Mechanism of the r-Process and Implications for Its Astrophysical Site

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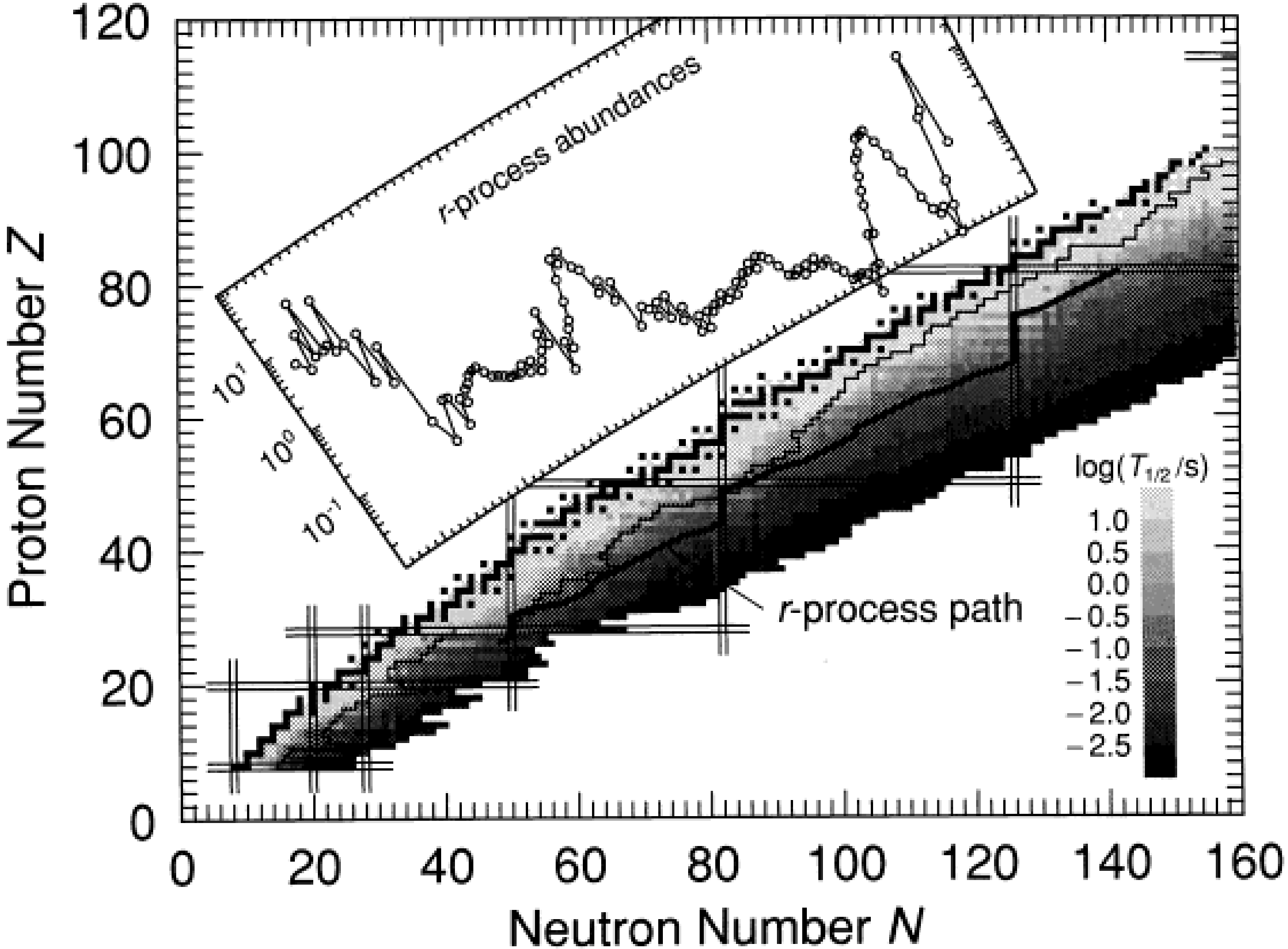
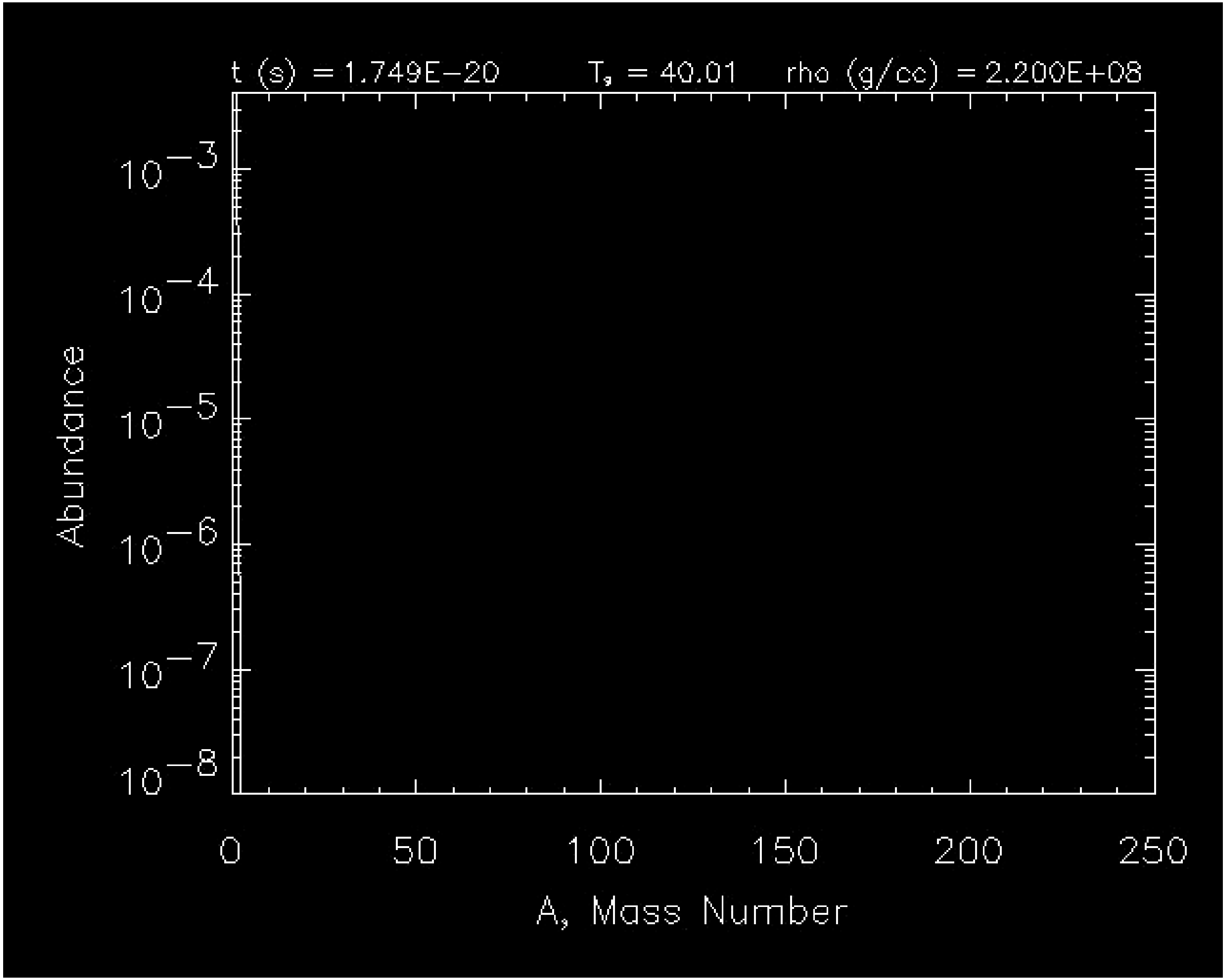
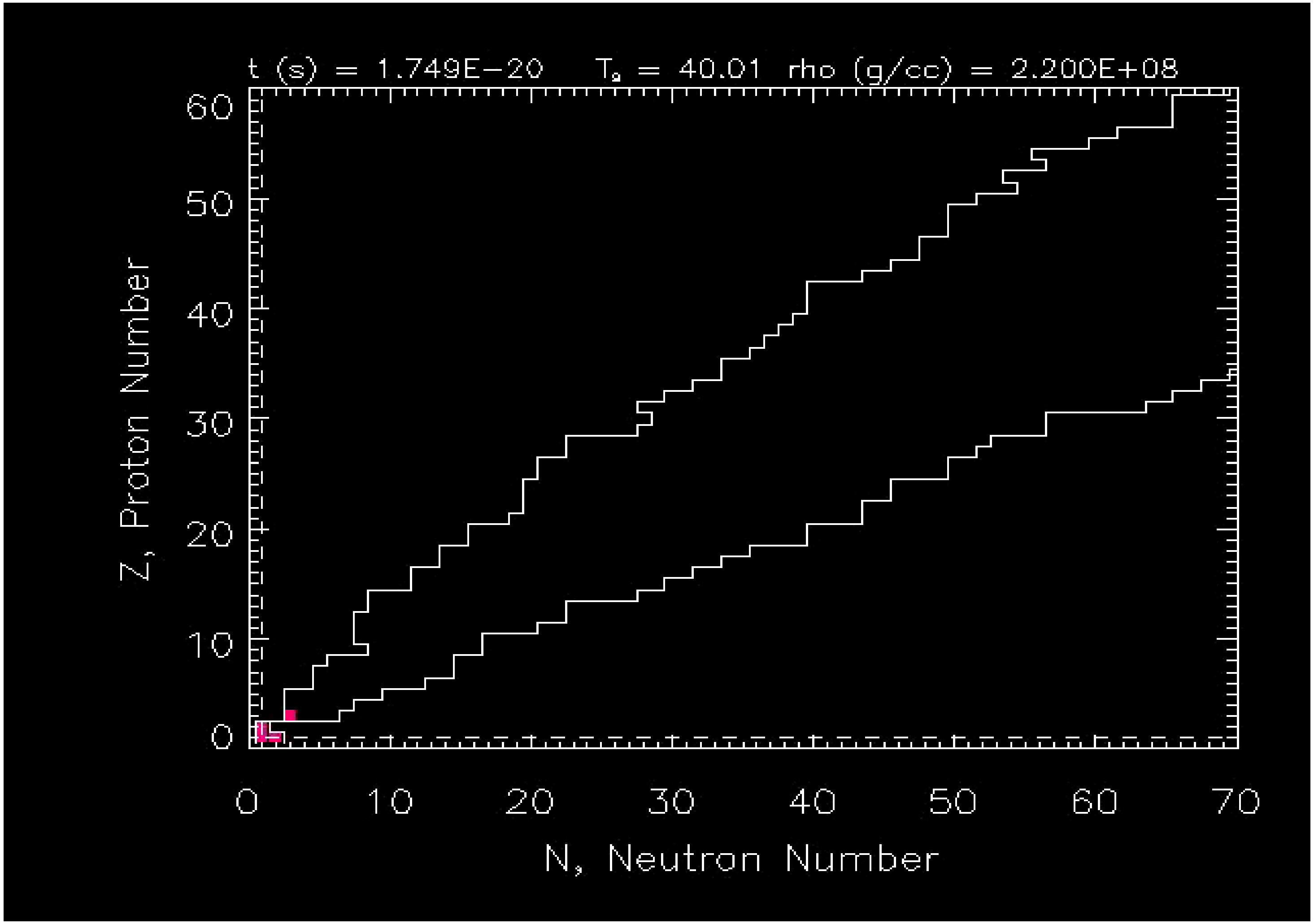


120
100
80
60
40
20
0
Proton Number Z
0
20
40
60
80
100
120
140
160
Neutron Number N
r-process abundances
10^1
10^0
10^-1
r-process path
log(T1/2 /s)
1.0
0.5
0.0
−0.5
−1.0
−1.5
−2.0
−2.5



t (s) = 1.749E−20
T9 = 40.01
rho (g/cc) = 2.200E+08
Abundance
10−3
10−4
10−5
10−6
10−7
10−8
0
50
100
150
200
250
A, Mass Number


t (s) = 1.749E-20 T9 = 40.01 rho (g/cc) = 2.200E+08
Z, Proton Number
N, Neutron Number
0
10
20
30
40
50
60
70

Hierarchy of Statistical Equilibria in Nucleosynthesis

More constraints on system

(0) Equilibrium with nonconstant nucleon number

(1) NSE with weak equilibrium

(2) NSE with fixed Ye

(3) QSE (equilibrium with fixed Ye and Yh)

(4) Two QSE clusters (equilibrium with fixed Ye, Yh1, and Yh2)

(5) Three QSE clusters (equilibrium with fixed Ye, Yh1, Yh2, and Yh3)

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Physically possible equilibria in nucleosynthesis (constant nucleon number)

More disorder in system

Parameters

- Y_e :
  - net number of electrons per nucleon
  - fraction of all nucleons that are protons
  - E.g., $Y_e = 0.5$ means equal numbers of neuetron and protons. $Y_e = 0$ means all neutrons. $Y_e=1$ means all protons.

Parameters (cont.)

- Entropy per nucleon (or ~number photons/nucleon)
  - Degrees of freedom per nucleon
  - In units of Boltzmann's constant k_B
  - E.g., all free nucleons: s/k_B = about 3
  - E.g., all nucleons in ^{56}Fe: s/k_B about 3/56
  - $s/k_B > 20$ typically means a lot of photons and electron-positron pairs around.

Parameters (cont.)

- Timescale τ:
  - Density expansion efolding timescale
  - Typically milliseconds to seconds

The Key for a Successful r-Process

- Get enough neutrons per seed nucleus (roughly 100 / seed).
- Where are the protons at the time the r-process begins? Assume protons in one heavy seed species h and in some other species o:

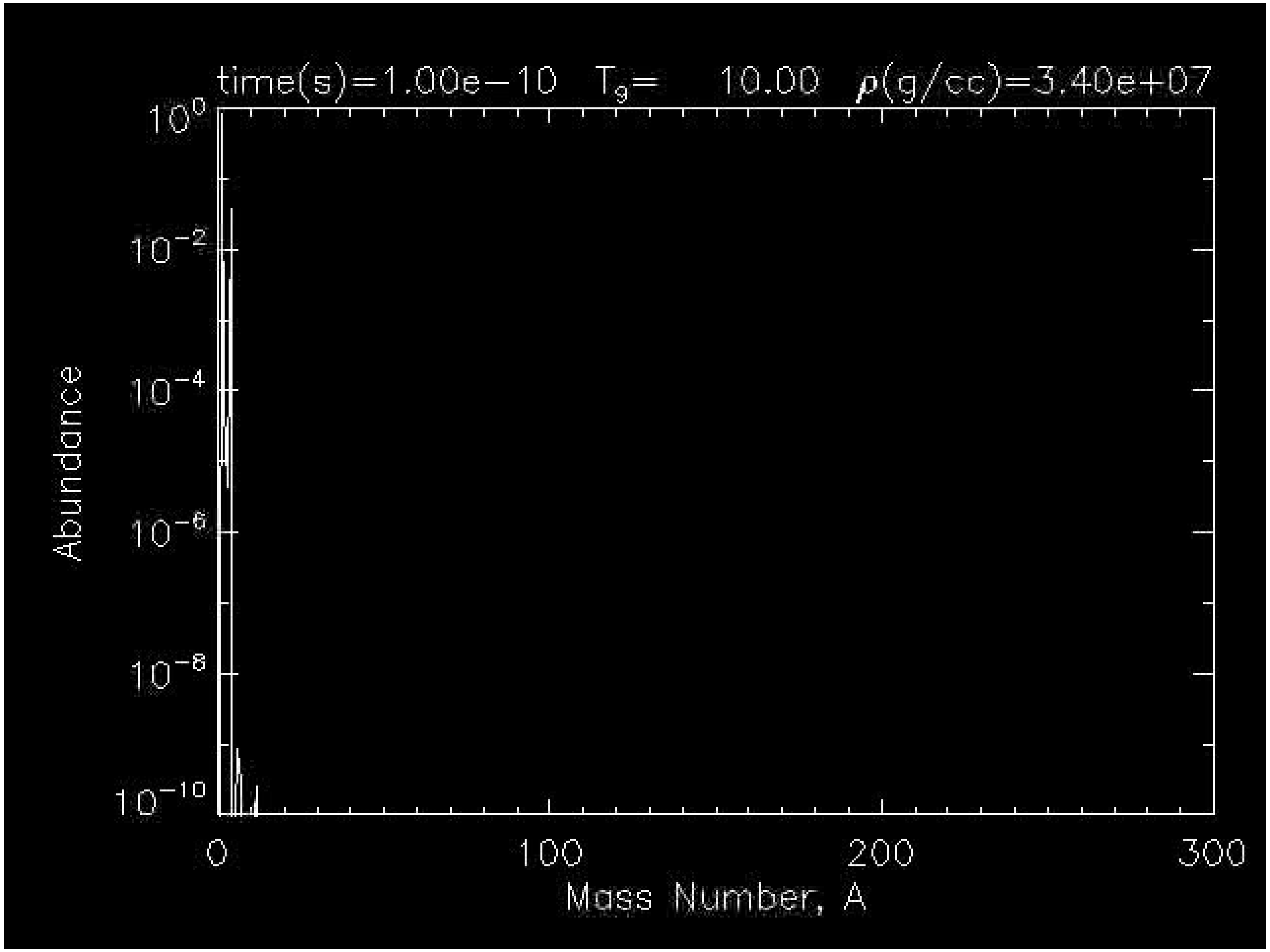
$$Y_e = \left[\frac{Z_0}{A_0} - \frac{Z_h}{A_h + 100} \right] X_0 + \frac{Z_h}{A_h + 100}$$

Three Broad Regimes

- Low entropy (s/k~1-10): all protons in heavy seed nuclei:
  - $X_0=0$
  - $Z_h\sim30$, $A_h\sim100 \Rightarrow Y_e\sim0.1\text{-}0.2$
  - Core material in supernovae, decompressing neutron star matter
- High entropy (s/k ~100, $\tau\sim0.1$ s): protons in heavy nuclei and alpha particles:
  - $X_0=0.5$ ($Z_0=2$, $A_0=4$)
  - $Z_h\sim40$, $A_h\sim100 \Rightarrow Y_e\sim0.35$
  - Neutrino-energized ejecta in supernovae
- High entropy, fast expansion (BBN regime!): protons mostly free, but some in heavy nuclei (s/k~100, $\tau\sim1$ ms):
  - $X_0 = 0.495$ ($Z_0=1$, $A_0=1$)
  - $Z_h\sim50$, $A_h\sim120 \Rightarrow Y_e\sim0.5$
  - Fallback ejected matter in supernova, shocked surface layers of O/Ne/Mg cores

Low-entropy

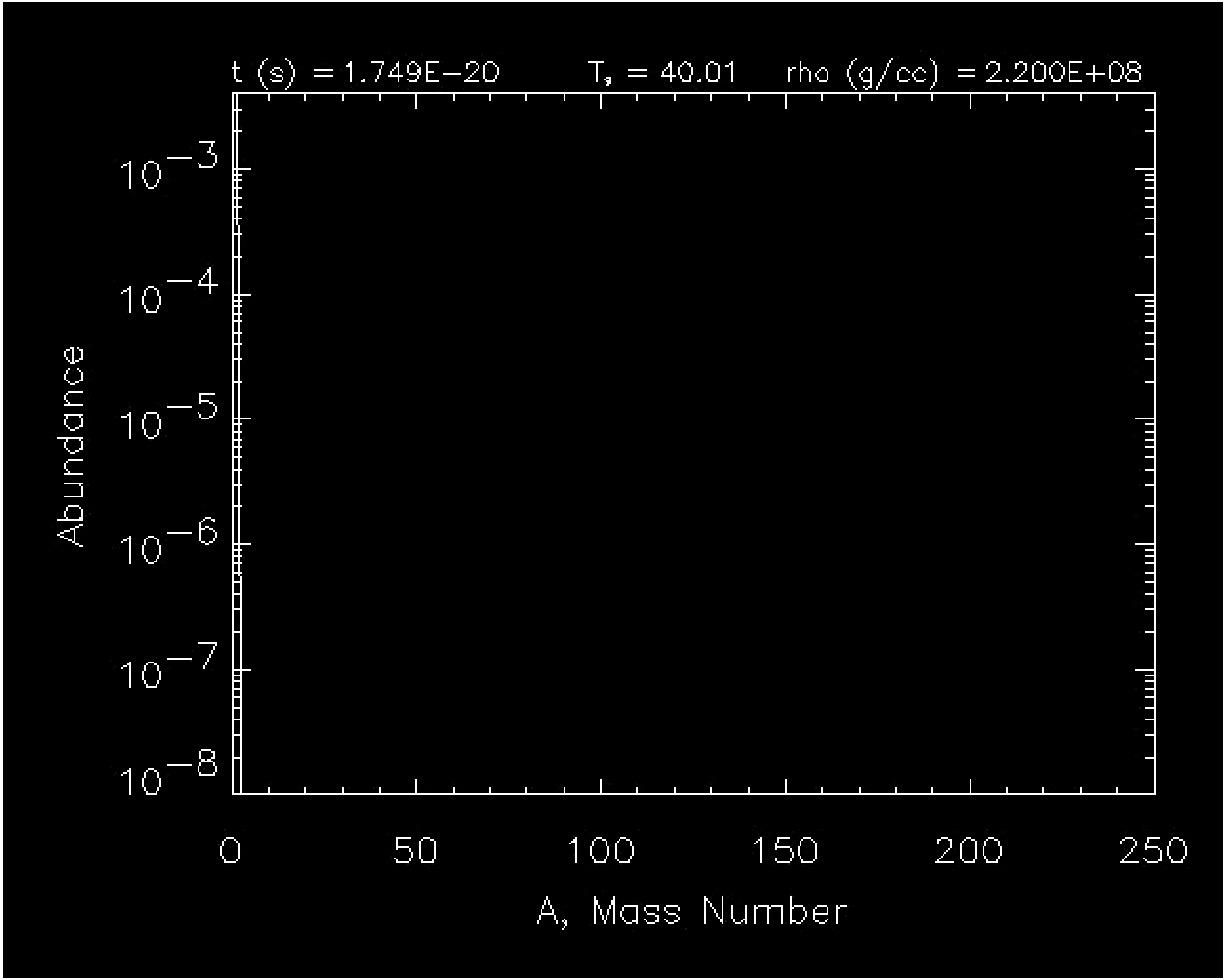
- Typical Y_e = 0.1-0.2
- Sites: ejection of neutron-rich supernova core matter, decompression of neutron star matter
- Neutrons produced by electron capture ➔ very high density
- Experimental issues: electron-capture rates, properties of neutron-rich nuclei
- Typical problem: ejection of too much matter



time(s)=1.00e−10 T9= 10.00 ρ(g/cc)=3.40e+07
Abundance
10^0
10^-2
10^-4
10^-6
10^-8
10^-10
0
100
200
300
Mass Number, A

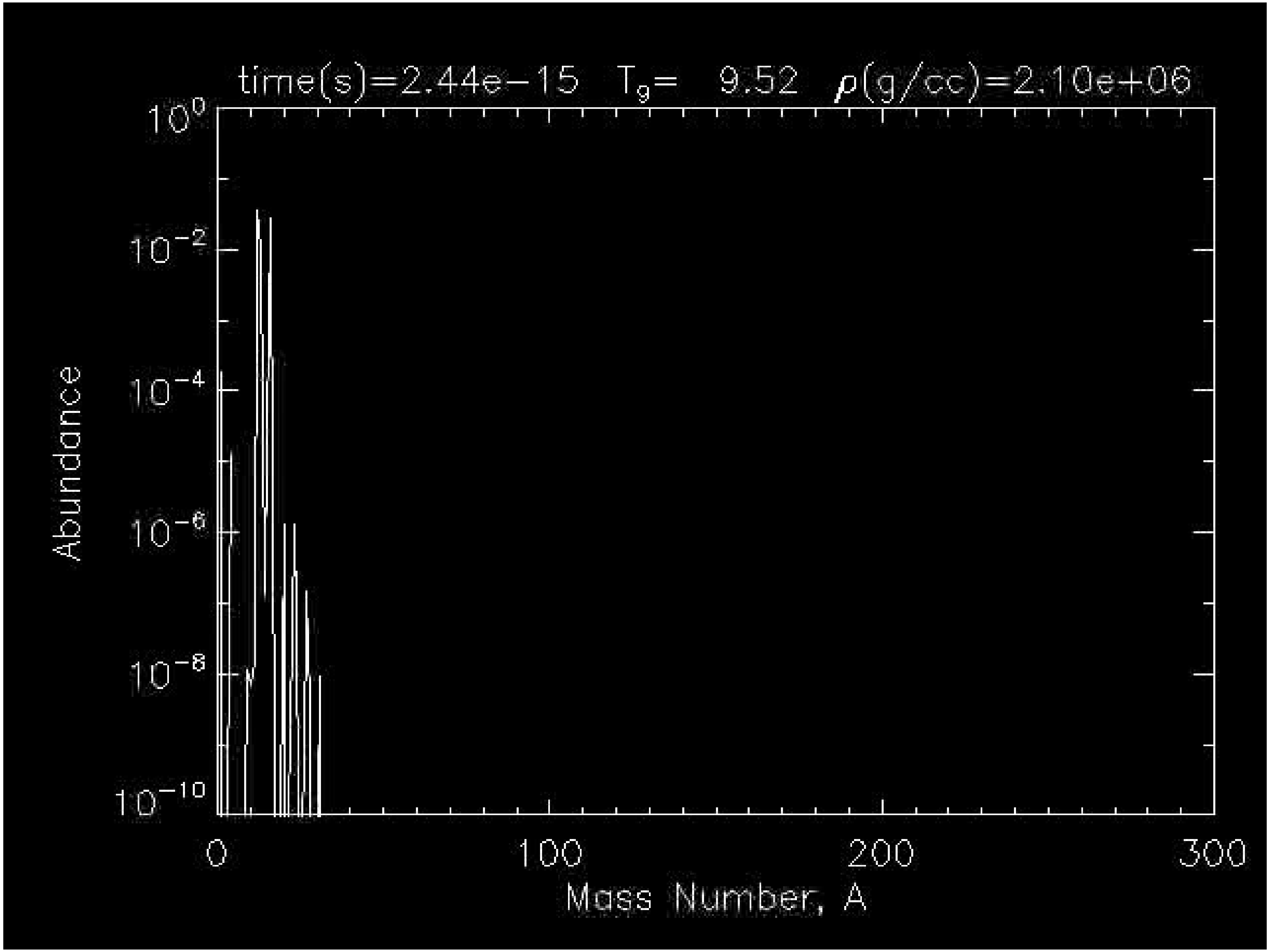
High-Entropy

- Typical Y_e=0.35
- Site: neutrino ejected matter from nascent neutron stars
- Neutron-richness from neutrino interactions on free nucleons
- Experimental issues: neutrino physics, physics of neutron-rich nuclei
- Typical problem: getting the high-enough entropy


t (s) = 1.749E−20
T_9 = 40.01
rho (g/cc) = 2.200E+08
Abundance
10^{-3}
10^{-4}
10^{-5}
10^{-6}
10^{-7}
10^{-8}
0
50
100
150
200
250
A, Mass Number

High-entropy, very fast expansion

- Typical Y_e=0.495
- Sites: fallback in core-collapse supernovae (Fryer et al. 2006), shocked surface layers in O/Ne/Mg cores (Ning et al. 2007)
- Neutron-richness from pre-supernova evolution ($^{12}C + p \rightarrow {}^{13}N + \gamma \rightarrow {}^{13}C + e^{+} + \nu$)
- Experimental issues: charged-particle reactions on heavy nuclei.
- Typical problem: getting fast enough expansion/high enough entropy


time(s)=2.44e−15 T9= 9.52 ρ(g/cc)=2.10e+06
10^0
10^−2
10^−4
10^−6
10^−8
10^−10
Abundance
0
100
200
300
Mass Number, A

Production of ^{4}He from n, p ($T_9 = 10 – 8$)

$$p(n,\gamma)^2H(n,\gamma)^3H(p,n)^3He(^2H,p)^4He$$

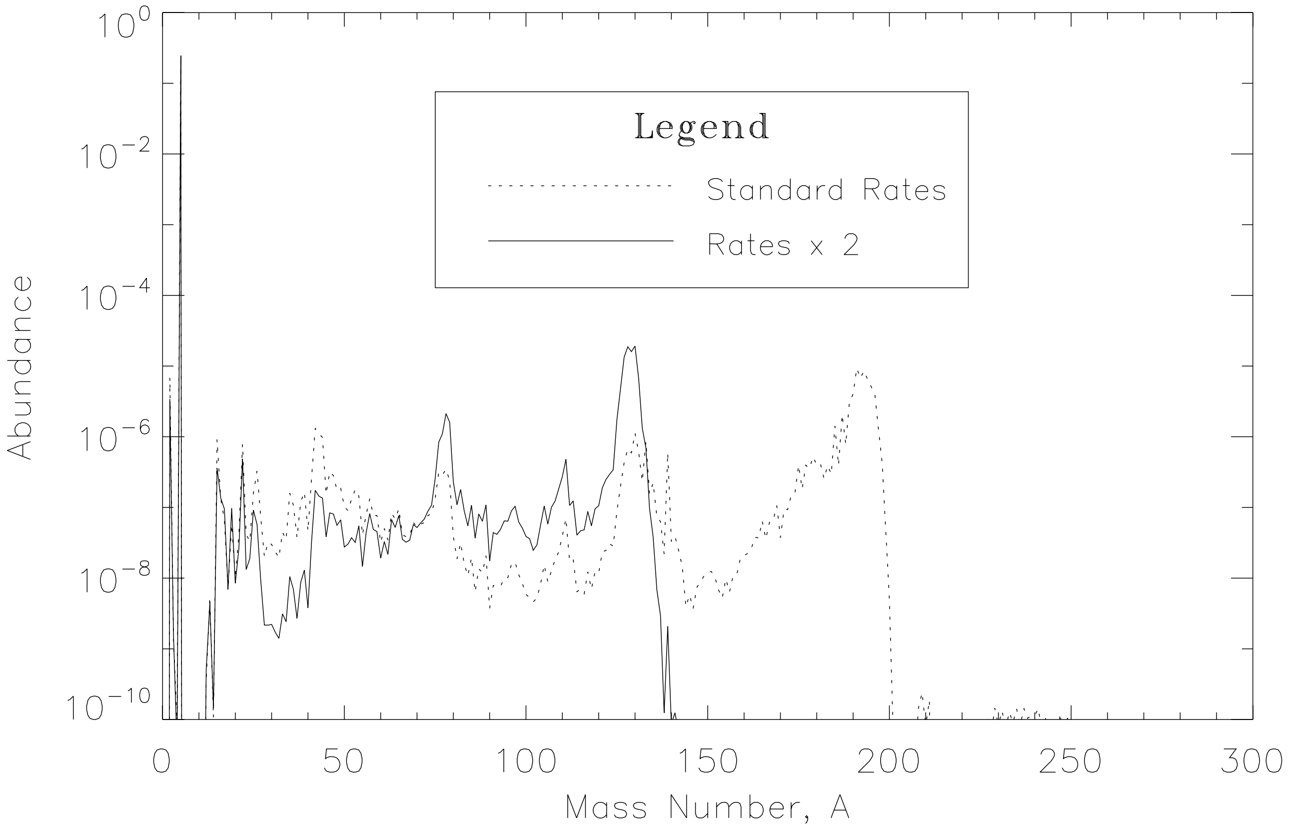
$$\Rightarrow n+n+p+p\rightarrow\alpha$$

Production of ^{4}He from n, p ($T_9 < 8$)

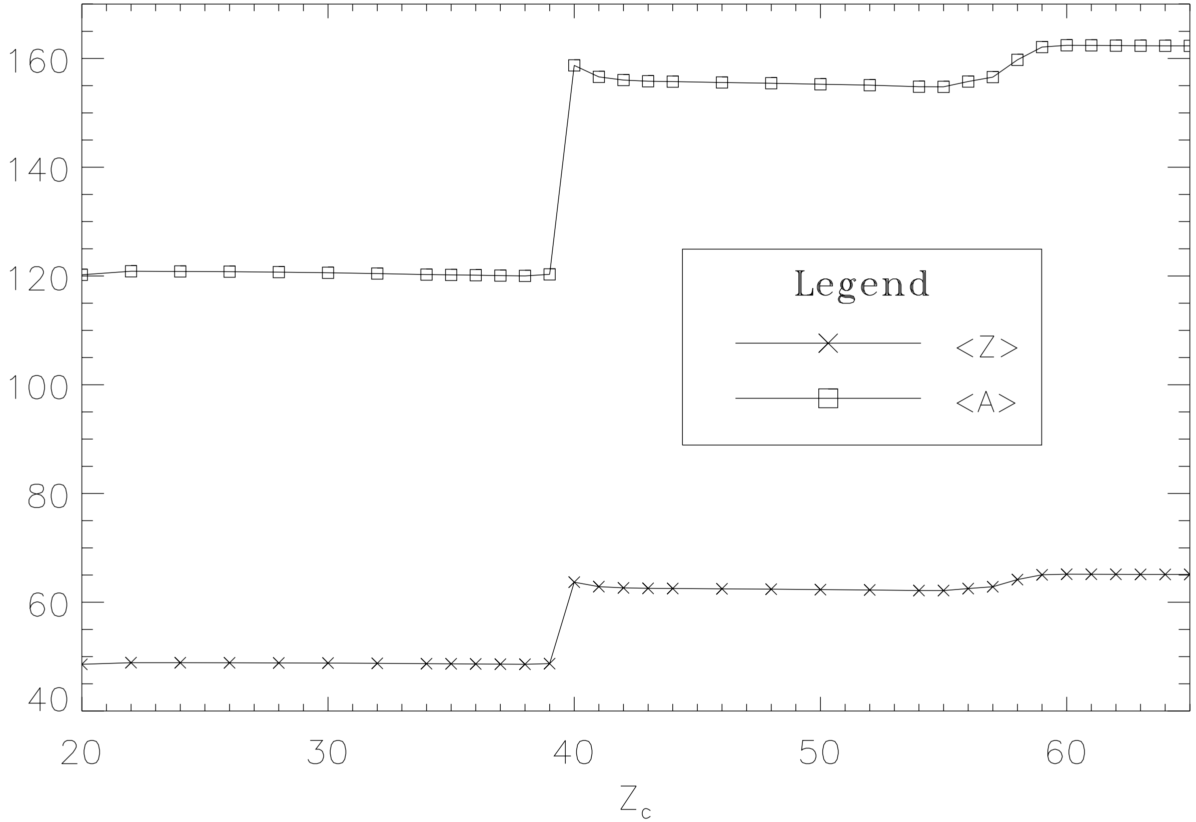
$$^{56}Ni(n,\gamma)^{57}Ni(n,\gamma)^{58}Ni(p,\gamma)^{59}Cu(p,\alpha)^{56}Ni$$

$$\Rightarrow n+n+p+p \rightarrow \alpha$$

Too few heavy nuclei➔neutrons and protons don’t assemble into alpha particles and heavier species➔many free neutrons and protons around to bombard the few heavy nuclei present



Meyer and Wang (2007)



Meyer and Wang (2007)

Libnucnet

- Free, open-source library of codes for storing and managing nuclear reaction networks.
- Released under the GNU General Public License.
- Available at www.webnucleo.org.

Conclusions

- Three broad regimes for obtaining enough neutrons per seed nucleus for a successful r-process.
- A single stellar site may achieve conditions in more than one regime.
- Observations will be needed to distinguish not only the stellar source of the r-process elements but also help to distinguish the mechanism.
- Determining mechanism of r-process is important for determining experimental issues
- Libnucnet, a free library of codes for storing and managing nuclear reaction networks, is available from www.webnucleo.org.