The influence of transport variables on isospin transport ratios

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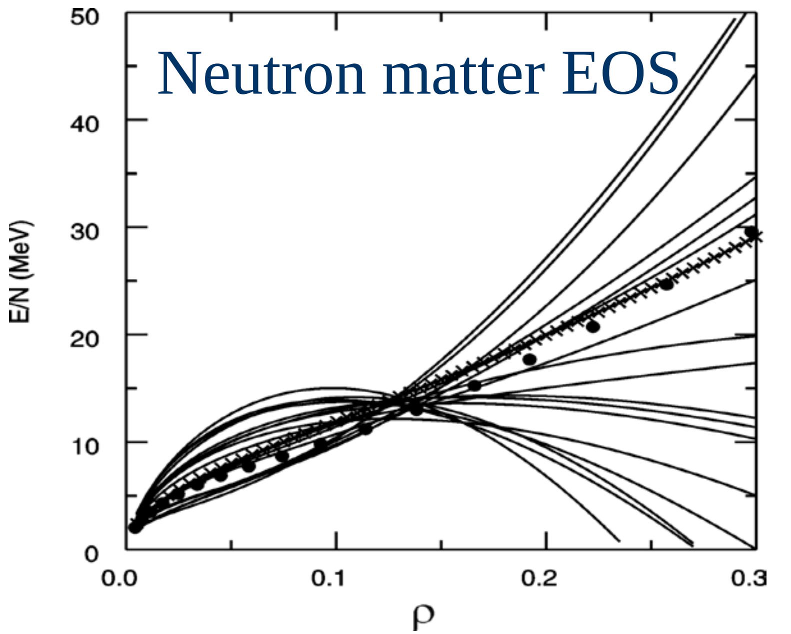
Asymmetric Nuclear Matter

$$B = a_V A - a_S A^{2/3} \pm \varepsilon - a_C \frac{Z(Z-1)}{A^{1/3}}$$
$$-C_{sym} \frac{(A-2Z)^2}{A}$$

Brown, Phys. Rev. Lett. 85, 5296 (2001)

$E/A\,(\rho, \delta) = E/A\,(\rho, 0) + \delta^2 \cdot S(\rho)$

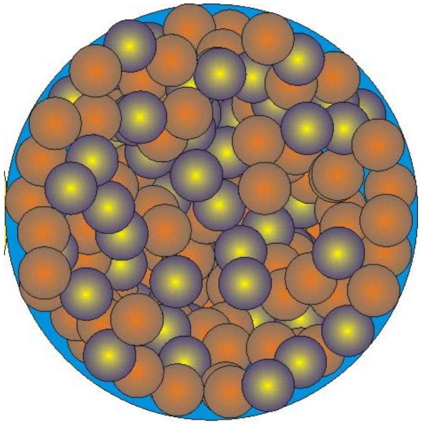
$\delta = (\rho_n - \rho_p)/(\rho_n + \rho_p) = (N-Z)/A$



Asymmetric Nuclear Matter

Symmetry energy impacts:

- Nuclear structure: Neutron skins in nuclei, giant resonances
- Nuclear astrophysics: Neutron Star radii, maximum masses, cooling rates
- Nuclear reactions: isospin diffusion



^{208}Pb

Artist's rendition of a neutron star

http://www.dailygalaxy.com/photos/uncategorized/2007/08/21/neutron_star_1_2.jpg

Isospin Diffusion

Probe the symmetry energy at subsaturation densities in peripheral A + B collisions, e.g. ^{124}Sn + ^{112}Sn

Isospin diffusion through low-density neck region

Non-isospin diffusion effects:

- Pre-equilibrium emissions
- Sequential decays
- Coulomb effects

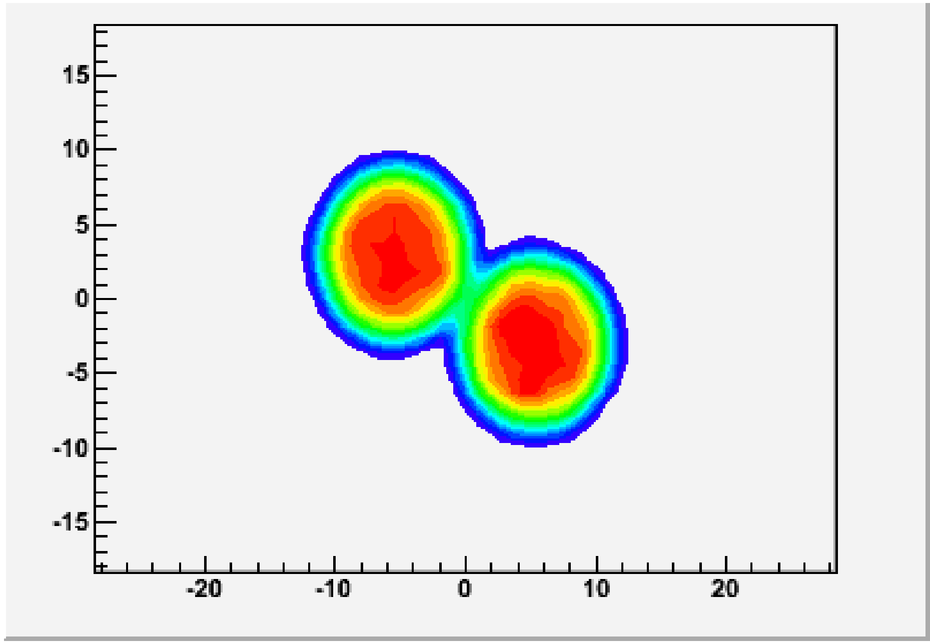
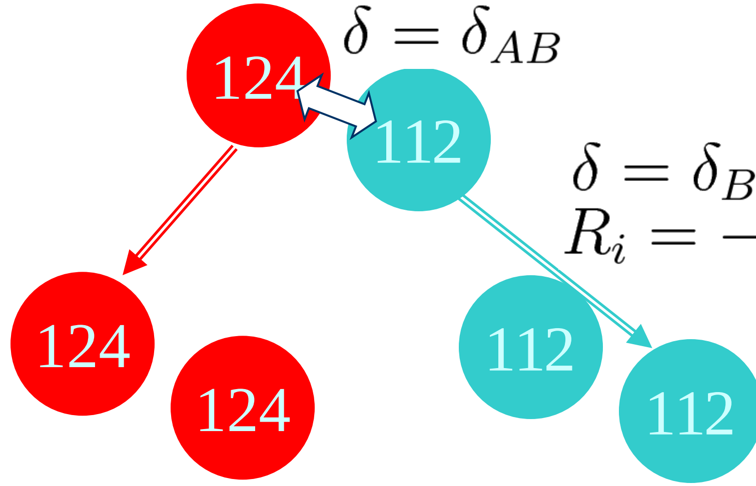


Figure courtesy M. Kilburn

Isospin Transport Ratio

Isospin diffusion occurs only in asymmetric systems A+B

No isospin diffusion between symmetric systems



$\delta = \delta_{AB}$

$\delta = \delta_{BB}$
$R_i = -1$

$\delta = \delta_{AA}$
$R_i = 1$

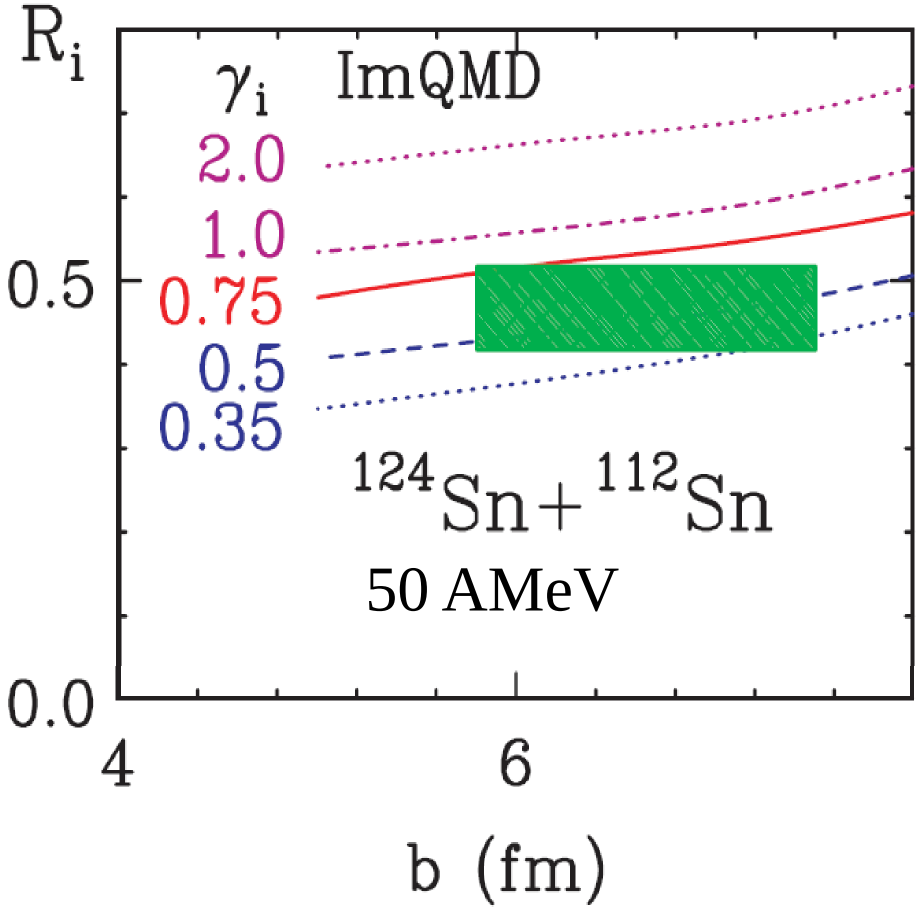
Non-isospin diffusion effects same for A in A+B & A+A; same for B in B+A & B+B

$$R_i = 2\frac{\delta - (\delta_{AA} + \delta_{BB})/2}{\delta_{AA} - \delta_{BB}}$$

Rami et al., PRL, 84, 1120 (2000)

$$\delta = (\rho_n - \rho_p)/(\rho_n + \rho_p) = (N-Z)/A$$

Previous Analysis



Some transport parameters other than symmetry energy are uncertain

M.B. Tsang et al. PRL 102, 122701 (2009)

Goals

- Theoretically, what affects isospin diffusion?
  - Vary parameters widely to find sensitivities
  - Find ways to constrain those sensitivities
  - This was the method used to determine the symmetric equation of state at high densities

- Experimentally, what can we measure to better compare to transport theory?

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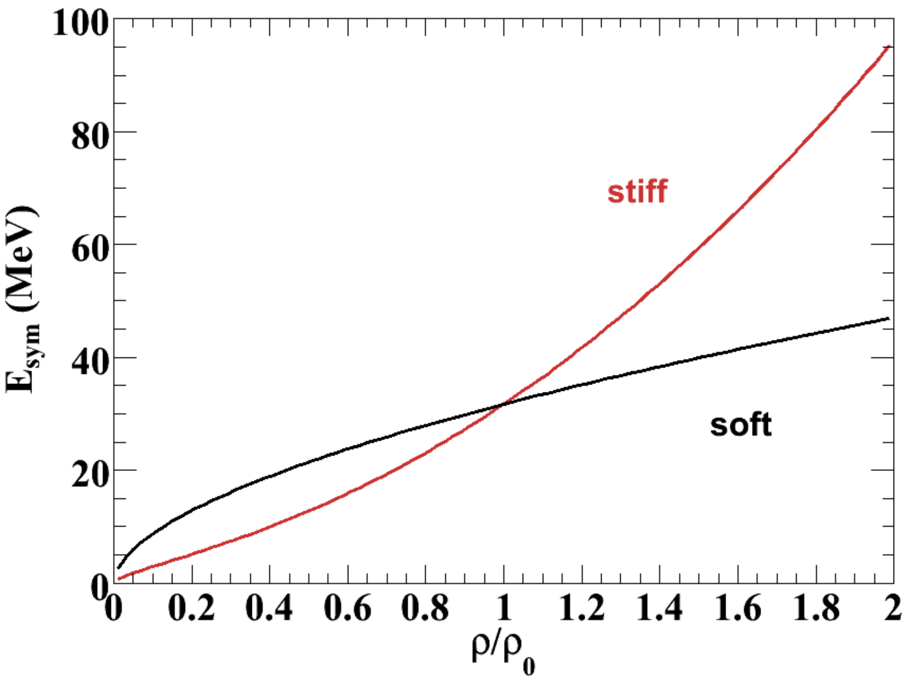
Setup of Transport Calculations

Boltzmann-Uehling-Uhlenbeck (BUU) model

P. Danielewicz, Nucl. Phys. **A673**, 375 (2000)



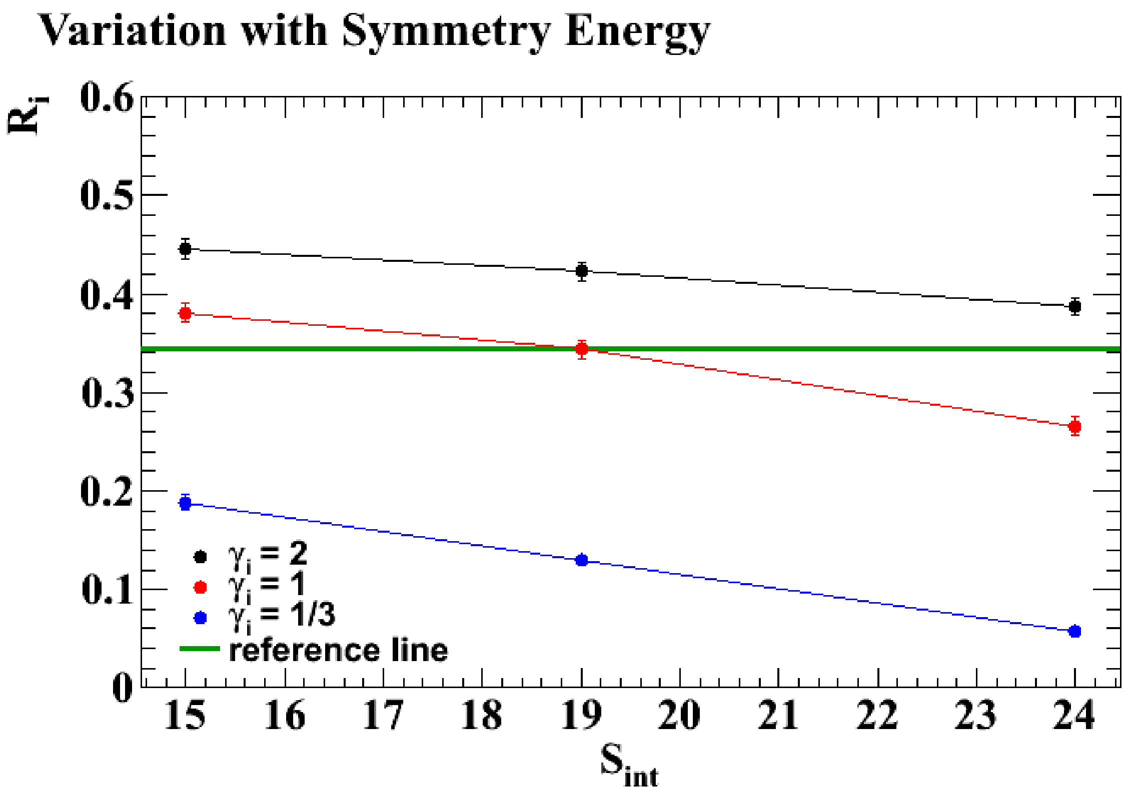
- $^{124}Sn + ^{112}Sn$
- E_{lab} = 50 MeV/A
- impact parameter = 6 fm

$$S(\rho) = 12.5(\rho/\rho_0)^{2/3} + S_{int}(\rho/\rho_0)^{\gamma_i}$$

Variation with Symmetry Energy

124Sn+112Sn, E_{lab} =50MeV, 6 fm

$$S(\rho) = 12.5(\rho/\rho_0)^{2/3} + S_{int}(\rho/\rho_0)^{\gamma_i}$$

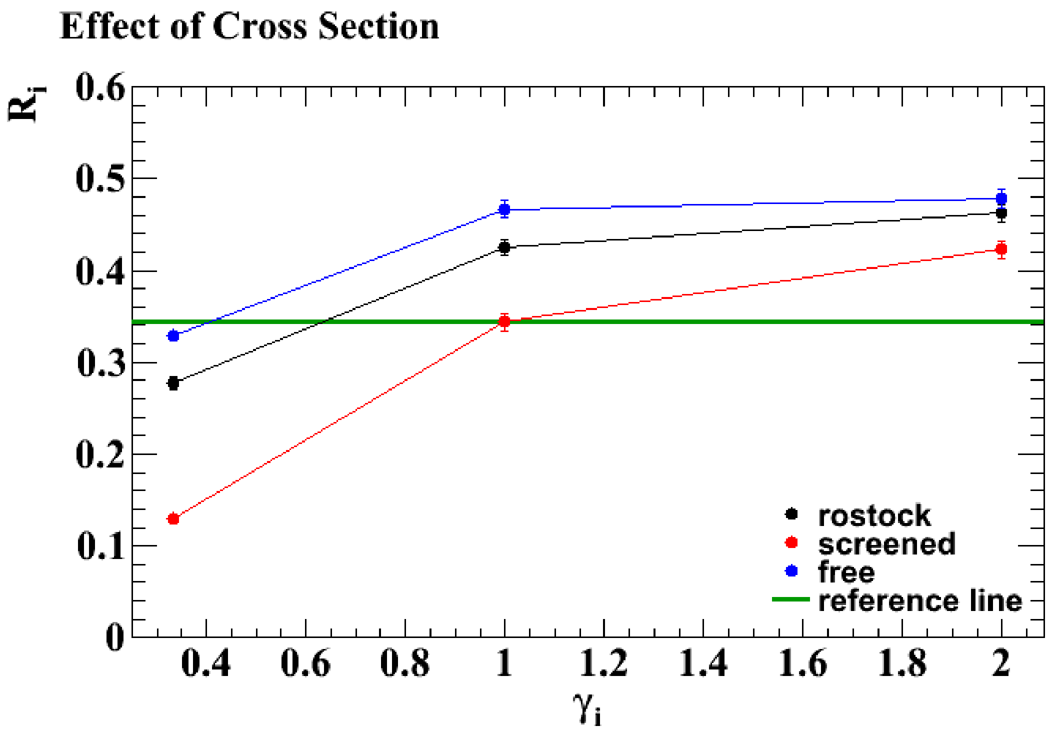


Stronger symmetry energy → more diffusion

Variation with cross section form

124Sn+112Sn, E_{lab} =50MeV, 6 fm

$$S(\rho) = 12.5(\rho/\rho_0)^{2/3} + S_{int}(\rho/\rho_0)^{\gamma_i}$$



Collision cross section reduced in medium

Need to find a way to constrain in-medium cross sections

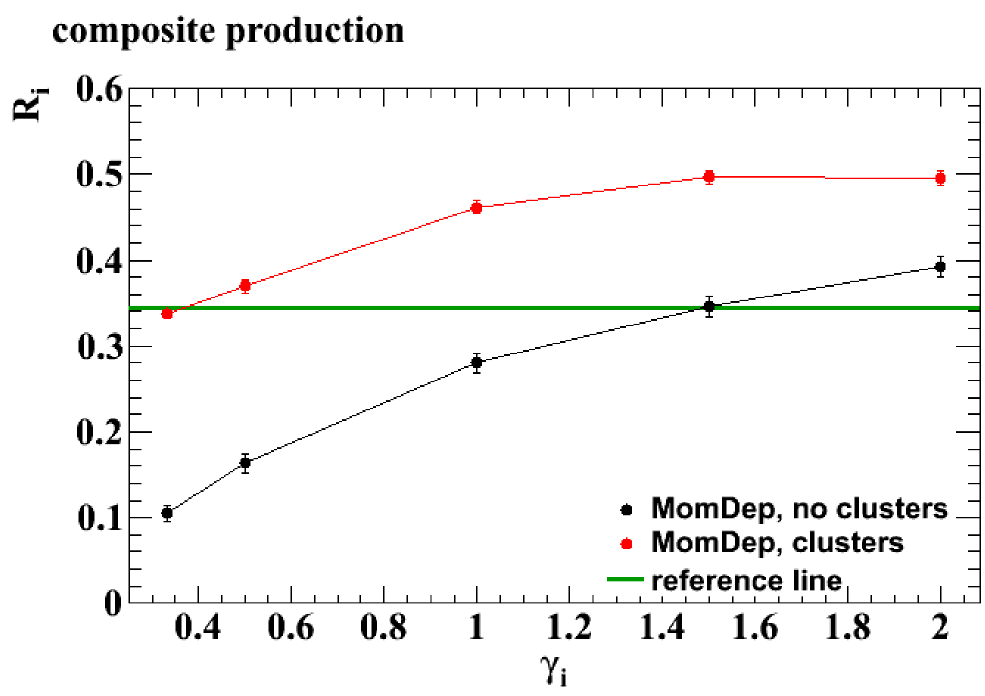
Composite Production

Create light (A <=3) clusters in the medium

Not a native BUU feature, but one form used in ImQMD analysis

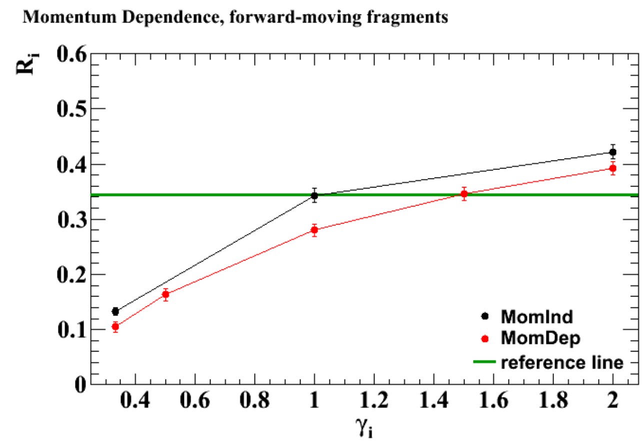
Very sensitive to cluster production – **needs to be better understood theoretically**

Reduces sensitivity to symmetry energy – **need a more precise measurement**

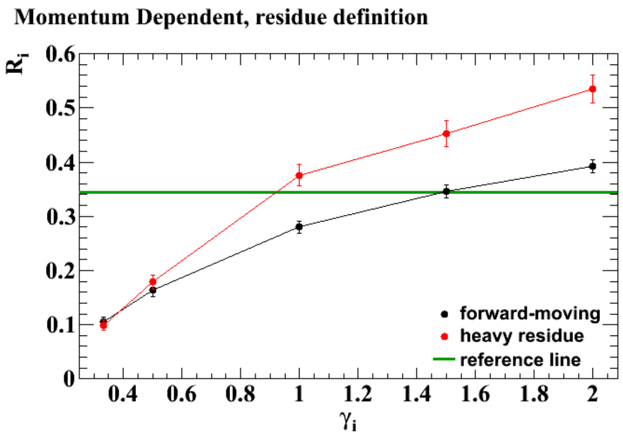


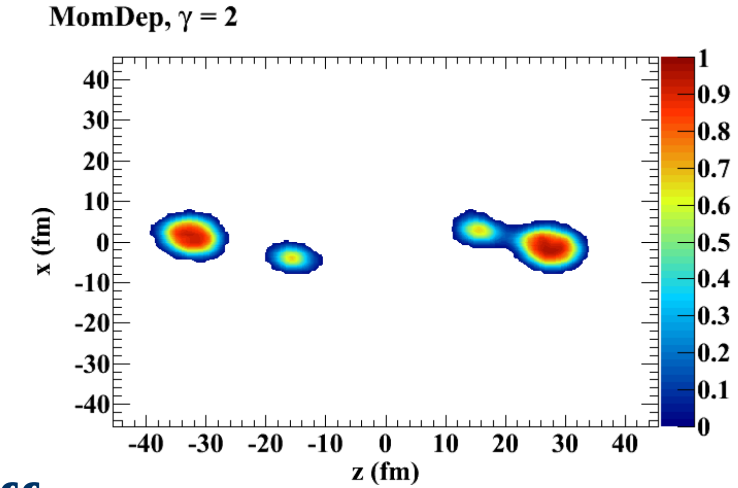
Momentum Dependent Mean Field

Decreases attraction of mean field at large relative momentum



Larger neck fragments formed – the dynamics of the system are changed





Experimentally measure IMF effect

Summary and Outlook

Isospin diffusion is sensitive to the nuclear symmetry energy at subsaturation densities, and the Isospin Transport Ratio selects for these effects

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Theoretically:

- Clustering is very important. We need a full clustering model to interpret isospin diffusion data.
- There are large uncertainties from other transport variables. Need to compare several observables to extract symmetry energy

Experimentally:

- More precise diffusion experiments are needed to place tighter constraints on the symmetry energy.
- IMFs and residues see different sized signals from symmetry energy. Need to measure both.
- Better impact parameter determination is needed.
- Our upcoming experiment will address these issues.

Acknowledgements

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- NSCL
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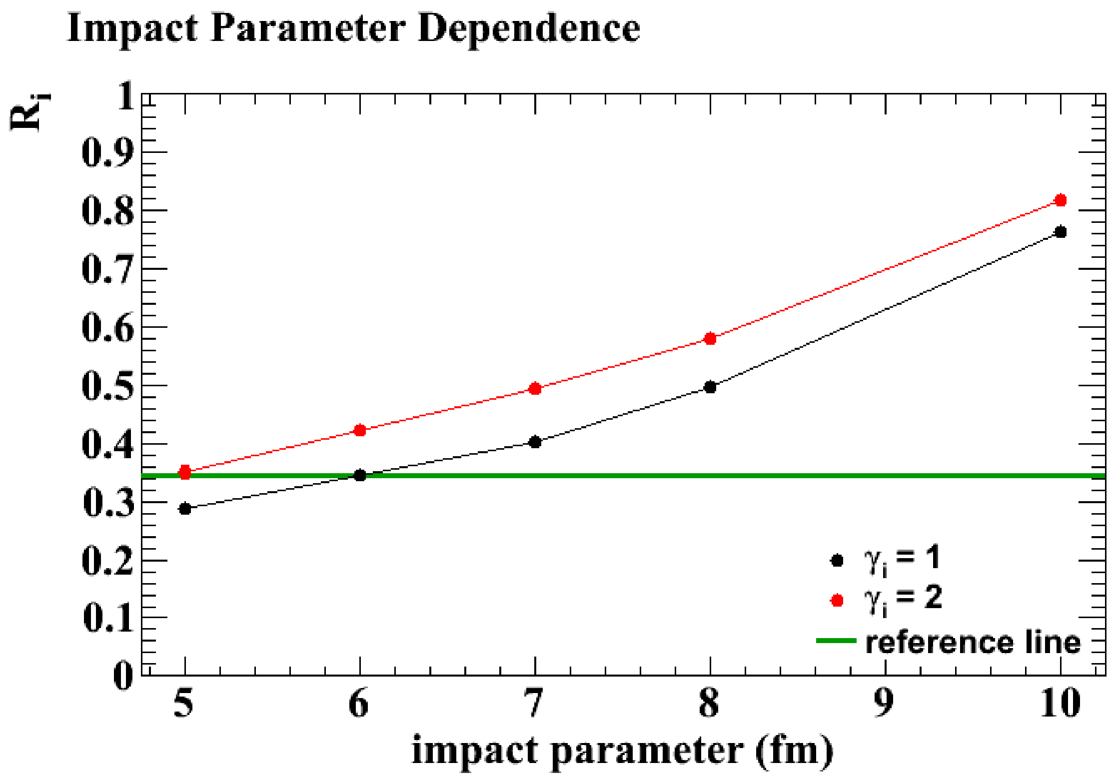
Variation with impact parameter

124Sn+112Sn, E_{lab} =50MeV



strong impact parameter dependence

Reduced Cross Sections

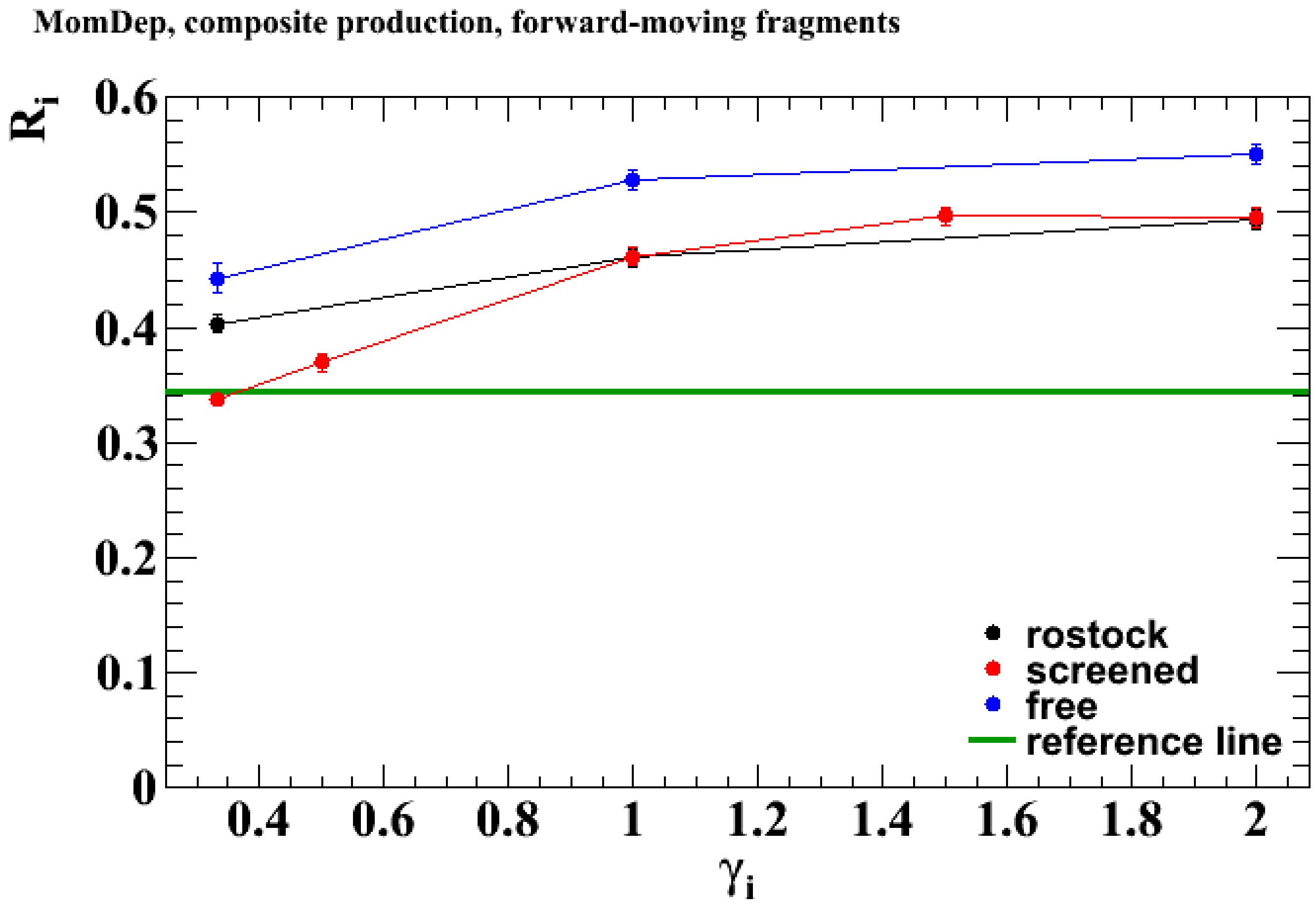
$$\sigma_{in,\eta} = \eta\rho^{-2/3}\tanh\left(\frac{\sigma_f}{\eta\rho^{-2/3}}\right)$$

Screened
•geometric reduction
•strongly density dependent

$$\sigma_{\text{Rostock}} = \sigma_{\text{f}} \exp\left[-0.6\frac{\rho}{\rho_0}\left(\frac{1}{1+\left(\text{KE}_{\text{cm}}/150\text{MeV}\right)^2}\right)\right]$$

Rostock
•Parameterized many-body result
•weakly density, energy dependent

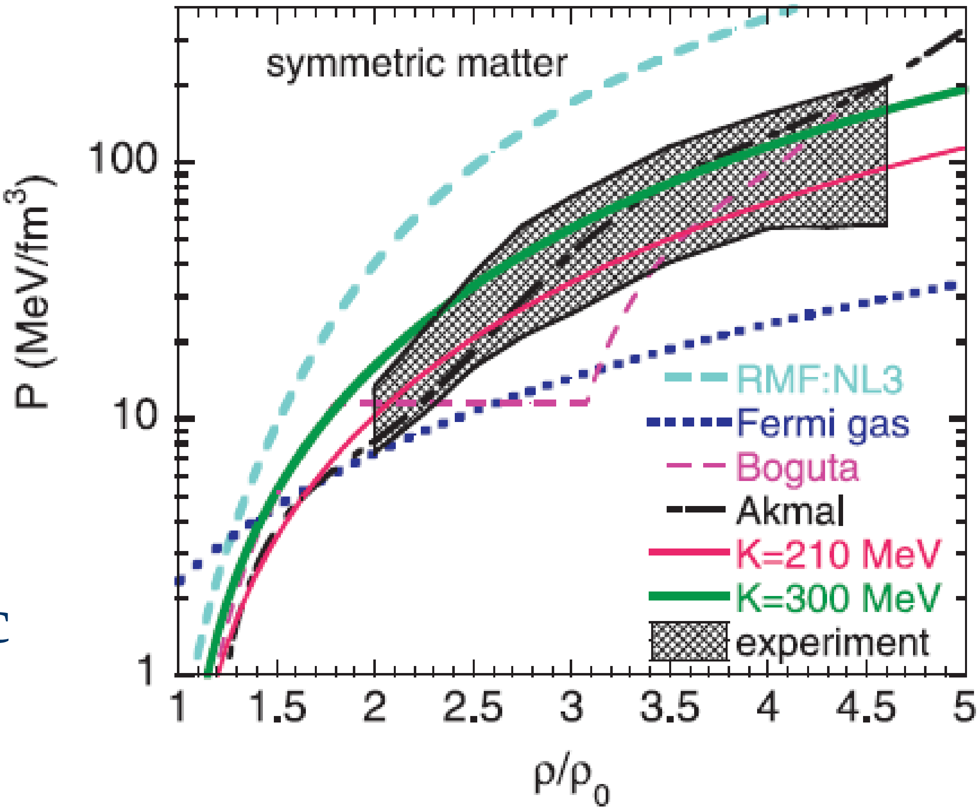
Clusters and Cross Sections



The Nuclear Equation of State

Nuclear EOS describes relationships between energy, density, pressure, temperature, and isospin asymmetry

Density dependence is well determined for symmetric matter



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