Fragment Production in Supernova Explosions: What can we Learn from Nuclear Multifragmentation.

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Thermal multifragmentation of nuclei:

Production of hot fragments at

$$T \approx 3 - 8 \text{ MeV}$$

$$\rho \approx (0.1 - 0.3)\rho_0$$

(Nuclear density: $\rho_0 \approx 0.15\text{fm}^{-3} = 2.5 \cdot 10^{14}\text{g cm}^{-3}$)

Interpretation: liquid-gas type phase transition in finite nuclei. A chance to investigate properties of hot fragments, which are different from their ground state properties.

Collapse of massive stars leading to Supernova II explosions:

We expect production of hot fragments in nuclear matter at

$$T \approx 1 - 10 \text{ MeV}$$

$$\rho \lesssim 0.5\rho_0$$

Characteristic times of the processes are very large (milliseconds), nuclear equilibrium is expected.

Properties of hot fragments influence the collapse and explosion!

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Hot Dense Matter and Stellar Collapse

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We calculate the equation of state for hot dense matter and discuss implications for stellar collapse.

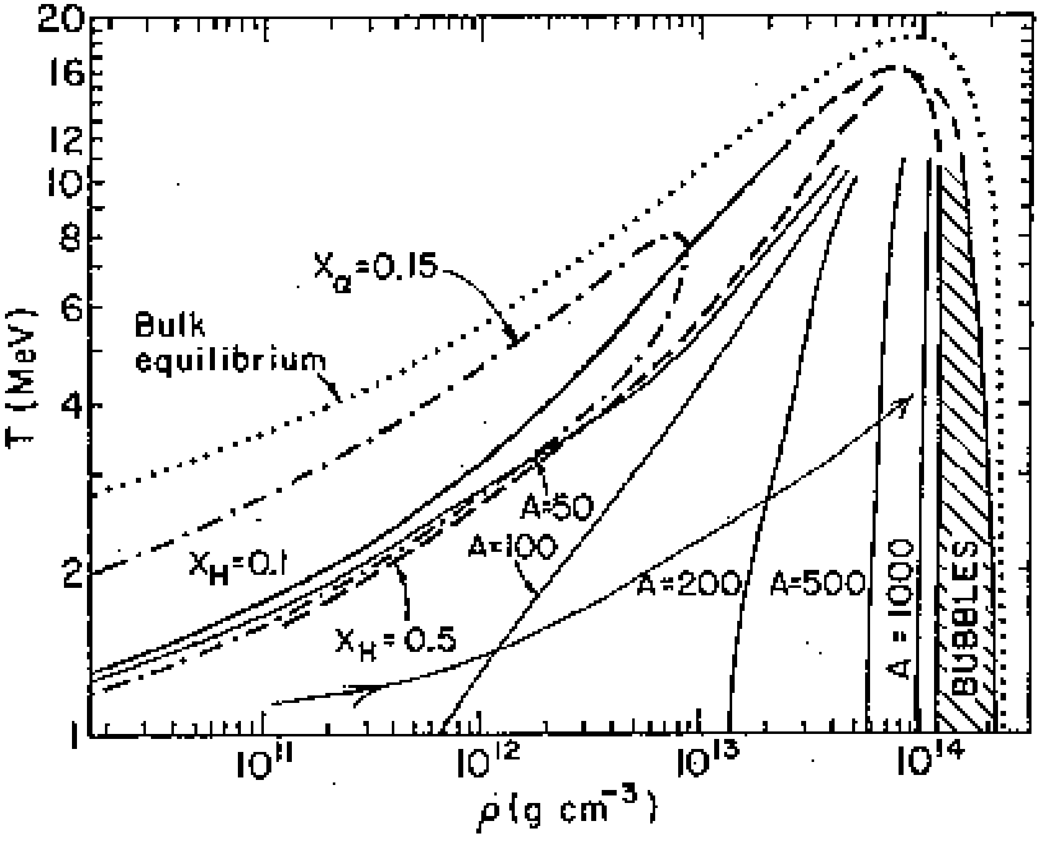


FIG. 1. Composition of hot dense matter for $Y_e=0.25$. For comparison, the dotted curve shows the boundary of the two-phase region for bulk equilibrium.

During the collapse many hot and exotic nuclei are produced. This influences the dynamics of the collapse and formation of proto-neutron star.

H.-T. Janka et al. astro-ph/0103015

Modeling supernova explosions:

The SN explosion is a complicated dynamical process with convection of matter and local fluctuations (of energy, neutrino and nuclear density, ...). This may lead to conditions favorable for production of large nuclei.

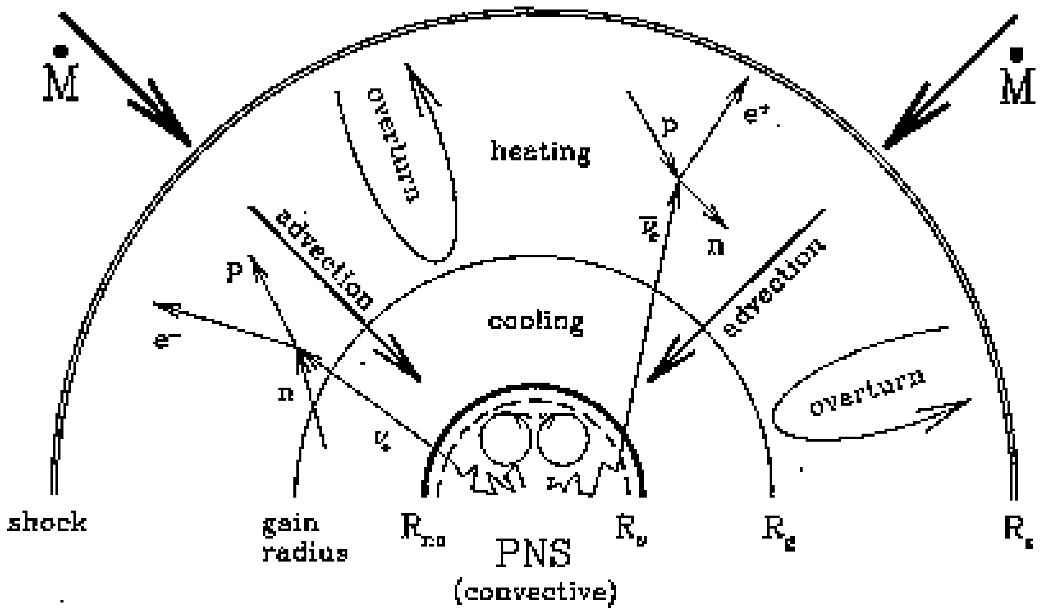


Fig. 1. Sketch of the post-collapse stellar core during the neutrino heating and shock revival phase. R_ν is the neutrinosphere radius, R_{ns} the protoneutron star radius, R_g the gain radius outside of which net neutrino heating exceeds neutrino cooling, and R_s is the shock radius. The shock expansion is impeded by mass infall at a rate $\dot{M}$, but supported by convective energy transport from the region of strongest neutrino heating into the post-shock layer. Convection inside the nascent neutron star raises the neutrino luminosities.

Development of the statistical multifragmentation model (SMM).

Grand Canonics: density of fragments with mass A and charge Z in nuclear matter

$$\langle \rho_{AZ} \rangle = g_{AZ} \frac{V_f}{V} \frac{A^{3/2}}{\lambda_T^3} \exp\left[-\frac{1}{T} \left(F_{AZ} - \mu A - \xi Z \right) \right] \qquad (1)$$

Total density $\rho = M/V = \Sigma \langle \rho_{AZ} \rangle$, M is number of nucleons and V is volume of the system. The 'free' volume $V_f \approx V$.

g_{AZ} is the degeneracy of fragments, $\lambda_T = \left((2\pi\hbar^2)/(m_N T) \right)^{1/2}$ is the nucleon thermal wavelength.

μ and ξ are the chemical potentials for the nucleon number and charge conservation in the system.

Free energy of fragments:

$$F_{AZ} = F^B_{AZ} + F^S_{AZ} + E^C_{AZ} + E^{sym}_{AZ}$$

Bulk energy: $F^B_{AZ} = (-W_0 - T^2/\epsilon_0)A$,
$W_0 = 16$ MeV is the binding energy of nuclear matter, and
$\epsilon_0 = 16$ MeV is the inverse level density.

Surface energy: $F^S_{AZ} = B_0 A^{2/3} ((T_c^2 - T^2)/(T_c^2 + T^2))^{5/4}$,
$B_0 = 18$ MeV is the surface coefficient, and $T_c = 18$ MeV is the critical temperature of nuclear matter.

Coulomb energy: $E^C_{AZ} = cZ^2/A^{1/3}$,
in the Wigner-Seitz in the case of electro-neutrality
$c = (3/5)(e^2/r_0)(1 - 1.5(\rho/\rho_0)^{1/3} + 0.5(\rho/\rho_0))$, with r_0=1.17 fm.

Symmetry energy: $E^{sym}_{AZ} = \gamma(A - 2Z)^2/A$,
$\gamma = 25$ MeV is the symmetry energy parameter.

Reactions with leptons, in equilibrium:

$$e^- + p \to n + \nu_e$$
$$e^+ + n \to p + \bar{\nu}_e$$

(and inverse reactions, also with all nuclei)

Including electrons.

density of electrons: $\rho_e = \rho_{e^-} - \rho_{e^+}$

charge conservation (electro-neutrality): $\sum \rho_{AZ} Z = \rho_e$
share of electrons: $Y_e = \rho_e / \rho$

equilibrium: $\mu_e = -\xi$

Relativistic degenerate electron gas:

$$\rho_e = \frac{1}{3\pi^2} \left(\frac{\mu_e}{\hbar c}\right)^3 \left[1 + \mu_e^{-2} \left(\pi^2 T^2 - \frac{3}{2} m_e^2 c^4\right)\right]$$

Including electron neutrinos.

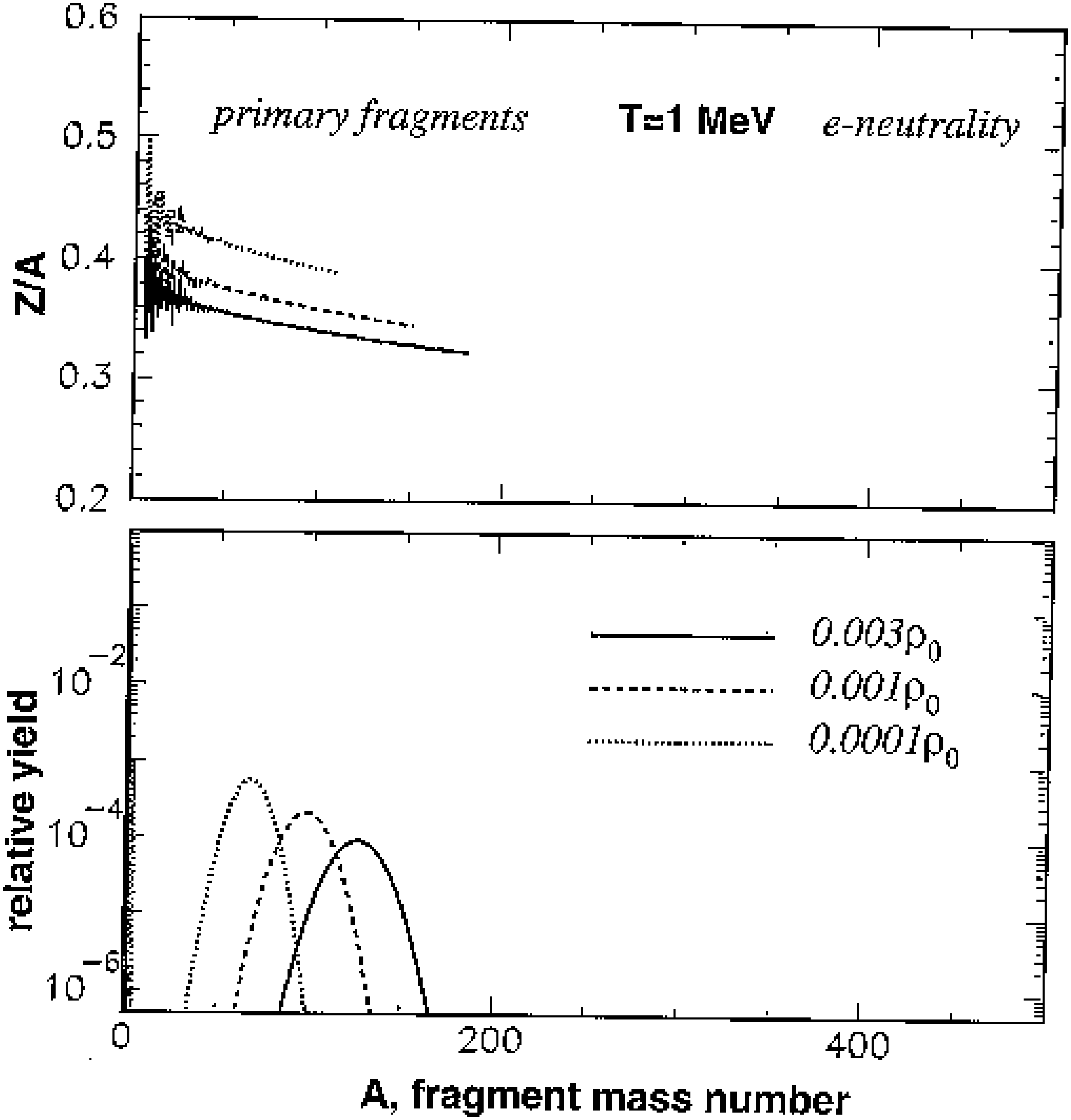
density of neutrinos: $\rho_\nu = \rho_{\nu_e} - \rho_{\bar{\nu}_e}$

conservation of leptons: $Y_{lept} = (\rho_e + \rho_\nu)/\rho = const$

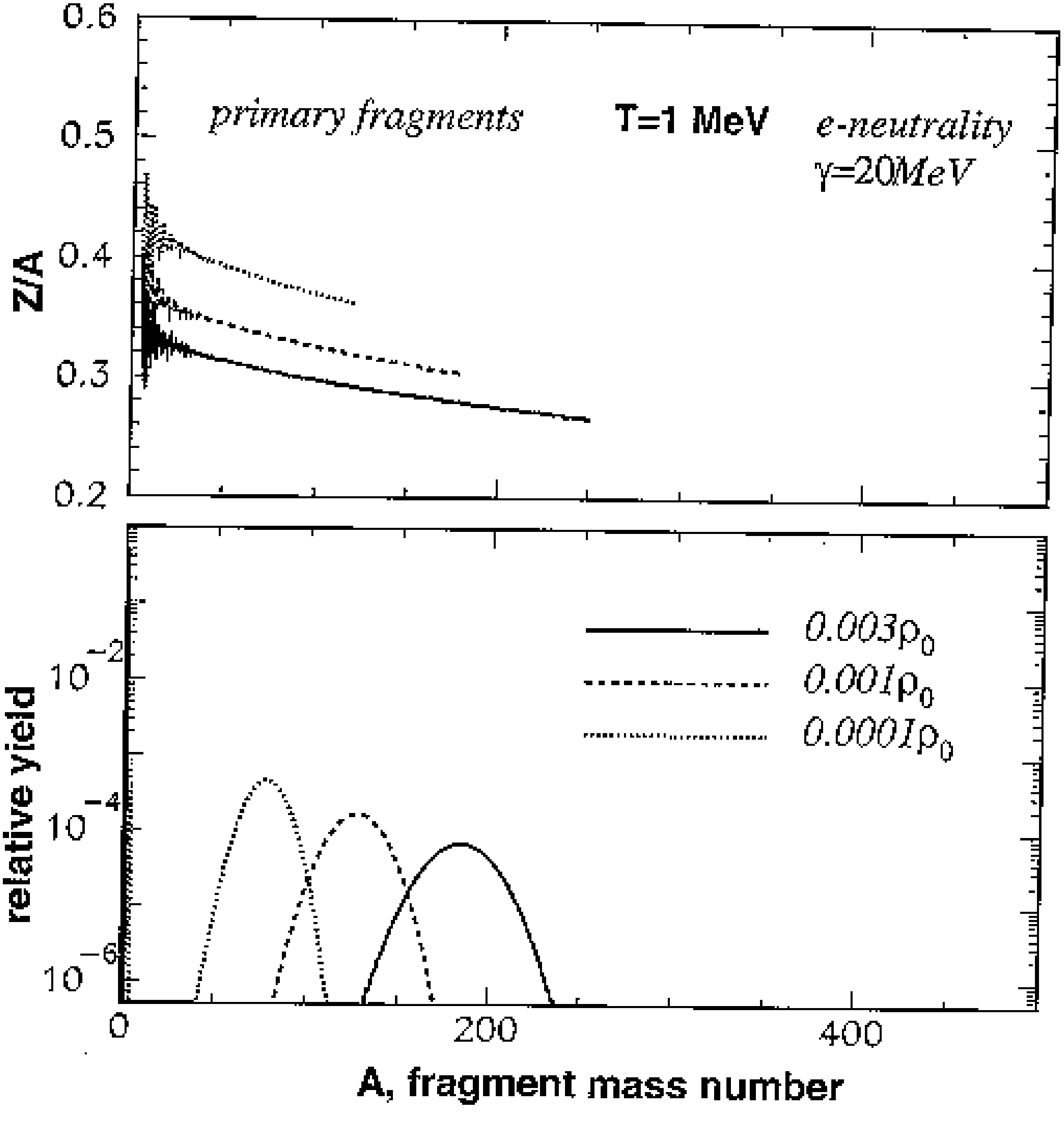
equilibrium: $\mu_e - \mu_\nu = -\xi$

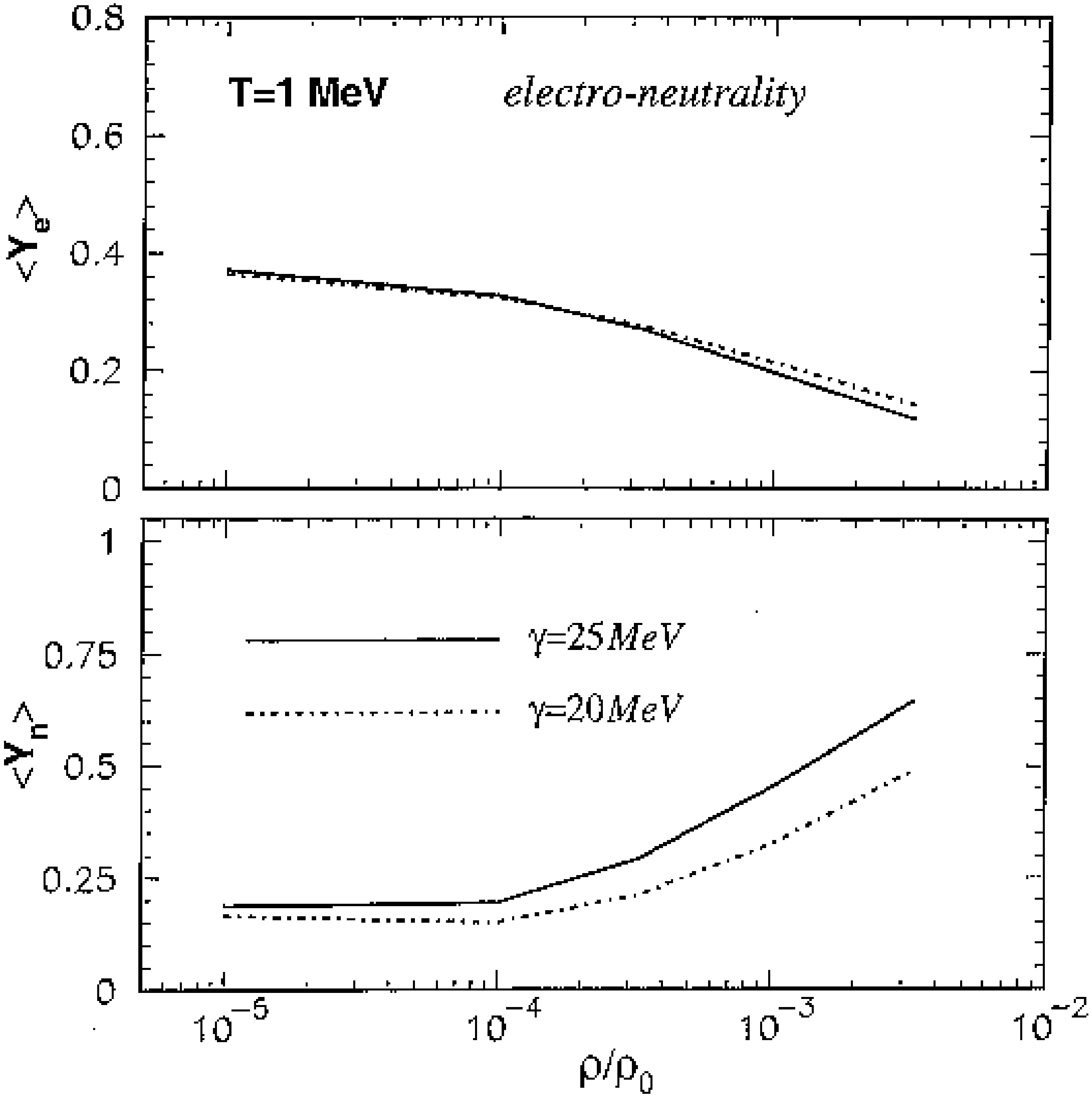
$$\rho_\nu = \frac{1}{6\pi^2} \left(\frac{\mu_\nu}{\hbar c}\right)^3 \left[1 + \mu_\nu^{-2} \pi^2 T^2\right]$$

Self-consistent calculation of all densities ρ_{AZ}, ρ_e, and ρ_ν !

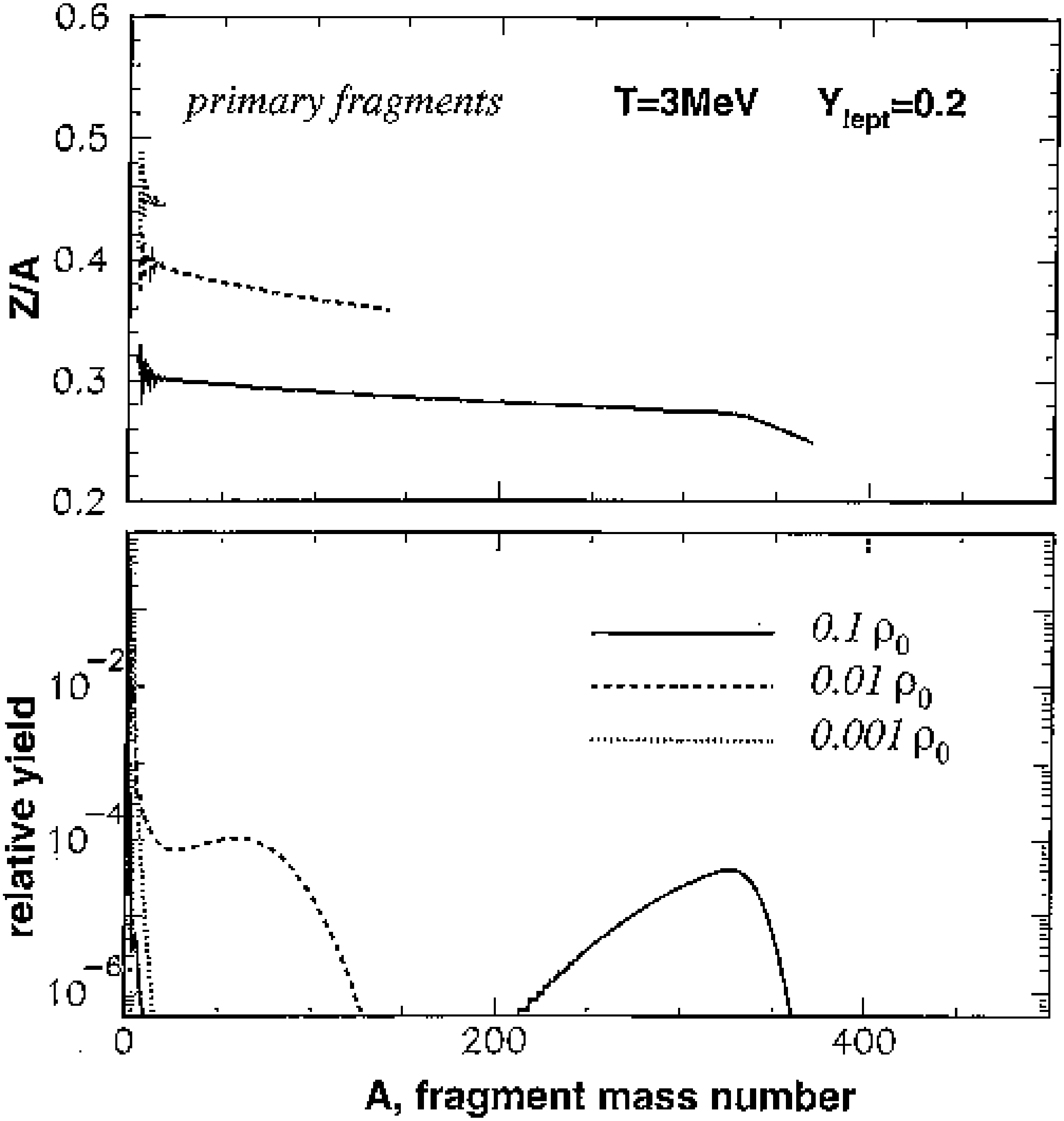


primary fragments
T=1 MeV
e-neutrality
Z/A
0.6
0.5
0.4
0.3
0.2
relative yield
10^{-2}
10^{-4}
10^{-6}
$0.003\rho_0$
$0.001\rho_0$
$0.0001\rho_0$
0
200
400
A, fragment mass number

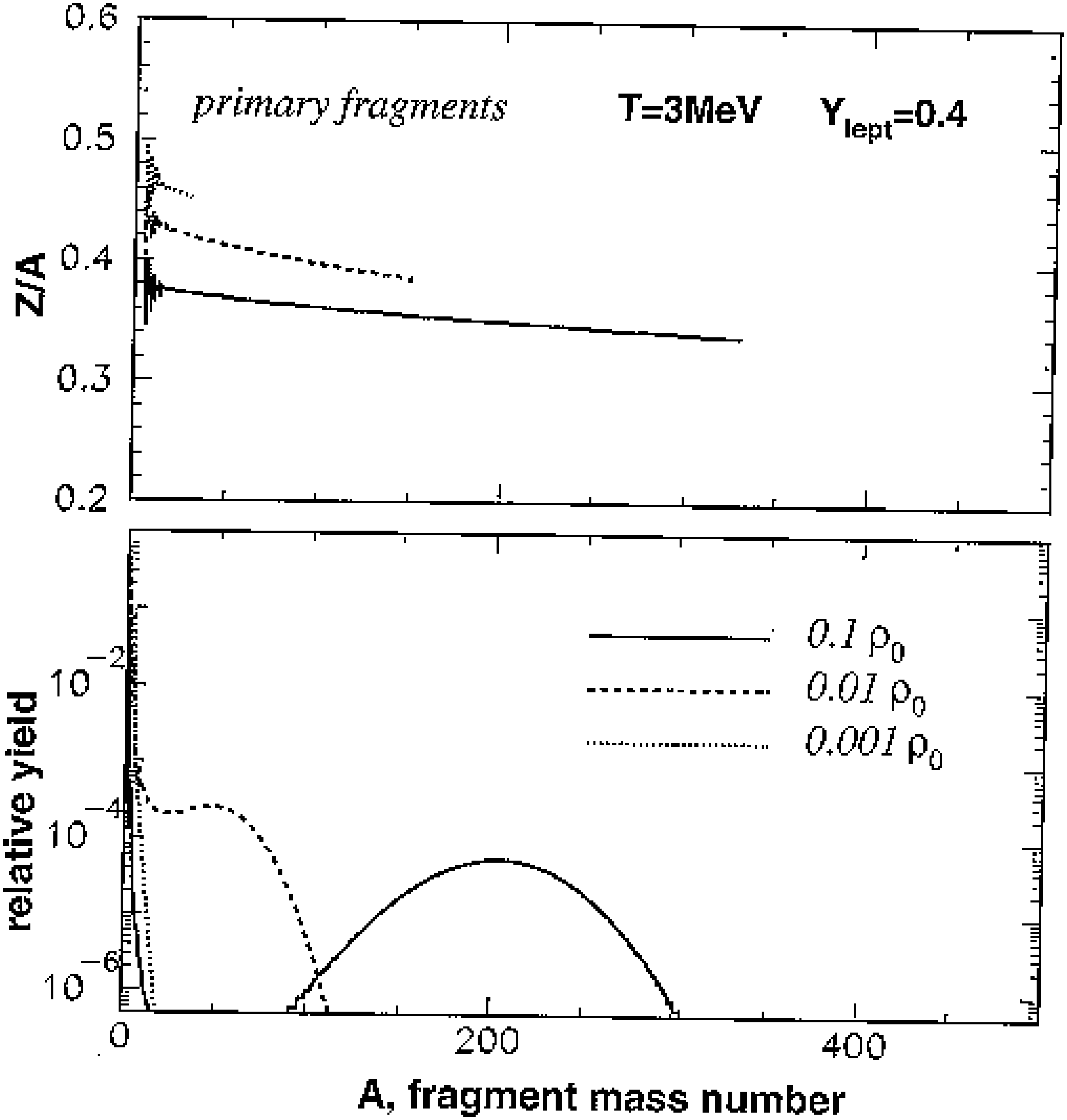

primary fragments
T=1 MeV
e-neutrality
γ=20MeV
Z/A
0.2
0.3
0.4
0.5
0.6
relative yield
10^{-2}
10^{-4}
10^{-6}
$0.003\rho_0$
$0.001\rho_0$
$0.0001\rho_0$
0
200
400
A, fragment mass number



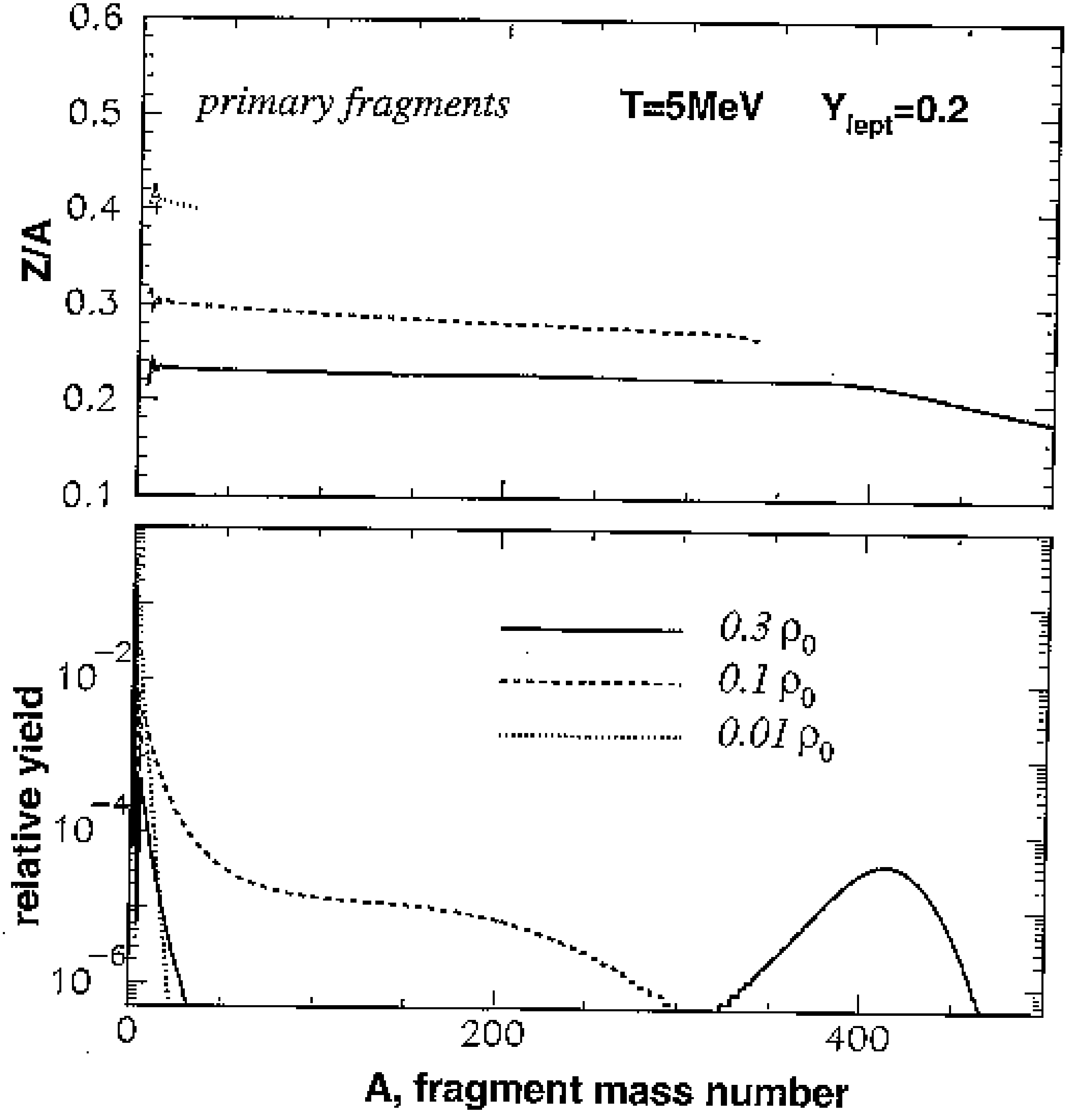
T=1 MeV
electro-neutrality
<Y_e>
0.8
0.6
0.4
0.2
0
<Y_n>
1
0.75
0.5
0.25
0
γ=25MeV
γ=20MeV
10^{-5}
10^{-4}
10^{-3}
10^{-2}
ρ/ρ_0



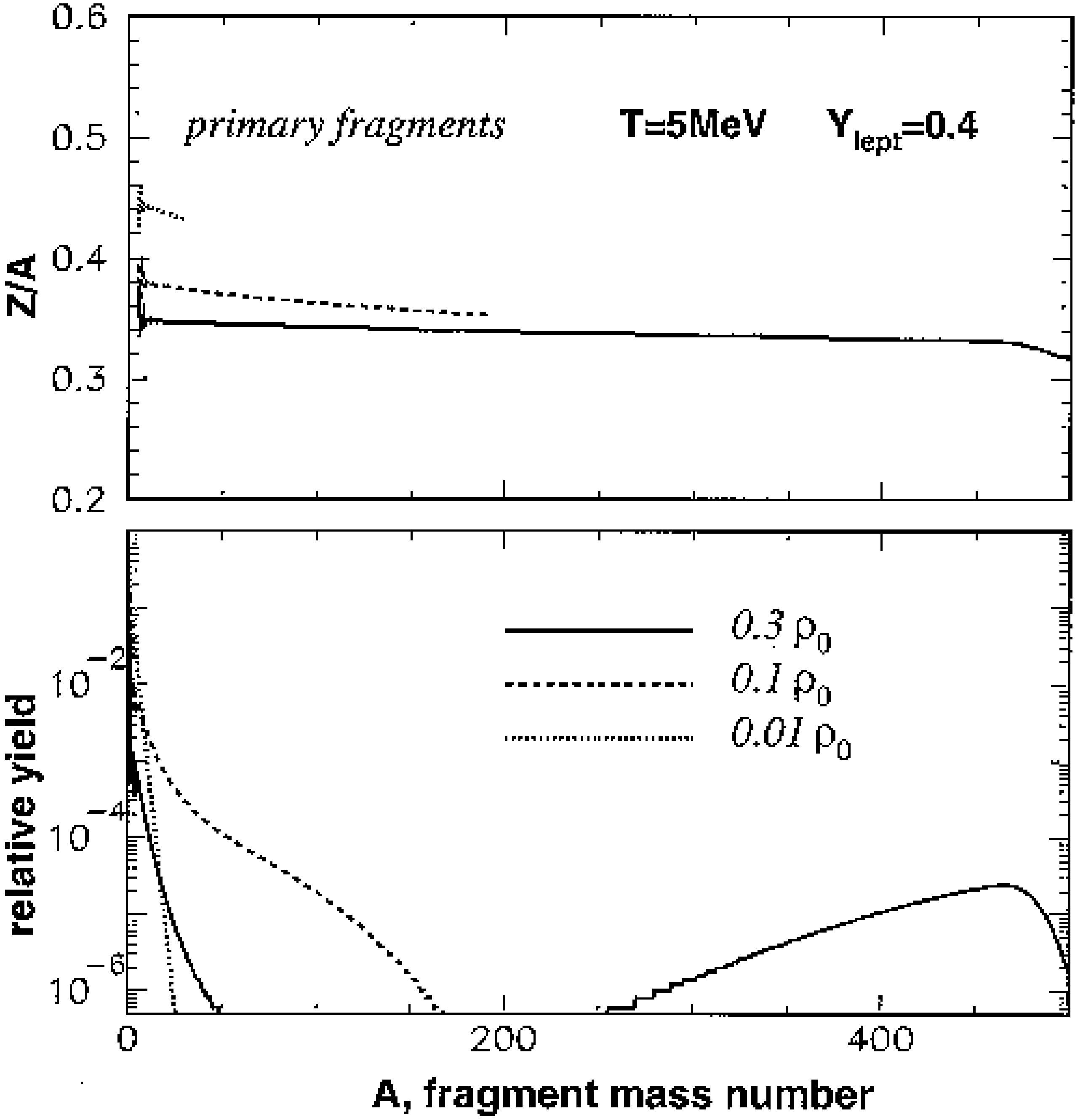
0.6
0.5
0.4
0.3
0.2
Z/A
primary fragments
T=3MeV
Y_{lept}=0.2
10^{-2}
10^{-4}
10^{-6}
relative yield
$0.1\ \rho_0$
$0.01\ \rho_0$
$0.001\ \rho_0$
0
200
400
A, fragment mass number

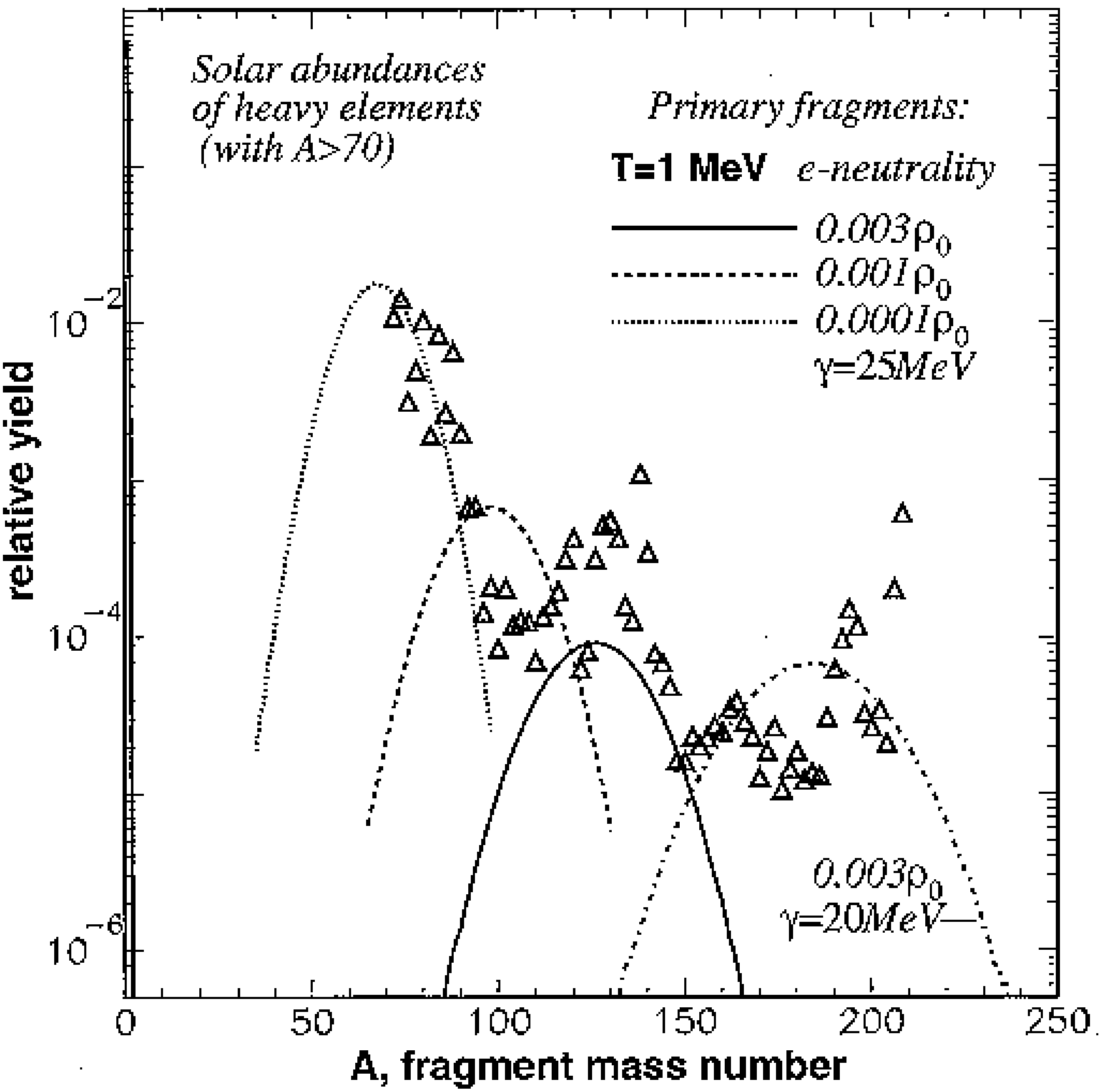


primary fragments
T=3MeV
Y_{lept}=0.4
Z/A
0.6
0.5
0.4
0.3
0.2
relative yield
10^{-2}
10^{-4}
10^{-6}
0.1 ρ_0
0.01 ρ_0
0.001 ρ_0
0
200
400
A, fragment mass number



primary fragments
T=5MeV
Y_{lept}=0.2
Z/A
0.6
0.5
0.4
0.3
0.2
0.1
relative yield
10^{-2}
10^{-4}
10^{-6}
0.3 ρ_0
0.1 ρ_0
0.01 ρ_0
0
200
400
A, fragment mass number


0.6
0.5
0.4
0.3
0.2
Z/A
primary fragments
T=5MeV
Y_lept=0.4
relative yield
10^-2
10^-4
10^-6
0.3 ρ_0
0.1 ρ_0
0.01 ρ_0
0
200
400
A, fragment mass number


Solar abundances
of heavy elements
(with A>70)
Primary fragments:
T=1 MeV e-neutrality
0.003ρ0
0.001ρ0
0.0001ρ0
γ=25MeV
0.003ρ0
γ=20MeV
relative yield
10−2
10−4
10−6
0
50
100
150
200
250
A, fragment mass number

Conclusions:

1. The calculations show that a broad variety of excited exotic nuclei can be produced during the gravitational collapse and explosion of a massive star.

2. Production of these nuclei influences the dynamics of the collapse (e.g. through the energy balance) and may be important for explanation of the following supernova explosion.

3. The explosion may also lead to an ejection of unstable exotic nuclei, which can essentially contribute to the nucleosynthesis.

4. Some properties of hot and exotic nuclei (e.g. surface and symmetry energies, and their temperature dependences) can be studied in multifragmentation reactions.