Probing the EOS of Dense Neutron-Rich Matter with High Energy Radioactive Beams

Bao-An Li
Arkansas State University

Collaborators:
Lie-Wen Chen, Vincenzo Greco and Che Ming Ko, Texas A&M University
Champak B. Das, Subal Das Gupta and Charles Gale, McGill University

Outline:

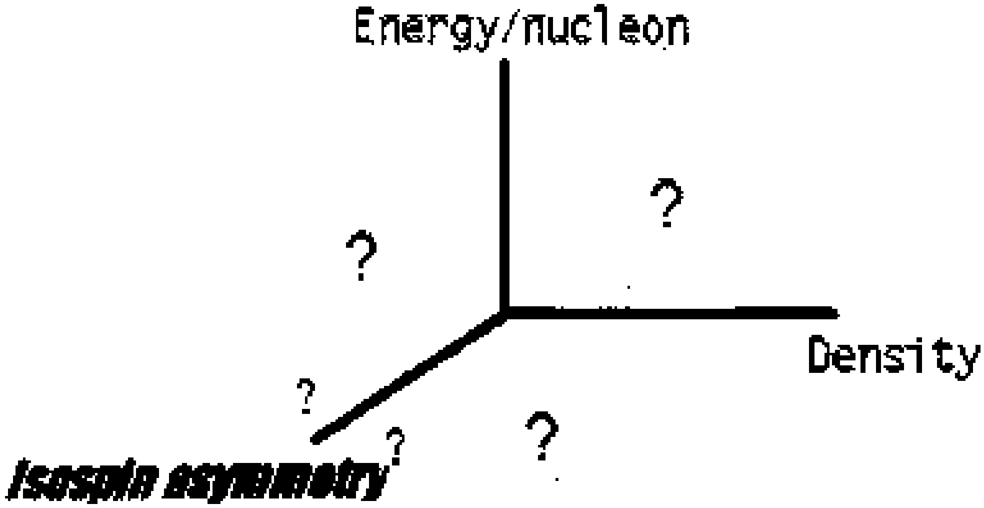
1. What is the most important issue?

2. Probes

3. A new development:
   Effects of the momentum-dependence of the symmetry potential

4. Summary

EOS of Asymmetric Nuclear Matter



Two examples: Skyrme Hartree-Fock and Relativistic Mean Field

K. Oyamatsu, I. Tanihata, Y. Sugahara, K. Sumiyoshi and H. Toki, NPA 634 (1998) 3.

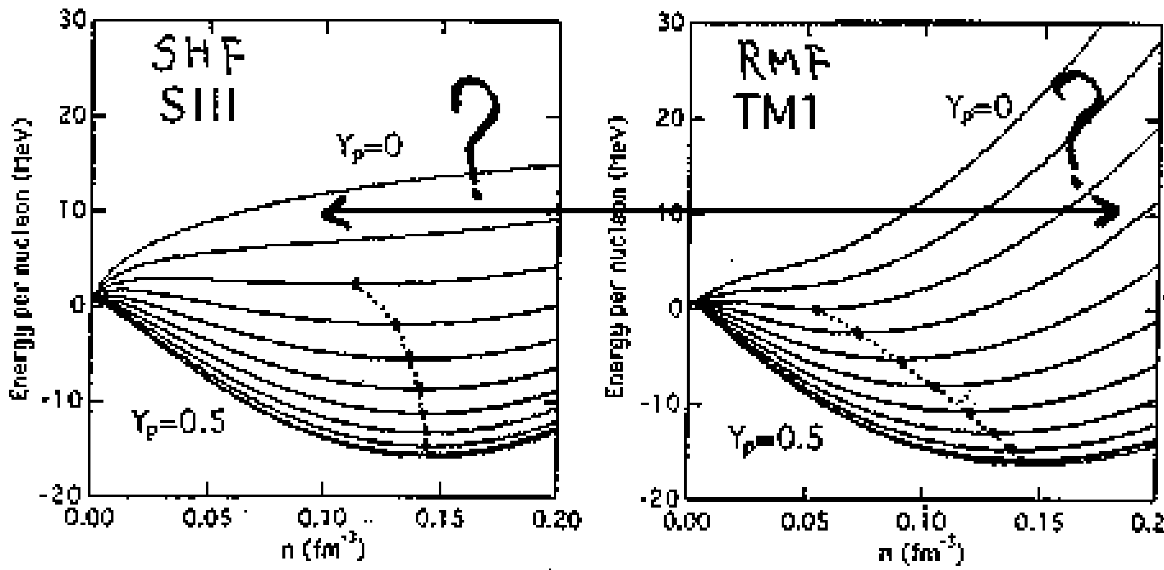
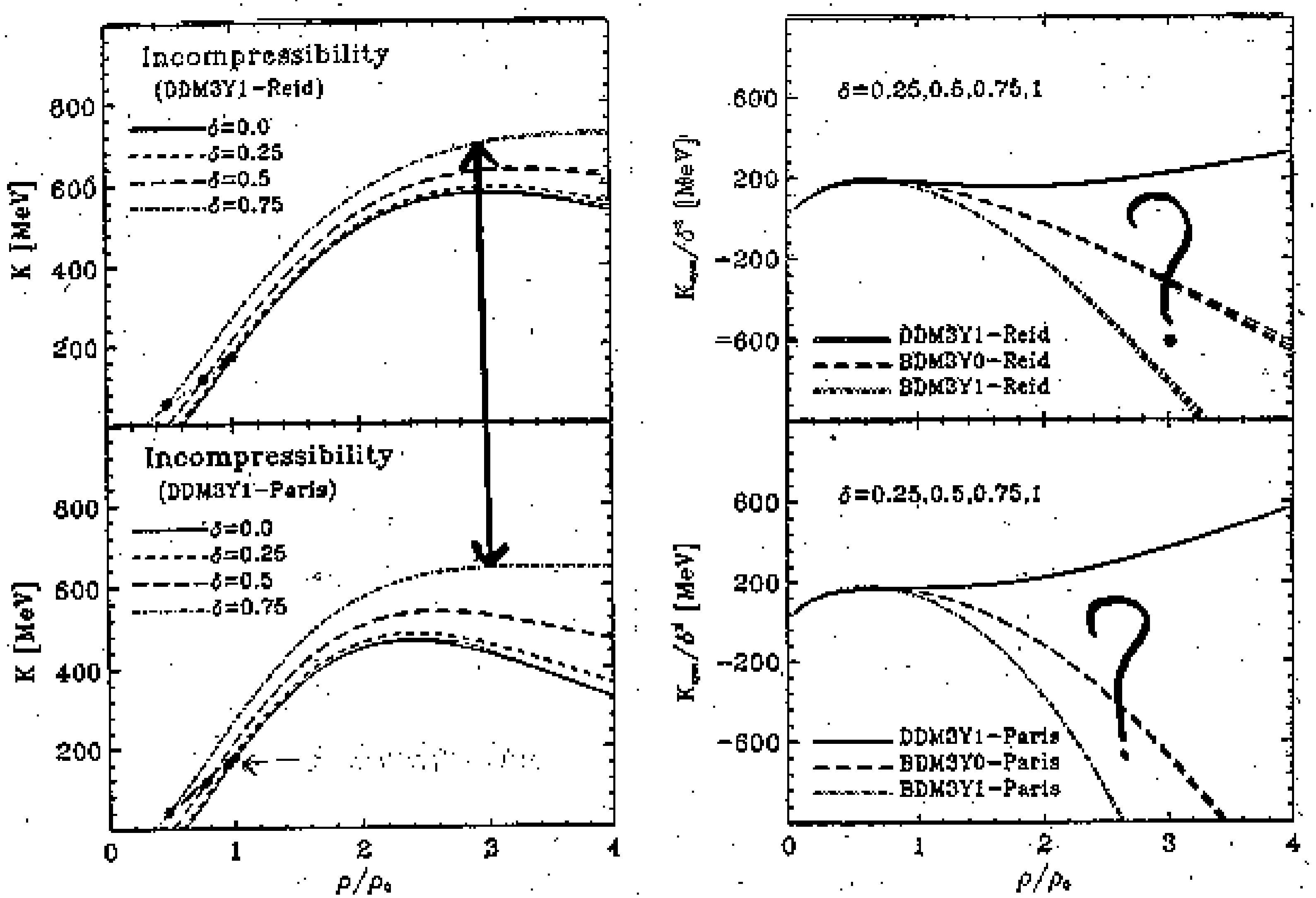


Fig. 1. EOS of asymmetric nuclear matter for SIII and TM1 with proton abundance Y_p = 0, 0.05, 0.1, 0.15, ..., up to 0.5. Also shown are the lines joining the saturation densities of asymmetric nuclear matter (dotted lines) for the SIII and TM1.

SHF:
- $\rho_0 = 0.145\ fm^{-3}$
- $E_0 = -15.9$ MeV
- $S_0 = 29$ MeV
- $K_\infty = 355$ MeV

RMF:
- $\rho_0 = 0.145\ fm^{-3}$
- $E_0 = -16.3$ MeV
- $S_0 = 38$ MeV
- $K_\infty = 281$ MeV

Incompressibility of Asymmetric Nuclear Matter



Dao Tien Khoa, W. von Oertzen and A.A. Ogloblin, NPA **602** (1996) 98.

EOS of Asymmetric Nuclear Mater

At density ρ and neutron-excess $\delta \equiv (\rho_n - \rho_p)/\rho$

$$e(\rho, \delta) \equiv E/A = \bar{T}_F(\rho, \delta) + V_0(\rho) + \delta^2 V_2(\rho)$$

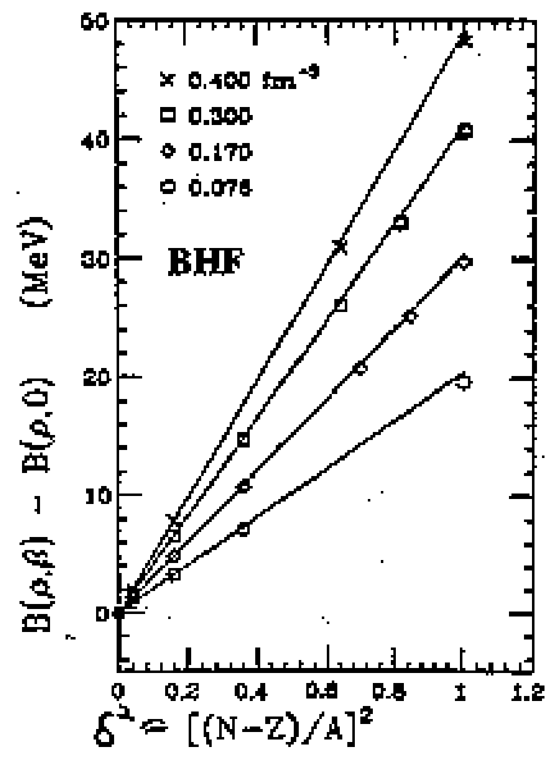
Empirical parabolic law:

$$e(\rho, \delta) = e(\rho, 0) + e_{sym}(\rho)\delta^2 + \mathcal{O}(\delta^4)$$

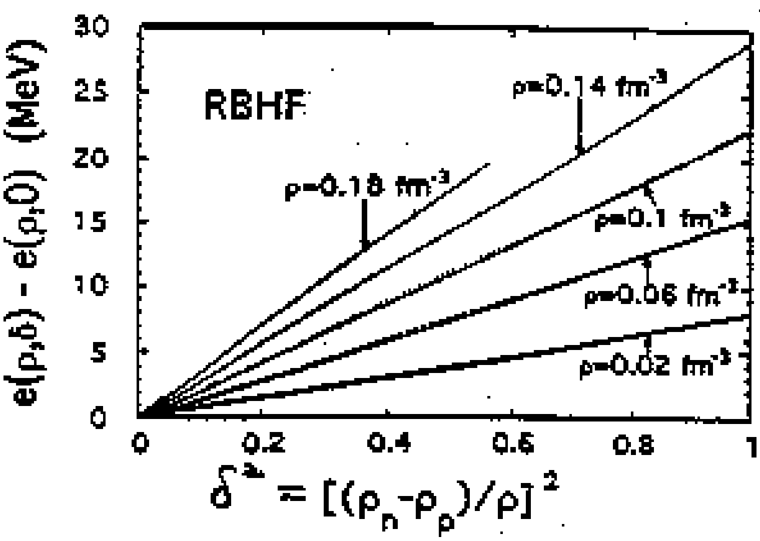
$\Longrightarrow e_{sym}(\rho) = e(\rho, \text{pure neutron matter}) - e(\rho, \text{symmetric nuclear matter})$

Theoretical evidence: essentially all many-body calculations

Two examples:



I. Bombaci and U. Lombardo. PRC 44 (1991) 1892

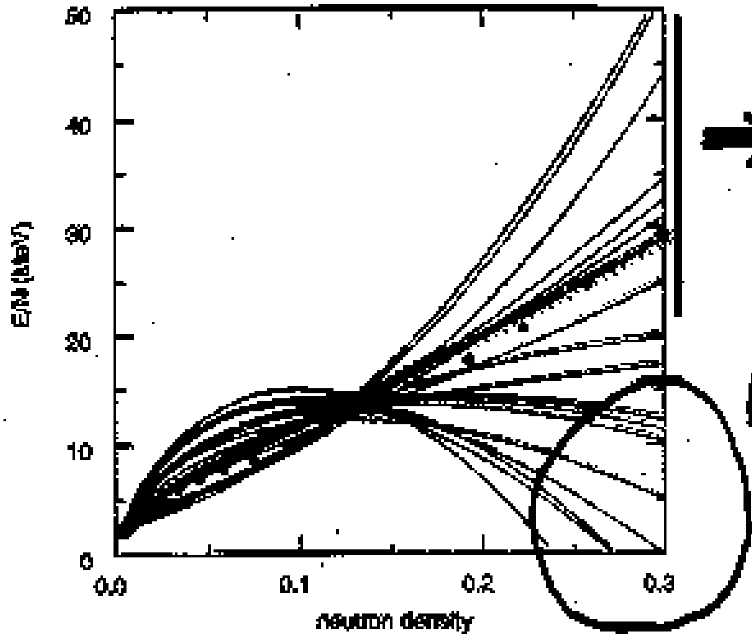


H. Huber, F. Weber and M.K. Weigel, PLB 317 (1993) 485.

EOS of pure neutron matter

Examples within Hartree-Fock approach:

(1)With **18** Skyrme interactions , B. A. Brown, Phys. Rev. Lett. **85** (2000) 5296.



$\Longrightarrow E_{sym}(\rho) > 0$

$(E/N)_{\text{neutron matter}} < (E/N)_{\text{symmetric matter}}$

$\Longrightarrow E_{sym}(\rho) < 0$

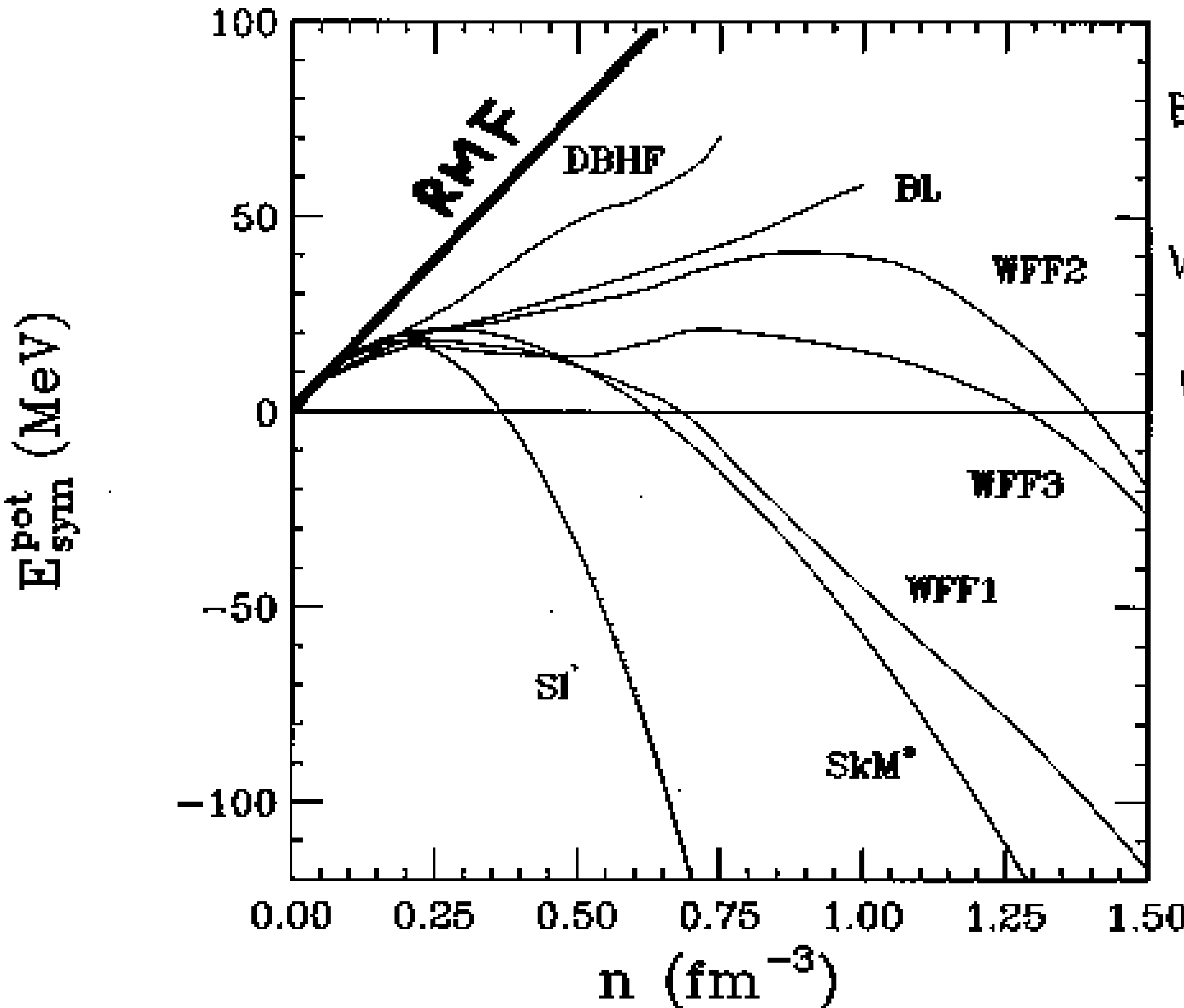
FIG. 2. The neutron EOS for 18 Skyrme parameter sets. The filled circles are the Friedman-Pandharipande (FP) variational calculations and the crosses are SkX. The neutron density is in units of neutron/fm^3.

(2)With **86** Skyrme effective interactions, J.R. Stone of the Univ. of Oxford recently found that **2/3** (***1/3***) of these interactions lead to **negative** (***positive***) symmetry energies at high densities.

(3)Other interactions, such as Gogny (Margueron, Navarro, Nguyen Van Giai, A. Ono, Subal Das Gupta et al.), density-dependent M3Y interactions (Khoa, Oertzen, Ogloblin) also give either **positive or negative** symmetry energies at high densities depending on the parameters used.

$\Longrightarrow$ We do not know about the sign of symmetry energy above $3\rho_0$!

$$e_{sym}(\rho) = \underbrace{0.35\, E_F^0 \left(\frac{\rho}{\rho_0}\right)^{2/3}}_{\text{Kinetic}} + E_{sym}^{\text{Potential}}(\rho)$$



RMF : Relativistic Mean Field

DBHF : Dirac Brueckner Hartree-Fock

BL : BHF by Bombaci and Lombardo

WFF : Wiringa, Fiks and Fabrocini

WFF1 : UV14 + TNI

WFF2 : UV14 + UVII

WFF3 : AV14 + UVII

SI and SKM* : Skyrme HF

I. Bombaci in "Isospin physics in heavy-ion collisions at intermediate energies" Eds. B.A. Li and W. Udo Schröder

Astrophysical implications of the density dependence of nuclear symmetry energy $E_{sym}(\rho)$

(A) Nucleosynthesis in pre-supernova evolution of massive stars

Rates of electron captures on nuclei and protons, thus the electron degenerate pressure and composition of pre-supernova collapsing core all depend critically on $E_{sym}(\rho)$.

(B) Mechanisms of supernova explosion

Isospin asymmetry stiffens the EOS: $E(\rho,\delta)= E(\rho,0)+E_{sym}(\rho)\delta^2$ at given ρ. Softened compressibility $K_0(\delta)=K_\infty(1-a\delta^2)$ along the saturation line $\rho_0(\delta)= \rho_0(1-b\delta^2)$. A 30% reduction of K_∞ at $\delta\approx1/3$ is necessary to cause the supernova explosion within the prompt explosion model.

(C) Composion of protoneutron stars

Proton/electron fraction x_p in protoneutron stars at β equilibrium is uniquely determined by: $\hbar c\,(3\pi^2\rho x_p)^{1/3} = 4\,E_{sym}(\rho)\,(1-2x_p)$

(D) Neutrino flux and cooling mechanisms of protoneutron stars

Fast cooling via direct URCA ($n\rightarrow p+e^-+\overline{\nu}_e$, $p+e^-\rightarrow n+\nu_e$) requires $x_p \geq 1/9$

(E) Kaon condensation in neutron stars

$e^-\rightarrow K^- + \nu_e$ if $\mu_e(\rho) \geq m_{K^-}$, where $\mu_e(\rho) = \mu_n(\rho) - \mu_p(\rho) = 4E_{sym}(\rho)\delta$

(F) Quark-hadron phase transition in neutron stars

The fraction of quark matter in the mixed phase depends on the $E_{sym}(\rho)$.

(G) Mass-radius correlation of neutron stars

It depends critically on the proton fraction x_p and thus $E_{sym}(\rho)$ by solving the Tolamn-Oppenheimer-Volkov equation.

(H) Isospin separation instability and structure of neutron stars

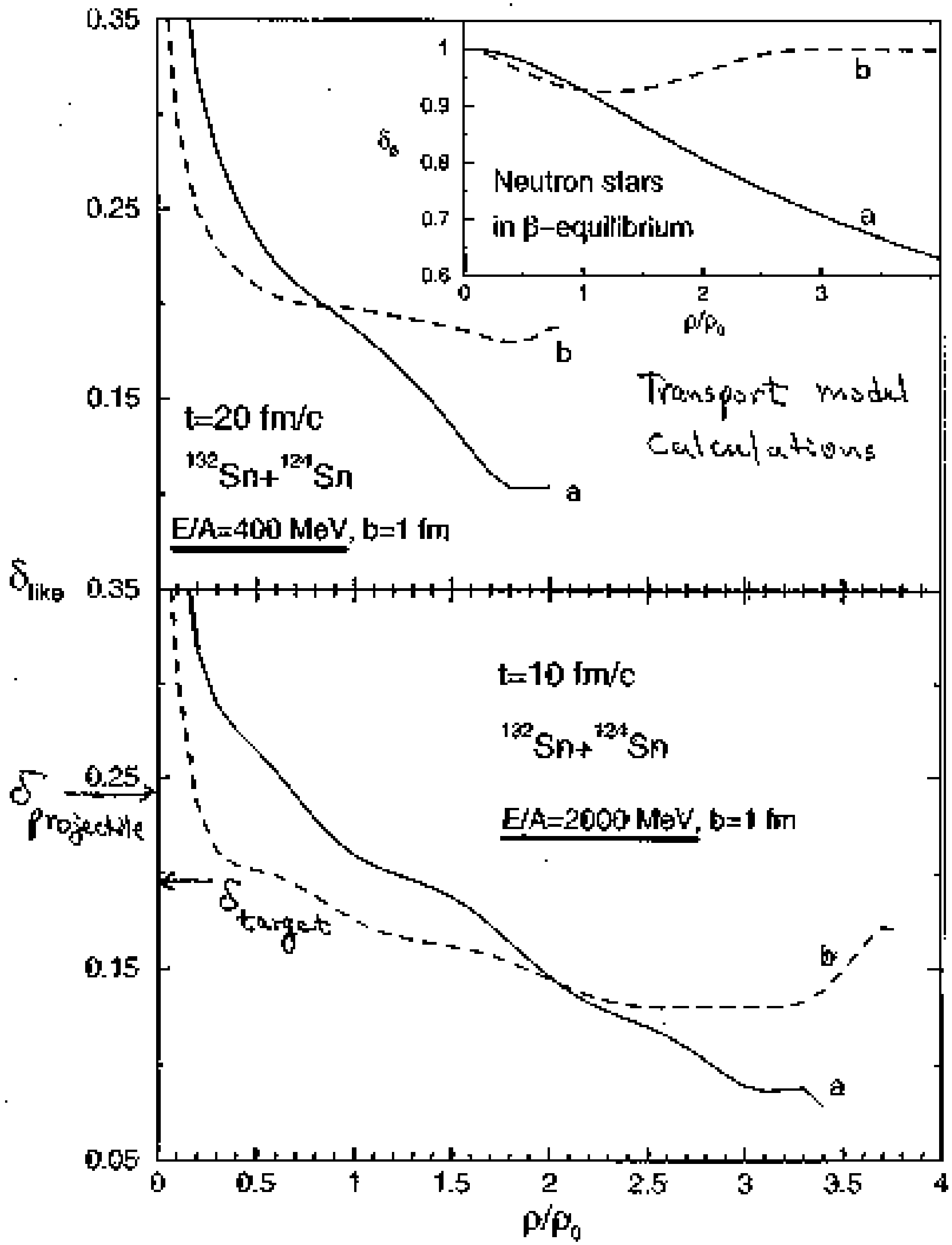
It was predicted by many microscopic many-body theories that the $E_{sym}(\rho)$ *becomes* negative above a critical density between $2.7\rho_0$ to $9\rho_0$, leading to the isospin separation instability-formation of pure neutron domains and/or neutron bubbles surrounding isolated protons.

Refs. (1) H. A. Bethe, Rev. of Modern phys. Vol. 62 (1990) 801

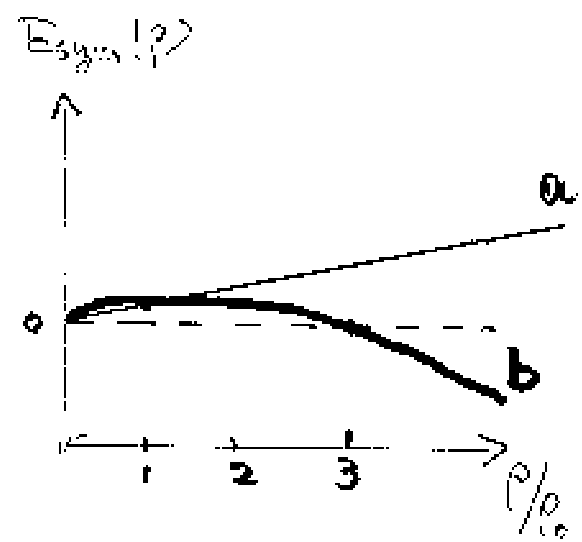
(2) C. J. Pethick and D. G. Ravenhall, Annu. Rev. Nucl. Part. Sci. 45 (95) 429

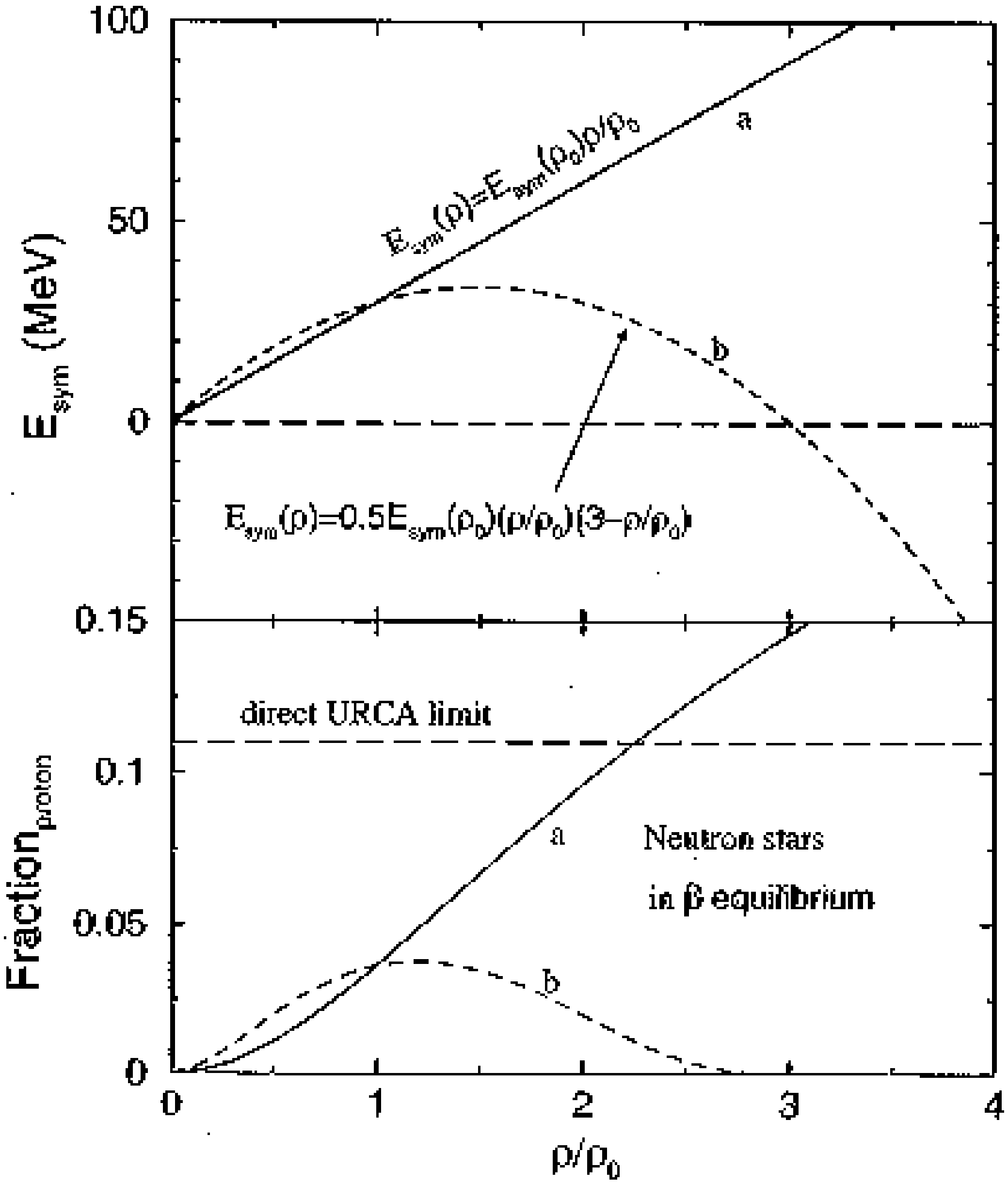
Bao-An Li

PRL 88 (2002) 192701



$$E(\rho,\delta) = E(\rho,0) + E_{sym}(\rho)\cdot\delta^2$$





Proton fraction X:

$$\hbar c\,(3\pi^2 \rho X)^{1/3} = 4E_{sym}(\rho)(1-2X)$$

Direct URCA Limit:

$$X_{critical} \geqslant \frac{1}{9}$$

Fast cooling process:

(direct URCA)

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

Slow cooling process:

(Modified URCA)

$(n,p) + p + e^- \to (n,p) + n + \nu_e$

$(n,p) + n \to (n,p) + p + e^- + \bar{\nu}_e$

Pion probe of N/Z of high density participants

Δ(1232) resonance model:

	π^+	π^0	π^-
nn	**0**	**1**	**5**
pp	**5**	**1**	**0**
np(pn)	**1**	**4**	**1**

Pion asymmetry: before re-absorption and re-scattering

$$\frac{\pi^-}{\pi^+} = \frac{5N^2 + NZ}{5Z^2 + NZ} \approx \left(\frac{N}{Z}\right)^2$$

Thermal model: (G.F. Bertsch, Nature 283 (1980) 281.)

$\frac{\pi^-}{\pi^+} \propto \exp[(\mu_n - \mu_p)/kT]$ (the same factor for n/p ratio !)

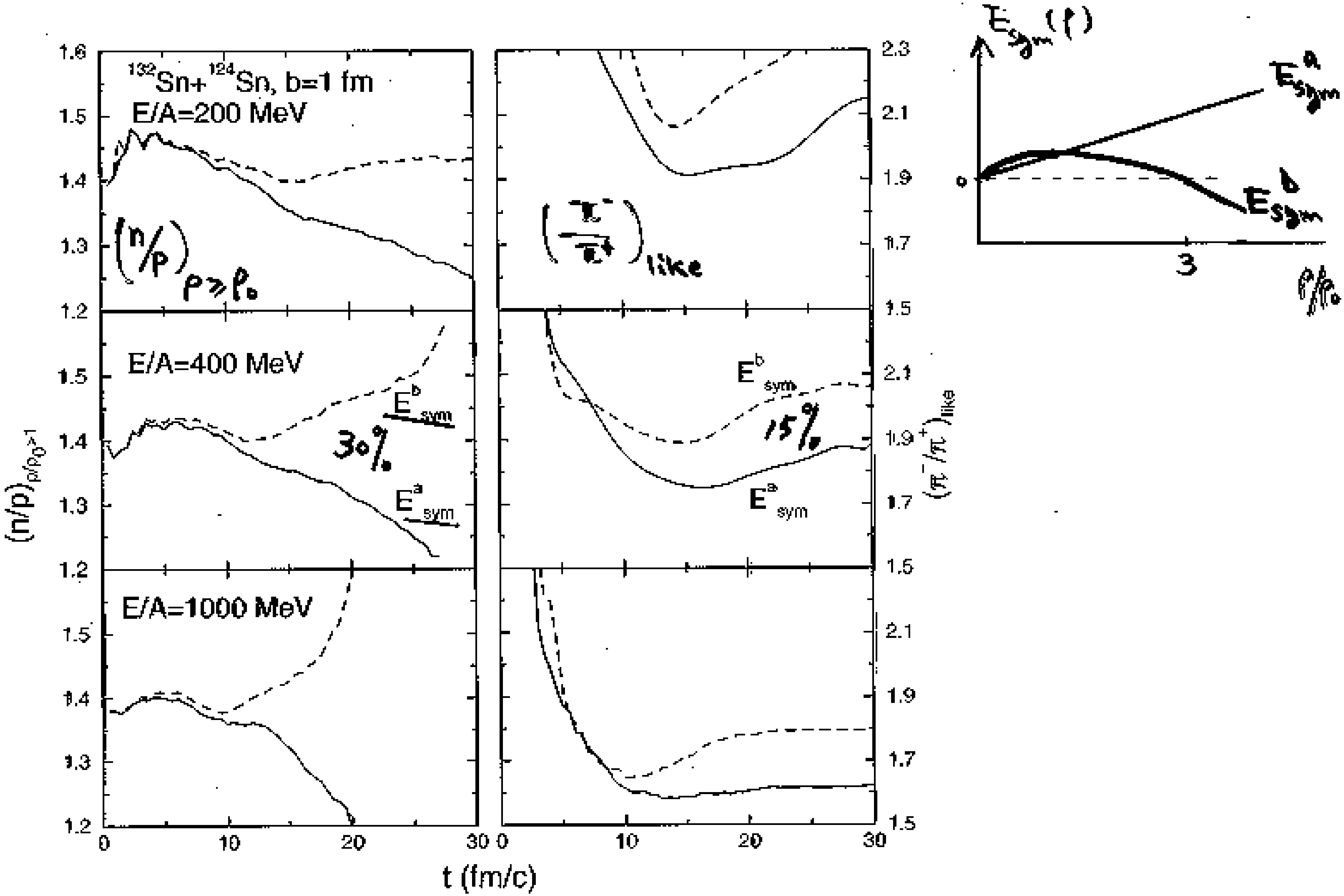
$\mu_n - \mu_p = 2V_{sym}(\rho)\delta - V_{Coul} + \underset{K}{\cancel{T}}\{\ln\frac{\rho_n}{\rho_p} + \sum_m \frac{m+1}{m} b_m (\frac{1}{2}\lambda_T^3)^m (\rho_n^m - \rho_p^m)\}$, Henry Jaqaman, Aram Mekjian PRC (1984) ...

λ_T is the thermal wavelength and b_m are constants.

$$\rightarrow \frac{n}{p}, \frac{\pi^-}{\pi^+} \propto \exp[(2V_{sym}(\rho)\delta - V_{cou})/kT]$$

Pion-like ratio during the reaction:

$$\left(\frac{\pi^-}{\pi^+}\right)_{like} = \frac{\pi^- + \Delta^- + \frac{1}{3}\Delta^0 + \frac{2}{3}N^{*0}}{\pi^+ + \Delta^{++} + \frac{1}{3}\Delta^+ + \frac{2}{3}N^{*+}} \xrightarrow{t\to\infty} \frac{\pi^-}{\pi^+}$$



^{132}Sn+^{124}Sn, b=1 fm
E/A=200 MeV
E/A=400 MeV
E/A=1000 MeV
$(n/p)_{\rho \geq \rho_0}$
$(\pi^-/\pi^+)_{like}$
E^b_{sym}
E^a_{sym}
30%
15%
$(n/p)_{\rho/\rho_0>1}$
$(\pi^-/\pi^+)_{like}$
t (fm/c)
$E_{sym}(\rho)$
ρ/ρ_0

Promising Probes of the $E_{sym}(\rho)$ in Nuclear Reactions
(an incomplete list !)

(a) At low densities

- **Sizes of n-skins of unstable nuclei from total reaction xsections**
- **Parity violating electron scattering studies of the n-skin in ^{208}Pb**
- **Multiplicity and spectrum of pre-equilibrium neutrons/protons**
- **Isospin fractionation and isoscaling in multifragmentation**
- **Proton differential elliptic flow at high transverse momenta**
- **Isospin dependence of transverse flow and balance energy**
- **Two-nucleon correlation functions at low relative momenta**

(b) Towards high densities

- **π^+/π^- ratio in heavy-ion collisions induced by high-energy radioactive beams**
- **Neutron-proton differential flow in heavy-ion collisions**
- **Precursor of *isospin separation instability* in the excitation function of nuclear collective flow**
- **Asymmetric nuclear matter induced unique ρ^0-ω mixing and its effects on dilepton and photon production**

Evidence of the momentum-dependence of symmetry potential

from the difference of optical potentials for neutron and proton scatterings

(1) Neutron and proton scatterings on the same nucleus at the same energy

$$U_n - U_p = 2\delta\, U_{sym} + U_{Coulomb\ correction}$$

(2) Neutron or proton scatterings on a sequence of isotopes

$$U_p(\text{isotope } 1) - U_p\,(\text{isotope } 2) = 2(\delta_1 - \delta_2)\, U_{sym}$$

n n

The finding: $U_{sym} = V_1 - \epsilon_R E$, $V_1 \approx 30$ MeV, $\epsilon_R \approx 0.1 - 0.2$

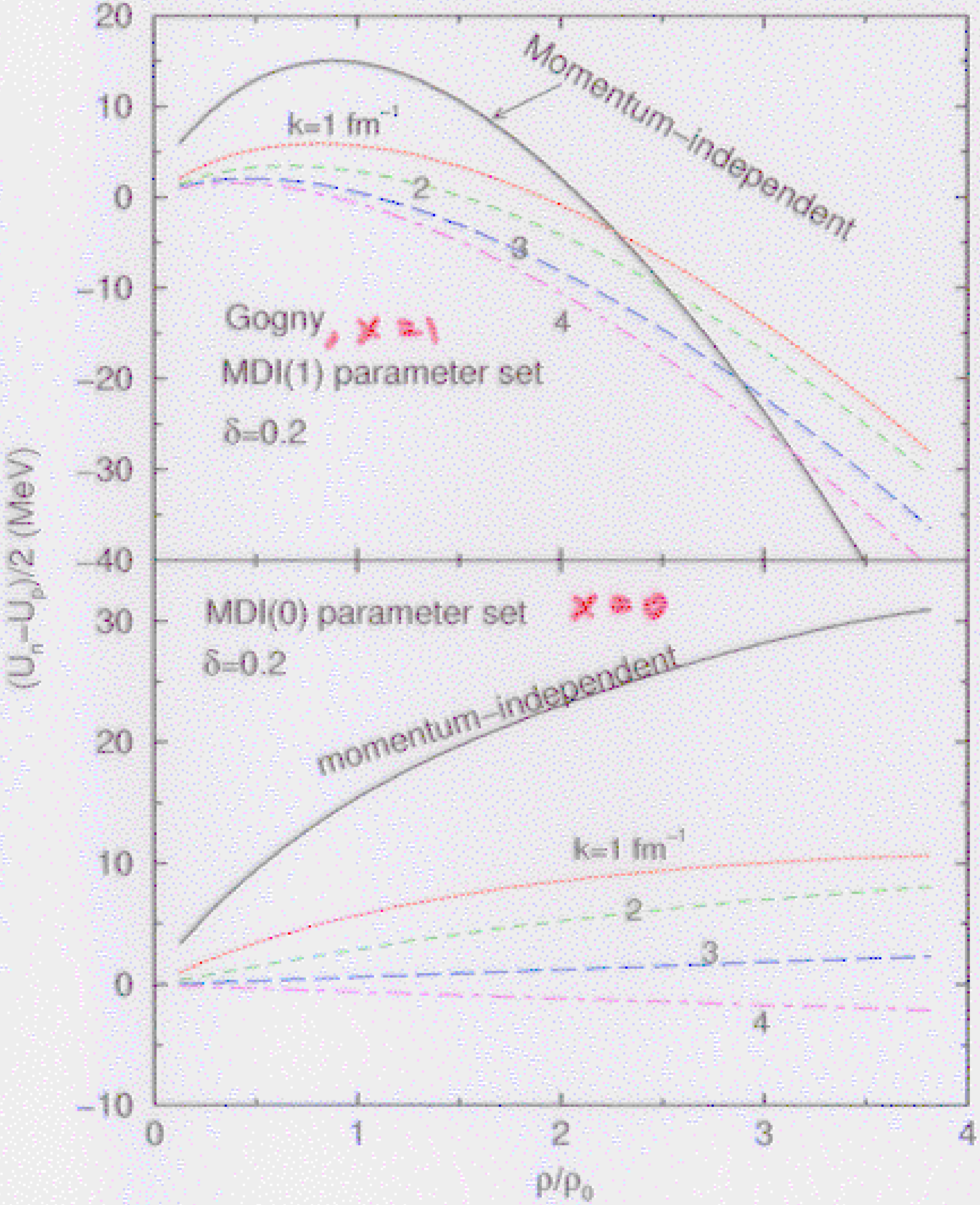
P.E. Hodgson, the Nucleon Optical Model, World Scientific, 1994

2.4.4. Energy dependence of isospin potential. **Some global analyses of neutron elastic scattering have been made that included a linear energy dependence of the asymmetry term. Values of the coefficients ϵ_R and ϵ_I in the expressions $(V_1 - \epsilon_R E)$ and $(W_1 - \epsilon_I E)$ are given in table 12.**

Table 12. Values of coefficient of linear energy dependence of isospin potential.

Reaction	E	Nucleus	ϵ_R	ϵ_I	Reference
		Theoretical analyses	0.1	—	Rook (1973)
		Theoretical analyses	0.17	—	Dabrowski and Haensel (1974)
		Theoretical analyses	0.1	—	Jeukenne *et al* (1977b)
(n, n)	7–26	^{40}Ca, ^{208}Pb	0.19	—	Rapaport *et al* (1979a, b)
(p, n)	25–45	^{48}Ca–^{208}Pb	0.18	—	Patterson *et al* (1976)
(n, n), p, p)	10–50	^{208}Pb	0.183 ± 0.008	—	De Vito *et al* (1981)
(n, n), (p, p)	10–40	^{208}Pb	—	0.178 ± 0.052	De Leo and Micheletti (1981)
(p, p)	100	^{58}Ni–^{208}Pb	0.12 ± 0.06	—	Kwiatkowski and Wall (1978)

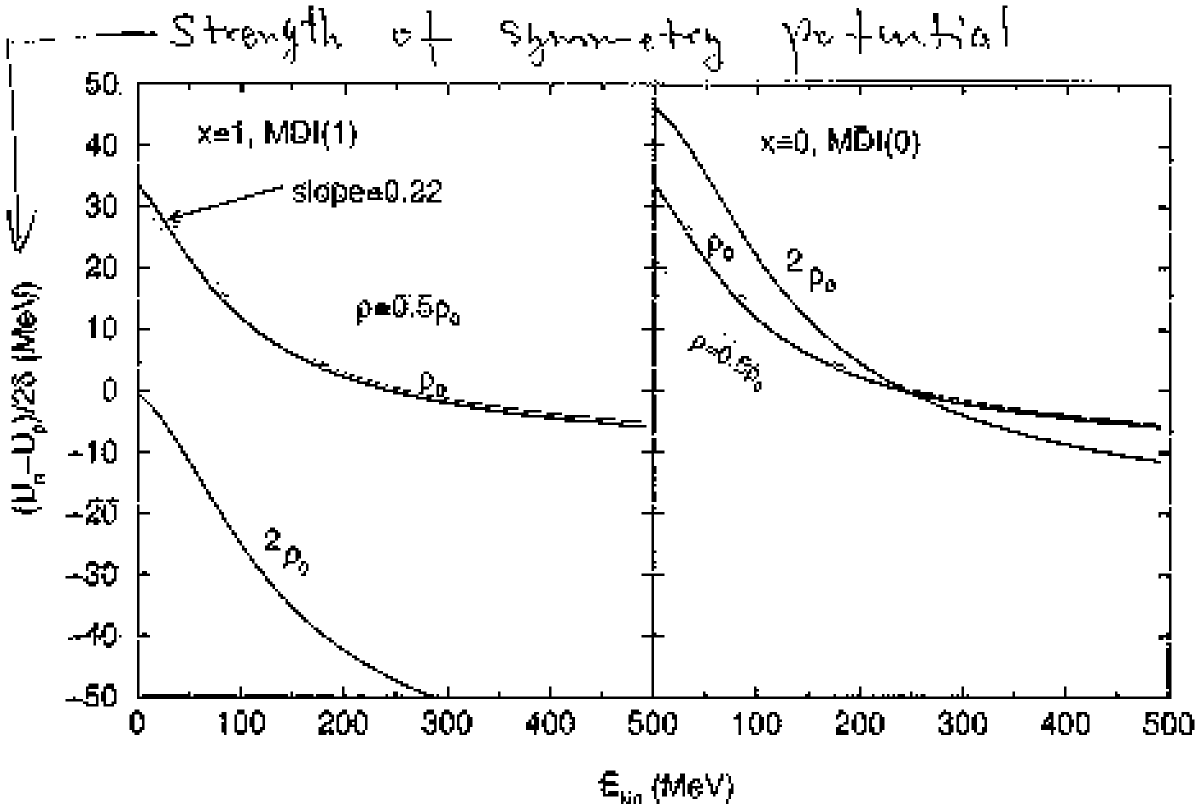
Symmetry Potential



Momentum-independent symmetry potential corresponding to the same symmetry energy $E_{sym}(\rho)$

$$U_{sym}^{m\text{-}ind}(\rho, \delta, \tau) = \partial W_{sym} / \partial \rho_\tau$$

$$W_{sym} = E_{sym}^{potential}(\rho) \cdot \rho \cdot \delta^2$$



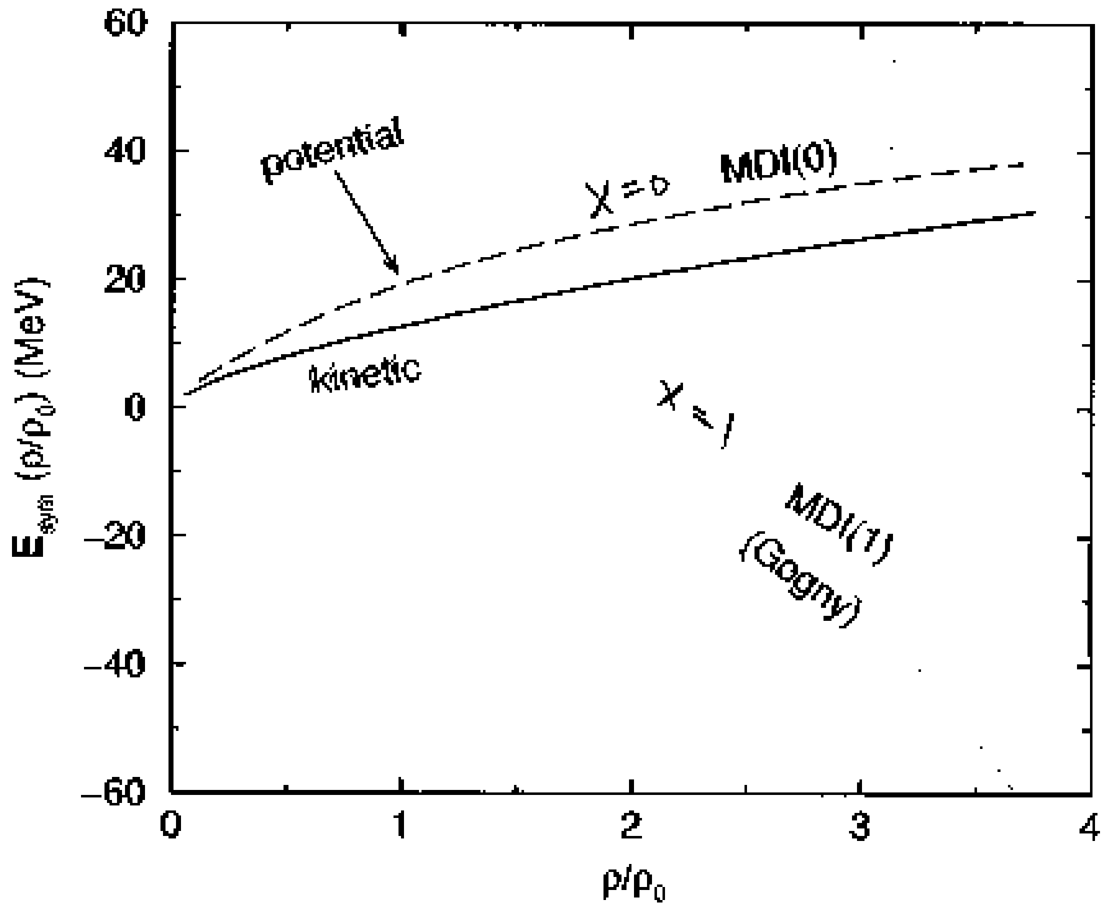
Momentum-dependence of the symmetry potential

$$U(\rho,\delta,\vec{p},\tau) = A_u\frac{\rho_{\tau'}}{\rho_0} + A_l\frac{\rho_\tau}{\rho_0} + B\left(\frac{\rho}{\rho_0}\right)^\sigma(1-x\delta^2) - 8\tau x\frac{B}{\sigma+1}\frac{\rho^{\sigma-1}}{\rho_0^\sigma}\delta\rho_{\tau'}$$
$$+\frac{2C_{\tau,\tau}}{\rho_0}\int d^3p'\frac{f_\tau(\vec{r},\vec{p}')}{1+(\vec{p}-\vec{p}')^2/\Lambda^2} + \frac{2C_{\tau,\tau'}}{\rho_0}\int d^3p'\frac{f_{\tau'}(\vec{r},\vec{p}')}{1+(\vec{p}-\vec{p}')^2/\Lambda^2}$$

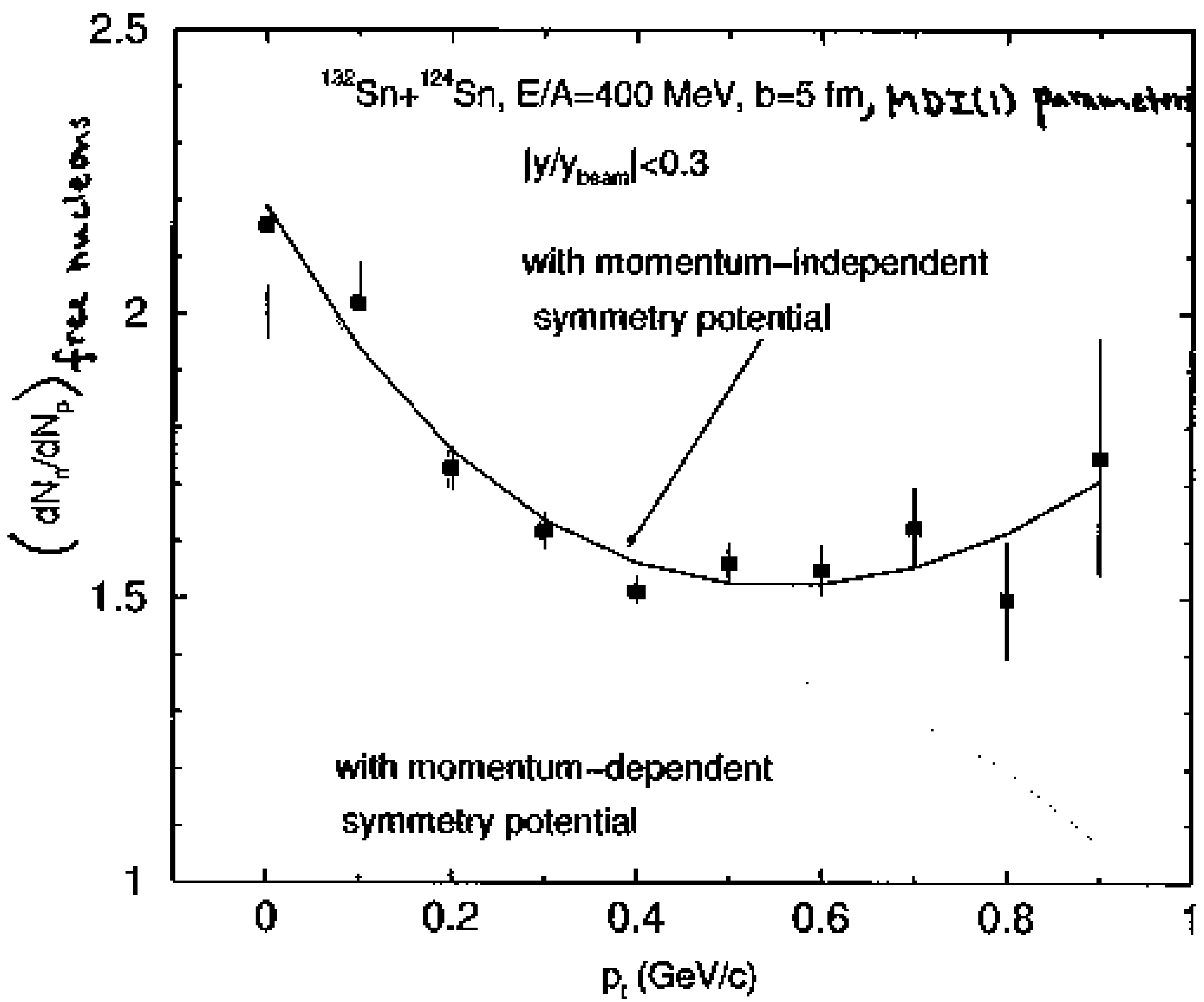
$C_{unlike} = -103.4$ MeV while $C_{like} = -11.7$ MeV.

references:

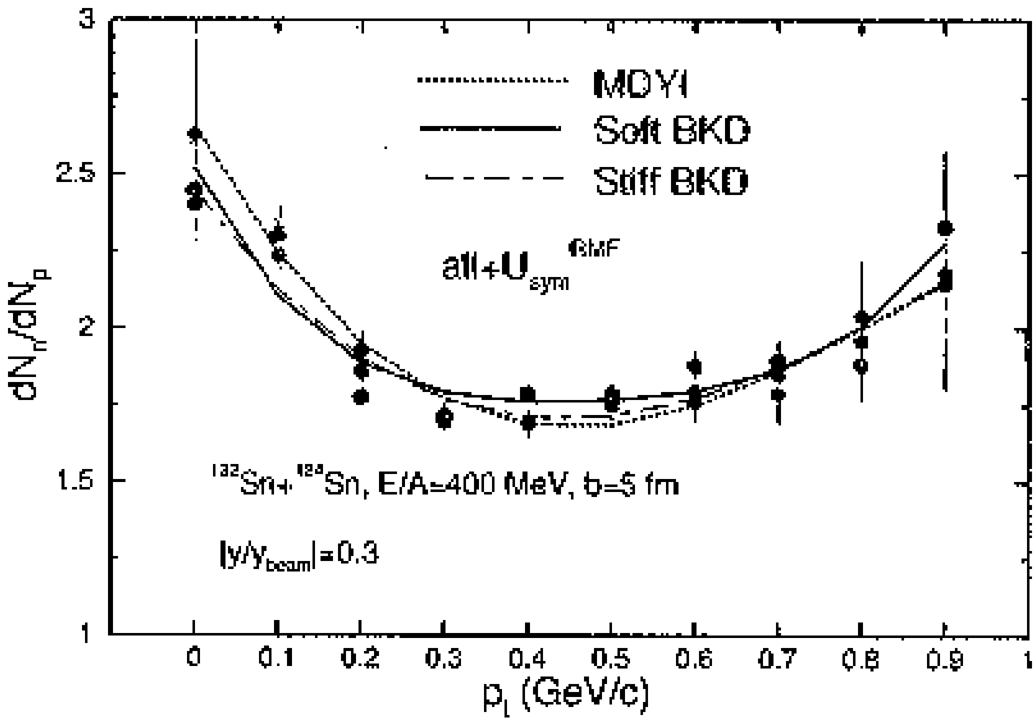
1. C.B. Das, S. Das Gupta, C. Gale and Bao-An Li, PRC 67, 034611 (2003).
2. Bao-An Li, C.B. Das, Subal Das Gupta and C. Gale, preprint (2003).



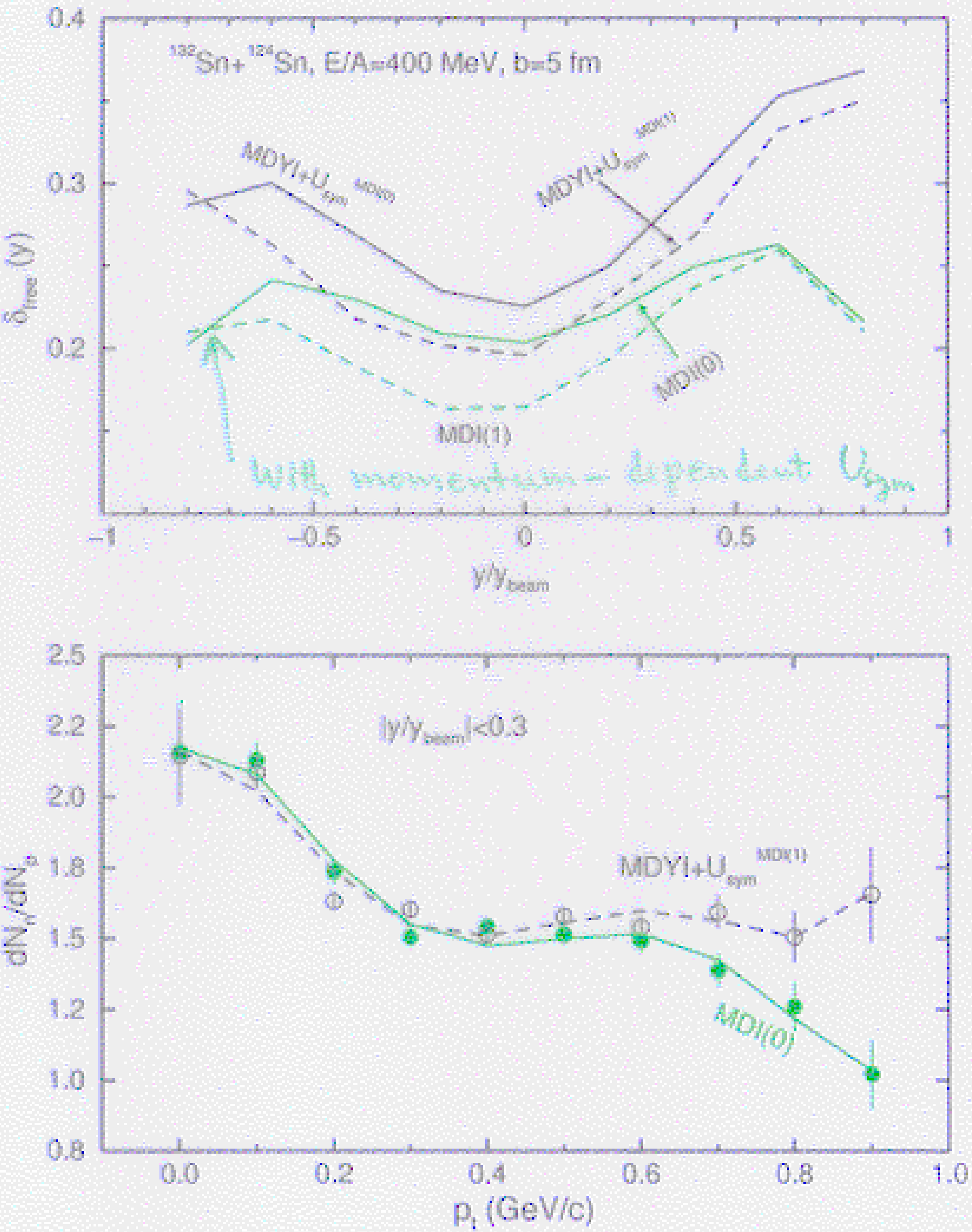
E_{sym} (ρ/ρ_0) (MeV)
60
40
20
0
−20
−40
−60
0
1
2
3
4
ρ/ρ_0
potential
kinetic
MDI(0)
MDI(1)
(Gogny)



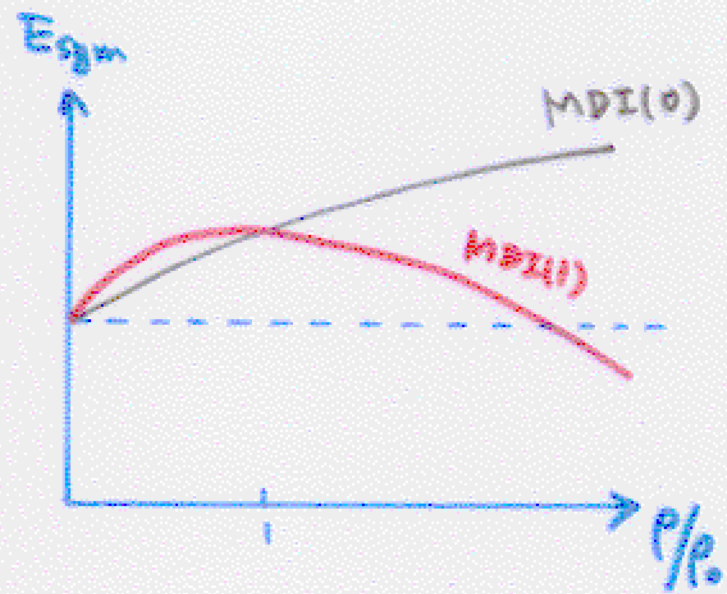
$^{132}Sn+^{124}Sn$, E/A=400 MeV, b=5 fm, MDI(1) parameters
$|y/y_{beam}|<0.3$
with momentum–independent symmetry potential
with momentum–dependent symmetry potential
$(dN_n/dN_p)_{free\ nucleons}$
2.5
2
1.5
1
0
0.2
0.4
0.6
0.8
1
p_t (GeV/c)



Free nucleons are identified as those having local baryon densities less than $1/8 \cdot \rho_0$



^{132}Sn+^{124}Sn, E/A=400 MeV, b=5 fm
MDYI+U$_{sym}^{MDI(0)}$
MDYI+U$_{sym}^{MDI(1)}$
MDI(0)
MDI(1)
With momentum-dependent U$_{sym}$
δ_{free} (y)
y/y$_{beam}$
|y/y$_{beam}$|<0.3
MDYI+U$_{sym}^{MDI(1)}$
MDI(0)
dN$_n$/dN$_p$
p$_t$ (GeV/c)



E$_{sym}$
MDI(0)
MDI(1)
1
ρ/ρ$_0$

Summary:

- The EOS of neutron-rich matter, especially at high densities, is very poorly known.
- The most important issue is the density-dependence of nuclear symmetry energy $E_{sym}(\rho)$.
- The $E_{sym}(\rho)$ is important for understanding not only structures of radioactive nuclei, reaction mechanisms of heavy-ion collisions but also many key issues in astrophysics.
- Several interesting isospin effects in heavy-ion collisions induced by high-energy radioactive beams can be used to extract the high-density behavior of $E_{sym}(\rho)$.