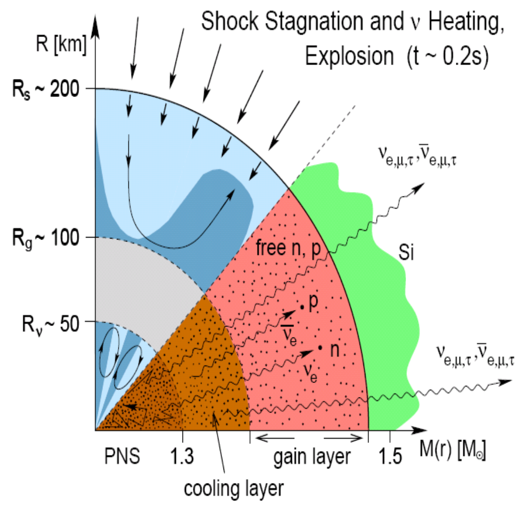


- Core collapse

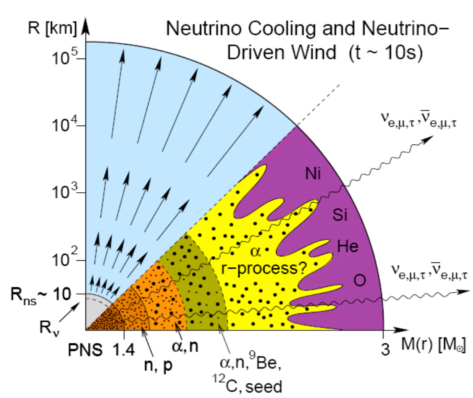





Shock Propagation and ν_e Burst
(t ~ 0.12s)
R [km]
R_{Fe}
R_s ~ 100 km
R_ν
position of shock formation
free n, p
Fe
Ni
Si
ν_e
0.5
1.0
M(r) [$M_\odot$]
nuclear matter
nuclei
Si−burning shell


Shock Stagnation and ν Heating, Explosion (t ~ 0.2s)
R [km]
R_s ~ 200
R_g ~ 100
R_ν ~ 50
free n, p
p
n
$\bar{\nu}_e$
ν_e
Si
$\nu_{e,\mu,\tau}, \bar{\nu}_{e,\mu,\tau}$
PNS
1.3
gain layer
1.5
M(r) [$M_\odot$]
cooling layer

- R-process


Neutrino Cooling and Neutrino−Driven Wind (t ~ 10s)
R [km]
10^5
10^4
10^3
10^2
R_{ns} ~ 10
R_ν
$\nu_{e,\mu,\tau}, \bar{\nu}_{e,\mu,\tau}$
Ni
Si
He
O
α
r−process?
PNS
1.4
n, p
α, n
α, n, ^{9}Be, ^{12}C, seed
3
M(r) [$M_\odot$]

Nuclear Physics Considerations in the R-process Path

We adopt a recent hydrodynamical model of type II supernovae as the realistic site for the r-process ; perform a nucleosynthesis calculation by allowing for a least number of adjustable parameters and compare the global outcome of r-process abundance curve with that of observed one. The particular model we have used is the delayed explosion of massive stars powered by neutrino energy deposition in a hot-bubble . 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 $5x10^{9}$ K, the reactions responsible for converting α-particles back into heavy nuclei begin fall out of equilibrium .
- By $3x10^{9}$ K , charged particle reactions freeze out . Below this temperature, the r-process occurs until the temperature reaches ~ 1-2 x 10^{9} K, where the neutrons also cease as the neutrons are depleted .

Using mass tables of Wapstra et al. (2003) for various N, the resulting average values have been plotted against N. Another form of averaging is then affected by 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.

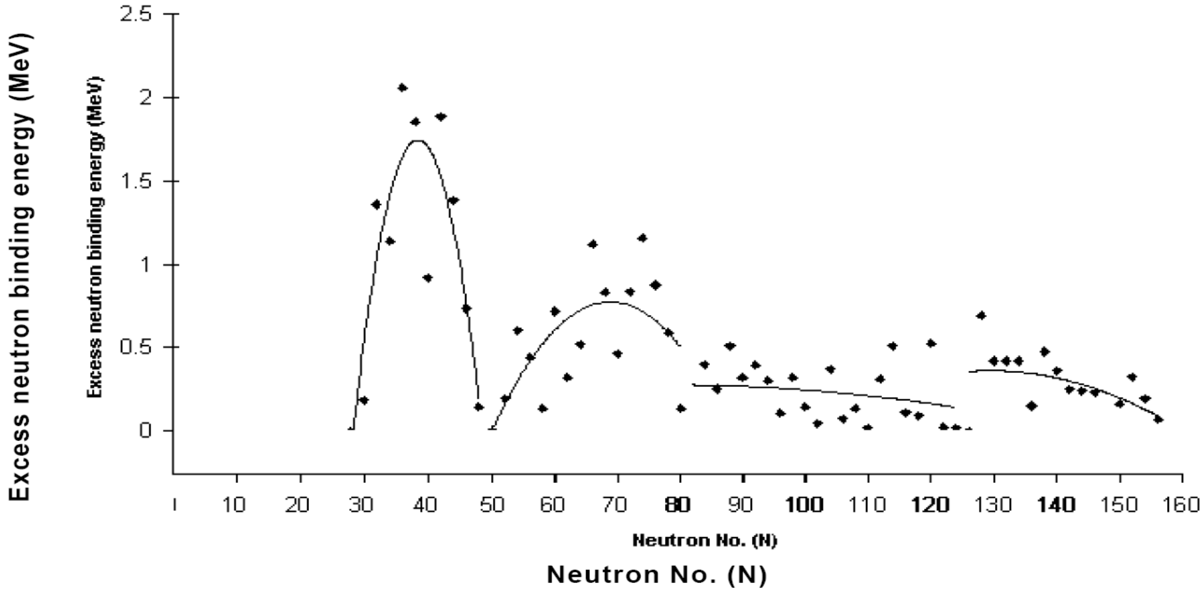


Fig. The average excess neutron binding energy for different N values.

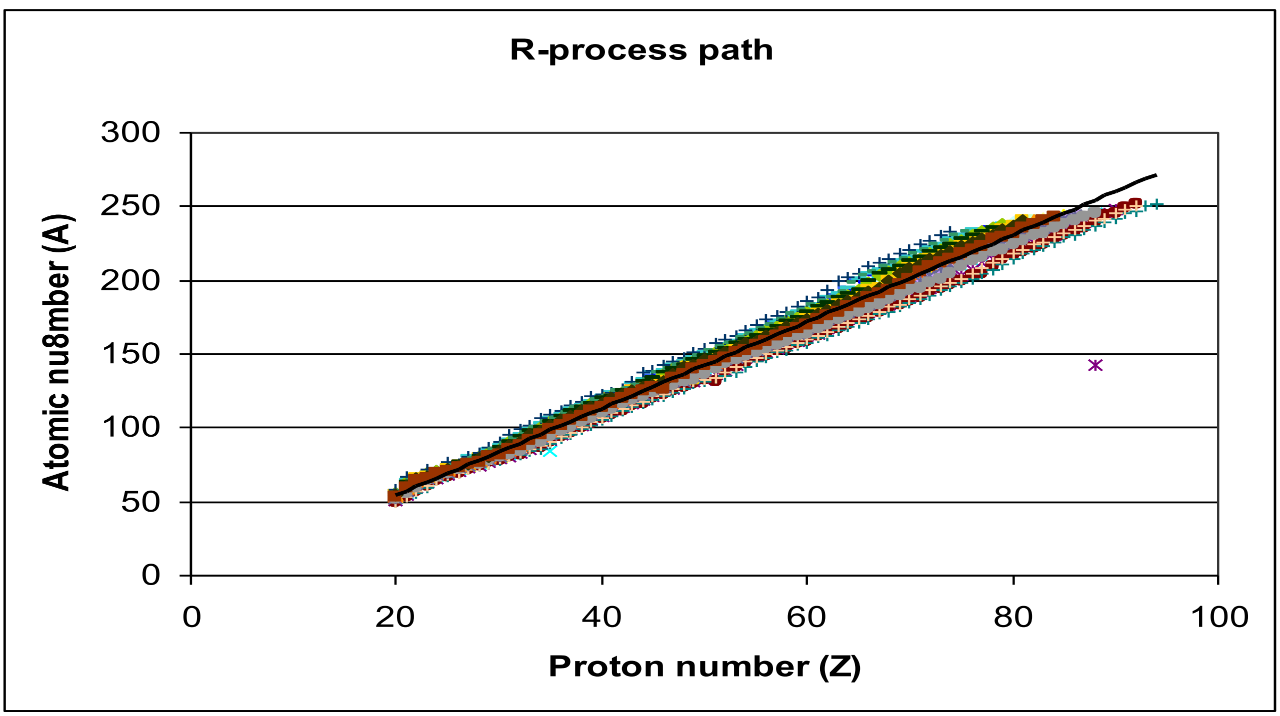


Fig. Average R-process path used in the calculation . The straight line shows the path at which they become stable

Table 1. Variation of Q_n values with temperature and density.

$T_9(10^9K)$	$n_n(cm-3)$	Q_n(Mev)	$T_9(10^9K)$	$n_n(cm-3)$	Q_n(Mev)
1.0	10^{20}	2.79	1.0	10^{22}	2.39
1.2	10^{20}	3.37	1.2	10^{22}	2.90
1.4	10^{20}	3.96	1.4	10^{22}	3.41
1.6	10^{22}	4.56	1.6	10^{22}	3.93
1.0	10^{24}	1.99	1.8	10^{22}	4.45
1.2	10^{24}	2.41	1.2	10^{26}	1.95
1.4	10^{24}	2.85	1.4	10^{26}	2.30
1.6	10^{24}	3.29	1.6	10^{26}	2.65
1.8	10^{24}	3.73	1.8	10^{26}	3.01
2.0	10^{24}	4.17	2.0	10^{26}	3.38
1.6	10^{28}	2.02	2.2	10^{26}	3.74
1.8	10^{28}	2.30	2.4	10^{26}	4.11
2.0	10^{28}	2.58	2.2	10^{30}	1.98
2.2	10^{28}	2.87	2.4	10^{30}	2.19
2.4	10^{28}	3.16	2.6	10^{30}	2.42
2.6	10^{28}	3.45	2.8	10^{30}	2.63
2.8	10^{28}	3.74	3.0	10^{30}	2.84
3.0	10^{28}	4.03			

Table 2. Chemical elements at the r-process site.

Element	$T_9(10^9$ K)	$n_n(cm^{-3})$
$_{56}Ba^{137}$	2.5	10^{20}
$_{82}Pb^{207}$	2.5	10^{22}
$_{92}U^{236}$	3.0	10^{22}
$_{98}Cf^{254}$	1.9	10^{20}

For double magic nuclei,

$_{28}Ni^{78}(50)$	1.0	10^{20}
	1.1	10^{22}
	1.2	10^{24}
	1.4	10^{26}
	2.0	10^{28}
$_{50}Sn^{132}(82)$	1.7	10^{20}
	1.9	10^{22}

Results :

For element formation ►

- We notice an element of mass 273 corresponding to atomic number 115, at temperature 3.0×10^9 K and neutron number density 10^{20} cm^{-3}
- At densities $>10^{30}$ cm^{-3}, the r-process chain does not show the elements as seen in data of Audi *et al.* (2003)
- We find the elements more prominently as we go from high to low density site

- Most of our observed elements are seen in the range of neutron number density 10^{20} cm^{-3} to 10^{24} cm^{-3} and temperature from 2.0×10^{9} K to 3.0×10^{9} K. This high temperature low density condition refers to high entropy environment.

- At density 10^{20} cm^{-3} and temperature $T_9 = 2.0$, that path contains all the elements as was given in the experimental data of Audi *et al.* (2003).

- Some specific elements formed are shown in Table 2.

- An entropy of ≈ 300 with $Y_e \approx 0.45$ can lead to a successful r-process. It produced heavy neutron-rich nuclei with $A \approx 80 - 240$. Later ejecta are neutron-rich ($Ye < 0.5$) and leaves behind a compact neutron star .

Sources :

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