What Nuclear Multifragmentation Reactions Imply for Equation of State of Stellar Matter

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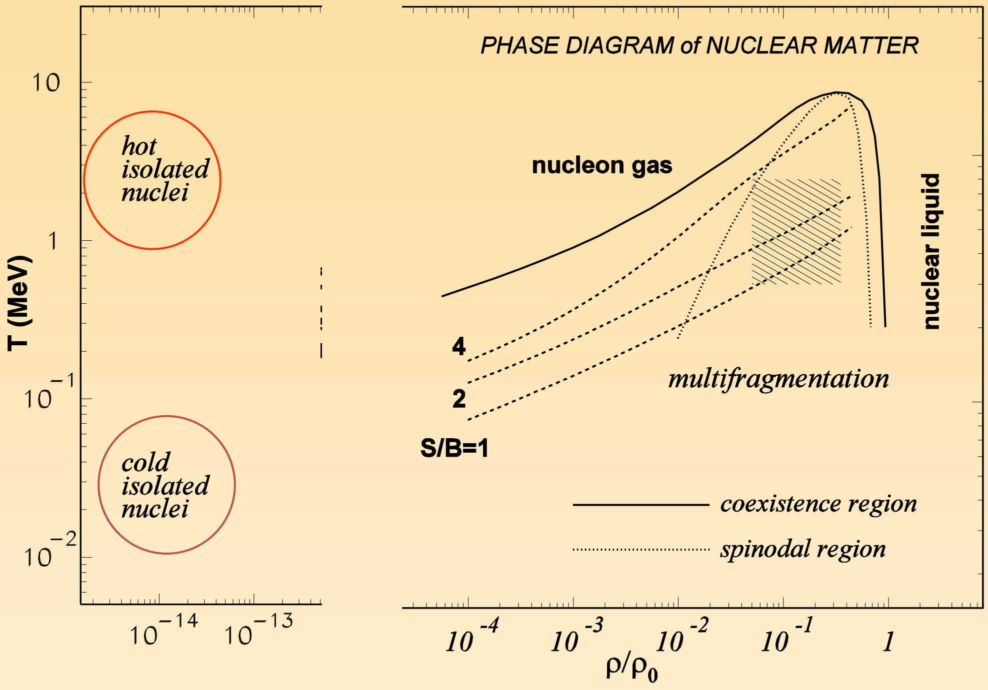
CONTENT

fragmentation of nuclear matter in nuclear reactions and astrophysical processes



Thermal multifragmentation of nuclei:

Production of hot fragments at

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

$\rho \approx 0.1\ \rho_0$

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

Interpretation: liquid-gas type phase transition in finite nuclei. A chance to investigate properties of hot fragments in dense environment of other nuclei and nucleons, which can be 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

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

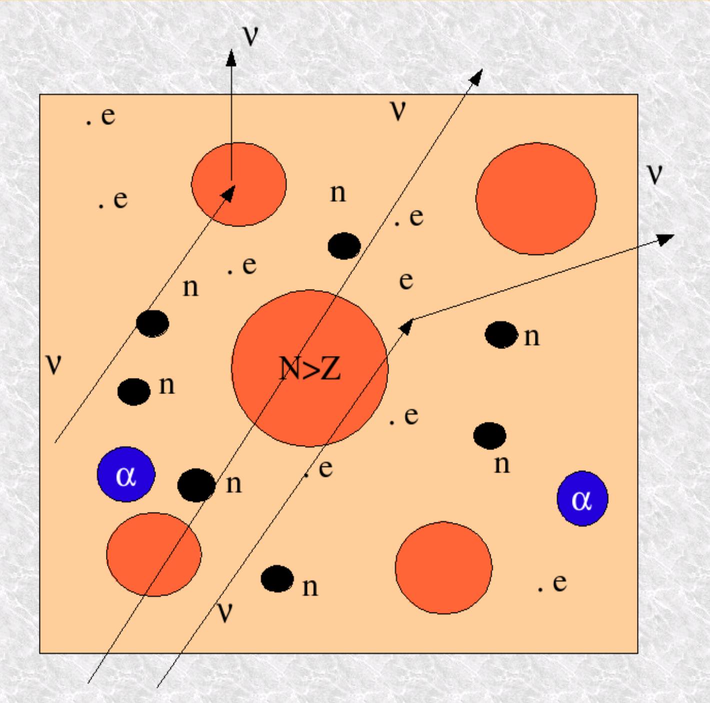
$\rho \leq 0.3\ \rho_0$

Characteristic times of the processes are very large (miliseconds), nuclear equilibrium is expected. Properties of hot fragments influence processes during the collapse and explosions.

Statistical Model for Supernova Matter (SMSM):A.S. Botvina, I.N. Mishustin, NPA 843, 98 (2010)

Statisticle ensemble

with fix T, ρ_B, $Y_{L(e)}$



Nuclei, nucleons, e,neutrinos,photons

Calculations in a box containing 1000 baryons, nuclear density fixed at ρ_0=0.15 fm^{-3}

$1 \leq A \leq 1000$ $0 \leq Z \leq A$

$$\mu_i = B_i \mu_B + Q_i \mu_Q + L_i \mu_L$$

For nuclear species (A,Z) : $\mu_{AZ} = A\mu_B + Z\mu_Q$

electrons e^- : $\mu_{e^-} = -\mu_Q + \mu_L = -\mu_{e^+}$

neutrinos ν : $\mu_\nu = \mu_L = -\mu_{\tilde{\nu}}$

Baryon number conservation :

$$\rho_B = \frac{B}{V} = \sum_{(A,Z)} A\langle n_{AZ}\rangle \text{ fixed} \quad \rightarrow \quad \mu_B$$

Electric neutrality

$$\rho_Q = \frac{Q}{V} = \sum_{(A,Z)} Z\langle n_{AZ}\rangle - n_e = 0 \quad \rightarrow \quad \mu_Q$$

Lepton number conservation

$$Y_L = \frac{L}{B} = \frac{n_e + n_\nu}{\rho_B} \text{ (trapped } \nu\text{) or } Y_e = \frac{n_e}{\rho_B} \text{ (free } \nu\text{)}$$

A.S.Botvina and I.N.Mishustin, Phys.Lett. B584, 233 (2004); Phys.Rev. C72, 048801 (2005)

Statistical Model for Supernova Matter:SMSM

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

$$\langle\rho_{AZ}\rangle = g_{AZ}(1-\frac{\rho}{\rho_0})\frac{A^{3/2}}{\lambda_T^3}\exp\left[-\frac{1}{T}(F_{AZ}-\mu_A-\xi_Z)\right]$$

Total density $\rho = M/V = \sum\langle\rho_{AZ}\rangle$, M is number of nucleons and V is volume of the system. g_{AZ} is the degeneracy of fragments, the nucleon thermal wavelenght is

$$\lambda_T = (2\pi\hbar^2/m_N T)^{1/2}$$

μ and ξ are the chemical potentials for the nucleon number and charge conservation in the system. Free energy of fragments :

$$F_{AZ}(T,\rho) = F_{AZ}^B + F_{AZ}^S + F_{AZ}^C + F_{AZ}^{sym}$$

Bulk energy:

$$F_{AZ}^B(T) = \left(-w_0 - \frac{T^2}{\varepsilon_0}\right)A, \qquad \omega_0 = 16MeV \quad \varepsilon_0 = 16MeV$$

Surface energy:

$$F_{AZ}^S(T) = \beta_0\left(\frac{T_c^2 - T^2}{T_c^2 + T^2}\right)^{5/4} A^{2/3} \qquad \beta_0 = 18MeV$$

Coulomb energy:

$$F_{AZ}^C(\rho) = \frac{3}{5}c(\rho)\frac{(eZ)^2}{r_0 A^{1/3}} \qquad c(\rho) = \left[1-\frac{3}{2}\left(\frac{\rho_e}{\rho_{0p}}\right)^{1/3} + \frac{1}{2}\left(\frac{\rho_e}{\rho_{0p}}\right)\right]$$

Symmetry energy:

$$F_{AZ}^{sym} = \gamma\frac{(A-2Z)^2}{A} \qquad \gamma = 25MeV$$

Reactions with leptons, in equilibrium:

$$e^- + p \rightarrow n + \upsilon_e$$

$$e^+ + n \rightarrow p + \bar{\upsilon}_e$$

(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

$$\rho_e = \frac{g_e}{6\pi^2}\left[\mu_e^3 + \mu_e\left(\pi^2 T^2 - \frac{3}{2}m_e^2\right)\right]$$

Including electron neutrinos

Density of neutrinos $\rho_{\upsilon e} = \rho_{\upsilon e} - \rho_{\bar{\upsilon} e}$

Conservation of leptons $Y_{lept} = (\rho_e + \rho_\upsilon)/\rho = \text{const}$

$$\mu_e - \mu_\upsilon = -\xi$$

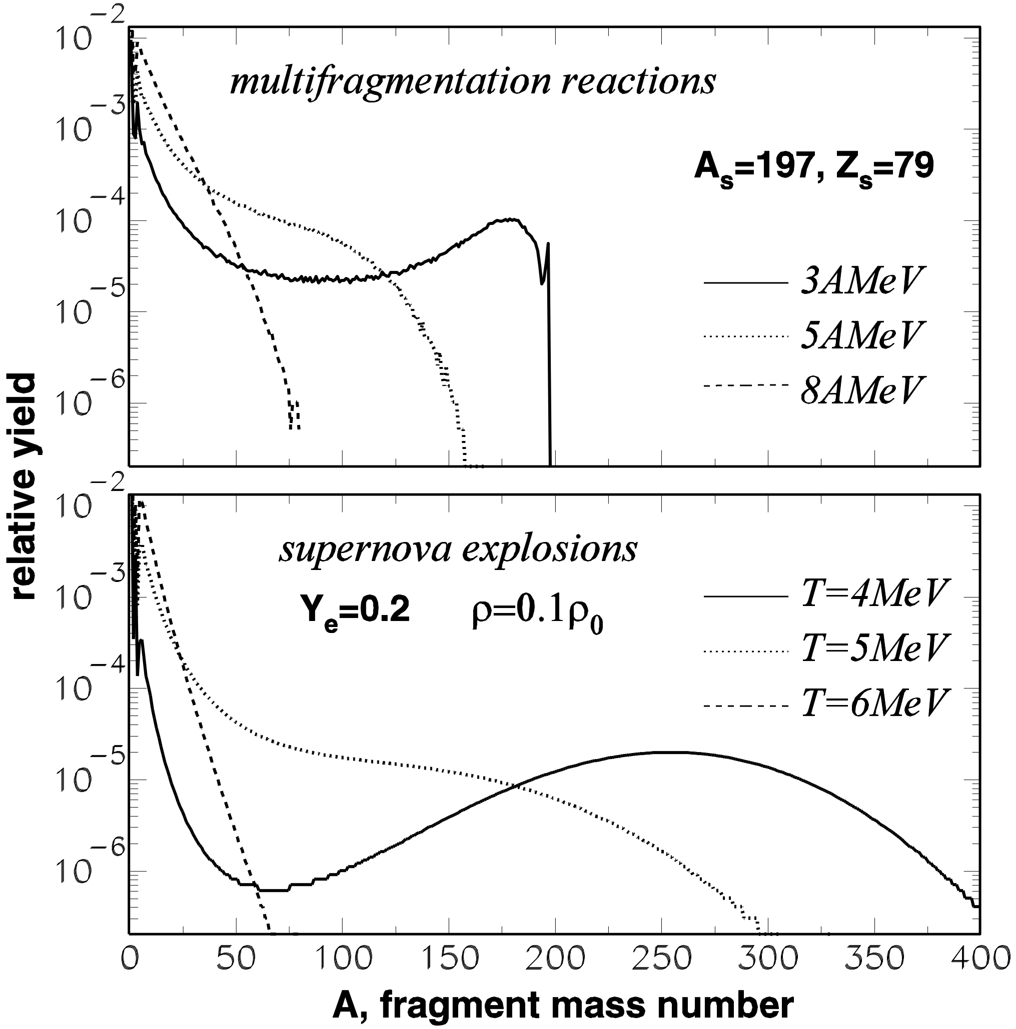
Equilibrium

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

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

+ including photons

Production of nuclear fragments in multifragmentation and supernova explosions



SMM

Variation of mass distribution with T and E*

U-shape
Power law
Exponential

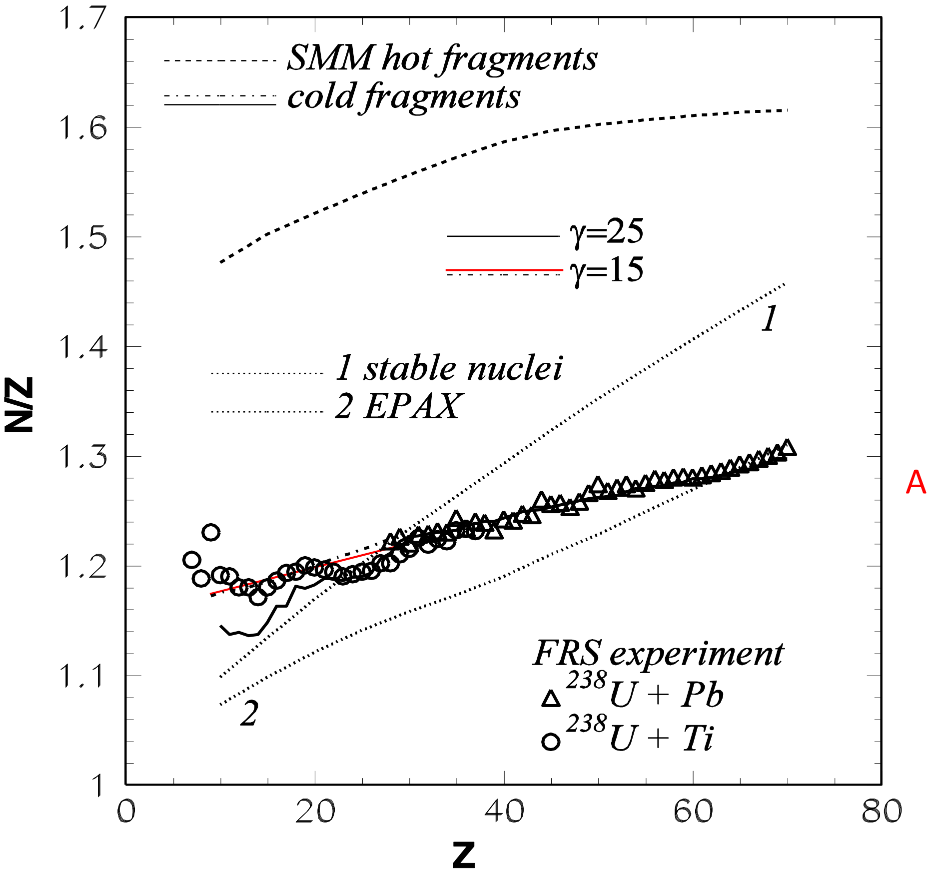
SMSM

Investigation of the symmetry energy term

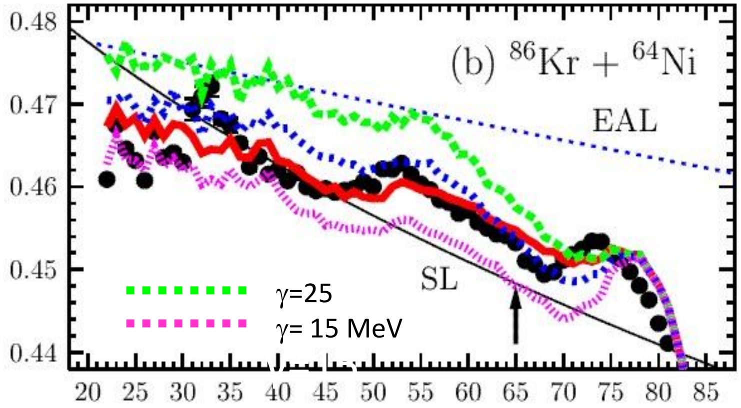
The symmetry energy coefficient γ was investigated in several independent experiments, which use both the isoscaling phenomenon and isotope distributions of fragments.

$$F_{AZ}^{sym} = \gamma(A-2Z)^2 / A,$$

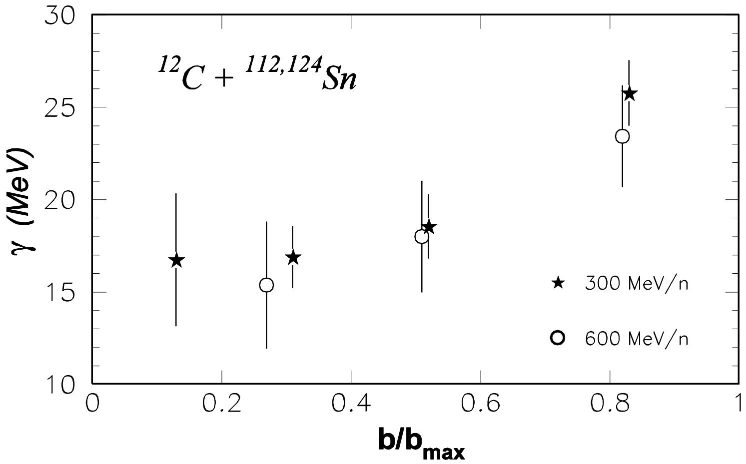
A.S.Botvina et al., PRC72(2005)048801



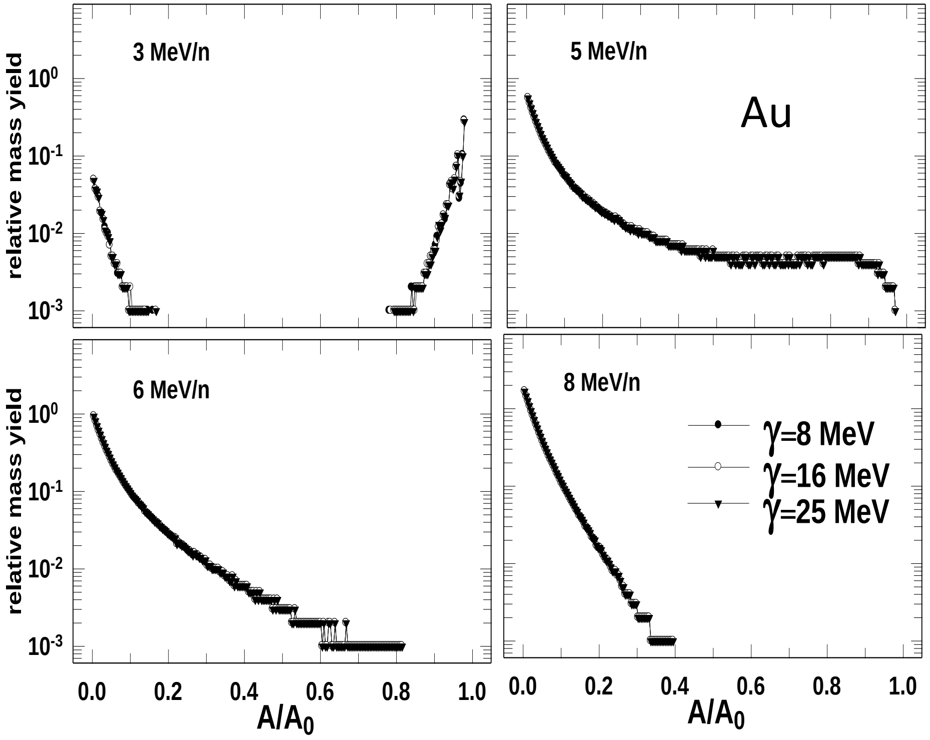
G.Souliotis et al., PRC75(2007)011601

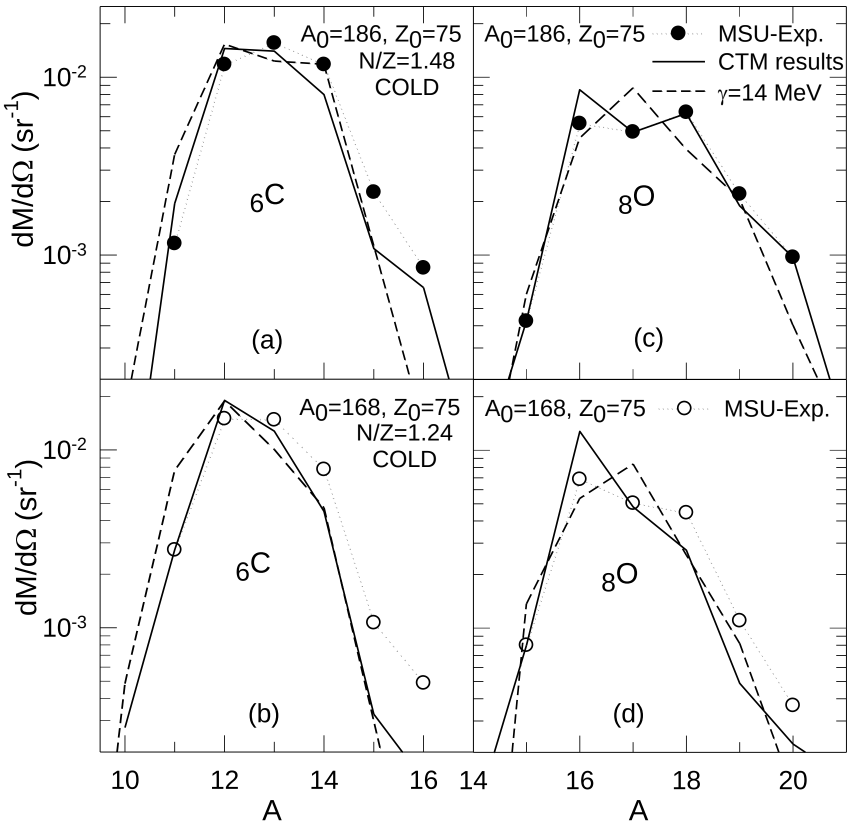


ALADIN: A. Le Fevre et al., Phys. Rev. Lett. 94, 162701 (2005).



Influence of the symmetry energy in nuclear reactions





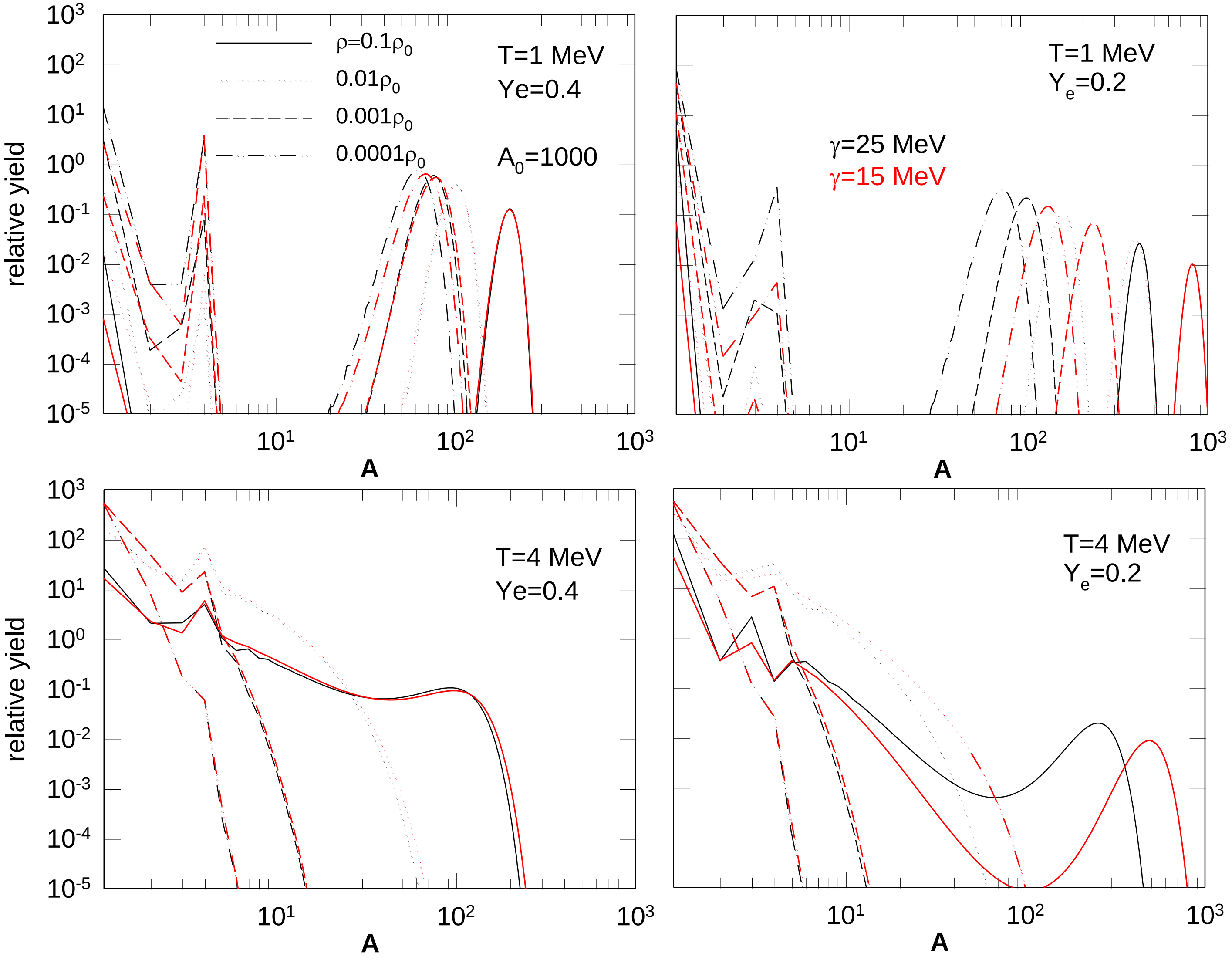
N. Buyukcizmeci, R. Ogul and A. S. Botvina, EPJ A 25, 57(2005).
A.S. Botvina, N. Buyukcizmeci, et al., Phys. Rev. C 74, 044609 (2006)

N. Buyukcizmeci, H. Imal, R. Ogul, A. S. Botvina, I.N. Mishustin
accepted J. Phys. G: Nucl. Part. Phys. 2012

MSU-:T.X. Liu, et al., *Phys. Rev. C 69, 014603 (2004).*

CTM:C.B. Das, S. Das Gupta, W. Lynch, A. Mekjian and B. Tsang,
Phys. Rep. 406, 1 (2005).

Influence of the symmetry energy term for stellar matter

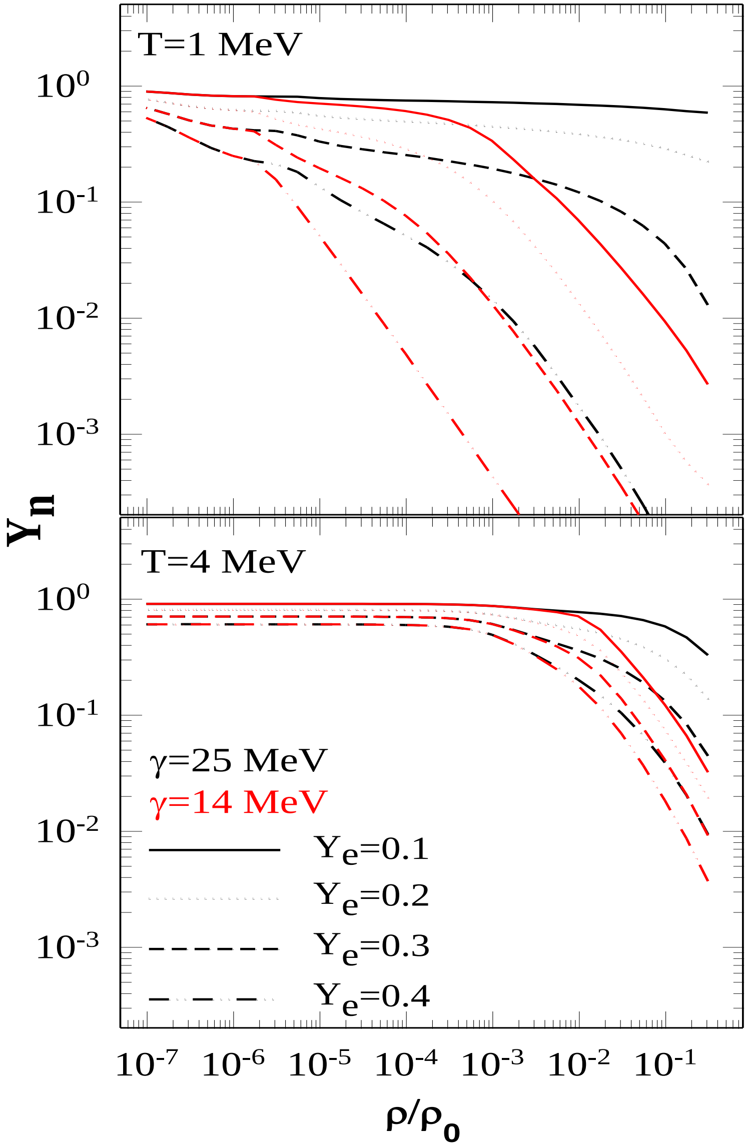


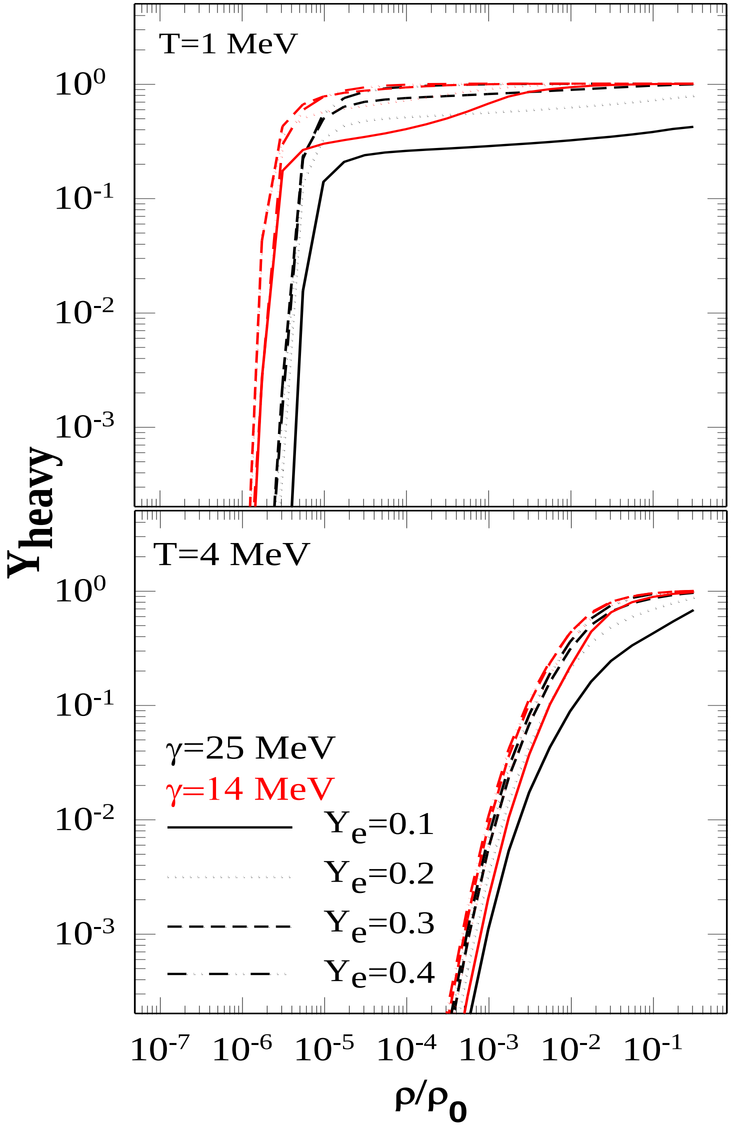
Ye=0.4
No considerable difference for $\gamma=25$ and 14 MeV.

Ye=0.2
Considerable difference for $\gamma=25$ and 14 MeV.

Buyukcizmeci N., A. S. Botvina, I. N. Mishustin, R. Ogul, *Jour. Phys. Con. Ser.* **202 (2010) 012003**

Influence of the symmetry energy term on Yn and Yheavy in stellar matter



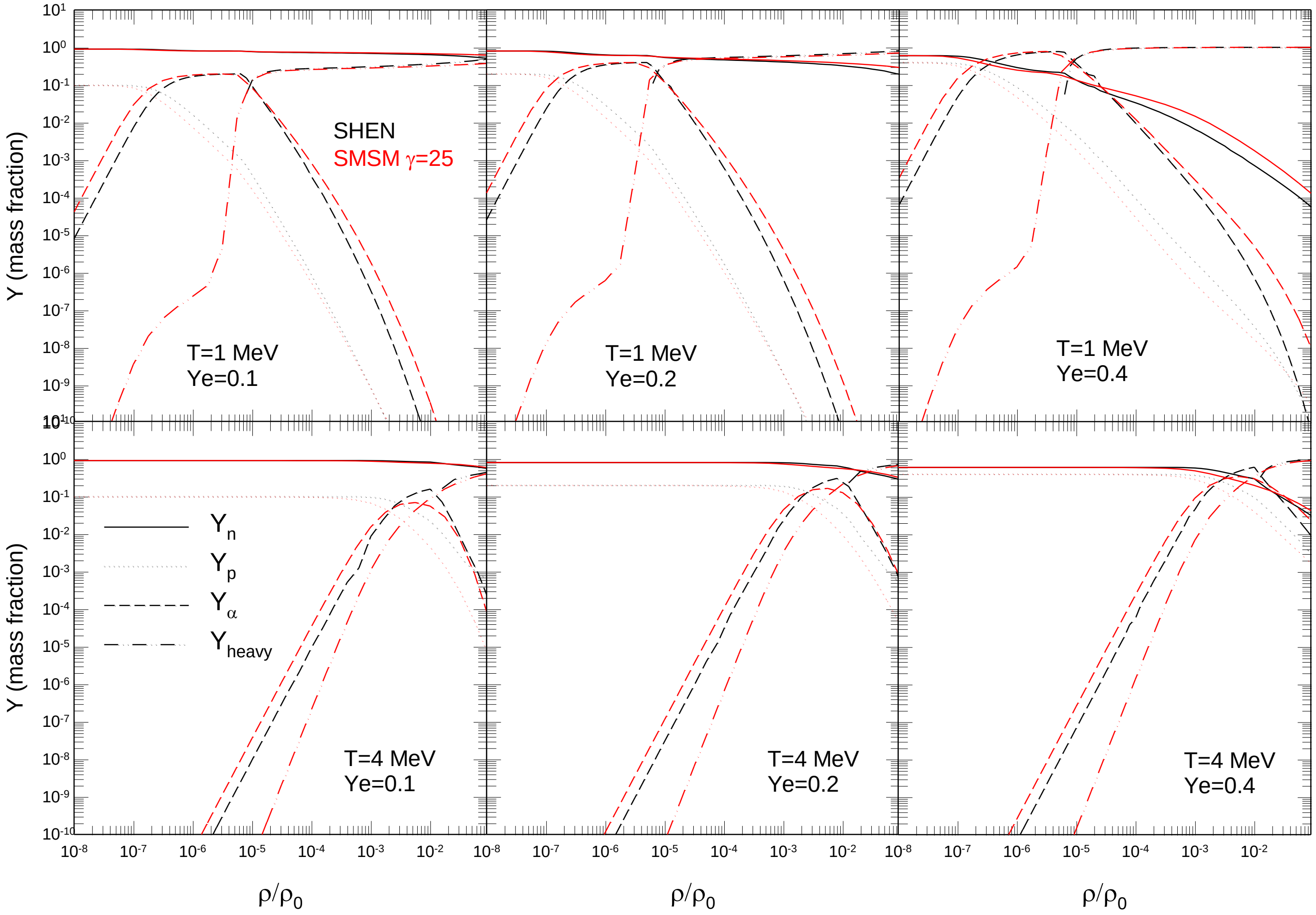


Considerable difference for γ=25 and 14 MeV.

Comparison of SMSM and SHEN EOS

SMSM : A.S. Botvina, I.N. Mishustin, NPA 843, 98 (2010)

SHEN : H.Shen, H.Toki, K.Oyamatsu, K.Sumiyoshi, Nucl. Phys. A 637 (1998) 435



One can see that two models predict similar mass fractions of neutrons, protons,alpha particles and heavy nuclei for different temperature and Ye.

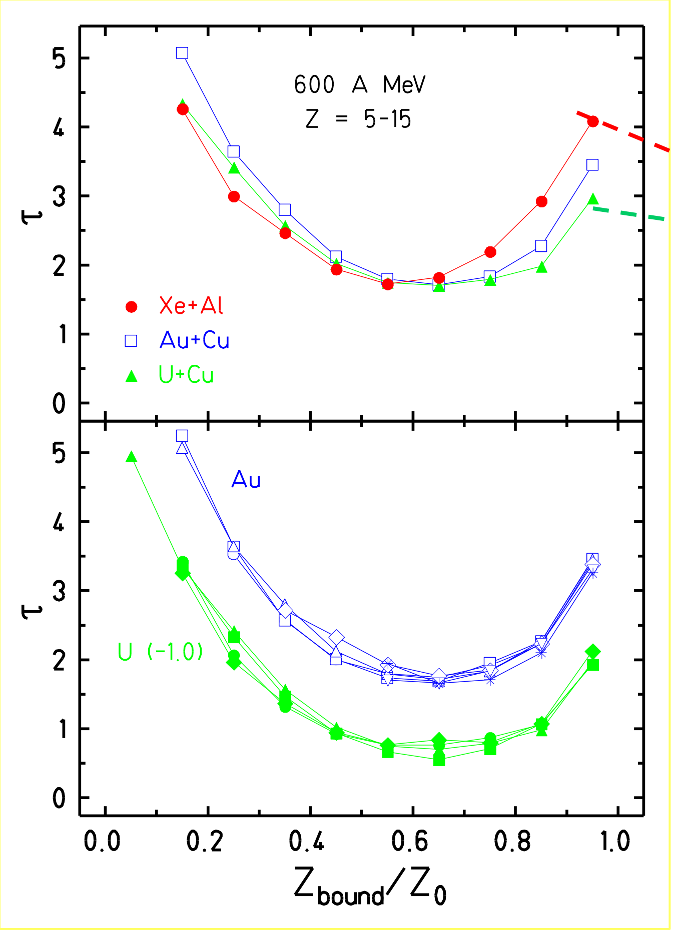
Properties of hot fragments: the surface energy term B_0

$Z^{-\tau}$ analysis of IMF yields

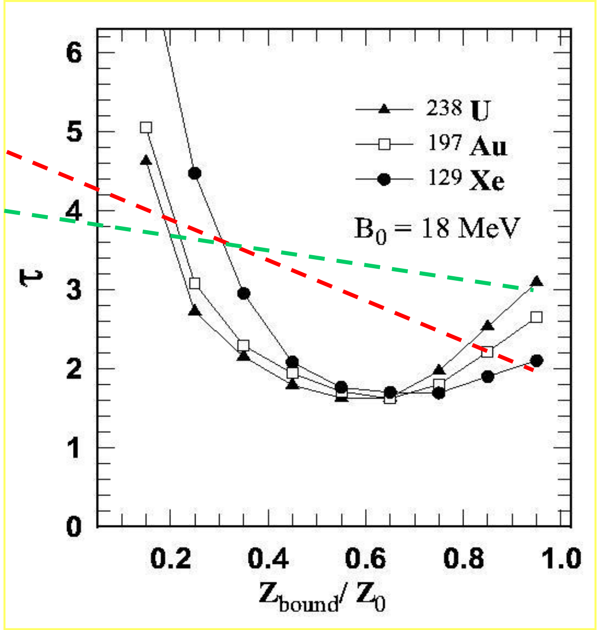
We obtain an evolution of the surface energy of hot fragments toward region of full multifragmentation

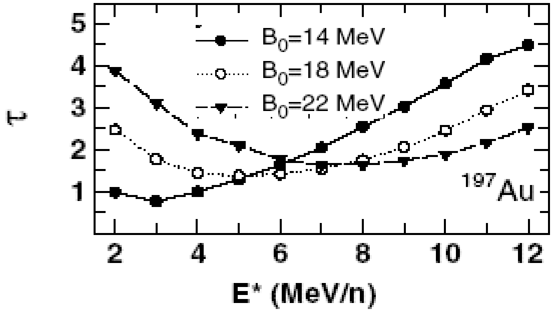
projectiles with different isospin

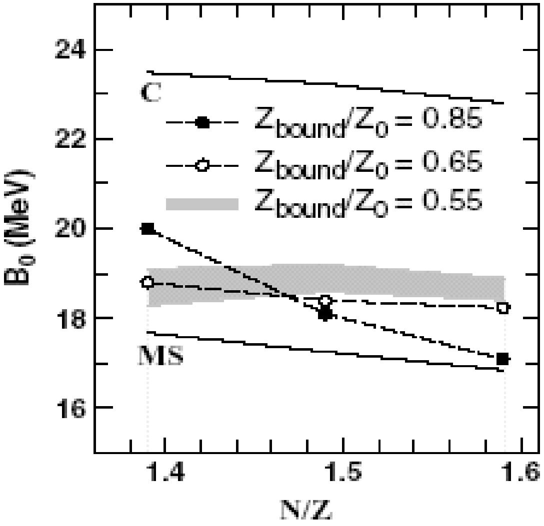
SMM



ALADIN







for single isolated nuclei:

C -- Cameron mass formula (1957)

MS -- Myers-Swiatecki mass formula (1966)

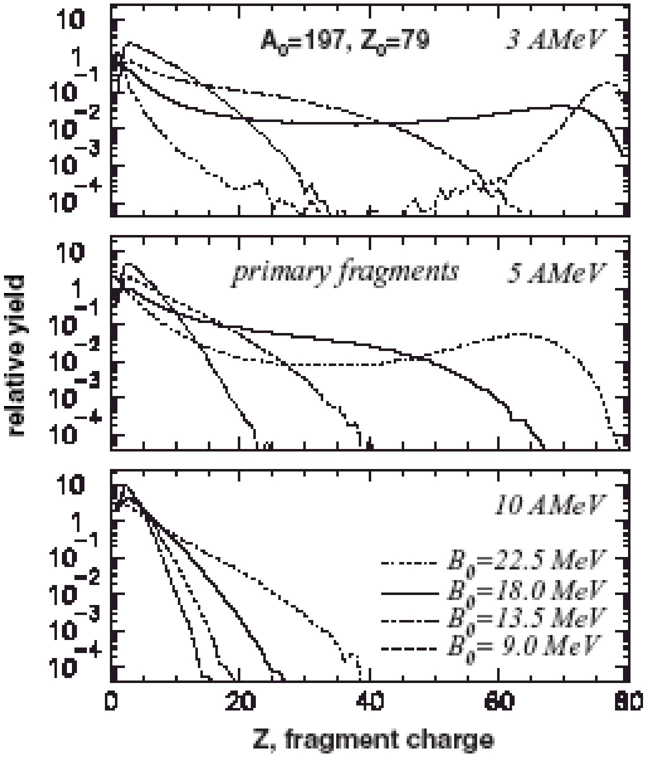
(include separate volume and surface contributions to the symmetry energy)

A.S.Botvina et al., PRC74(2006)044609

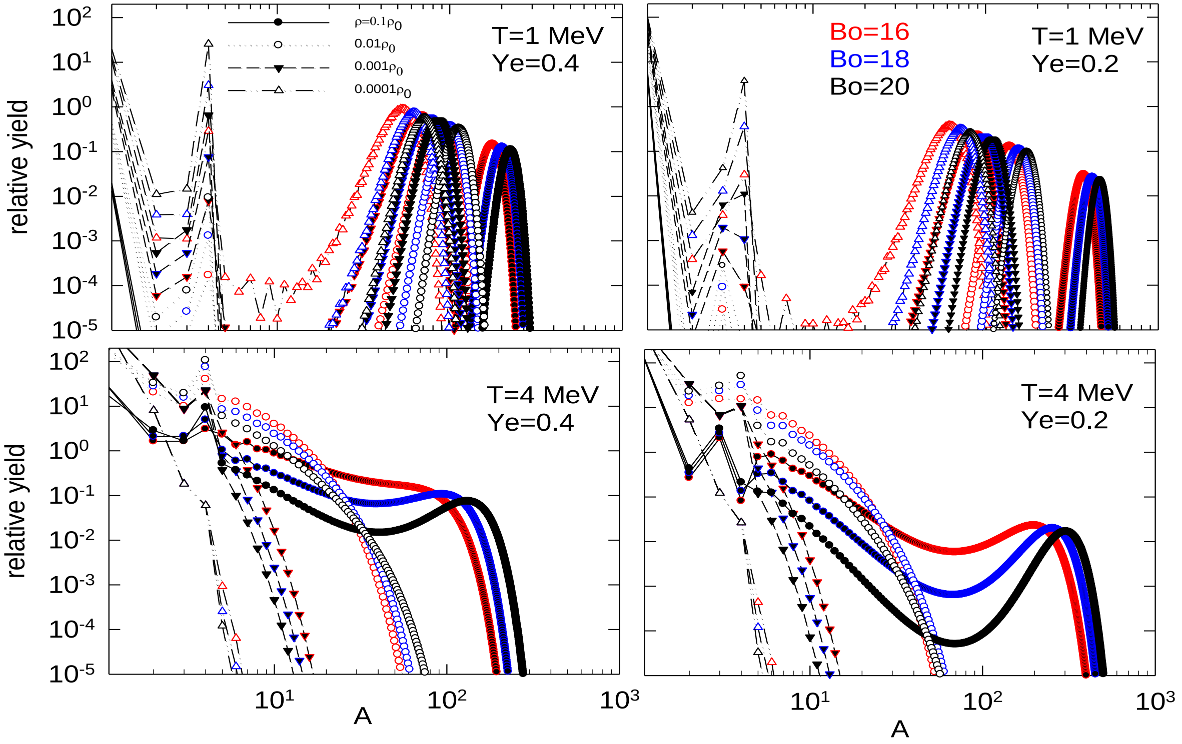
Influence of the surface energy term on mass distributions

nuclear reactions

stellar matter



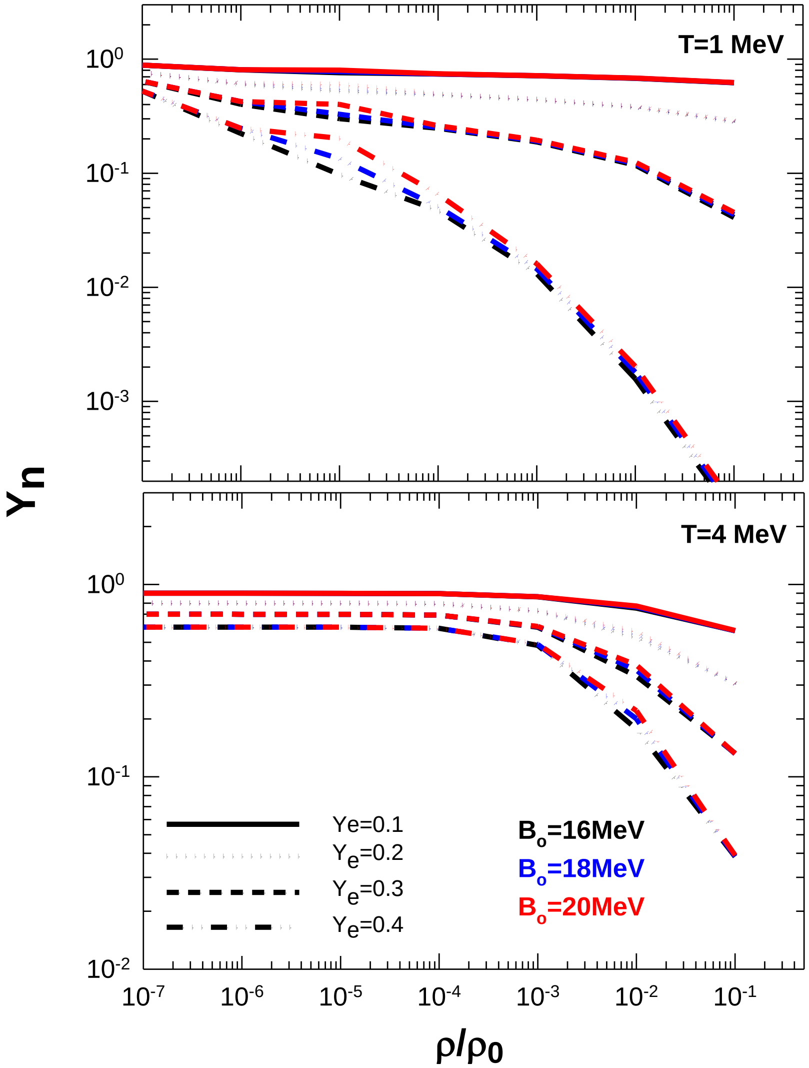
A.S.Botvina et al., PRC74(2006)044609

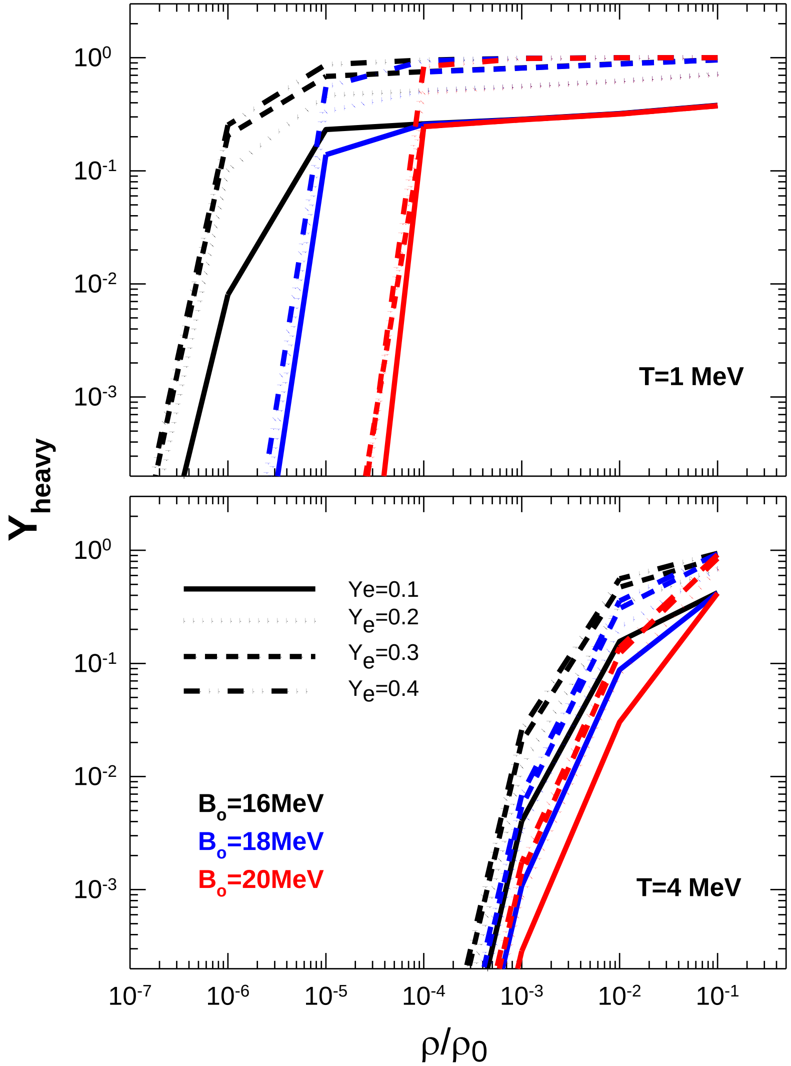


This study

Even small variations of the surface energy coefficient B0 lead to considered changing in fragment production
Similarty !

Influence of the surface energy term on Yn and Yheavy in stellar matter

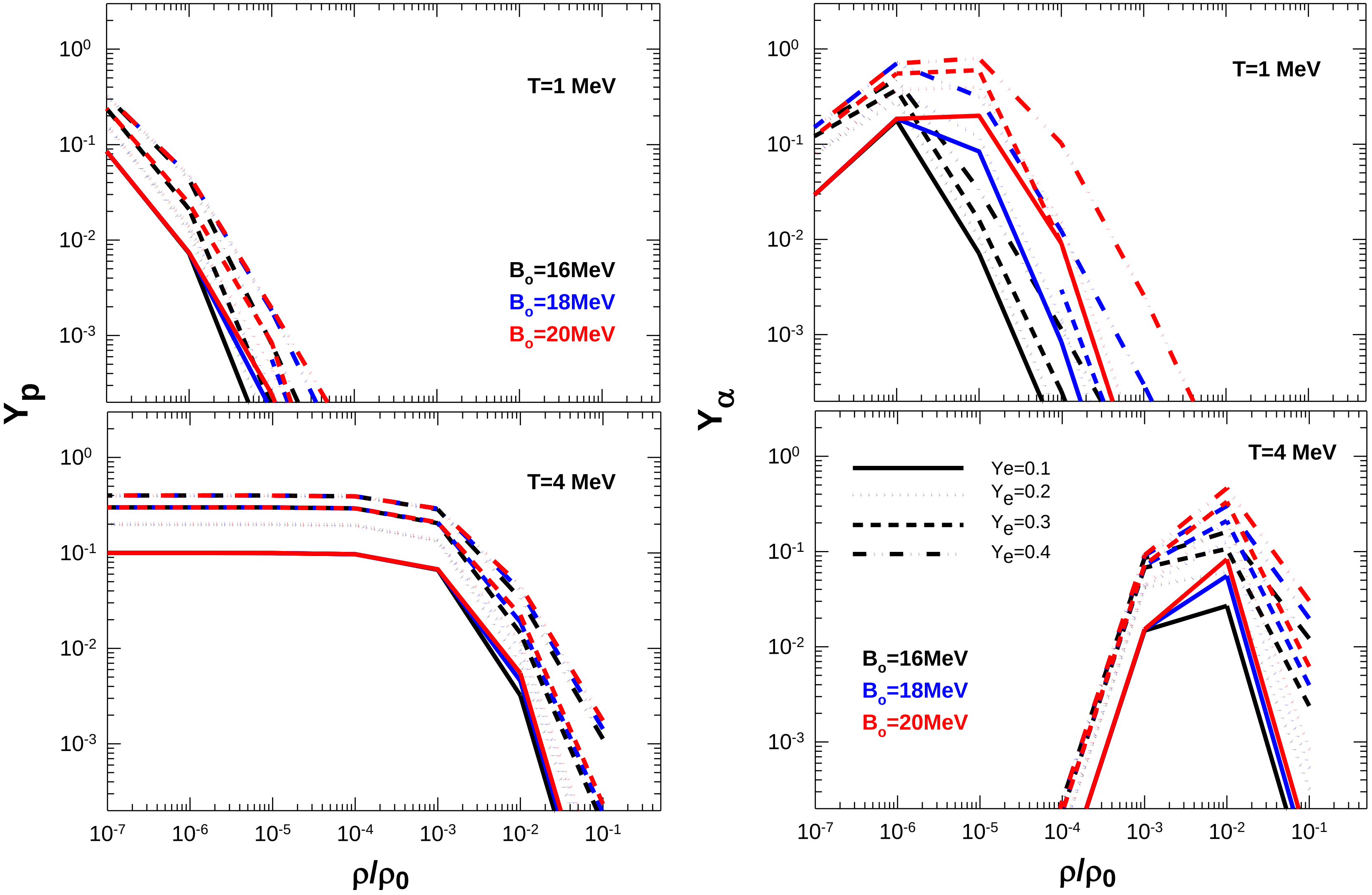




Variations of the surface energy coefficient B0 (from 16 to 20 MeV) lead to practically no effect

Even small variations of the surface energy coefficient B0 (from 18 to 20 MeV) lead to considered changing in fragment production at T=4 MeV.

Influence of the surface energy term on Yp and Yα in stellar matter



Important Results: connection of nuclear multifragmentation with astrophysics

1. Similar conditions of nuclear matter are reached in multifragmentation reactions and during the collapse and explosion of massive stars.

2. The statistical models successfully applied for nuclear multifragmentation can be generalized for astrophysical conditions. Nuclear parameters of the models, in particular, the symetry energy, can be extracted from multifragmentation experiments.

3. Broad variety of nuclear species including, exotic and neutron rich nuclei, are produced in stellar matter. Modification of the symmetry energy and surface energy of nuclei in dense hot medium is important for rates of electro-weak reactions, and for synthesis of heavy elements.