上海交通大學
Shanghai Jiao Tong University

1st International Workshop on Quasi-free Scattering with Radioactive Ion Beams: QFS-RB 08, ECT* Trento, Italy, April 7-11, 2008

In-medium nucleon-nucleon cross-sections in asymmetric nuclear matter

Lie-Wen Chen

(Physics Department and Institute of Theoretical Physics, Shanghai Jiao Tong University)

Collaborators: Wei-Zhou Jiang (TAMU-Commerce/SIAP, CAS)
Che Ming Ko (TAMU-College Station)
Bao-An Li (TAMU-Commerce)
Hong-Ru Ma (SJTU)
Jun Xu (SJTU)
Gao-Chan Yong (IMP,CAS, Lanzhou)

Contents

- Motivation
- In-medium NN cross sections at low and intermediate energies
- Relativistic impulsive approximation to high energy NN cross sections in asymmetric nuclear matter
- Probing NN cross sections in asymmetric nuclear matter using heavy-ion collisions
- Summary and Outlook

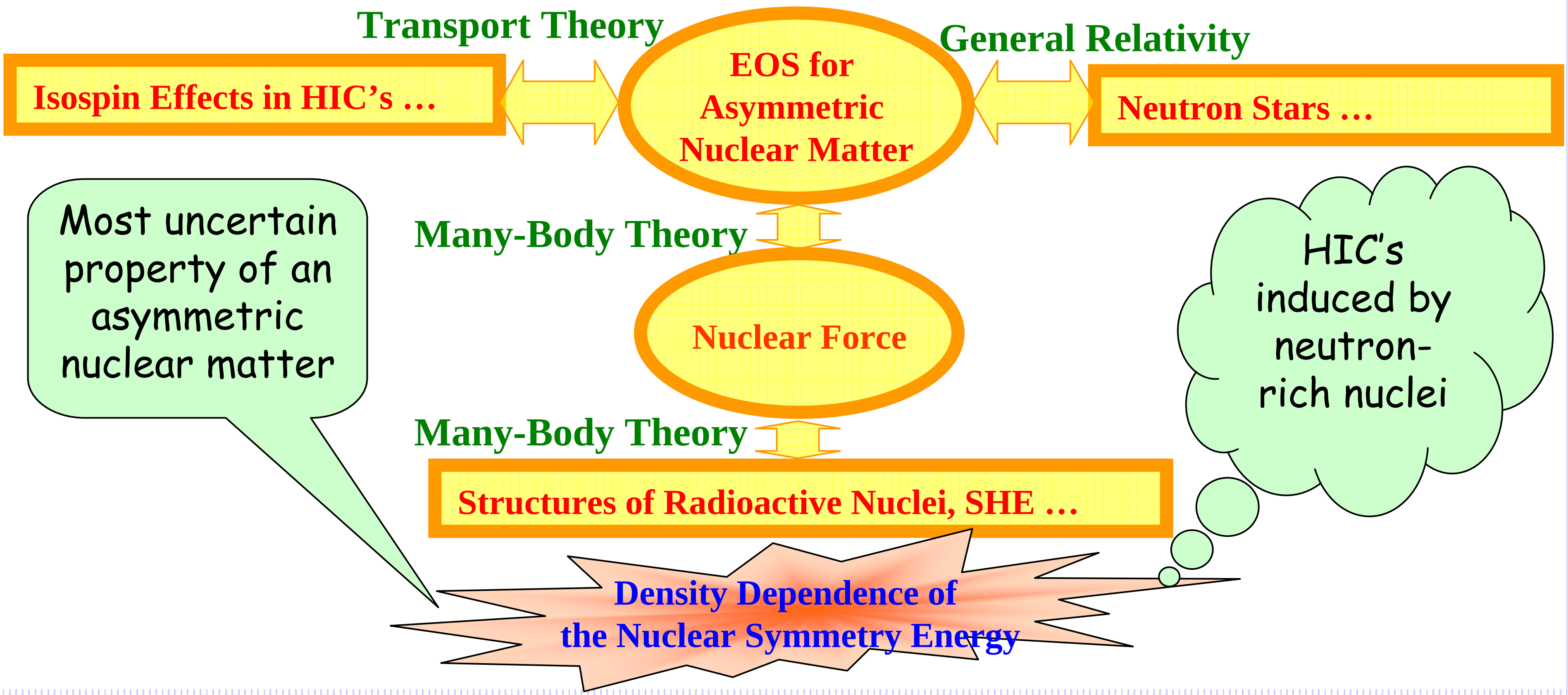
Motivation

Why are we interested in NN cross sections in asymmetric nuclear matter?

Isospin physics in medium energy nuclear physics

Ultimate goal:

To explore the isospin dependence of in-medium nuclear effective Interactions which determines both the EOS of asymmetric nuclear matter and the NN cross sections in asymmetric nuclear matter

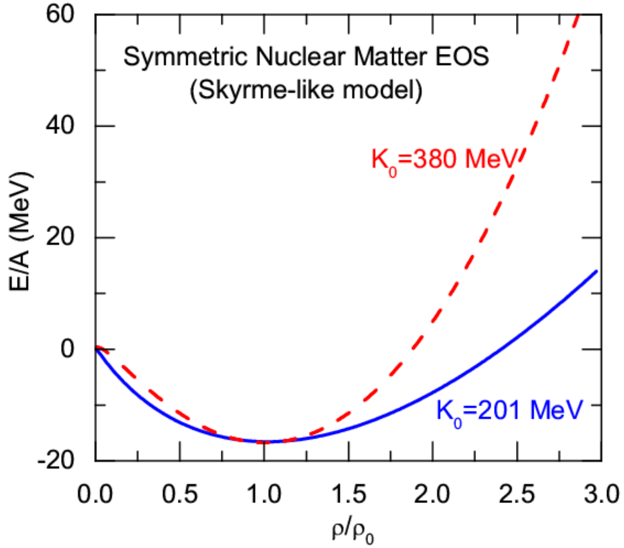


Equation of State of *symmetric nuclear matter* is relatively well determined

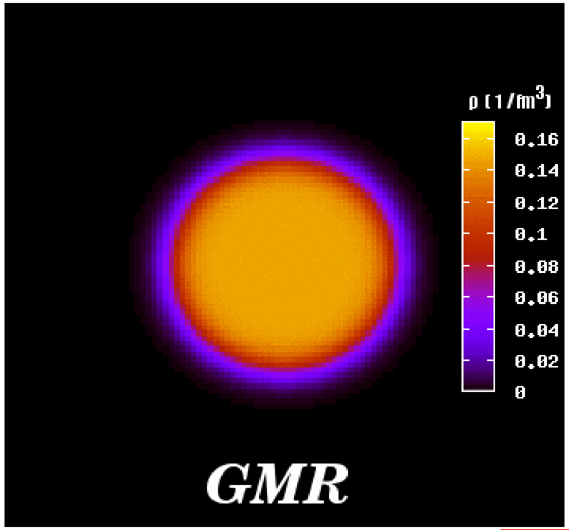
after 30 years of hard work of many people in the nuclear physics community

(1) EOS of symmetric matter around the saturation density ρ_0

Incompressibility: $K_0 = 9\rho_0^2 \left(\frac{d^2E}{d\rho^2}\right)_{\rho_0}$



Giant Monopole Resonance



Frequency $f_{GMR} \propto \sqrt{K_0}$

K_0=231±5 MeV

PRL82, 691 (1999)

Recent results:

K_0=230±10 MeV

U. Garg et al.

VOLUME 82, NUMBER 4 PHYSICAL REVIEW LETTERS 25 JANUARY 1999

Incompressibility of Nuclear Matter from the Giant Monopole Resonance

D. H. Youngblood, H. L. Clark, and Y.-W. Lui

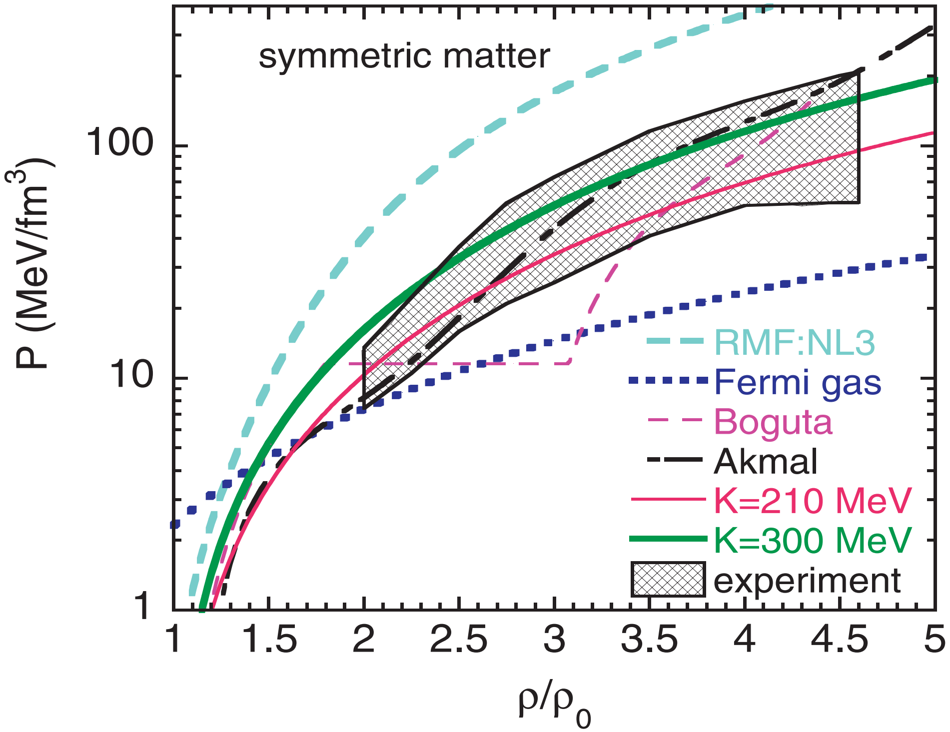
Cyclotron Institute, Texas A&M University, College Station, Texas 77843

(Received 30 July 1998)

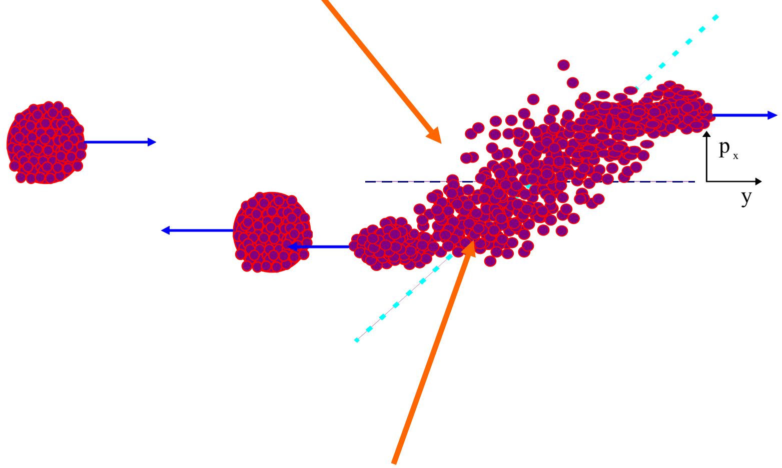
$E0$ strength distributions in ^{90}Zr, ^{116}Sn, ^{144}Sm, and ^{208}Pb have been measured with inelastic scattering of 240-MeV α particles between $0° \le \theta_{lab} \le 6°$ to greater precision than previously available. In Sn, Sm, and Pb, $E0$ strength was concentrated in approximately symmetric peaks, whereas in ^{90}Zr it had a significant high energy tail. Comparing with microscopic calculations using the Gogny interaction, these and our previously reported results for ^{40}Ca are consistent with a nuclear matter incompressibility of 231 ± 5 MeV. Previous data gave an average of 215 MeV and the value for different nuclei disagreed by up to 40 MeV. [S0031-9007(98)08291-X]

(2) Present constraints on the EOS of symmetric nuclear matter for $2\rho_0 < \rho < 5\rho_0$ using flow data from BEVALAC, SIS/GSI and AGS

P. Danielewicz, R. Lacey and W.G. Lynch, Science 298, 1592 (2002)



The highest pressure recorded under laboratory controlled conditions in nucleus-nucleus collisions



High density nuclear matter
2 to 5 ρ_0

- Use constrained mean fields to predict the EOS for symmetric matter
  - Width of pressure domain reflects uncertainties in comparison and of assumed momentum dependence.

$$\text{Pressure } P(\rho) = \rho^2 \bullet \left(\frac{\partial E}{\partial \rho}\right)_s$$

EOS of Asymmetric Nuclear Matter

(Parabolic law)

$$E(\rho,\delta)=E(\rho,0)+E_{\rm sym}(\rho)\delta^2+O(\delta^4),\quad \delta=(\rho_n-\rho_p)/\rho$$

Nuclear Matter Symmetry Energy

$$E_{\rm sym}(\rho)\equiv\frac{1}{2}\frac{\partial^2E(\rho,\delta)}{\partial\delta^2}$$

$$E_{\rm sym}(\rho)=E_{\rm sym}(\rho_0)+\frac{L}{3}\left(\frac{\rho-\rho_0}{\rho_0}\right)+\frac{K_{\rm sym}}{18}\left(\frac{\rho-\rho_0}{\rho_0}\right)^2,\quad (\rho\sim\rho_0)$$

$E_{\rm sym}(\rho_0)\approx 30$ MeV (LD mass formula: *Meyer & Swiatecki, NPA81; Pomorski & Dudek, PRC67*)

$$L\equiv 3\rho_0\left.\frac{\partial E_{\rm sym}(\rho)}{\partial\rho}\right|_{\rho=\rho_0}$$ (Many-Body Theory: $L: -50\sim 200$ MeV; Exp: ???)

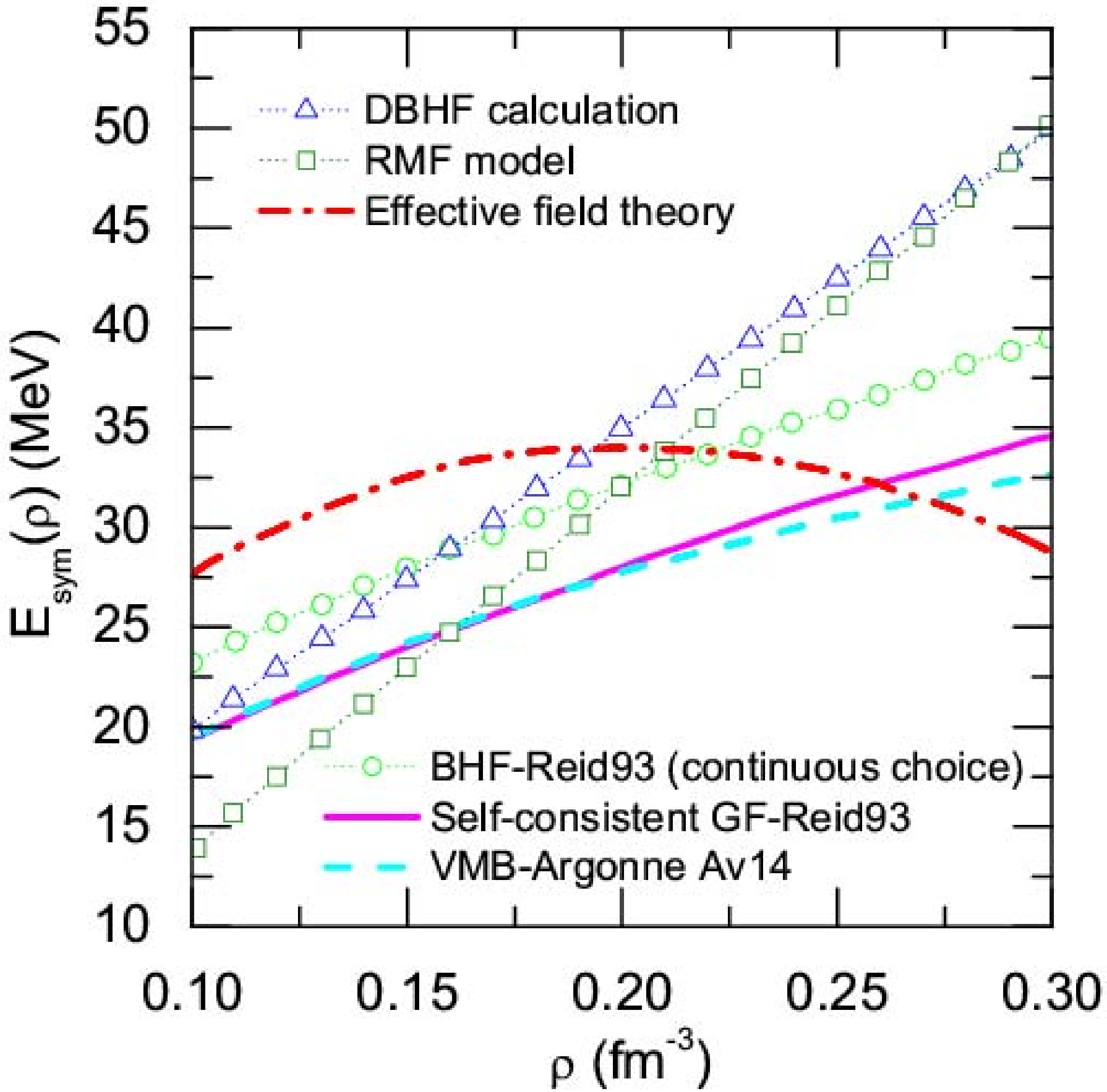
$$K_{\rm sym}\equiv 9\rho_0^2\left.\frac{\partial^2E_{\rm sym}(\rho)}{\partial\rho^2}\right|_{\rho=\rho_0}$$ (Many-Body Theory: $K_{\rm sym}: -700\sim 466$ MeV; Exp: ???)

The isospin part of the isobaric incompressiblity $K_{\rm asy}$ of asymmetric nuclear matter

$$K_{\rm asy}\approx K_{\rm sym}-6L$$

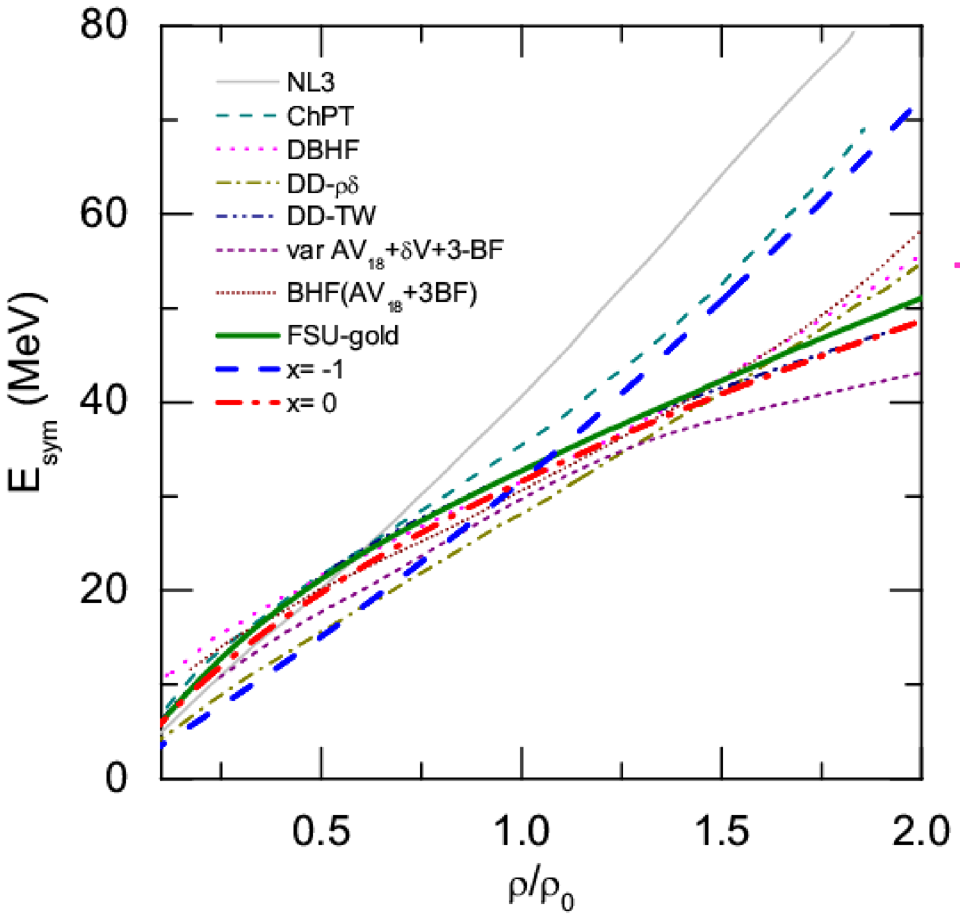
(GMR : Sharma, et al.,*PRC*38 : -320 ± 180MeV; Shlomo&Youngblood,*PRC47*: $-566\pm1350\sim34\pm159$MeV;Li,Garg, et al.,PRL99 : -550 ± 100MeV)

The Symmetry Energy from Microscopic Many-Body Theory



A.E.L. Dieperink et al. PRC 68, 064307 (2003).

The Symmetry Energy from Microscopic and Phenomenological Models



Yong/Li/Chen, PLB650, 344 (2007)

The subnormal density behavior of the symmetry energy is relatively well determined !

The high density behavior varies widely !

Present constraints of the Symmetry Energy at subnormal densties:

- X=0 and -1: Isospin diffusion data (Tsang et al., Chen/Ko/Li)
- X=0: Isoscaling data (Shetty/Souliotis/Yennello et al.)
- FSU-Gold: GMR in ^{90}Zr and ^{208}Pb, and the isovector GDR of ^{208}Pb (Piekarewicz/Todd-Rutel)

Why are we interested in NN cross sections in asymmetric nuclear matter?

The NN cross sections are also important for many observables

The EOS of ANM: Much experimental and theoretical effort has been made
The NN cross sections in ANM: Little effort has been made so far

The in-medium NN cross sections depend particularly on the short-range part of nuclear effective interactions.

- Transport properties of ANM
  Mean free path, transport coefficients

- Structure of exotic nuclei
  Glauber model, …

- Basic input of transport model
  BUU, QMD, …

- Dynamics of heavy-ion collisions

- Dynamics of Quasi-free scattering

- … …

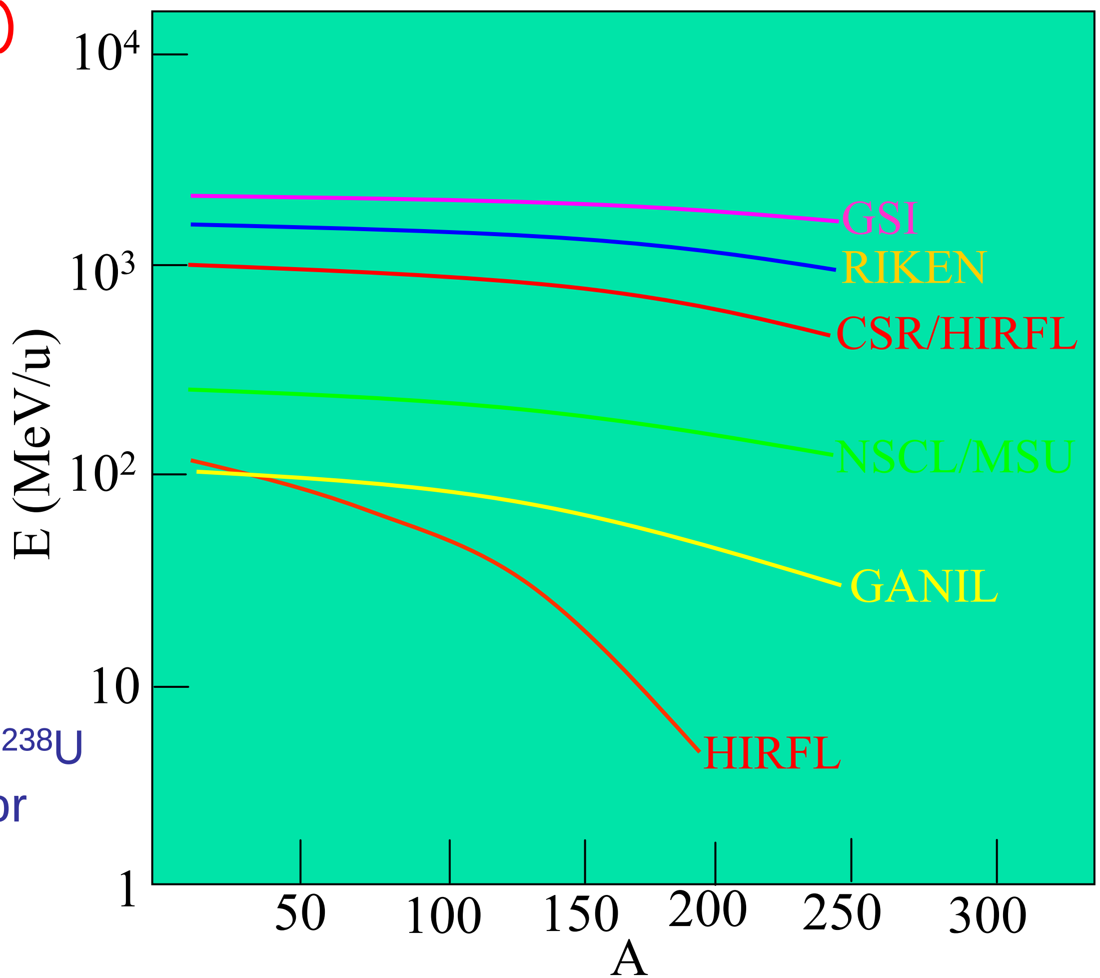
The Radioactive Ion Beams provide great opportunity to explore the NN cross sections in ANM !

- Heavy-Ion Accelerators at Intermediate and High Energies

1. HIRFL, CSR/HIRFL (China)
2. GANIL (France)
3. GSI (Germany)
4. NSCL/MSU
5. RIKEN (Japan)

Dubna, LBL, ORNL, TAMU, INFN, KVI,…

(BNL, CERN)

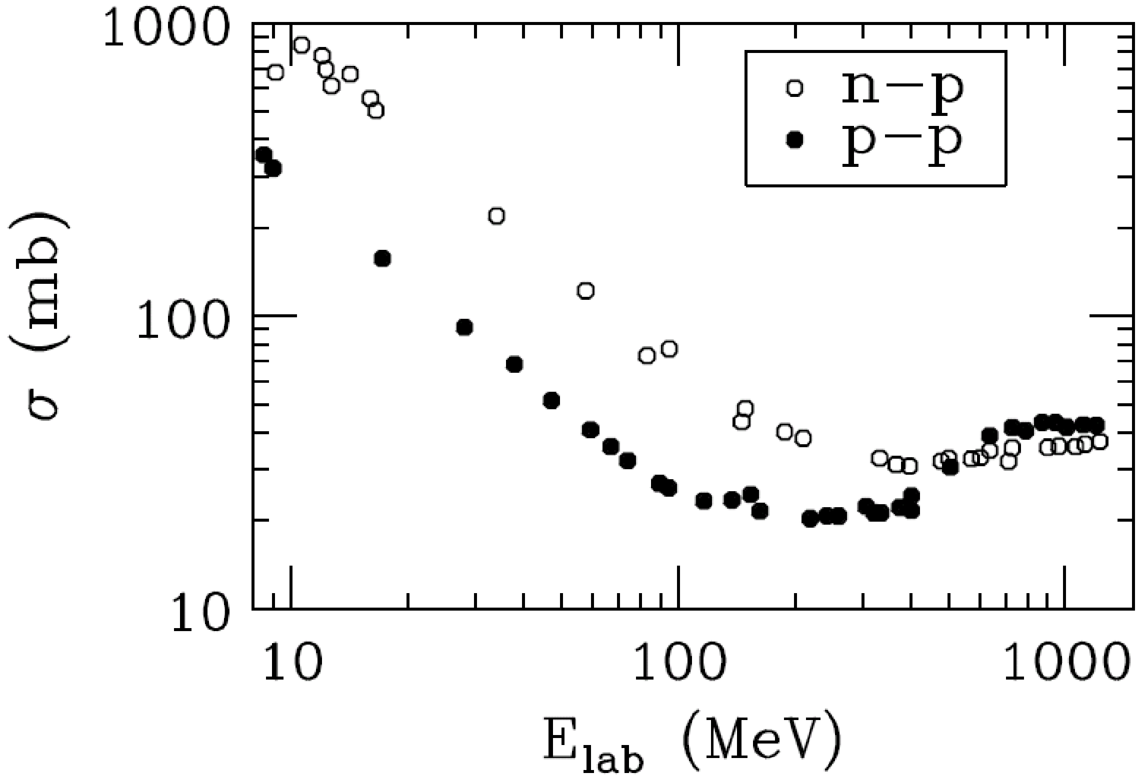


High energy neutron-rich beams:
CSR/Lanzhou: up to 500 MeV/A for ^{238}U
FRIB/USA: up to 400(200) MeV/A for ^{132}Sn
FAIR/GSI: up to 2 GeV/A for ^{132}Sn

In-medium NN cross sections at low and intermediate energies

Isospin dependence of NN cross sections in free-space

G. Alkahzov, et al., Nucl. Phys. A 280 (1977) 365.



$E_{Lab} \le 300$ MeV/nucleon:

$\sigma_{np} / \sigma_{pp} \approx 2 \sim 3$

$E_{Lab} \ge 500$ MeV/nucleon

$\sigma_{pp} \ge \sigma_{np}$

S.K. Charagi, S.K. Gupta, Phys. Rev. C 41 (1990) 1610.

$$\sigma_{np}^{\rm free} = -70.67 - 18.18\beta^{-1} + 25.26\beta^{-2} + 113.85\beta \text{ (mb)},$$

$$\sigma_{pp}^{\rm free} = 13.73 - 15.04\beta^{-1} + 8.76\beta^{-2} + 68.67\beta^{4} \text{ (mb)},$$

where $\beta \equiv v/c$ is the velocity of the projectile nucleon.

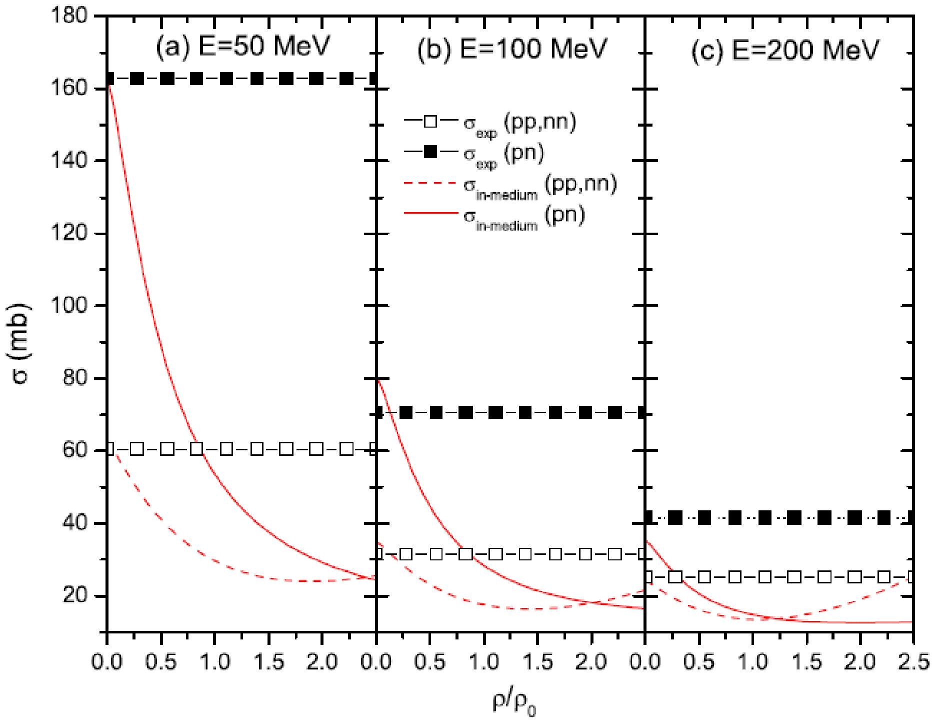
Isospin dependence of NN cross sections in symmetric nuclear matter

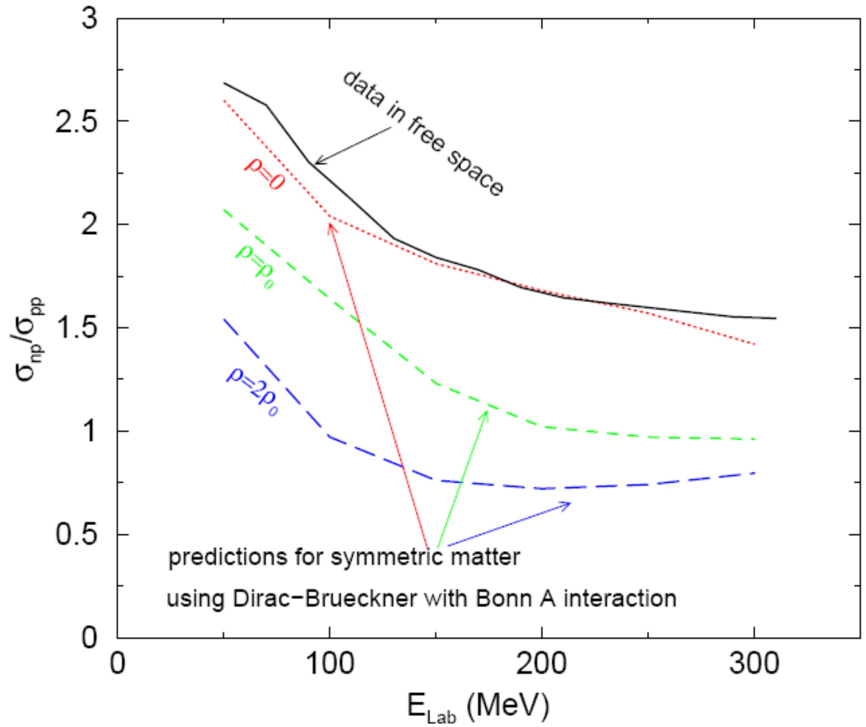
Dirac-Brueckner-Hartree-Fock with Bonn A potentail

G.Q. Li, R. Machleidt, Phys. Rev. C 48 (1993) 1702; ibid, C 49 (1994) 566.

$$\sigma_{np}^{\mathrm{medium}} = \left[31.5 + 0.092abs(20.2 - E_{\mathrm{lab}}^{0.53})^{2.9}\right] \cdot \frac{1.0 + 0.0034E_{\mathrm{lab}}^{1.51}\rho^2}{1.0 + 21.55\rho^{1.34}} \ (\mathrm{mb}),$$

$$\sigma_{pp}^{\mathrm{medium}} = \left[23.5 + 0.0256(18.2 - E_{\mathrm{lab}}^{0.5})^4\right] \cdot \frac{1.0 + 0.1667E_{\mathrm{lab}}^{1.05}\rho^3}{1.0 + 9.704\rho^{1.2}} \ (\mathrm{mb}).$$





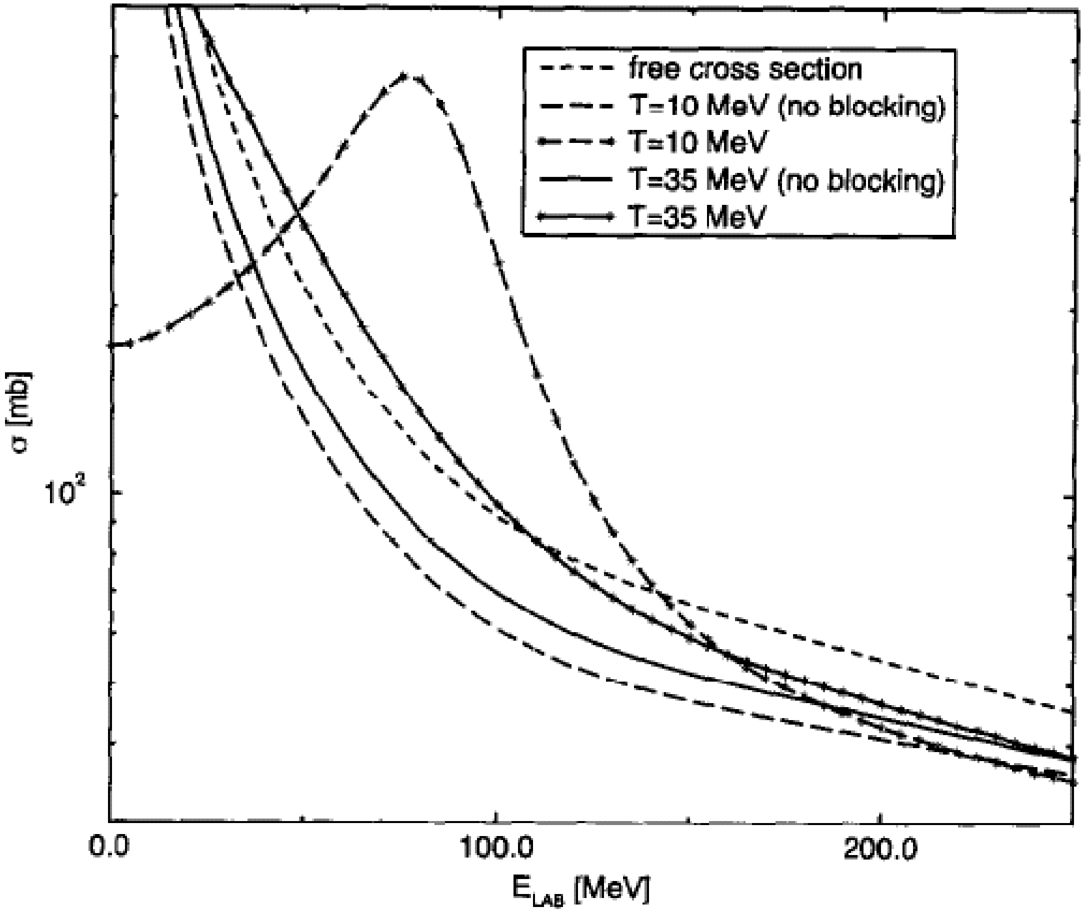
Chen/Ko/Li. PRC 68, 014605 (2003).

Strong medium effects !

Isospin-average in-medium NN cross sections at finite temperature

T-matrix approach based on Matsubara Green functions

T. Alm, G. Röpke, W. Bauer, F. Daffin, M. Schmidt, Nucl. Phys. A 587 (1995) 815.



The peak at T=10 MeV: precursor effect of the superfluid phase transition in nuclear matter

- The self-energy correction suppresses the cross section
- The Pauli blocking operator for intermediate states enhances the cross section

Isospin dependence of NN cross sections in neutron-rich nuclear matter

Effective mass scaling model

Medium effects:

effective mass on the incoming current in initial state and level density of the final state

$$\sigma_{medium} / \sigma_{free} \approx \left(\frac{\mu^*_{NN}}{\mu_{NN}} \right)^2$$

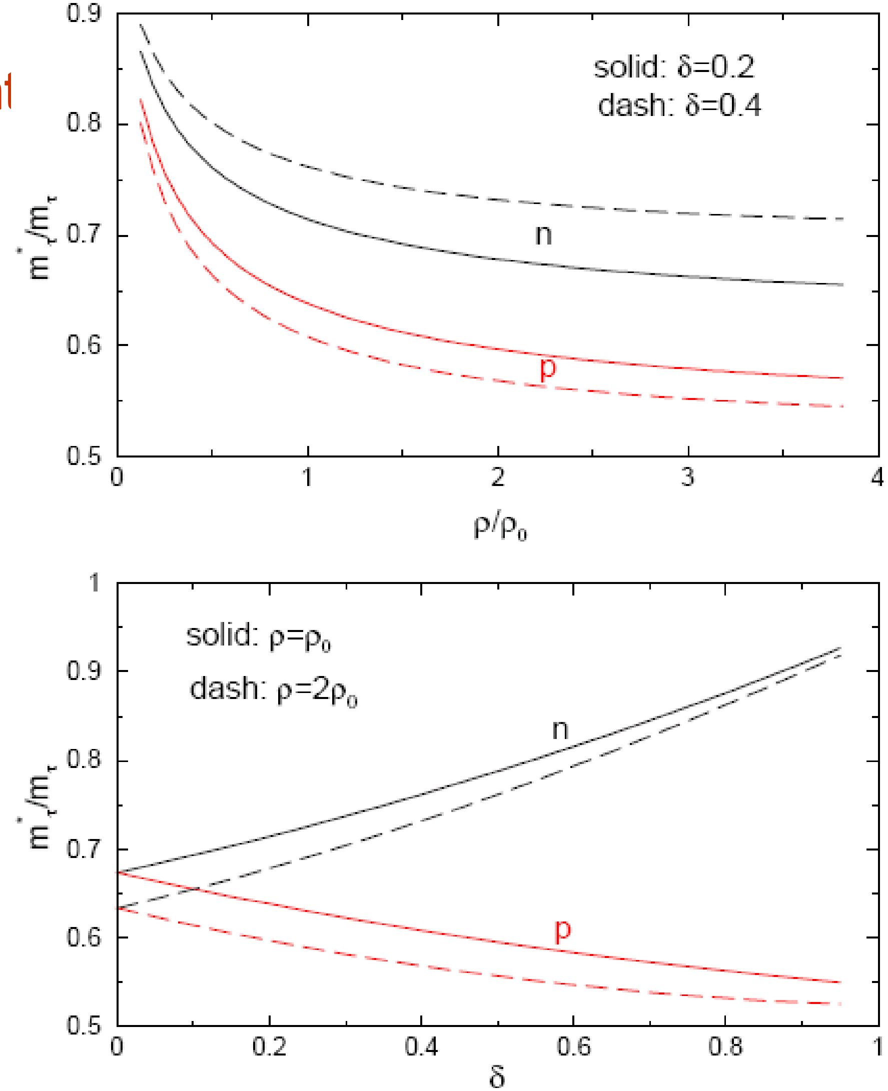
μ^*_{NN} is the reduced mass of the colliding pair NN in medium

J.W. Negele and K. Yazaki, PRL 47, 71 (1981)
V.R. Pandharipande and S.C. Pieper, PRC 45, 791 (1992)
M. Kohno et al., PRC 57, 3495 (1998)
D. Persram and C. Gale, PRC65, 064611 (2002).

Neglecting medium effects on the transition matrix

Li/ Chen, PRC72 (2005)064611

MDI interaction

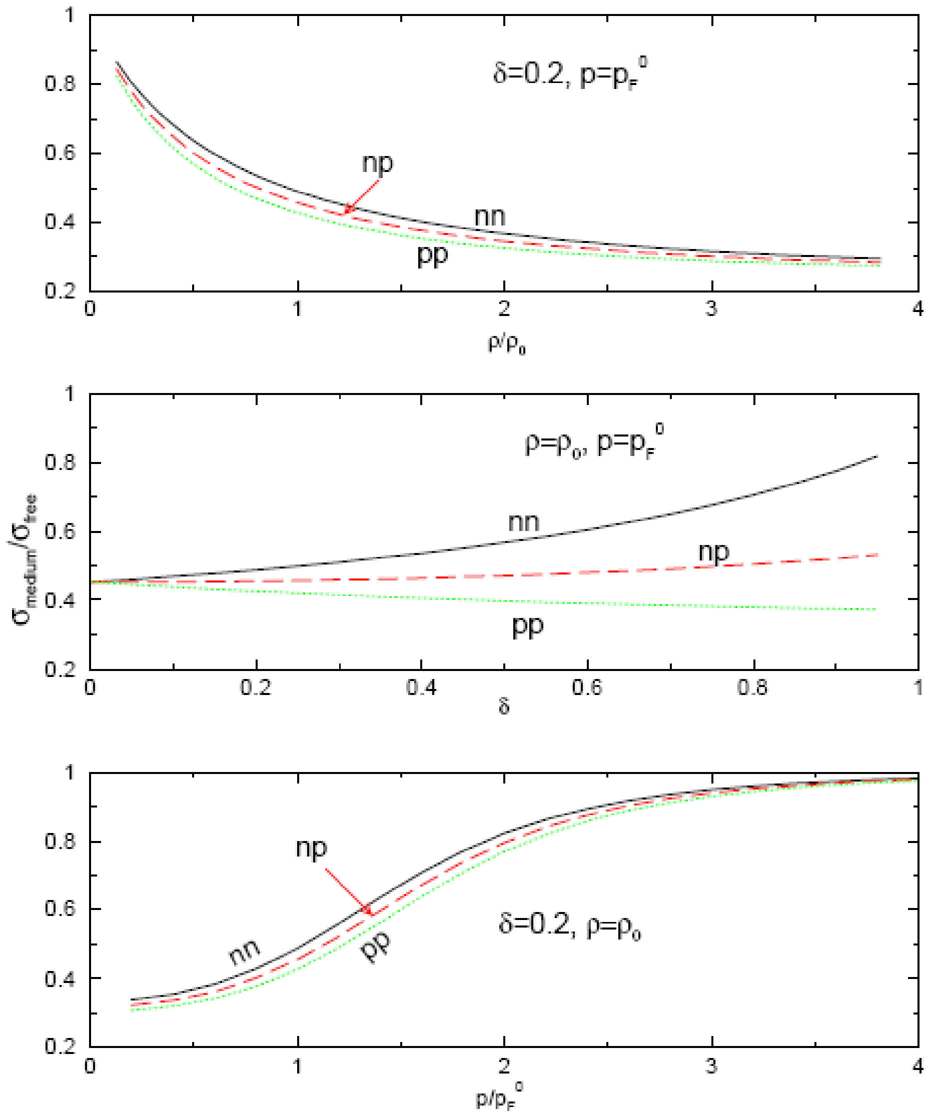


Isospin dependence of NN cross sections in neutron-rich nuclear matter

Effective mass scaling model

$$\sigma_{medium} / \sigma_{free} \approx \left(\frac{\mu^*_{NN}}{\mu_{NN}} \right)^2$$

$\sigma_{medium} / \sigma_{free}$ in neutron-rich matter



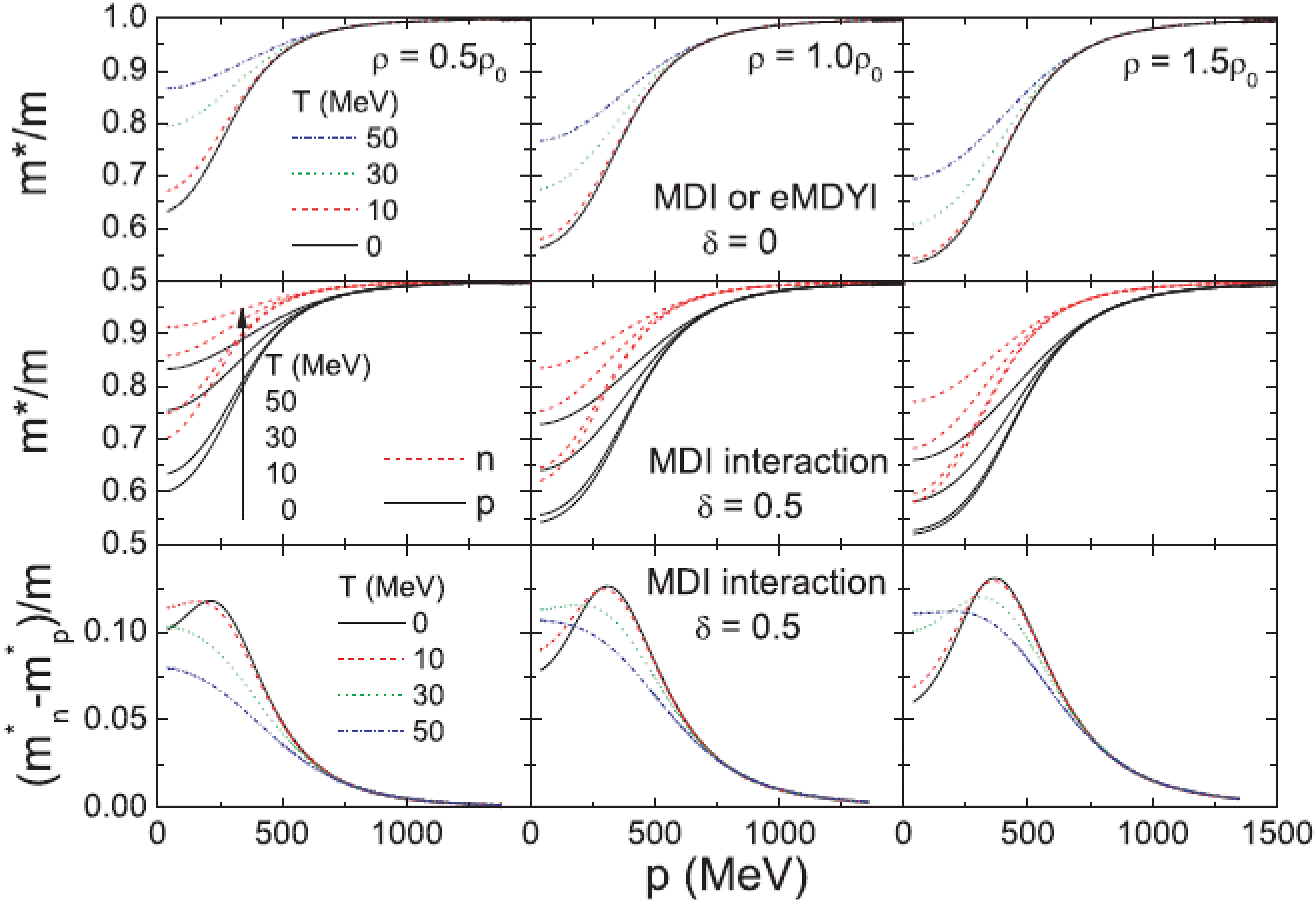
1. In-medium cross sections are reduced
2. nn and pp cross sections are splitted due to the neutron-proton effective mass slitting in neutron-rich matter

Li/ Chen, PRC72 (2005)064611

Isospin dependence of NN cross sections in neutron-rich nuclear matter

Effective mass scaling model

Temperature effects from MDI interaction

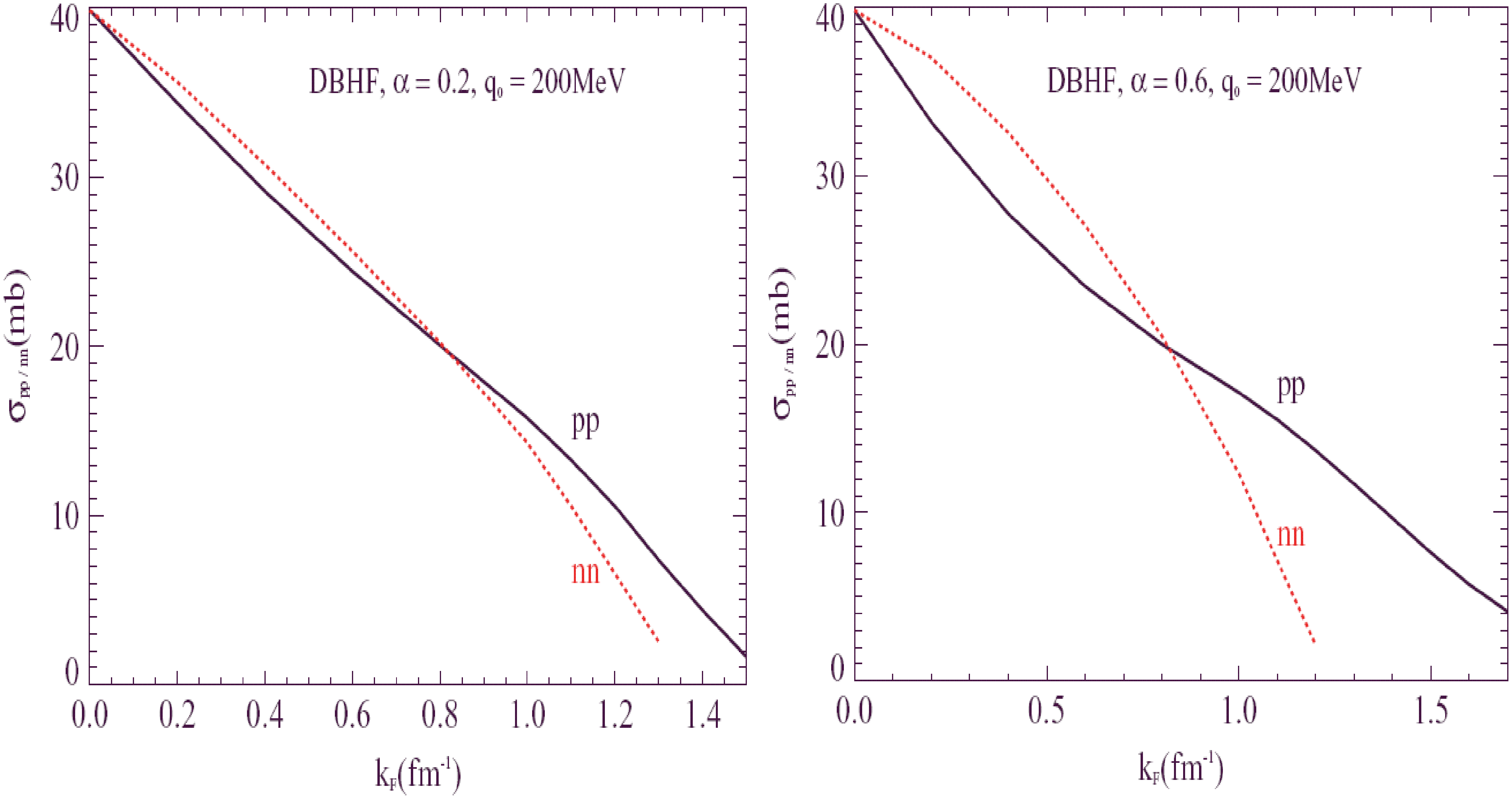


Xu/Chen/Li/Ma, PRC77 (2005)014302

Isospin dependence of NN cross sections in neutron-rich nuclear matter

Dirac-Brueckner-Hartree-Fock with Bonn B potentail

Sammarruca/Krastev, PRC73 (2006)014001



Pauli blocking of final states has been included

(For isospin-dependent Pauli Blocking in ANM, see also L.W. Chen et al, PRC64, 064315 (2001))

Relativistic impulsive approximation to high energy NN cross sections in ANM

Relativistic Impulsive Approximation (RIA)

- RIA provides a successful method to describe elastic nucleon-nucleus scattering at high energies (above ~ 500 MeV)
- The microscopic relativistic Dirac optical potential can be derived from RIA with very little phenomenological freedom
- The basic ingredients in RIA are the free Lorentz-invariant NN scattering amplitude and the scalar and vector densities in nuclear matter

The free Lorentz-invariant NN scattering amplitude

$$\widehat{F} = F_S + F_V \gamma_1^{\mu} \gamma_{2\mu} + F_T \sigma_1^{\mu\nu} \sigma_{2\mu\nu} + F_P \gamma_1^5 \gamma_2^5 + F_A \gamma_1^5 \gamma_1^{\mu} \gamma_2^5 \gamma_{2\mu}$$

The five complex amplitudes F_S, F_V, F_T, F_P, F_A can be determined directly from the NN phase shifts extracted from the NN scattering data. For a spin-saturated nucleus, only the scalar and the zeroth component of the vector amplitudes dominate the contribution to the optical potential.

Relativistic Impulsive Approximation (RIA)

Dirac optical potential in momentum space:

$$\tilde{U}(\mathbf{q}) = \frac{-4\pi i p_{\text{lab}}}{M}[F_S(q)\tilde{\rho}_S(\mathbf{q}) + \gamma_0 F_V(q)\tilde{\rho}_V(\mathbf{q})]$$

Dirac optical potential in coordinate space (infinite nuclear matter):

$$U = \frac{-4\pi i p_{\text{lab}}}{M}[F_{S0}\rho_S + \gamma_0 F_{V0}\rho_V] \qquad F_{S0} \equiv F_S(q=0) \text{ and } F_{V0} \equiv F_V(q=0)$$

$$U_{\text{opt}} = U_S^{\text{tot}} + \gamma_0 U_0^{\text{tot}} \qquad U_S^{\text{tot}} = U_S + iW_S, \;\; U_0^{\text{tot}} = U_0 + iW_0$$

Schrodinger equivalent potential (SEP)

$$U_{\text{SEP}} = U_S^{\text{tot}} + U_0^{\text{tot}} + \frac{1}{2M}(U_S^{\text{tot2}} - U_0^{\text{tot2}}) + \frac{U_0^{\text{tot}}}{M}E_{\text{kin}}$$

Isoscalar optical potential

$$\bar{U}_{\text{sep}} = (U_{\text{sep}}^n + U_{\text{sep}}^p)/2 \qquad \text{and} \qquad \bar{W}_{\text{sep}} = (W_{\text{sep}}^n + W_{\text{sep}}^p)/2.$$

Isovector optical potential (Nuclear symmetry potential)

$$U_{\text{sym}} = \frac{U_{\text{sep}}^n - U_{\text{sep}}^p}{2\delta} \qquad W_{\text{sym}} = \frac{W_{\text{sep}}^n - W_{\text{sep}}^p}{2\delta} \qquad \delta = (\rho_n - \rho_p)/\rho_B$$

Relativistic Impulsive Approximation (RIA)

Dispersion relation:

$$(E_k - U_0^{\rm tot})^2 = \mathbf{k}^2 + (M + U_S^{\rm tot})^2 \qquad E_k = E_{\rm kin} + M$$

$$\frac{k_\infty^2}{2M} = \frac{k^2}{2M} + U_{\rm sep}^{\rm tot}(E_{\rm kin}) \qquad k_\infty^2 = E_{\rm kin}^2 + 2ME_{\rm kin} \qquad U_{\rm sep}^{\rm tot} = U_{\rm sep} + iW_{\rm sep}$$

Complex momentum:

$$k = k_R + ik_I$$

Mean free path:

$$\lambda = \frac{1}{2k_I} = \frac{1}{2}\left[-M\left(E_{\rm kin} + \frac{E_{\rm kin}^2}{2M} - U_{\rm sep}\right) + M\left(\left(E_{\rm kin} + \frac{E_{\rm kin}^2}{2M} - U_{\rm sep}\right)^2 + W_{\rm sep}^2\right)^{1/2}\right]^{-1/2}$$

$$\lambda_i = \frac{1}{2k_I^i} = -\frac{k_R^i}{2MW_{\rm sep}^i}, \qquad i = p, n. \qquad k_R \approx (E_{\rm kin}^2 + 2ME_{\rm kin} - 2MU_{\rm sep})^{1/2}$$

$$\lambda_i = (\rho_p\sigma_{ip}^* + \rho_n\sigma_{in}^*)^{-1}, \qquad i = p, n \qquad k_I \approx -W_{\rm sep}\left(\frac{k_R}{M} + \frac{\partial U_{\rm sep}}{\partial k_R}\right)^{-1}$$

NN cross sections:

$$\tilde{\Lambda}^{-1} = \frac{1}{2}\left(\frac{1}{\lambda_n} + \frac{1}{\lambda_p}\right) = \frac{2M}{k_R}\bar{W}_{\rm sep} \qquad \tilde{\lambda}^{-1} = \frac{1}{2\delta}\left(\frac{1}{\lambda_n} - \frac{1}{\lambda_p}\right) = \frac{2M}{k_R}W_{\rm sym};$$

$$\sigma_{nn}^* = (\tilde{\Lambda}^{-1} + \tilde{\lambda}^{-1})/\rho_B \quad \text{and} \quad \sigma_{np}^* = (\tilde{\Lambda}^{-1} - \tilde{\lambda}^{-1})/\rho_B.$$

Here it is assumed that $\sigma_{nn}^* = \sigma_{pp}^*$

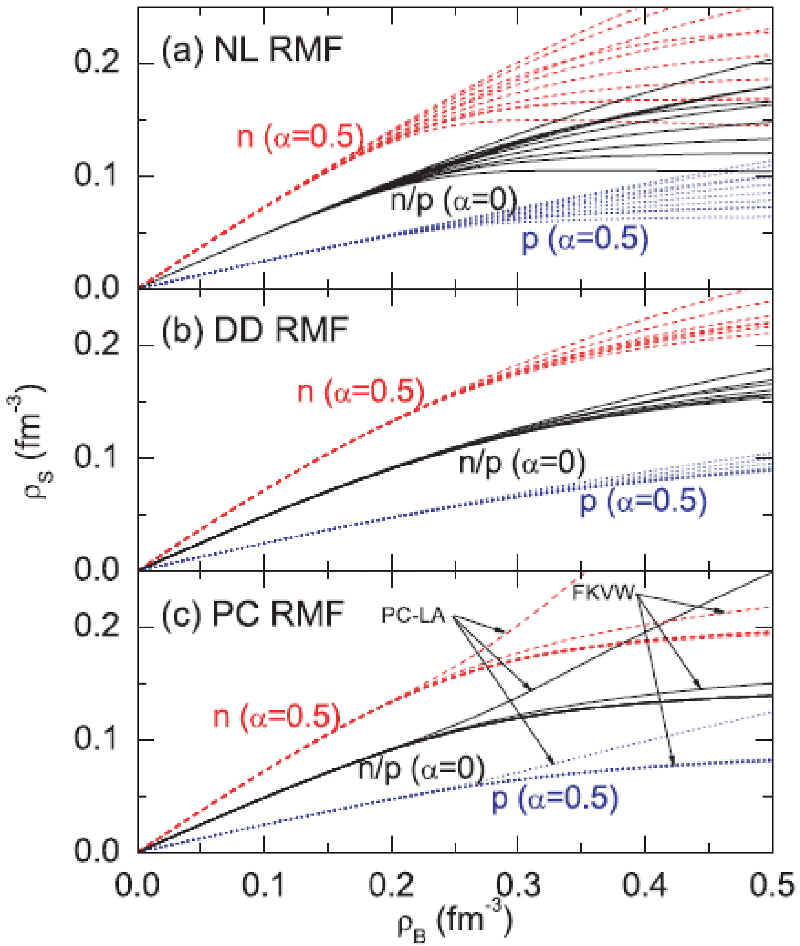
Relativistic Impulsive Approximation (RIA)

For infinite nuclear matter

- Empirical NN scattering amplitudes F_{S0} and F_{V0} determined by McNeil, Ray, and Wallace (MRW) have been used

  J.A. McNeil, J.R. Shepard, S.J. Wallace, Phys. Rev. C 27 (1983) 2123

- The scalar density can be obtained from the RMF model



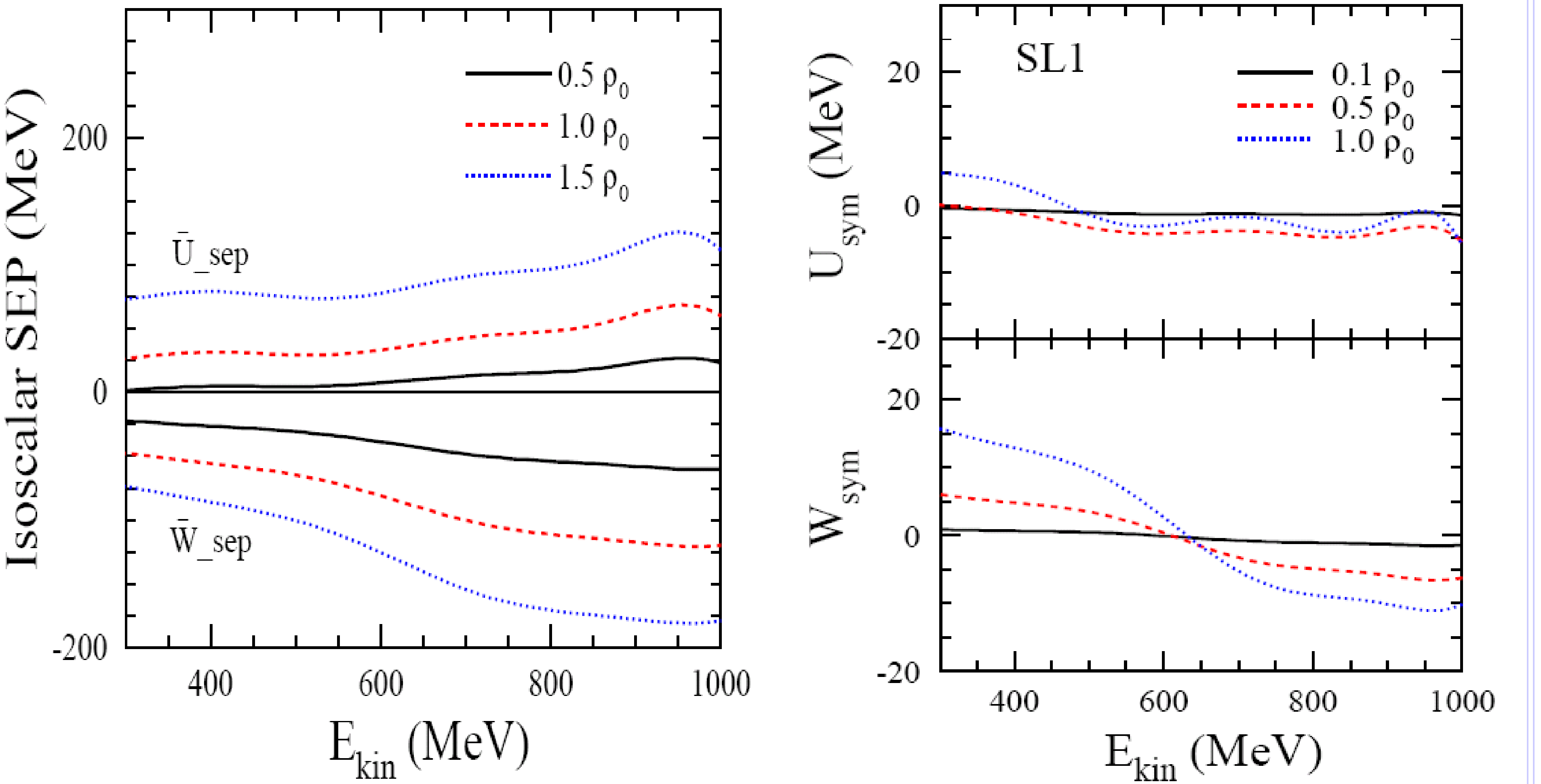
The scalar density and its isospin dependence at lower densities are almost model independent

$$\rho_{S,i} \approx \frac{2}{(2\pi)^3}\int_0^{k_F^i} d^3k \, \frac{M_i^*}{M_i^*} = \frac{2}{(2\pi)^3}\int_0^{k_F^i} d^3k = \rho_{B,i}, \qquad i = p, n.$$

Chen/Ko/Li,
PRC 72, 064606 (2005),
PRC 76, 054316 (2007).

Energy dependence of isoscalar SEP and nuclear symmetry potential

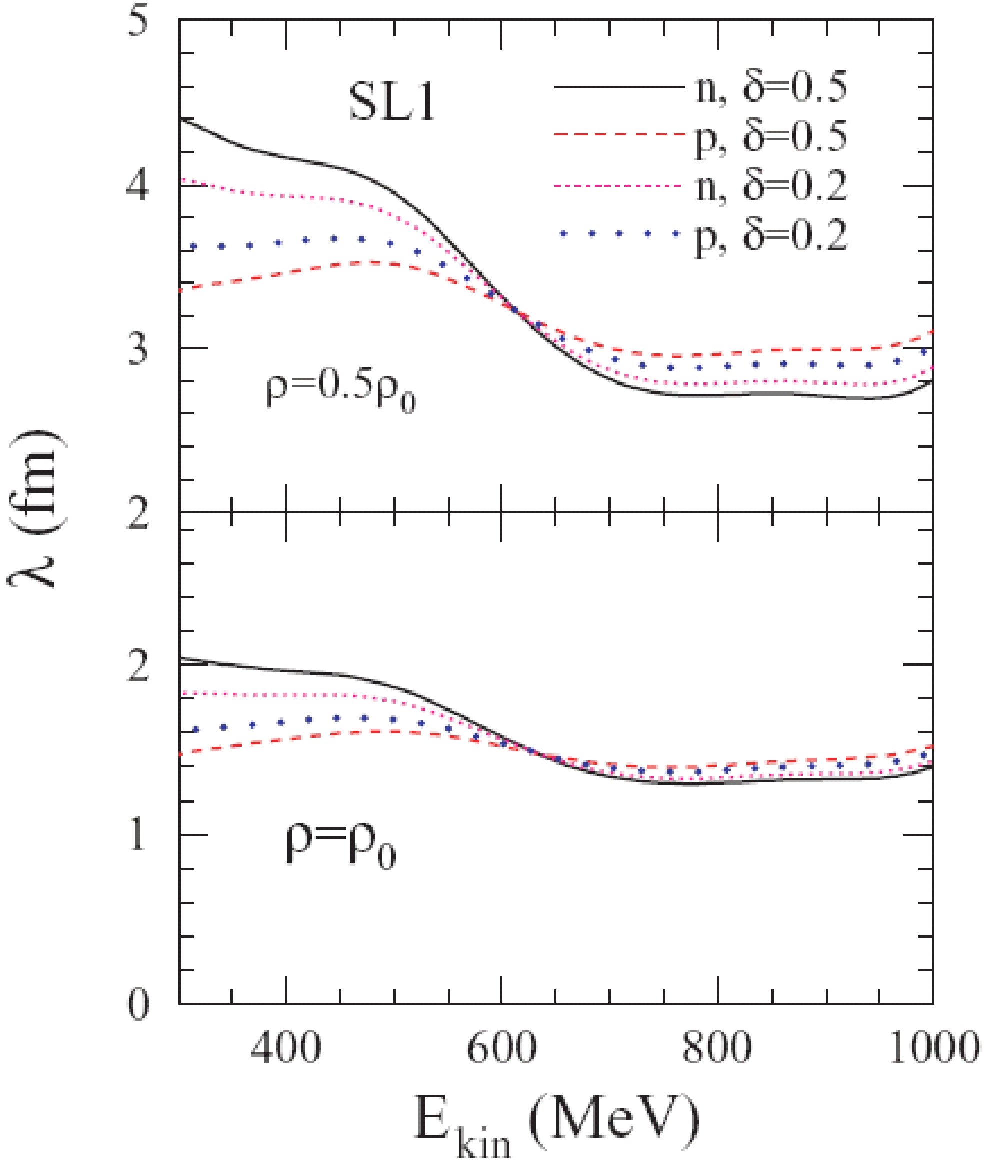
Jiang/Li/Chen. PRC 76, 044604 (2007).



- Both isoscalar and isovector SEP are independent of the isospin asymmetry
- U_{sym} is essentially zero at higher energies

Energy dependence of nucleon mean-free path in ANM

Jiang/Li/Chen, PRC 76, 044604 (2007).



- The isospin-splitting between the neutron and proton MFP changes sign at about 600 MeV

- This behavior is determined by the imaginary part of the symmetry potential

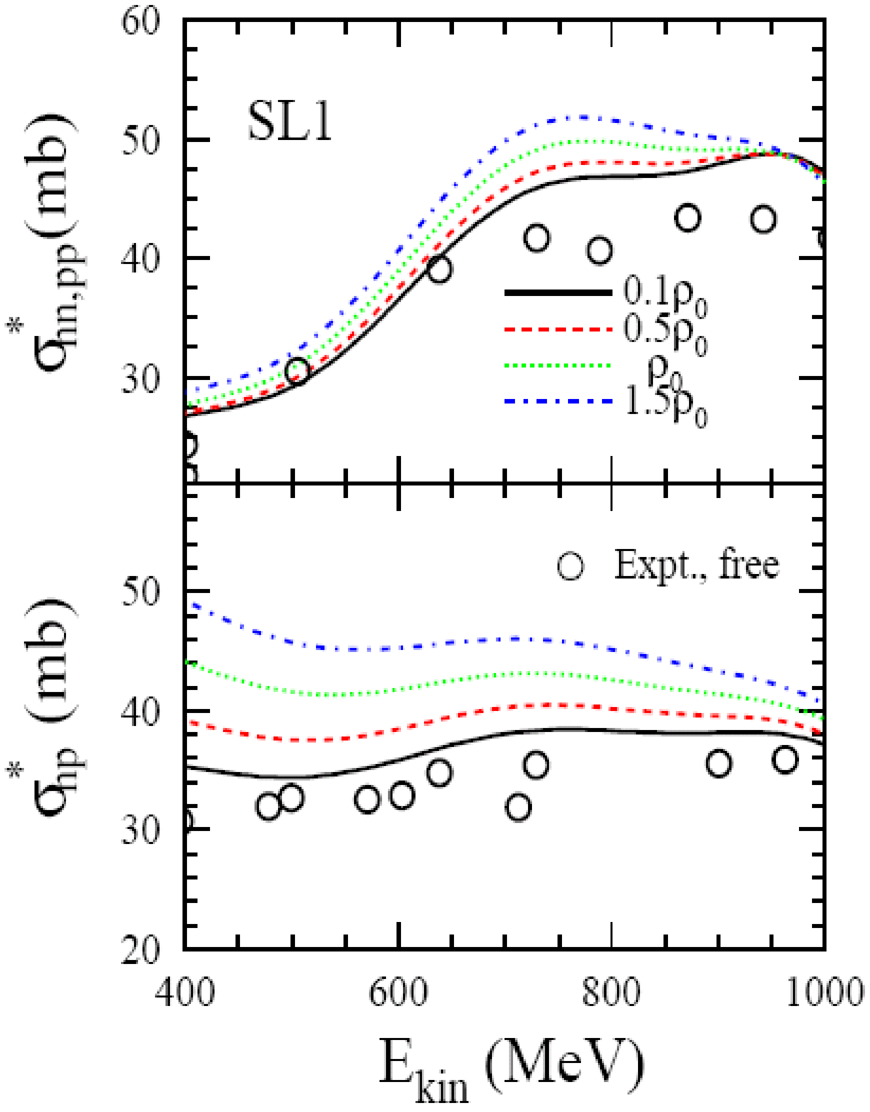
$$\lambda_i = \frac{1}{2k_I^i} = -\frac{k_R^i}{2MW_{\text{sep}}^i}, \qquad i = p, n.$$

$$k_R \approx (E_{\text{kin}}^2 + 2ME_{\text{kin}} - 2MU_{\text{sep}})^{1/2}$$

$$\approx k_R^{n,p}$$

Energy dependence of in-medium NN cross sections

Jiang/Li/Chen, PRC 76, 044604 (2007).



- In-medium NN cross sections increase with density
- In-medium NN cross sections are independent of the isospin asymmetry

$$\tilde{\Lambda}^{-1} = \frac{1}{2}\left(\frac{1}{\lambda_n} + \frac{1}{\lambda_p}\right) = \frac{2M}{k_R}\bar{W}_{\rm sep}$$

$$\tilde{\lambda}^{-1} = \frac{1}{2\delta}\left(\frac{1}{\lambda_n} - \frac{1}{\lambda_p}\right) = \frac{2M}{k_R}W_{\rm sym}$$

$$\sigma^*_{nn} = (\tilde{\Lambda}^{-1} + \tilde{\lambda}^{-1})/\rho_B$$

$$\sigma^*_{np} = (\tilde{\Lambda}^{-1} - \tilde{\lambda}^{-1})/\rho_B$$

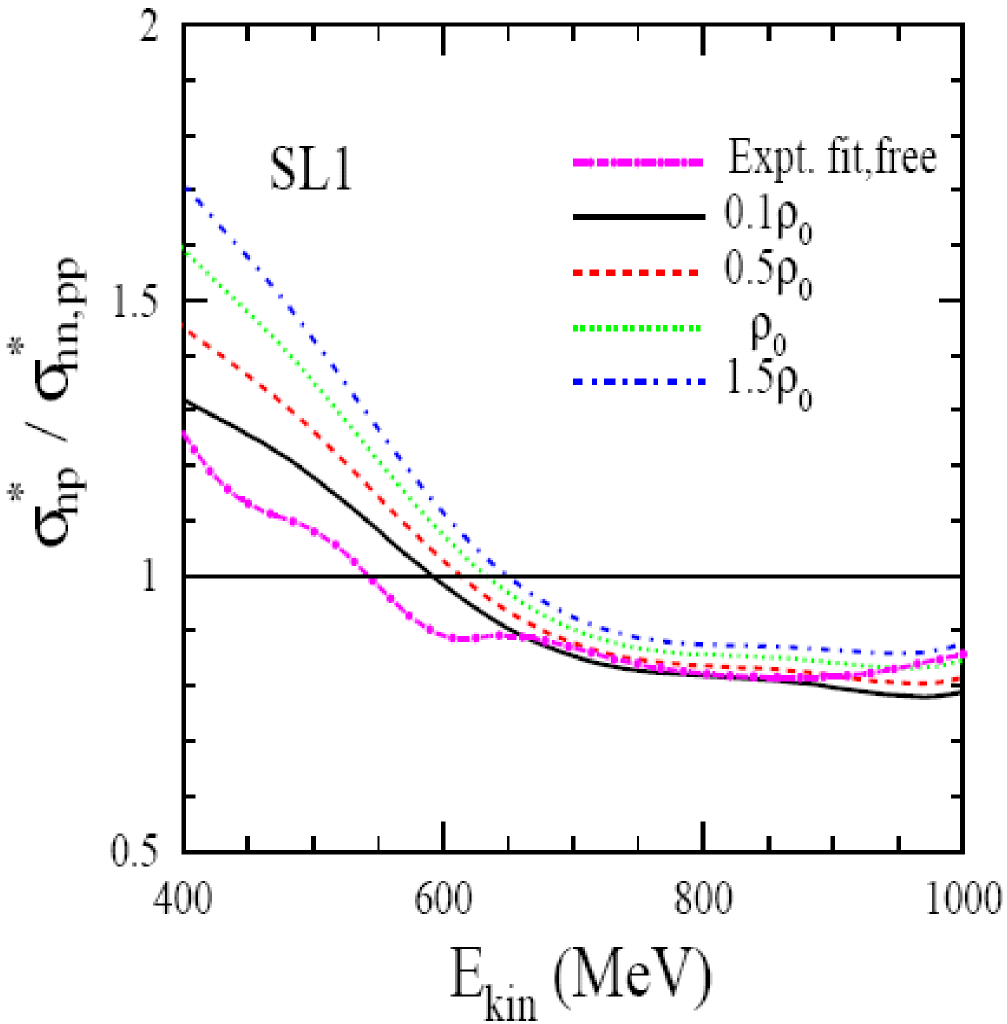
Implicitly assuming

$$k_R \approx (E^2_{\rm kin} + 2ME_{\rm kin} - 2MU_{\rm sep})^{1/2}$$

$$\approx k_R^{n,p}$$ <=> $U_{sym} << E_{kin}$

Energy dependence of the ratio σ_{np}/σ_{pp}

Jiang/Li/Chen, PRC 76, 044604 (2007).



- σ_{np}/σ_{pp} increases with density
- σ_{np}/σ_{pp} decreases with energy but saturates at high energies
- Above ~600 MeV, $\sigma_{np} < \sigma_{pp}$

Probing NN cross sections in asymmetric nuclear matter using heavy-ion collisions

- Experimentally, strong evidences supporting reduced in-medium NN cross sections have been found in heavy-ion collisions at intermediate energies

G.D. Westfall, et al., Phys. Rev. Lett. 71 (1993) 1986. P. Danielewicz, Acta. Phys. Polon. B 33 (2002) 45 (2002)
H.M. Xu, Phys. Rev. Lett. 67 (1991) 2769; Phys. Rev. C 46 (1992) R389.

- An empirical relation(D. Klakow, G. Welke, W. Bauer, Phys. Rev. C 48 (1993) 1982)

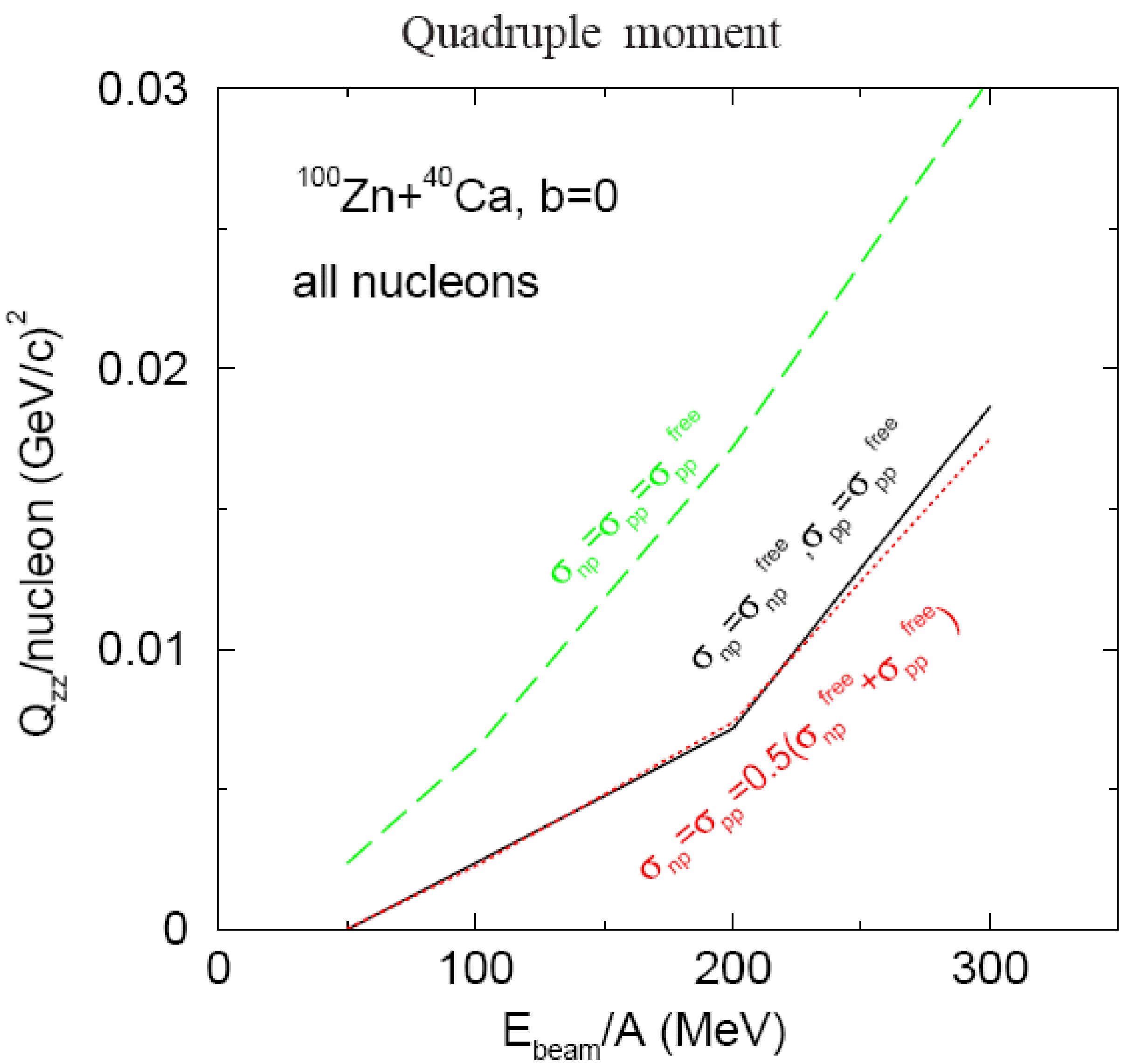
$$\sigma_{NN}^{\rm medium} = \left(1 + \alpha\frac{\rho}{\rho_0}\right)\sigma_{NN}^{\rm free}$$

with the parameter $\alpha \approx -0.2$ has been found to better reproduce the flow data compared to transport model calculations using the free-space NN cross sections.

- Very recently, in studying the stopping power and collective flow in heavy-ion collisions at SIS/GSI energies, there were indications that the in-medium NN cross sections were reduced at low energies but enhanced at high energ(Y. Zhang, Z.X. Li, P. Danielewicz, Phys. Rev. C 75 (2007) 034615.)

All these analyses have been done assuming simply some overall reduction of all NN scattering cross sections ! How about the isospin dependence?

Global stopping power in heavy-ion reactions

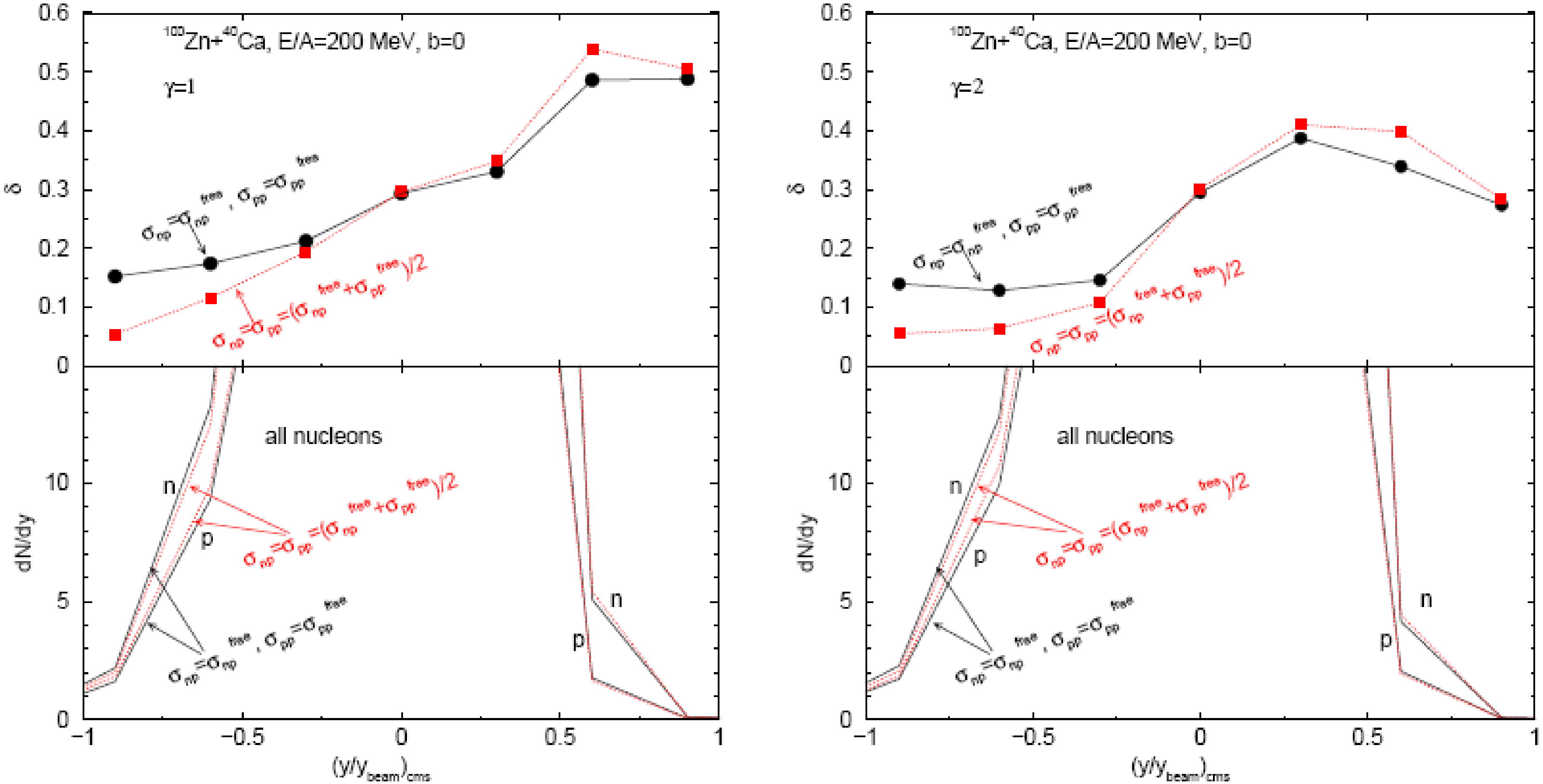


B.A. Li, P. Danielewicz, W.G. Lynch, Phys. Rev. C 71 (2005) 054603.

- The nuclear stopping power is indeed sensitive to the in-medium NN cross sections
- The stopping power alone is insufficient to determine simultaneously both the magnitude and the isospin dependence of the in-medium NN cross sections (the ratio σ_{np}/σ_{pp}).

The backward neutron/proton ratio as a measure of the isospin dependence of the in-medium NN cross sections

B.A. Li, P. Danielewicz, W.G. Lynch, Phys. Rev. C 71 (2005) 054603.

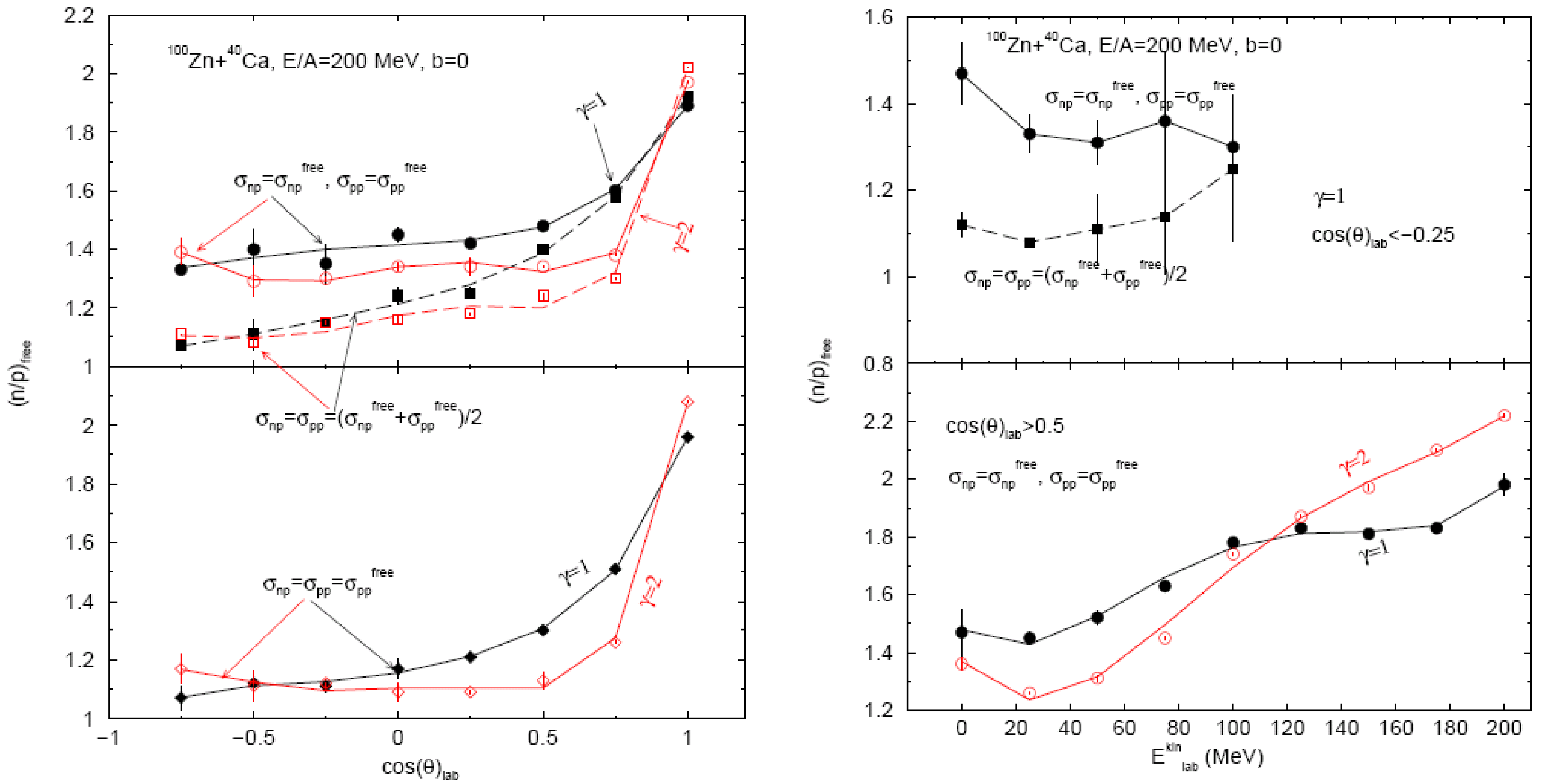


- The isospin tracers at backward rapidities/angles are less affected by the nuclear symmetry potential.
- The isospin tracers at backward rapidities/angles are sensitive to σ_{np}/σ_{pp}

The backward neutron/proton ratio as a measure of the isospin dependence of the in-medium NN cross sections

B.A. Li, P. Danielewicz, W.G. Lynch, Phys. Rev. C 71 (2005) 054603.

Isospin transport +inverse kinematics



- The isospin tracers at backward rapidities/angles are less affected by the nuclear symmetry potential.
- The isospin tracers at backward rapidities/angles are sensitive to σ_{np}/σ_{pp}

Summary and Outlook

- The in-medium NN cross sections and its isospin dependence at low and intermediate energies need further study (density, isospin asymmetry, and temperature effects)
- At high energies (above ~500 MeV), the in-medium NN cross sections:
  1. do not depend on the isospin asymmetry of the medium
  2. increase with baryon density
  3. σ_{np}/σ_{pp} increases with baryon density
  4. σ_{np}/σ_{pp} decreases with energy but saturates at high energies
  5. Above ~600 MeV, $\sigma_{np} < \sigma_{pp}$
- The backward neutron/proton ratio in heavy-ion collisions may provide a good probe for the isospin dependence of the in-medium NN cross sections

Thanks!