Nuclear Dynamics of the Freezeout Phase of the r Process

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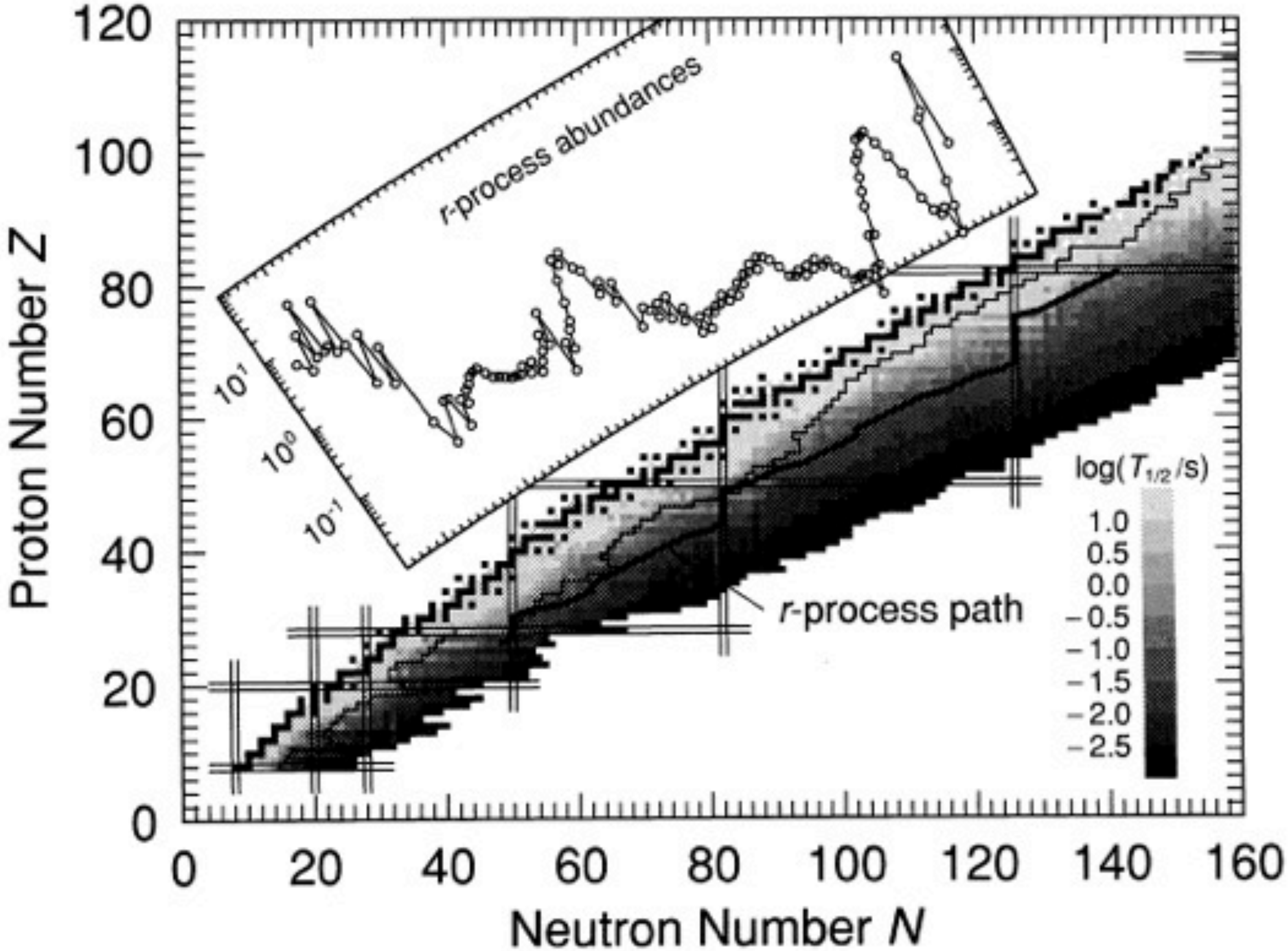


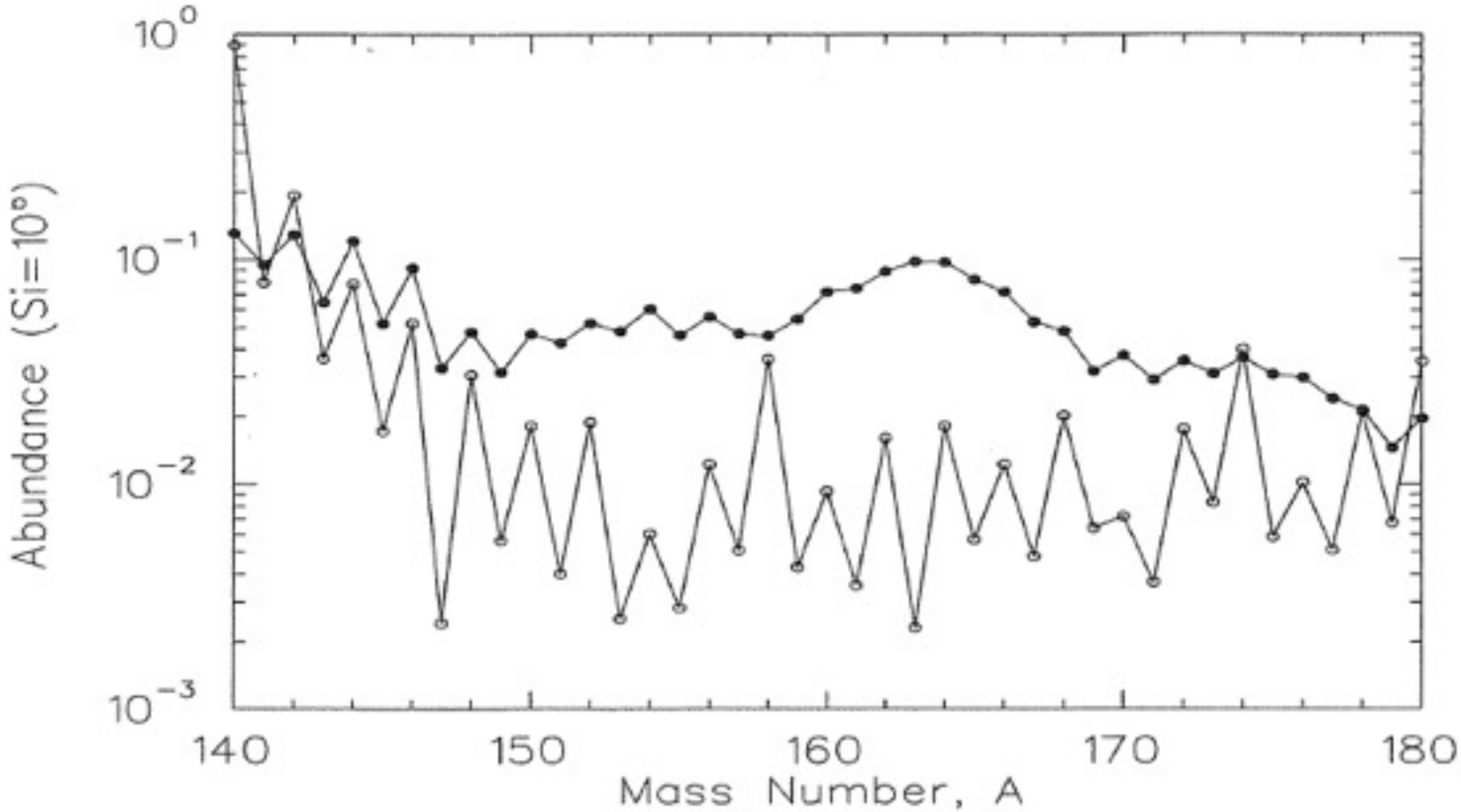
r-process abundances
10^{1}
10^{0}
10^{-1}
r-process path
log($T_{1/2}$/s)
1.0
0.5
0.0
−0.5
−1.0
−1.5
−2.0
−2.5
Proton Number Z
Neutron Number N
0
20
40
60
80
100
120
140
160

Some potential astronomical r-Process Observables

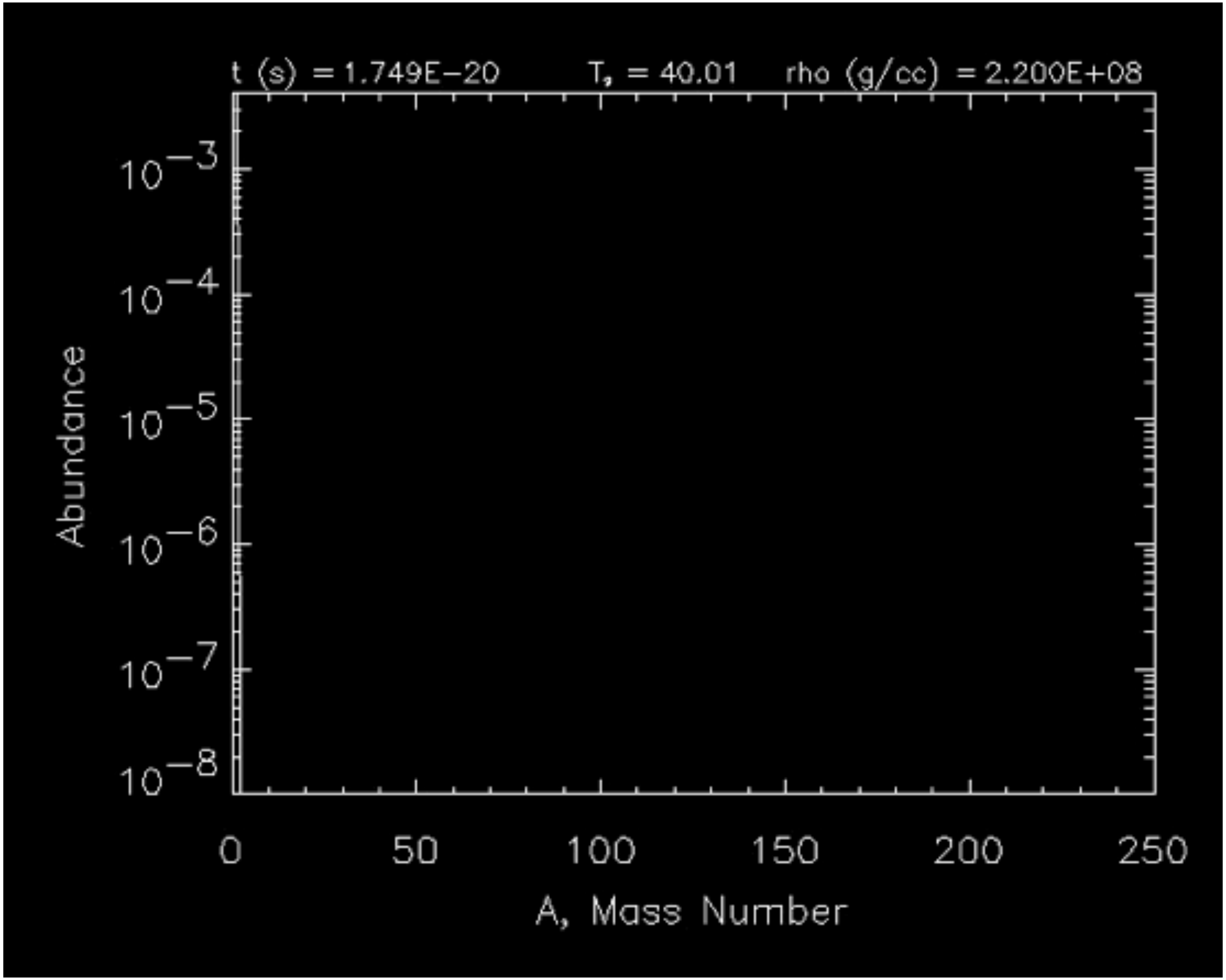
- Bulk CI meteoritic abundances (“solar”--sum of many r-processes)
- Metal-poor stars (primarily elemental abundances)
- Presolar grains (not yet found—maybe no r-process grains form)
- Extinct short-lived radioactivities in meteorites (e.g.,^{107}Pd, ^{129}I, ^{182}Hf, ^{244}Pu).

(Intrinsic) R-Process Observables

- Production of heavy elements:
  - Neutron-to-seed ratio (~100)
  - Dependent on weak-interaction physics and nuclear reactions at $T_9 > 4$
- Details of final abundance distribution
  - Peaks (including REE peak)
  - Freezeout abundances—smoothing
  - Dependent on nuclear reactions for $T_9<3$



10^0
10^{-1}
10^{-2}
10^{-3}
Abundance (Si=10^6)
140
150
160
170
180
Mass Number, A



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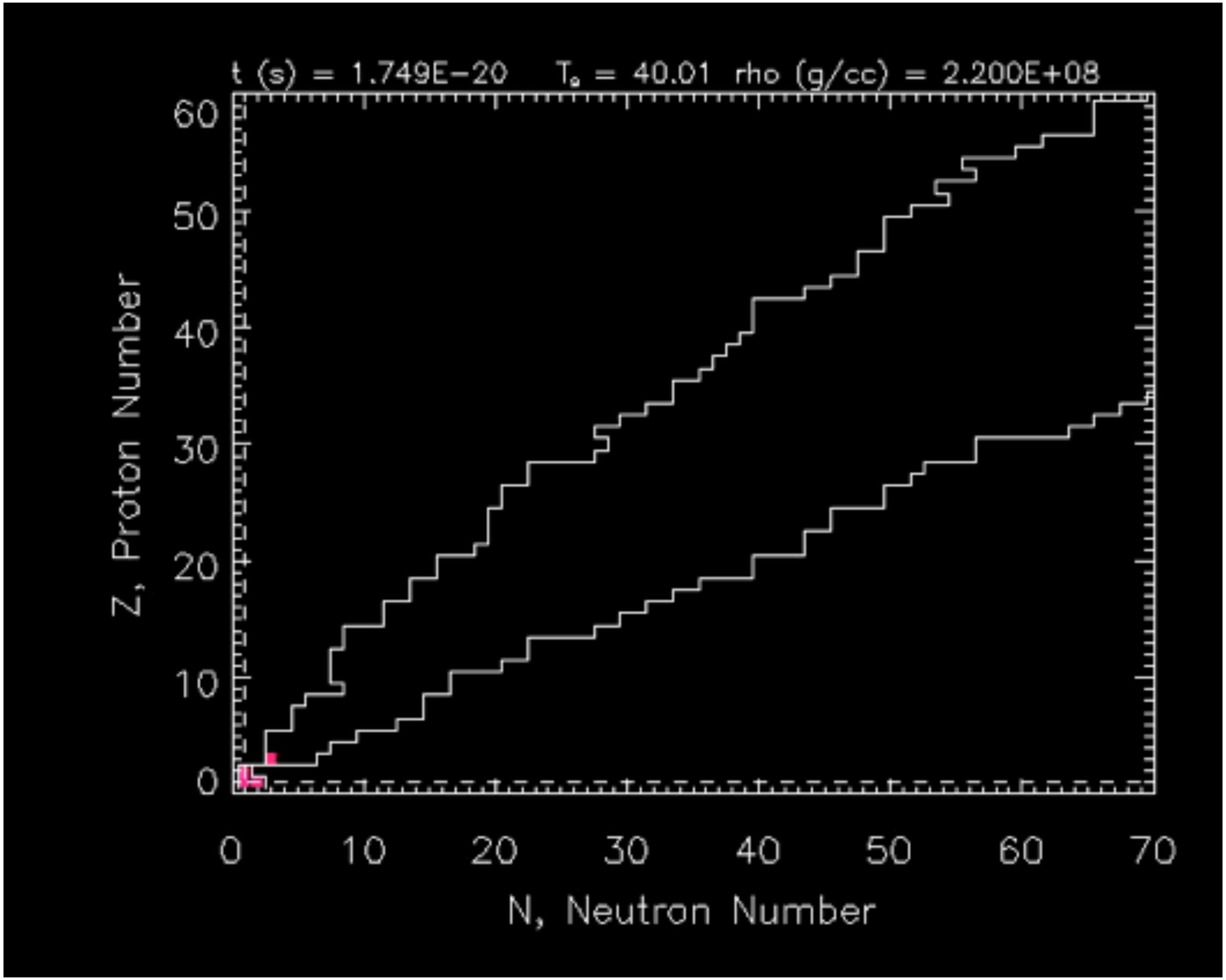

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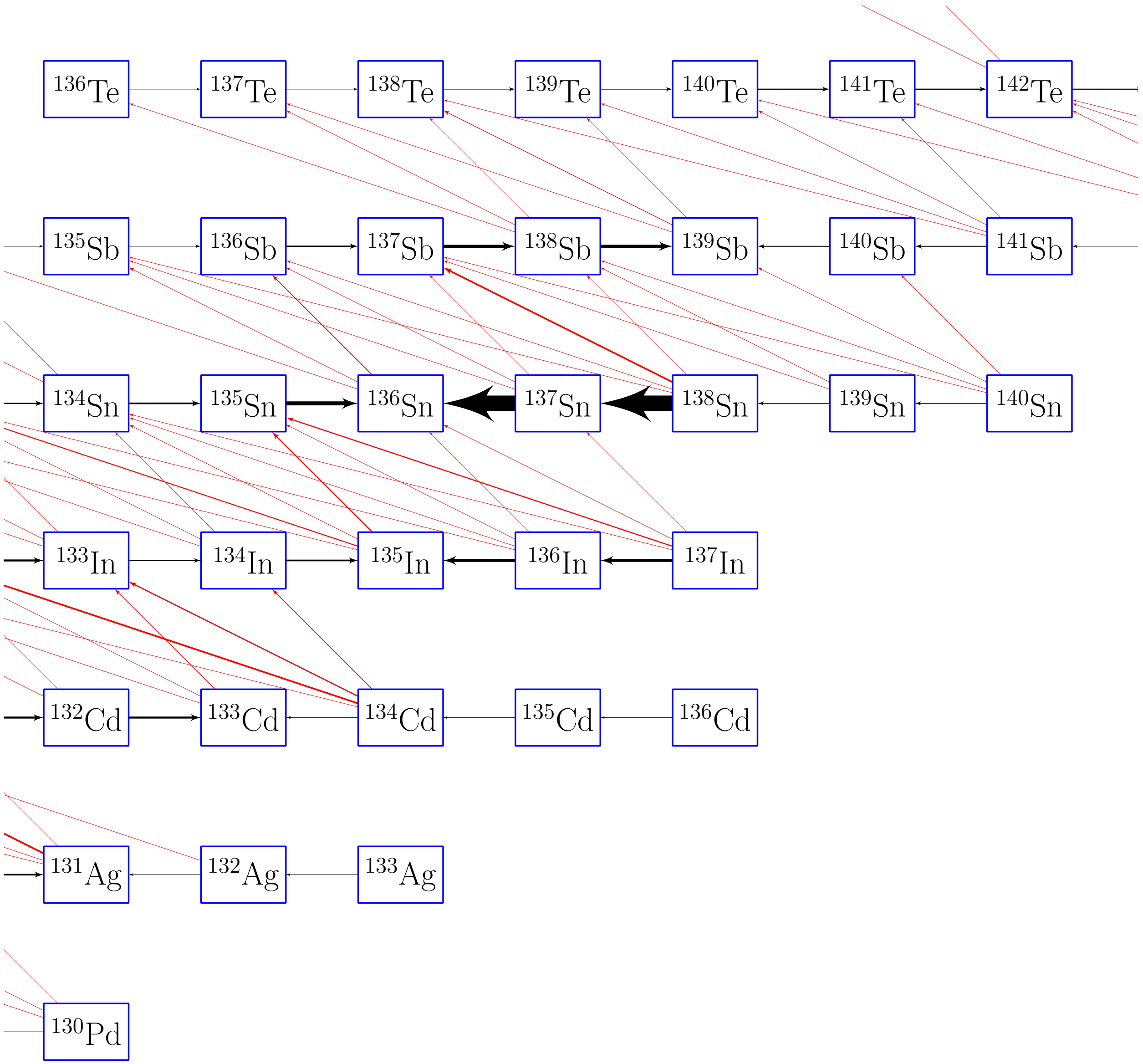


136Te
137Te
138Te
139Te
140Te
141Te
142Te
135Sb
136Sb
137Sb
138Sb
139Sb
140Sb
141Sb
134Sn
135Sn
136Sn
137Sn
138Sn
139Sn
140Sn
133In
134In
135In
136In
137In
132Cd
133Cd
134Cd
135Cd
136Cd
131Ag
132Ag
133Ag
130Pd

(n,g)-(g,n) equilibrium

The key is the neutron binding.

Neutron binding inside the nucleus (neutron separation energy)

$$S_n^{in}(Z,A) = M(Z,A-1)c^2 + M_n c^2 - M(Z,A)c^2$$

Neutron binding outside the nucleus

$$dF = \mu_n dN$$

$$\Rightarrow dN = -1 \Rightarrow dF = -\mu_n$$

$$S_n^{out} = -\mu_n + M_n c^2$$

“Classical” neutrons

$$S_n^{out} = kT \ln \left[\frac{2}{n_n} \left(\frac{M_n kT}{2\pi\hbar^2} \right)^{3/2} \right]$$

(n,g)-(g,n) equilibrium

$$S_n^{in} = S_n^{out}$$

$$\rightarrow S_n^{in} = kT \ln\left[\frac{2}{n_n}\left(\frac{M_n kT}{2\pi\hbar^2}\right)^{3/2}\right]$$

Myers-Swiateck Mass Formula (1966)

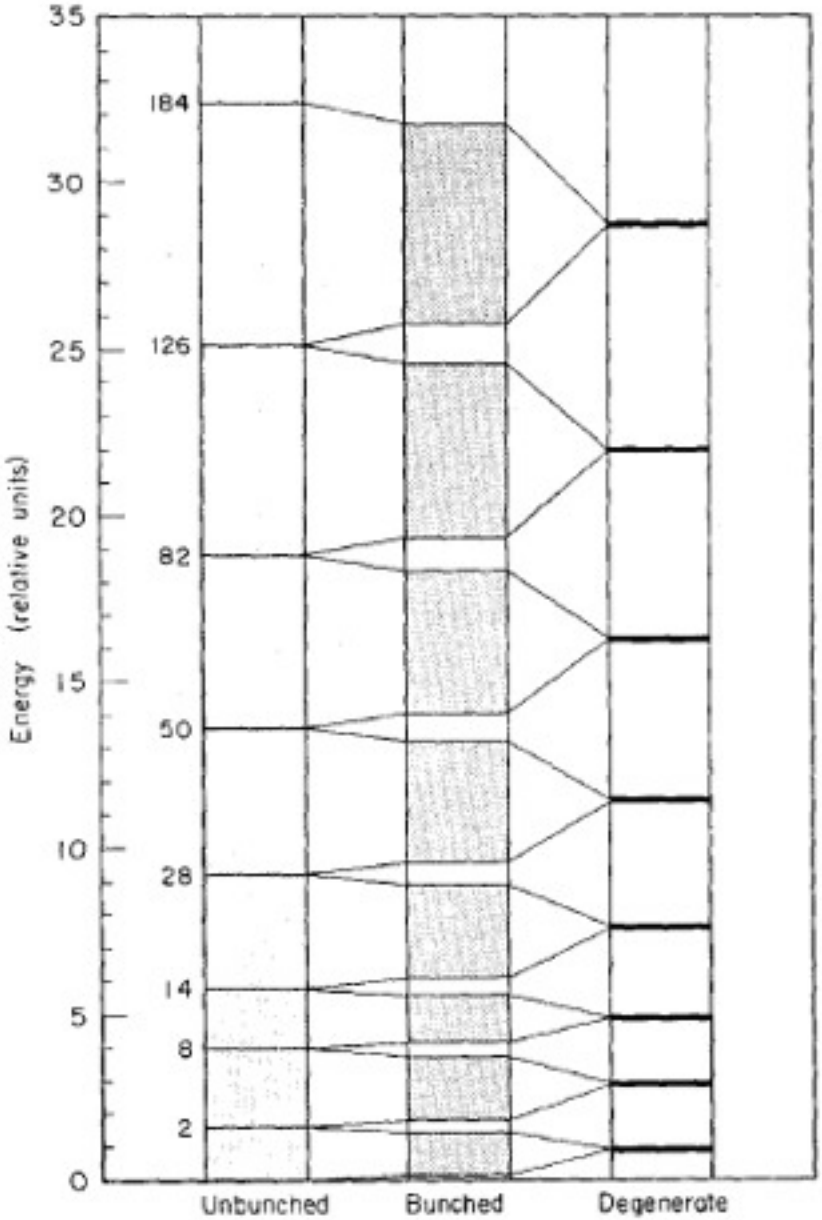
$$M(N, Z, \text{shape}) = M_n N + M_H Z + (\text{volume energy}) + (\text{surface energy}) + (\text{Coulomb energy}) + \delta + S(N, Z)\exp[-\overline{(\delta R)^2}/a^2].$$

$$\text{volume energy} = -c_1 A,$$

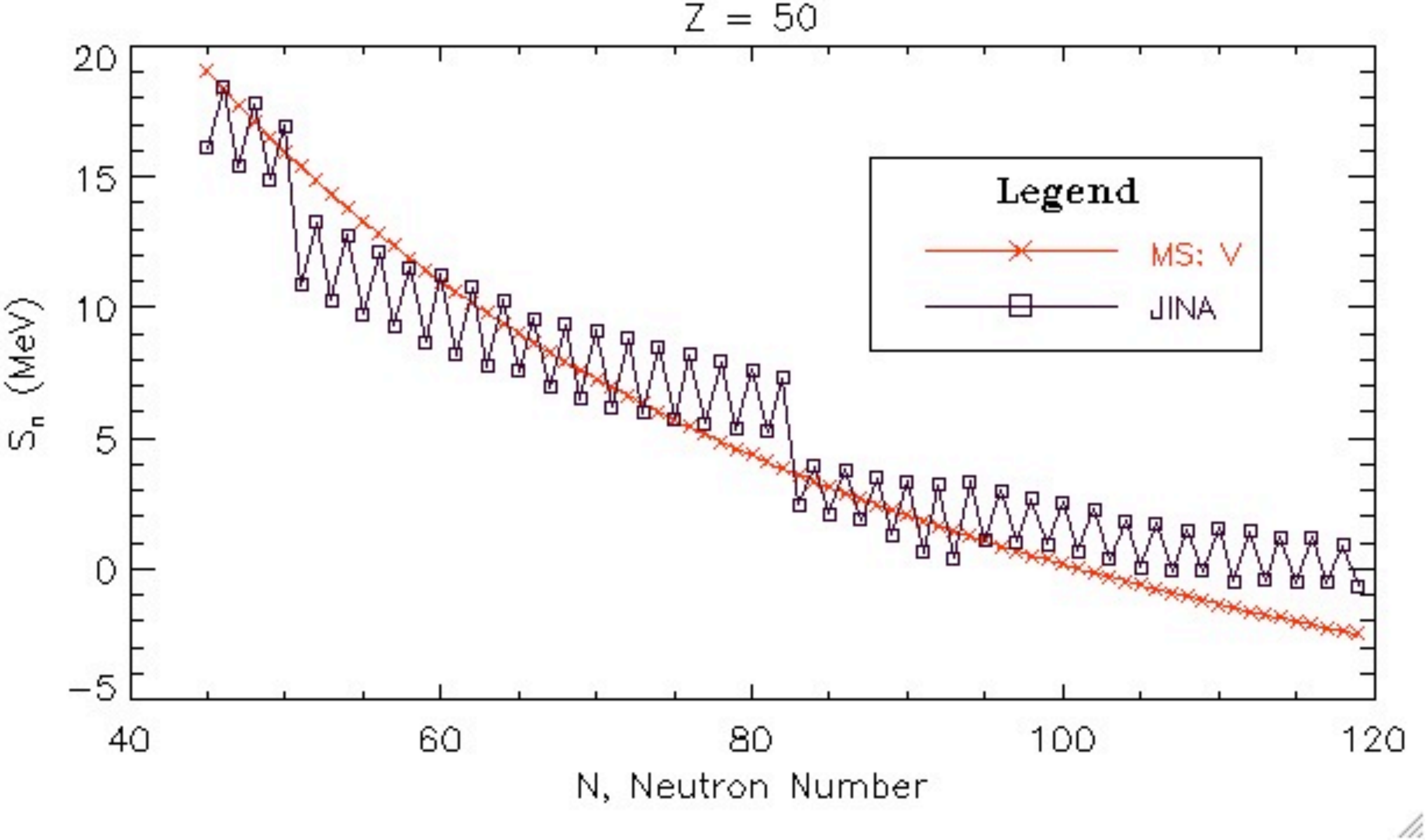
$$\text{surface energy} = c_2 A^{\frac{2}{3}} f(\text{shape}).$$

$$c_1 = a_1 \left[1 - \kappa \left(\frac{N-Z}{A}\right)^2\right] \qquad c_2 = a_2 \left[1 - \kappa \left(\frac{N-Z}{A}\right)^2\right]$$

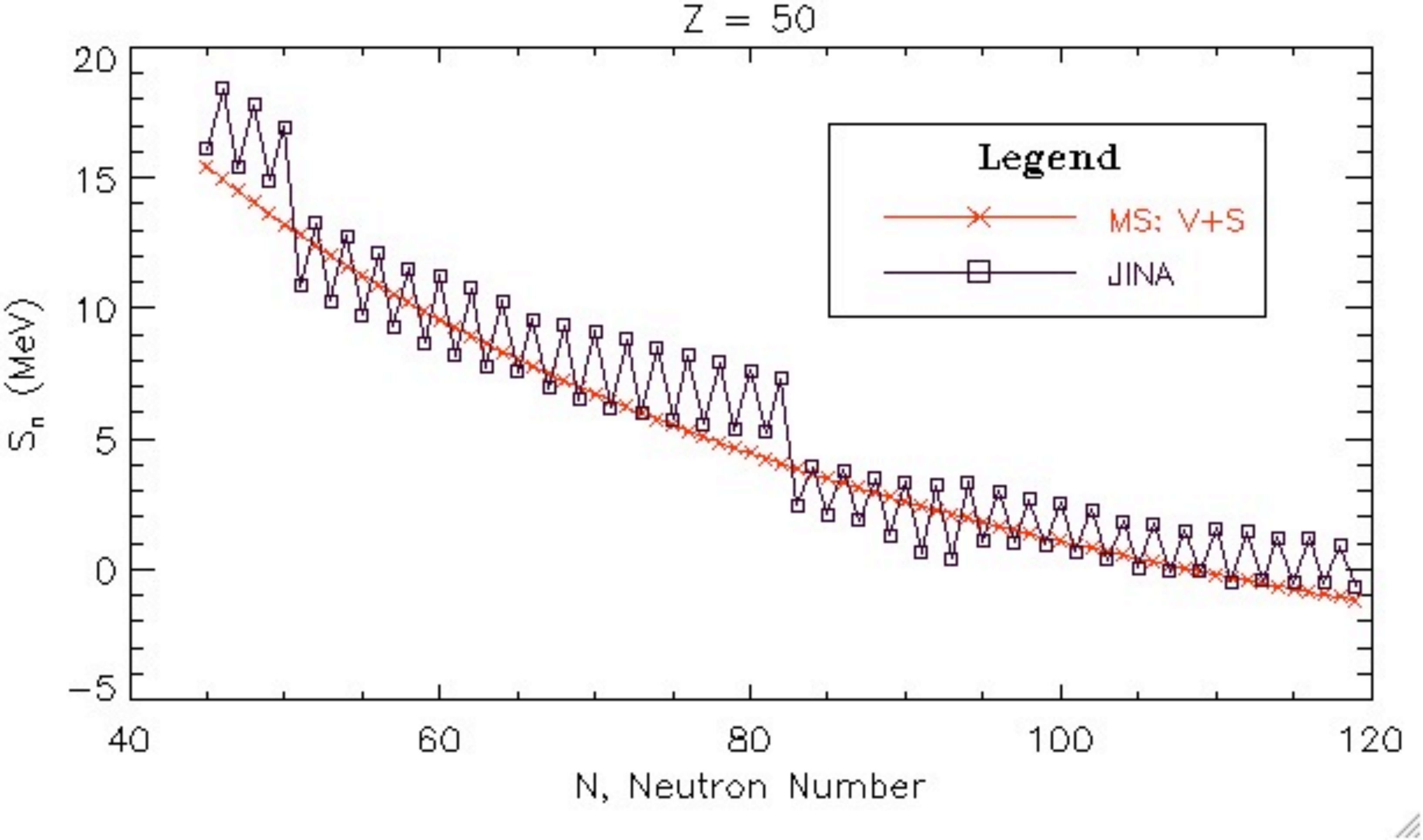
$$\text{electrostatic energy} = \frac{3}{5} \frac{e^2}{r_0} \frac{Z^2}{A^{\frac{1}{3}}} g(\text{shape}) - \frac{\pi^2}{2} \frac{e^2}{r_0} \left(\frac{d}{r_0}\right)^2 \frac{Z^2}{A}$$



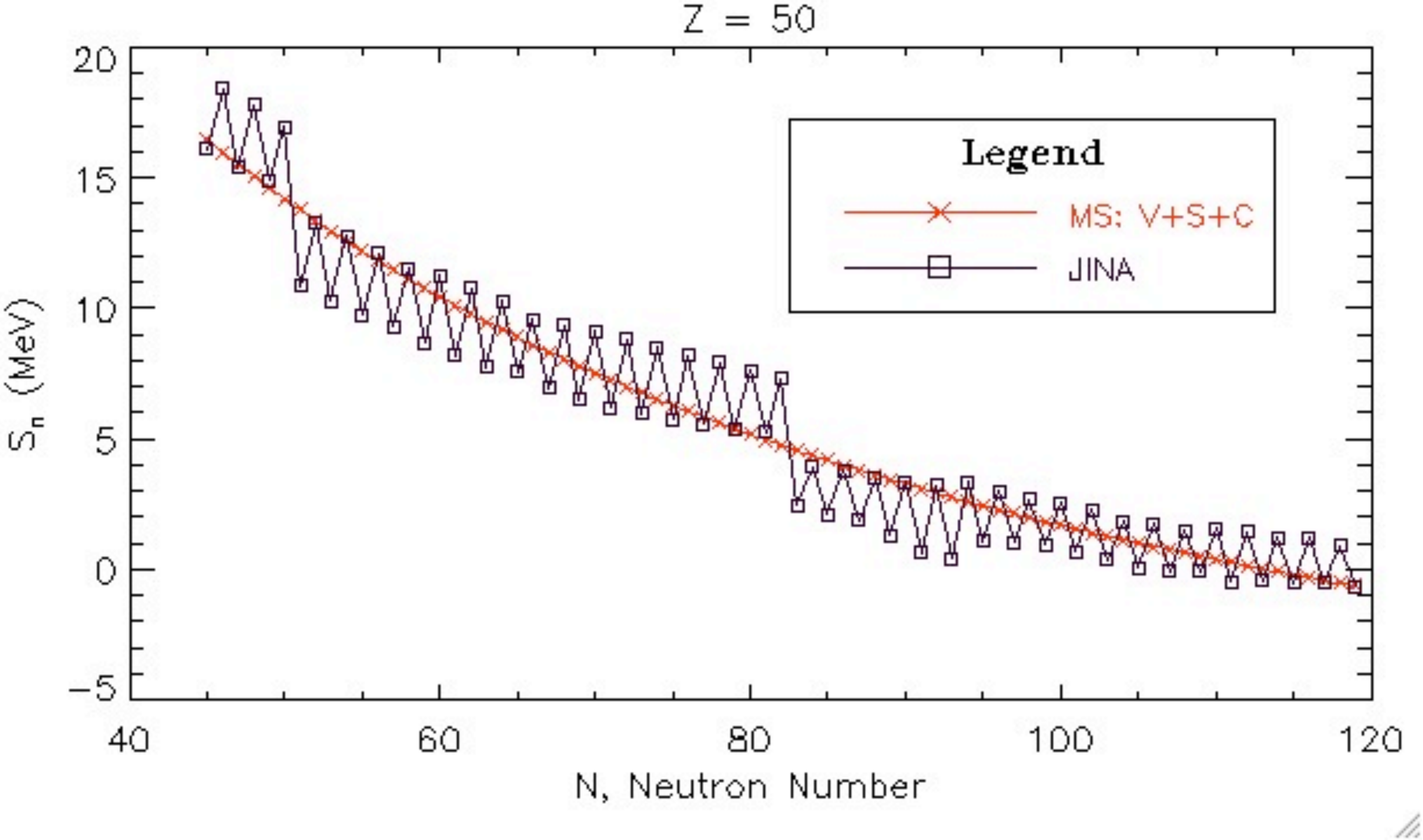
Energy (relative units)
35
30
25
20
15
10
5
0
184
126
82
50
28
14
8
2
Unbunched
Bunched
Degenerate

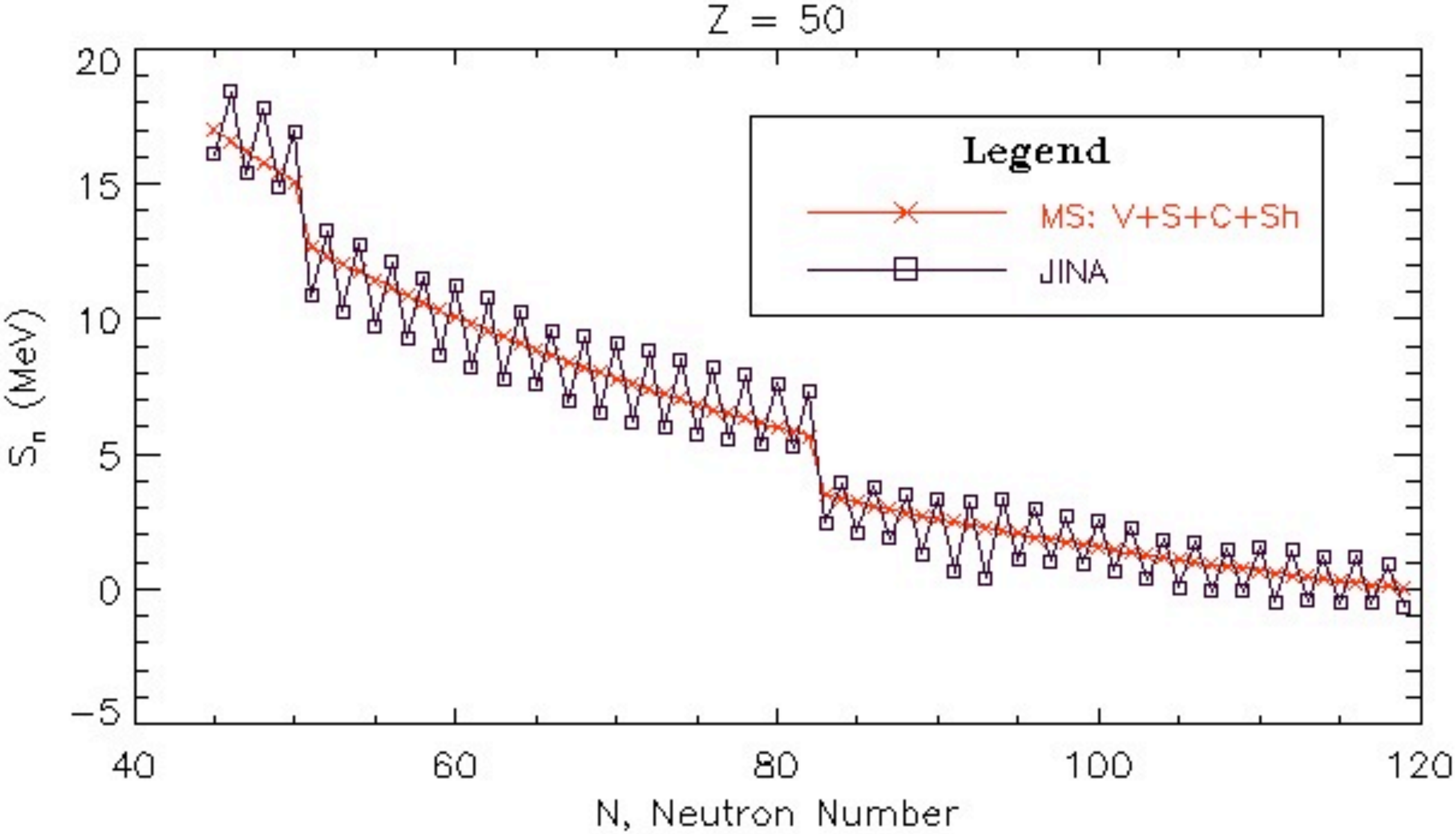


Z = 50
Legend
MS: V
JINA
S_n (MeV)
N, Neutron Number
20
15
10
5
0
−5
40
60
80
100
120

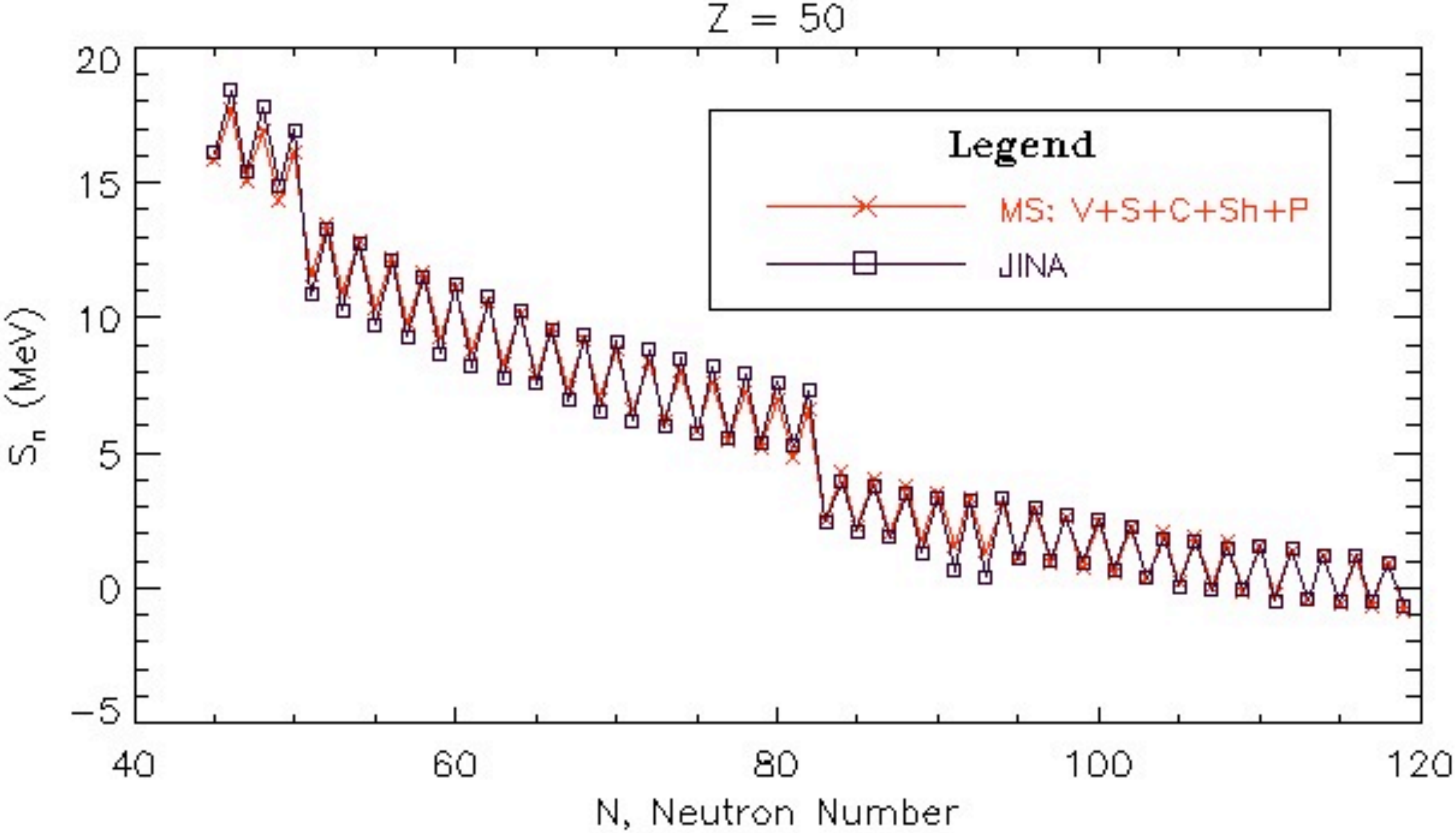


Z = 50
Legend
MS: V+S
JINA
S_n (MeV)
N, Neutron Number
20
15
10
5
0
−5
40
60
80
100
120


Z = 50
Legend
MS: V+S+C
JINA
S_n (MeV)
20
15
10
5
0
−5
40
60
80
100
120
N, Neutron Number



Z = 50
Legend
MS: V+S+C+Sh
JINA
S_n (MeV)
20
15
10
5
0
−5
40
60
80
100
120
N, Neutron Number


Z = 50
Legend
MS: V+S+C+Sh+P
JINA
S_n (MeV)
N, Neutron Number
20
15
10
5
0
−5
40
60
80
100
120

NucNet Tools

- A C++ toolkit that wraps libnucnet.
- Libnucnet itself built on top of libxml (the gnome XML parser and toolkit) and gsl (the GNU scientific library).
- Released under the GNU General Public License (see http://sourceforge.net/p/nucnet-tools/home).

Features of libnucnet

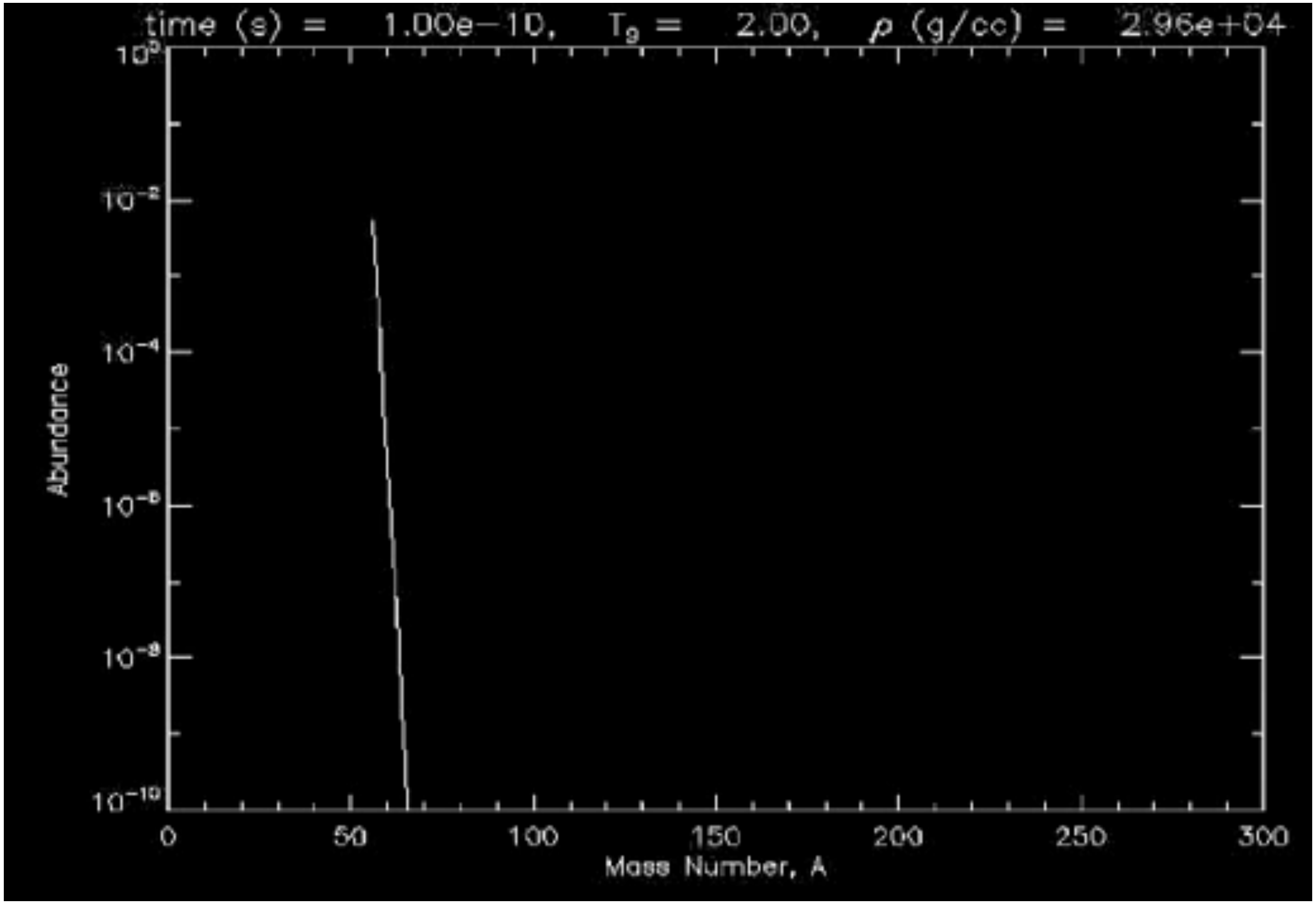
- Intrinsically 3-d
- Easily handles an arbitrary nuclear network (bbn to r-process), including (any number of) isomeric states
- Reactions are handled the way humans think about them: “c12 + he4 → o16 + gamma” or “o15 → n15 + positron + neutrino_e”
- Hierarchically structured
- Naturally uses xml as input (allows for schemas, stylesheets, xpath selection, etc.)
- Read and validate data across the web
- Allows for user-supplied screening, NSE correction factor functions, and rate fit functions.

Our calculations

- Start at $T_9 = 3$, $\rho=10^5$ g/cc, $Y_n / Y_h = 104$.
- Initial seeds: Ni
- ρ proportional to T^3.
- $N_A \langle\sigma v\rangle = 10^4$.
- Beta-decay rates from Seeger, Fowler, and Clayton (1965):

$$\lambda_\beta(Z,\ A) = \frac{10^{-5}}{18 \ln 2} \frac{W_o{}^6}{\Delta} \sec^{-1}$$

MS: V + constant T9



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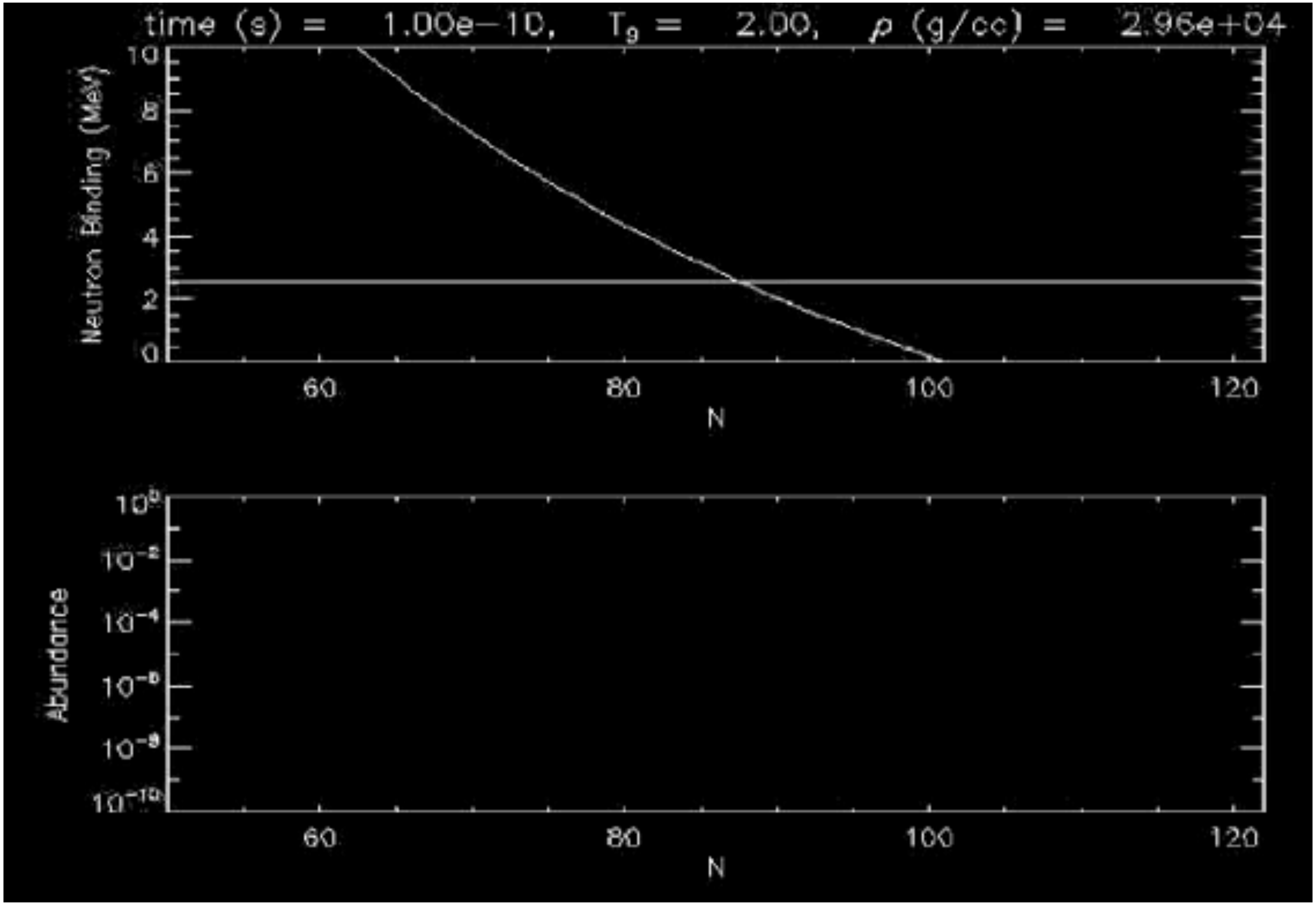
MS: V + constant T9



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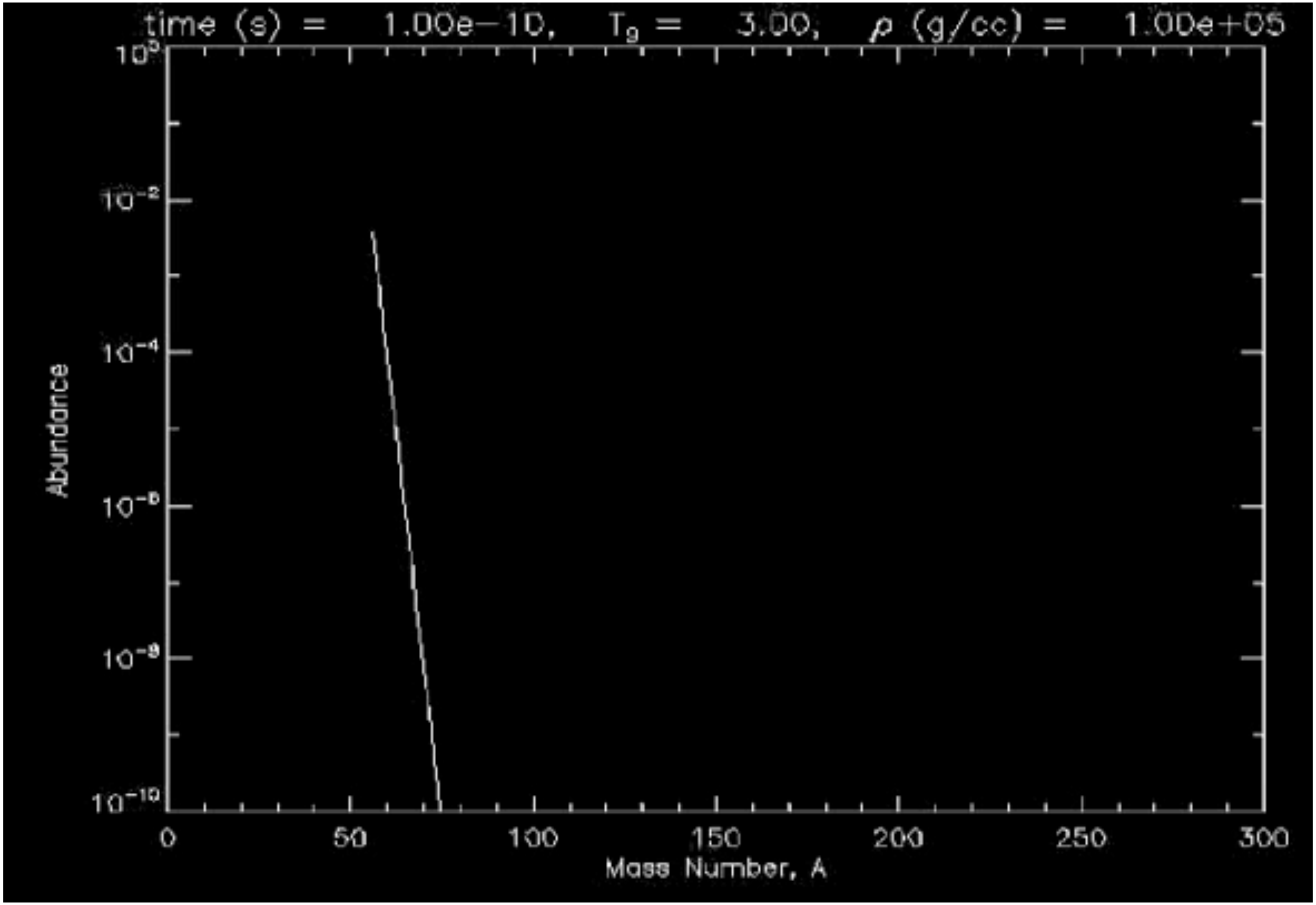
Spread in Isotopic Abundances

$$\sigma \approx \sqrt{\frac{kT}{\left|S_n^{'}\right|}}$$

MS: V + declining T



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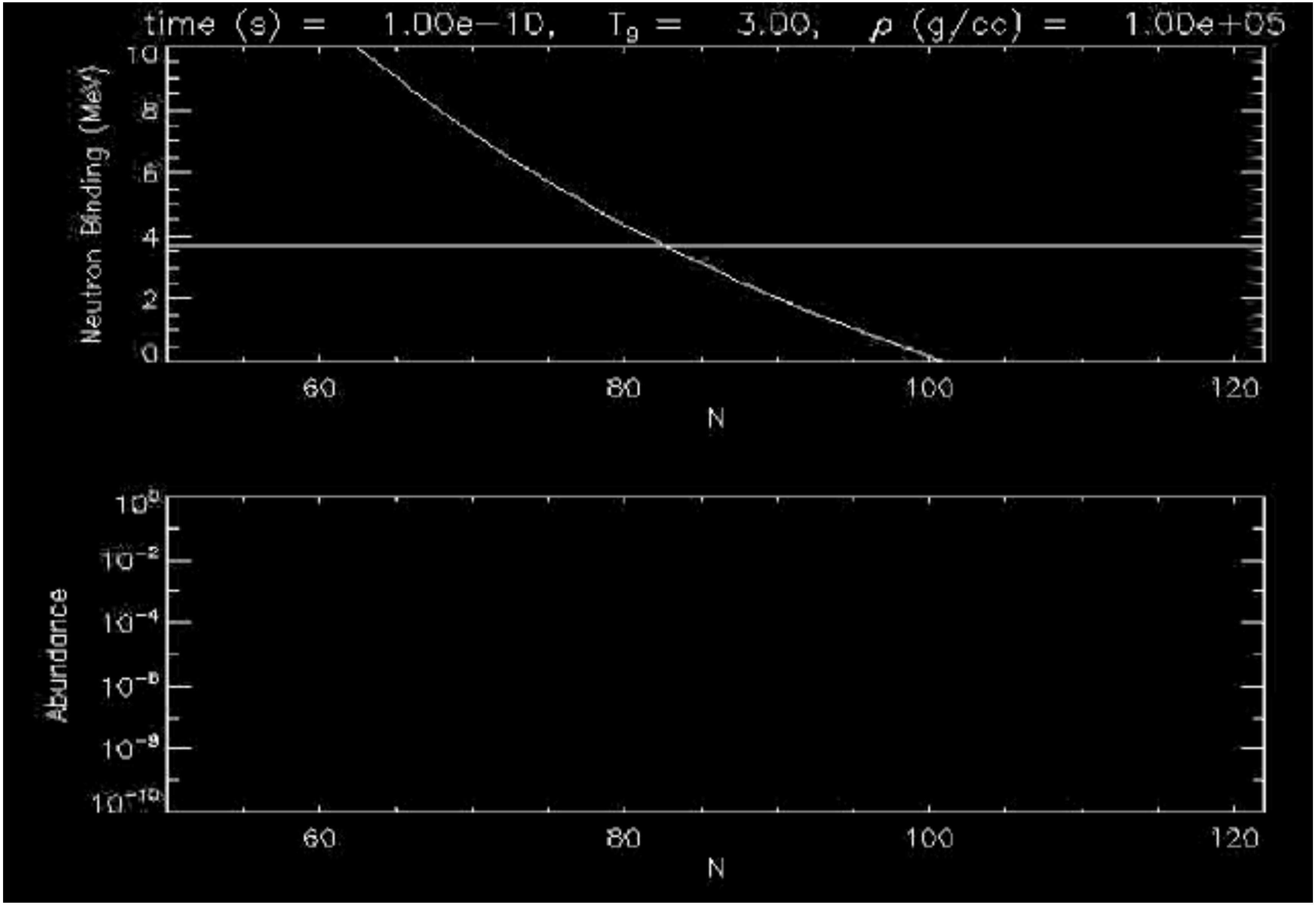

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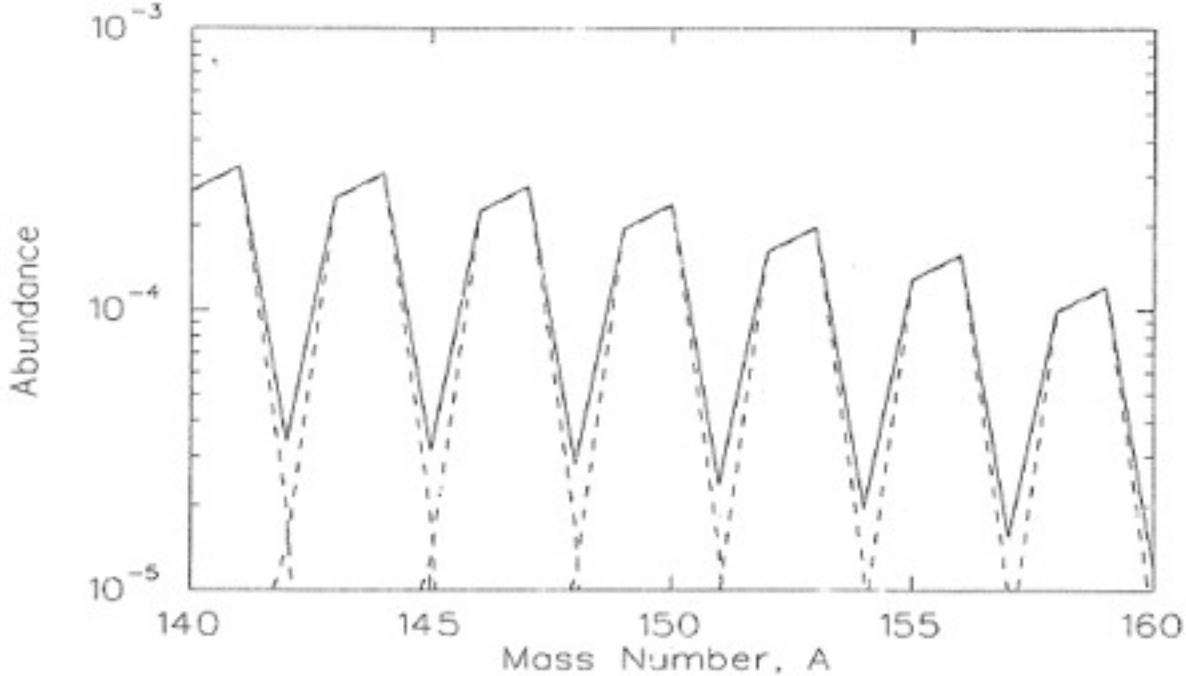
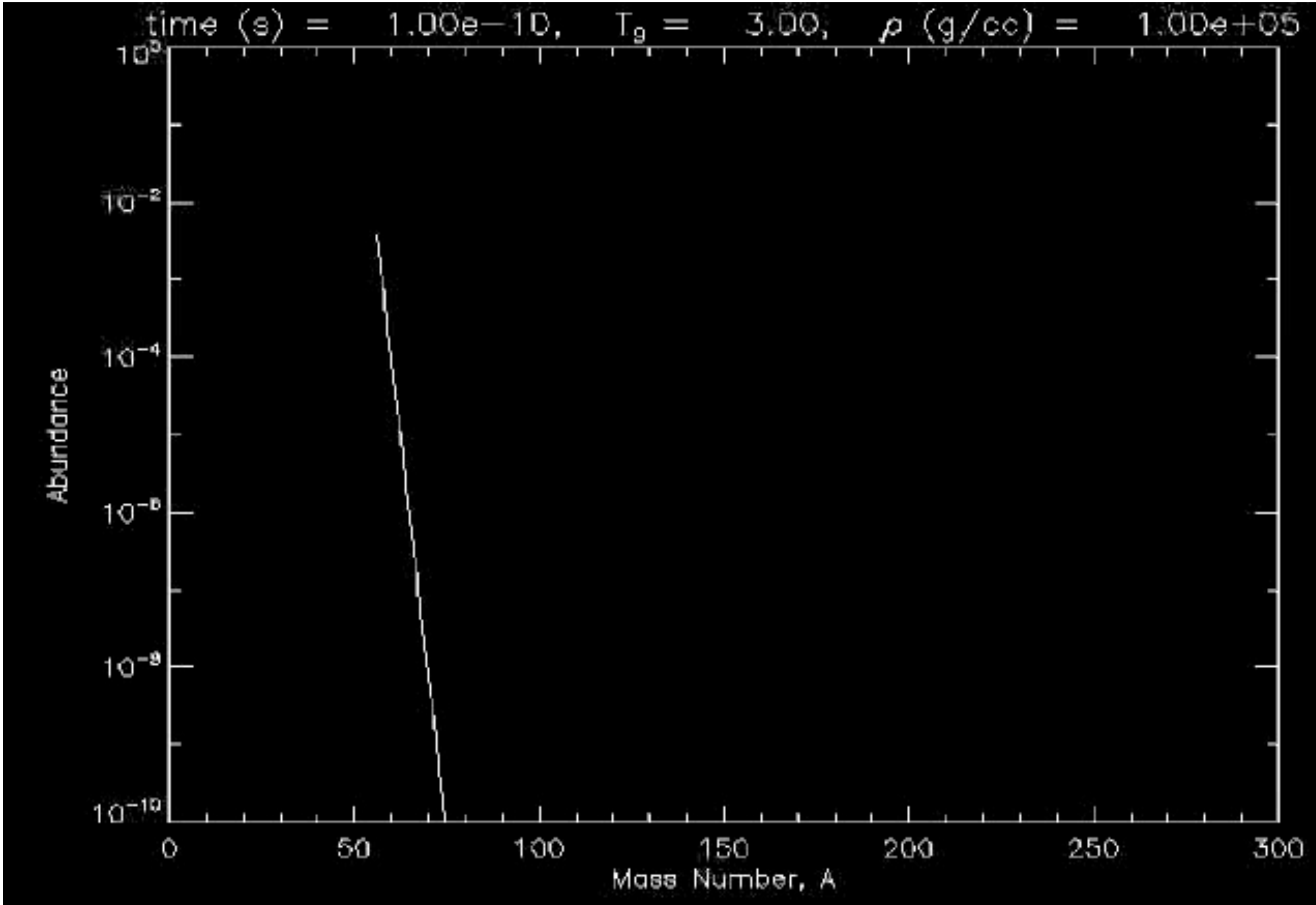


10^{-3}
10^{-4}
10^{-5}
Abundance
140
145
150
155
160
Mass Number, A

MS: V+S+C



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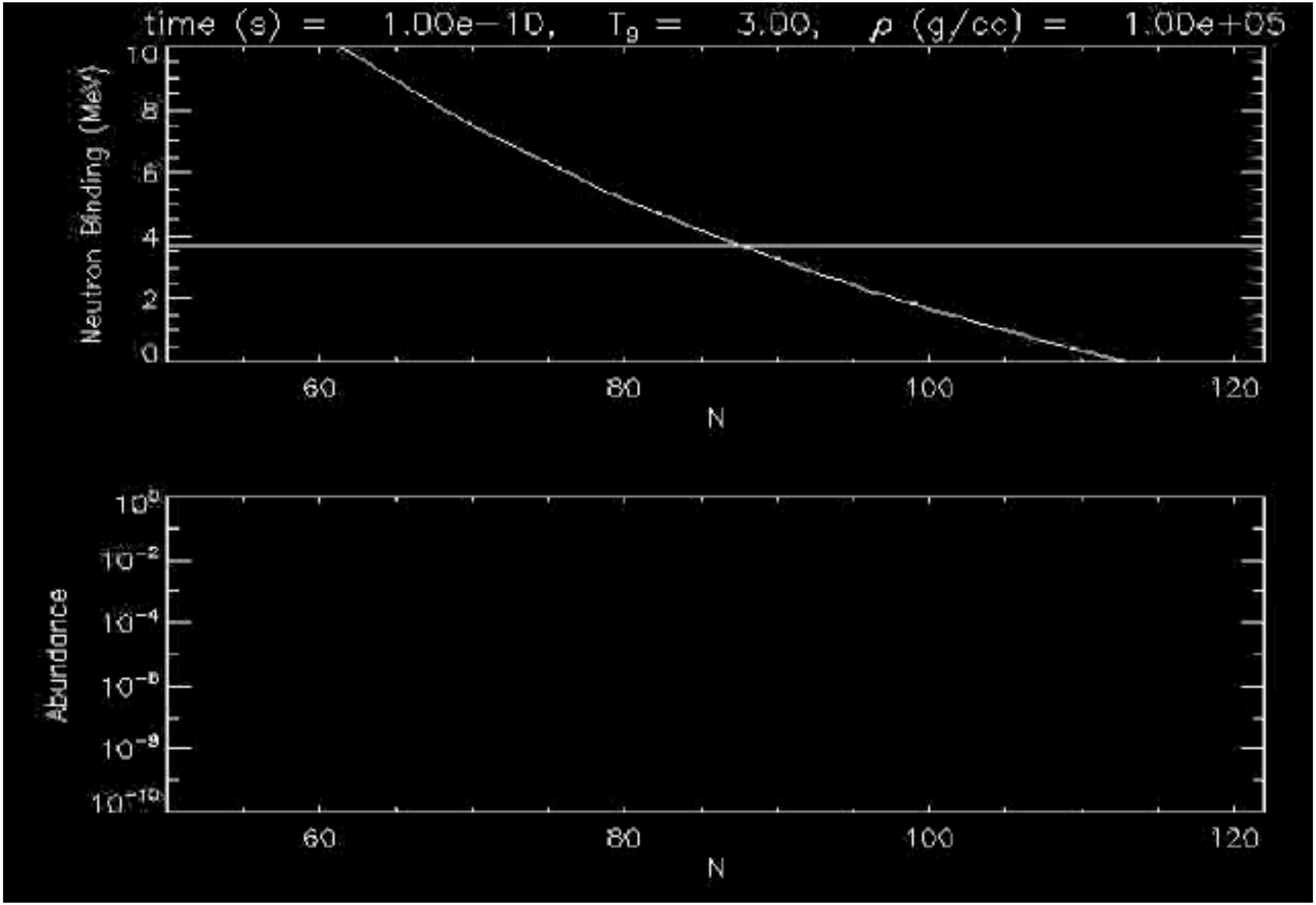

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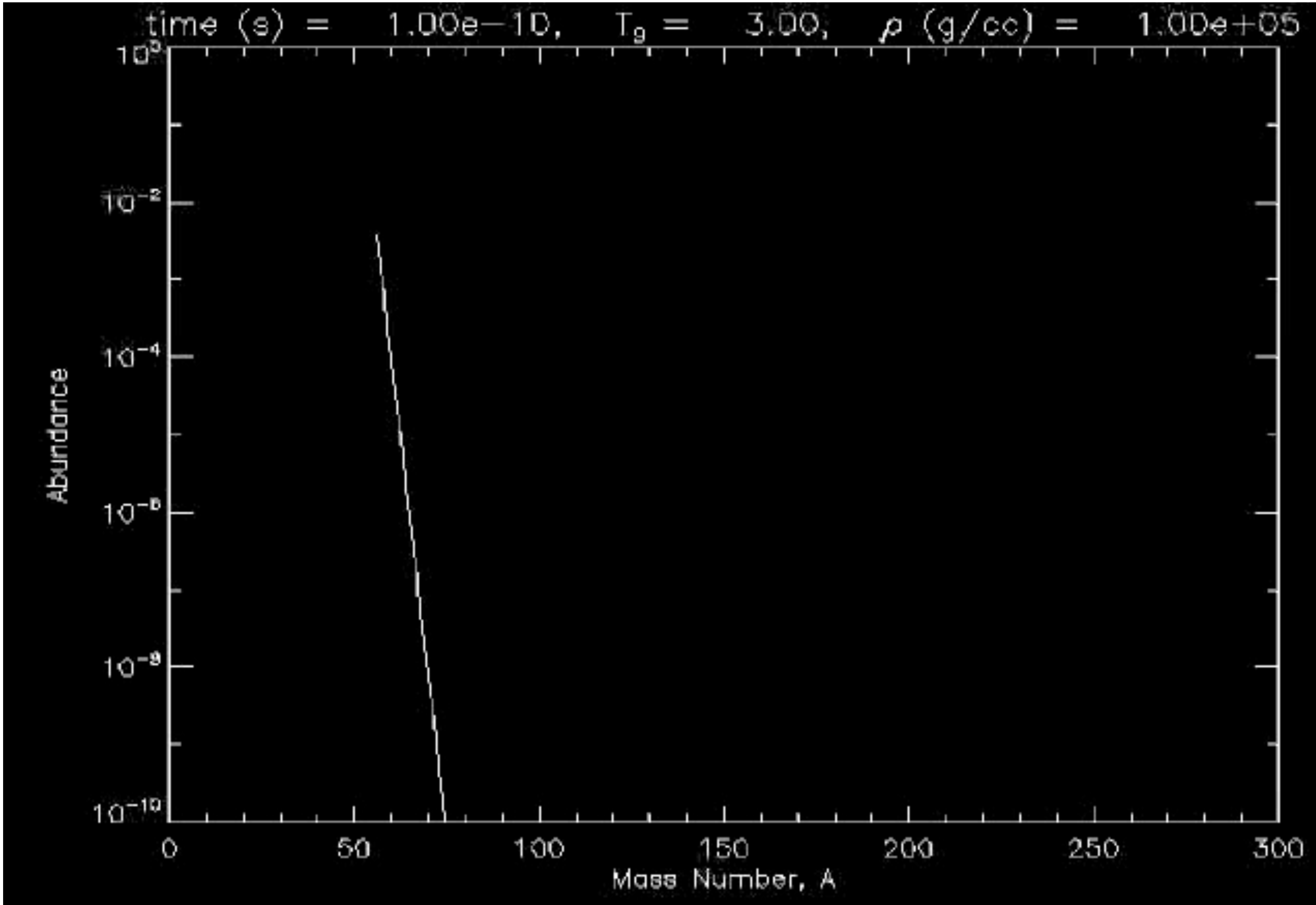
MS: V+S+C+Sh



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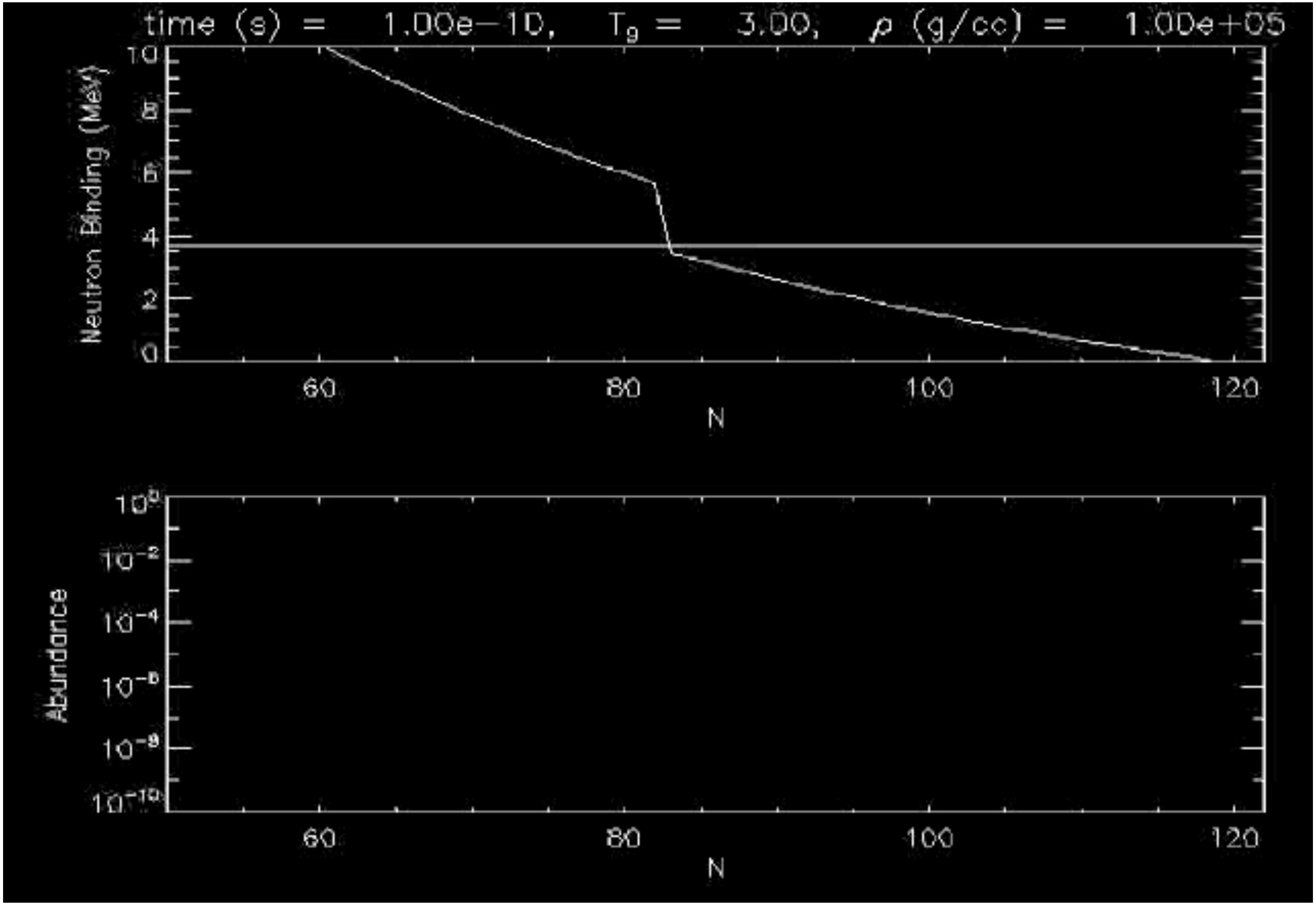
Z=50



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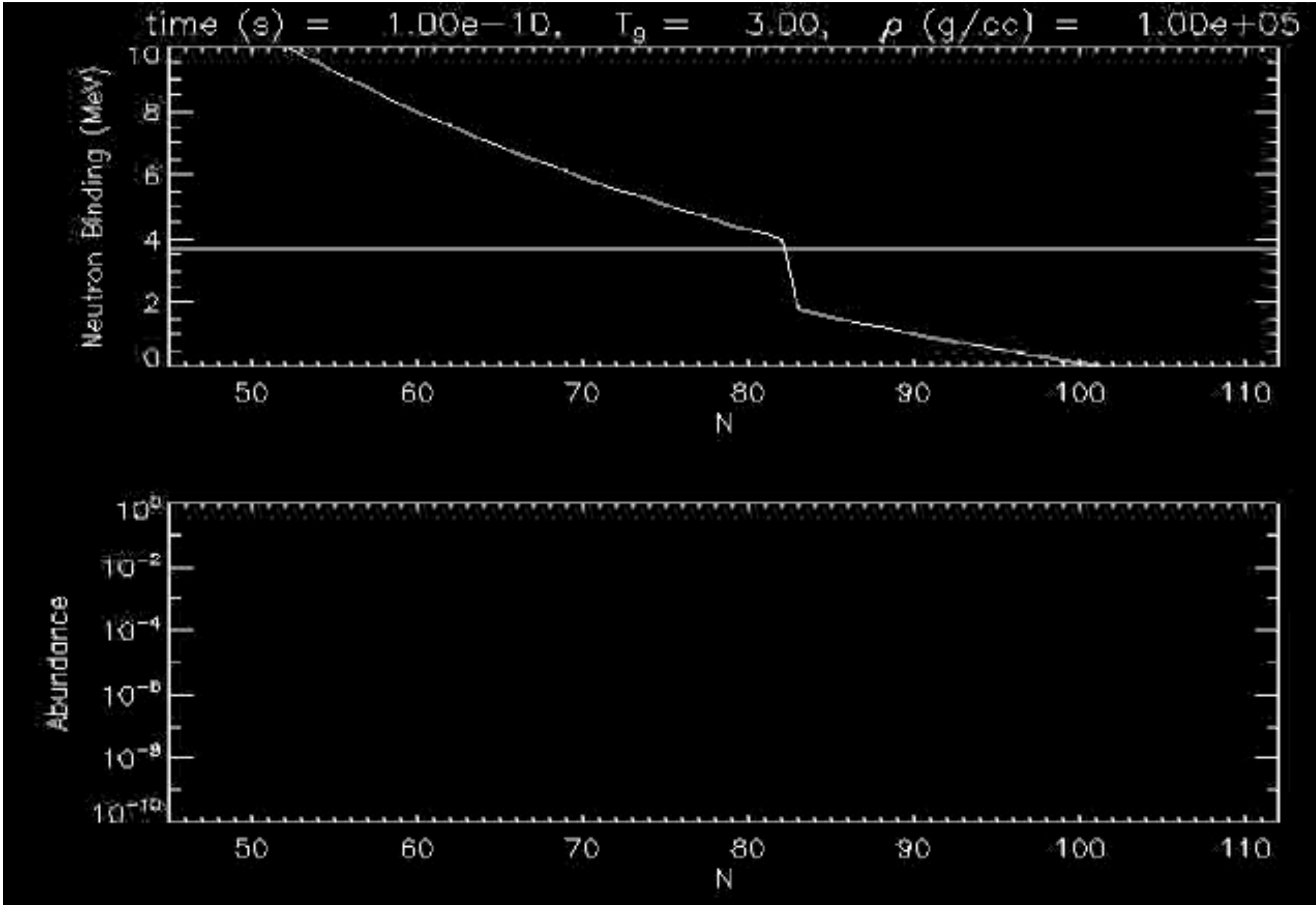
Z=45



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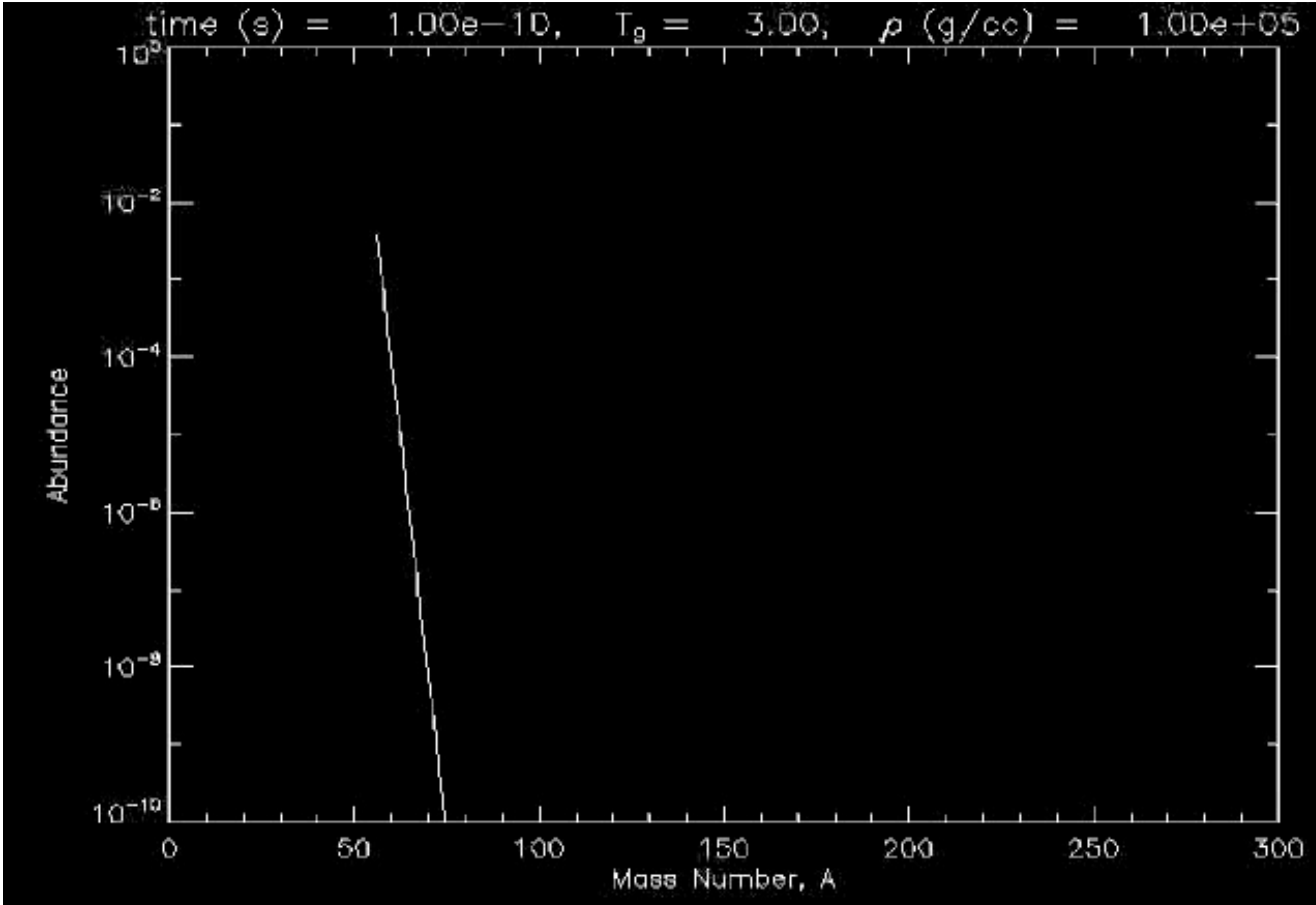
MS: V+S+C+Sh+P



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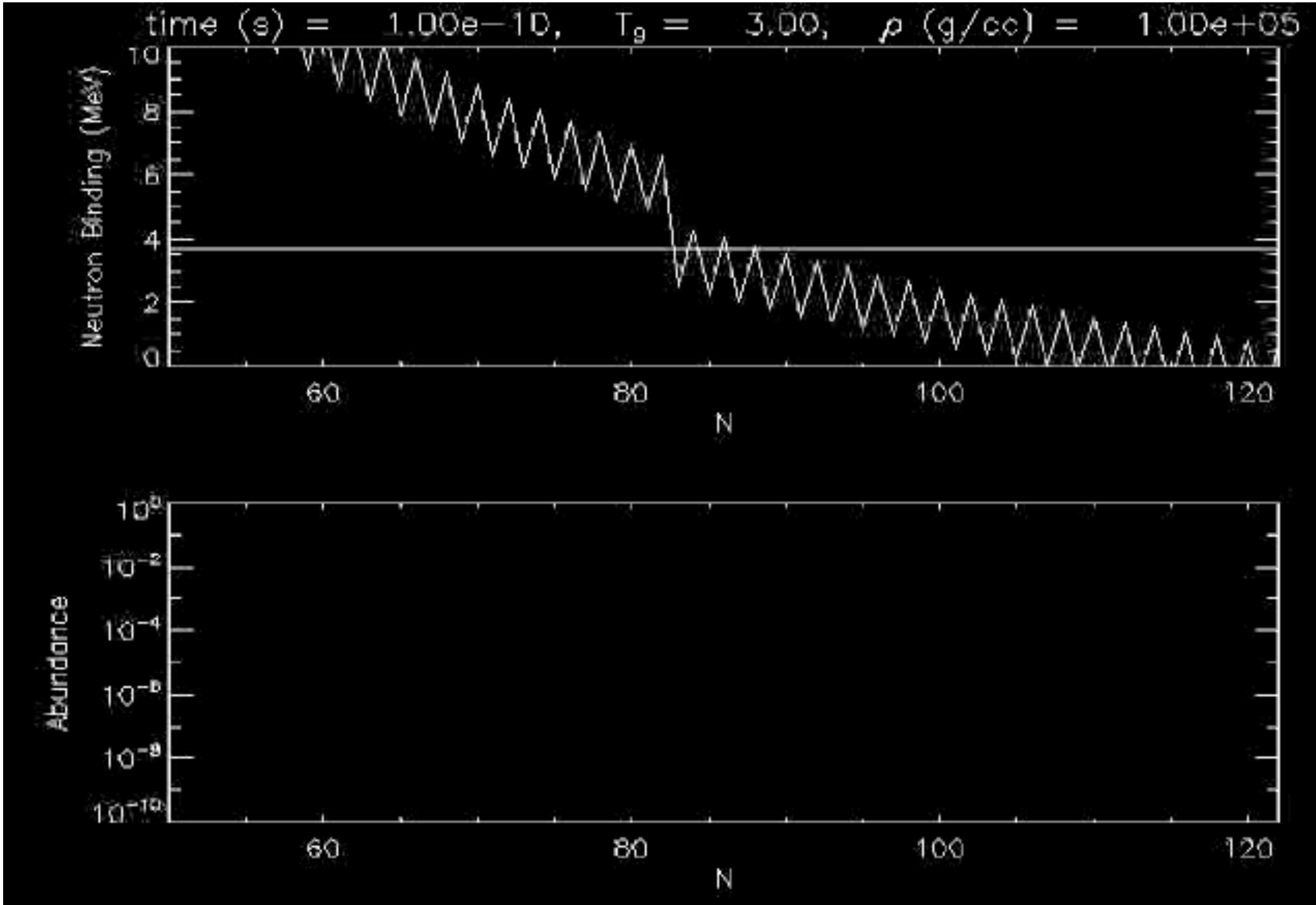
Z=50



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