Effects of isospin asymmetry on nuclear stopping

Kyungil Kim

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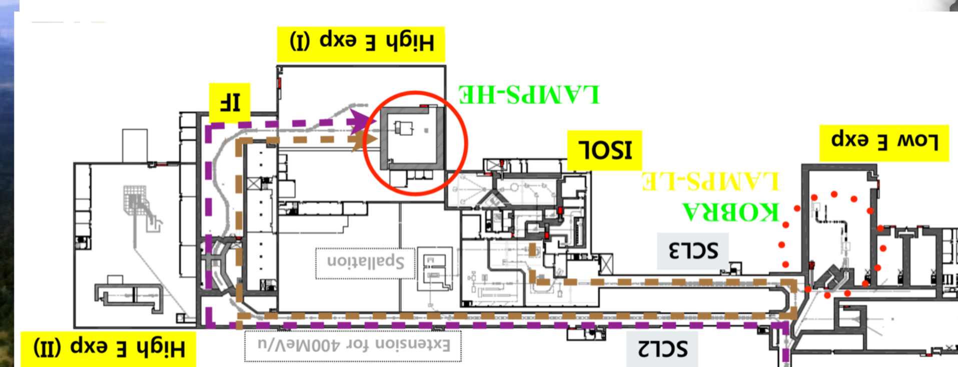
RISP
Rare Isotope Science Project

RAON

Mar. 2018



From Y.K.Kwon's Slide

중이온가속기 시설건설사업 건립공사 시공 현황 (건물/구역별) (`18.9.12, 현재)

SCL2구역 (터널 벽체 철근배근 및 Conc 타설)

SCL3구역 (갤러리 벽체 철근배근)

저에너지AB구역 (B1F 벽체 철근배근 및 Conc 타설)

ISOL구역 (B1F 벽체 철근배근 및 Conc 타설)

IF/고에너지A구역 (B1F 벽체 철근배근 및 Conc 타설)

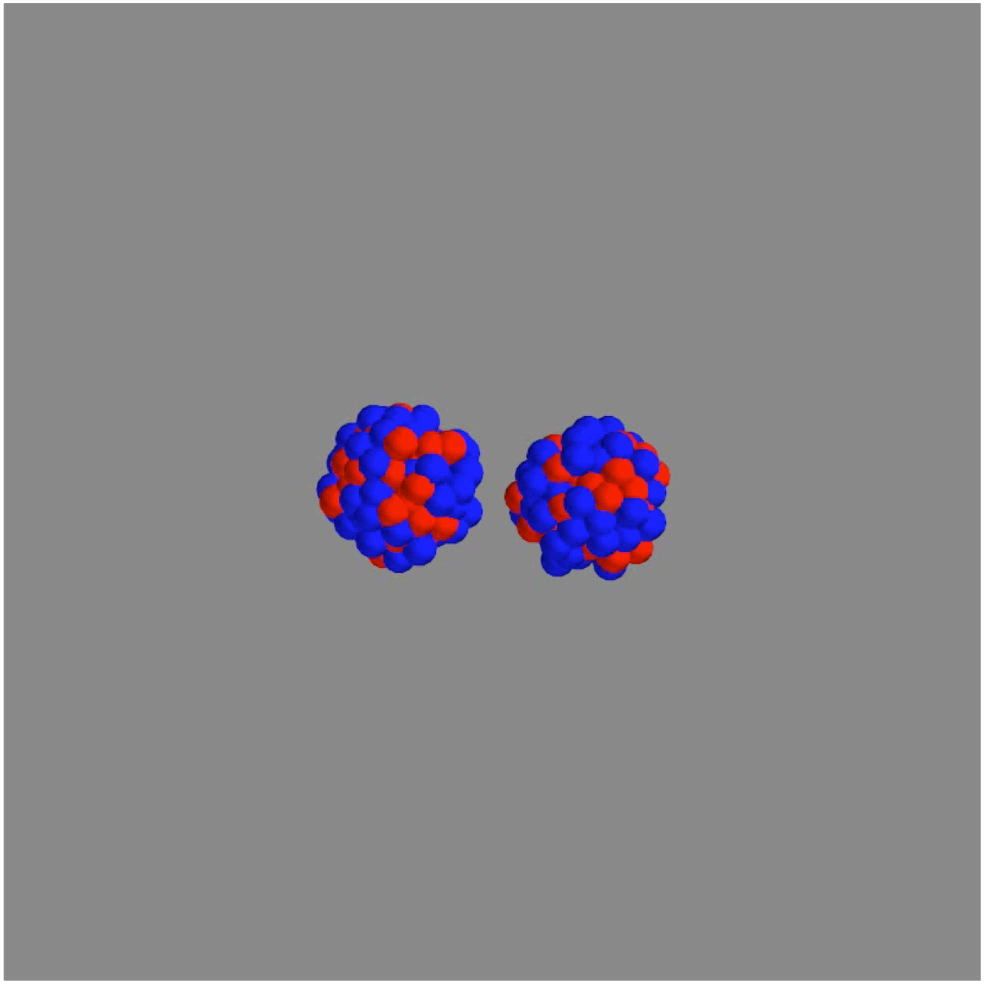
고에너지B구역 (B1F 벽체 철근배근 및 Conc 타설)

From Y.K.Kwon's Slide

	
SRF시험동 (내부 마감 공사)	초전도조립동 (내부 마감 공사)
	
수전설비동 (하지철물 설치)	중앙제어센터 (2F 벽체 철근배근)
	
유틸리티동 (1F 벽체 철근배근 및 Conc 타설)	본부동 (터파기)

From Y.K.Kwon's Slide

Transport Model



$^{129}Xe + ^{120}Sn$

E_{beam} = 65 MeV/n

b=1 fm

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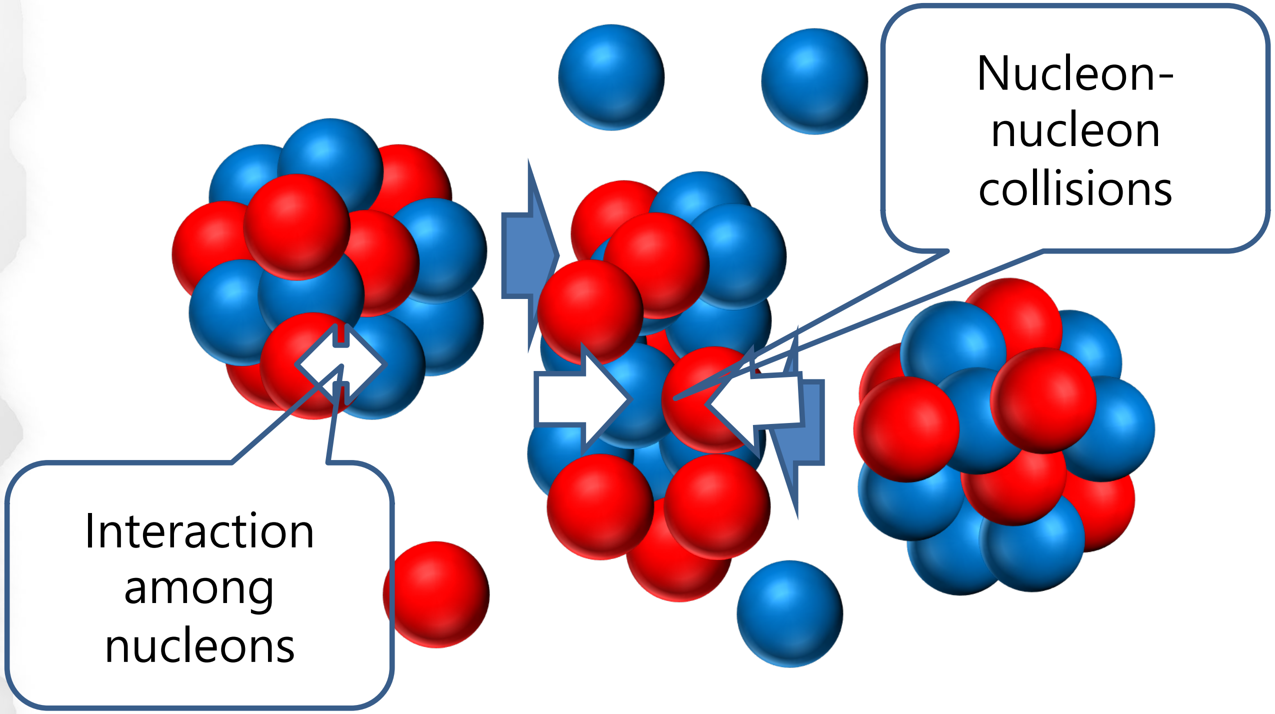
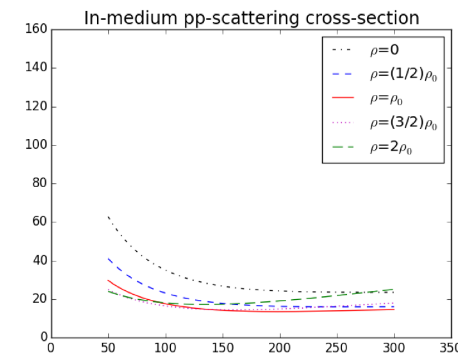
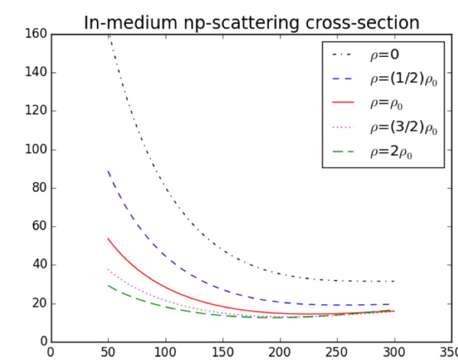
Transport Model



In-medium cross-section :





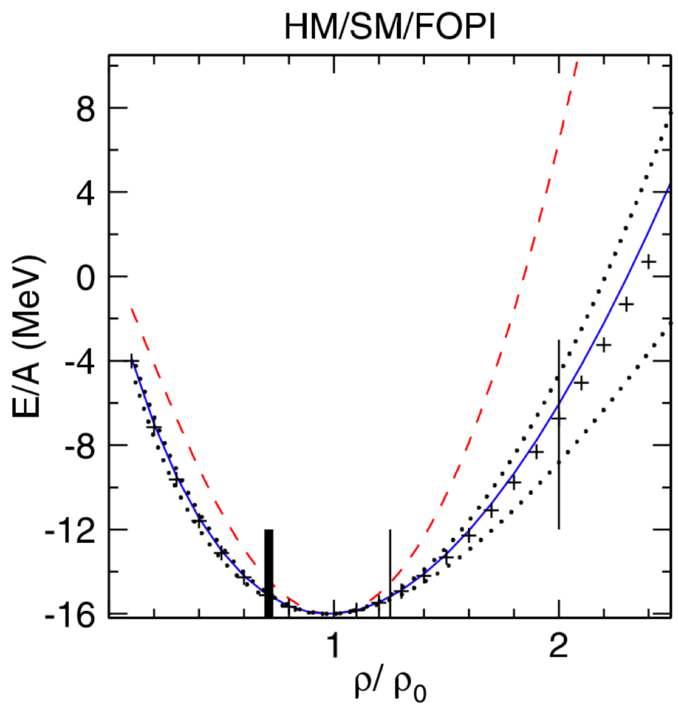
Wavefunction : $\psi_i(\vec{r},t) = \frac{1}{(2\pi\sigma_r^2)^{3/4}} \exp\left(-\frac{(\vec{r}-\vec{r_i})^2}{4\sigma_r^2} + \frac{i}{\hbar}(\vec{p_i}\cdot\vec{r})\right)$

Potential : $H = \sum_i \frac{\vec{p_i}^2}{2m} + U^{2body} + U^{3body} + U^{surf} + U^{sym} + U^{Coul}$

What Can I Do with QMD?

- Reproduction of experimental results
- Test of various potentials
- Test of EOS parameters
- Finding new observables
- …

Nuclear Equation of State



<Incompressbility>

$$K = -V\frac{\partial p}{\partial V} = 9\rho^2\frac{\partial^2 E/A(\rho)}{(\partial\rho)^2}|_{\rho=\rho_0}.$$

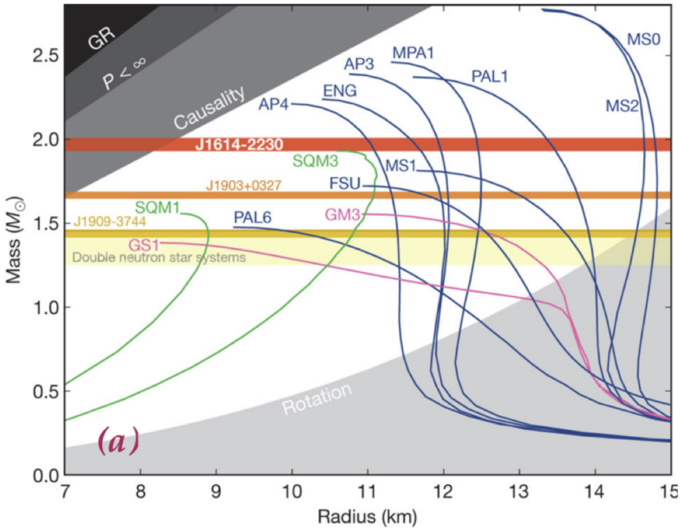
ref. A. Le Fevre, et al. NPA 945 (2016) 112

K=380 MeV

K=200 MeV

Nuclear Symmetry Energy

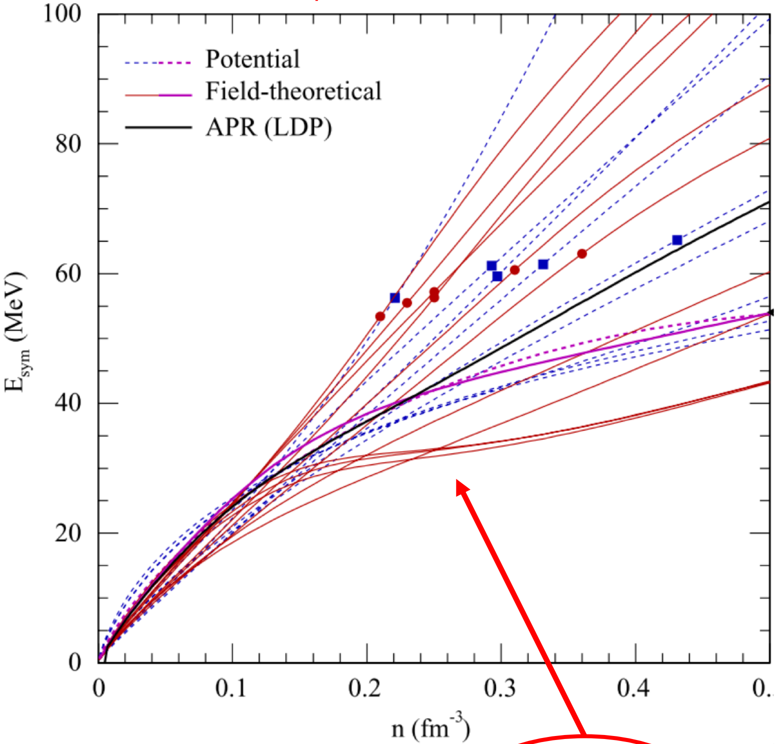
<Neutron star>



P. Demorest et al. Nature 467, 1081–1083 (2010)

various symmetry energy assumption

A. W. Steiner, et al. P.Rept 411 (2005) 325



$$E/A(\rho,\delta) = E/A(\rho,\delta=0) + E_{\rm sym}(\rho)\cdot\delta^2 + \mathcal{O}(\delta^4).$$

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Nucleon Effective Mass

B.-A. Li et al. / Progress in Particle and Nuclear Physics 99 (2018) 29–119

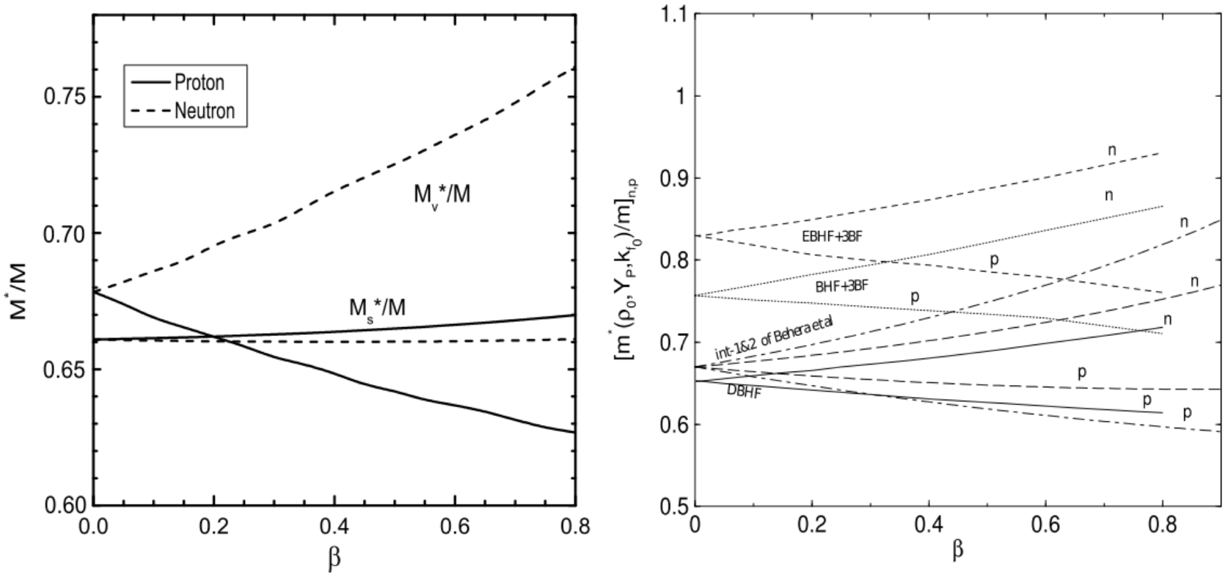
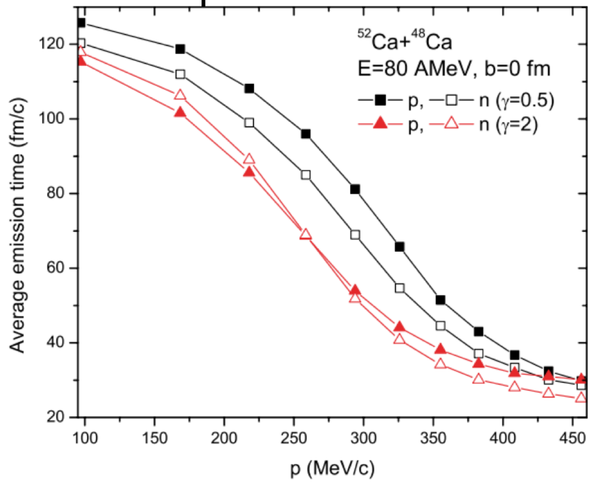


Fig. 9. Left: Nucleon Lorentz-scalar (Dirac) effective mass M_s^* and Lorentz-vector effective masses M_v^* at a nucleon energy of $E = 50$ MeV in neutron-rich matter of isospin-asymmetry β with $k_F = 1.36\,\text{fm}^{-1}$. Taken from Ref. [59]. Right: Comparisons of nucleon effective masses as a function of isospin asymmetry β at saturation density predicted by (1) the DBHF theory [123], (2) the BHF+3-body force, (3) the extended BHF+3-body force [58] as well as the energy density functional using two forms (int-1&2) of isospin-dependent interactions [28]. Modified from a figure in Ref. [28].

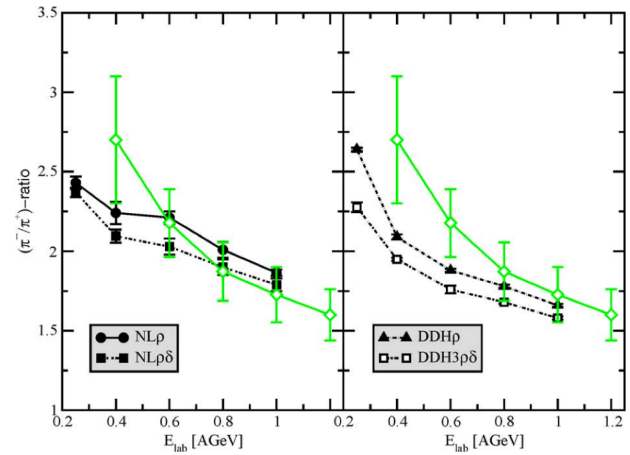
Observables

neutron-proton correlation

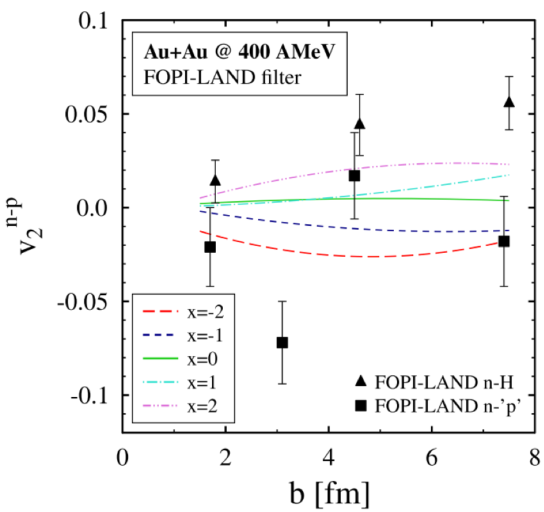


ref. Lie-Wen Chen, et al. PRL 90 (2003) 162701

pion production ratio



ref. T. Gaitanos, et al. NPA 732 (2004) 24



Flow observables

ref. P. Russotto, et al. EPJA 50 (2014) 38

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New Observables

- neutron-to-proton ratio
- neutron-proton differential flow
- neutron-proton correlation function
- t/^{3}He, π^+/ π^-, K^0/K^-, …
- …

What is the new observable at RAON?

Transport Model

Development of a new QMD code

Transport model

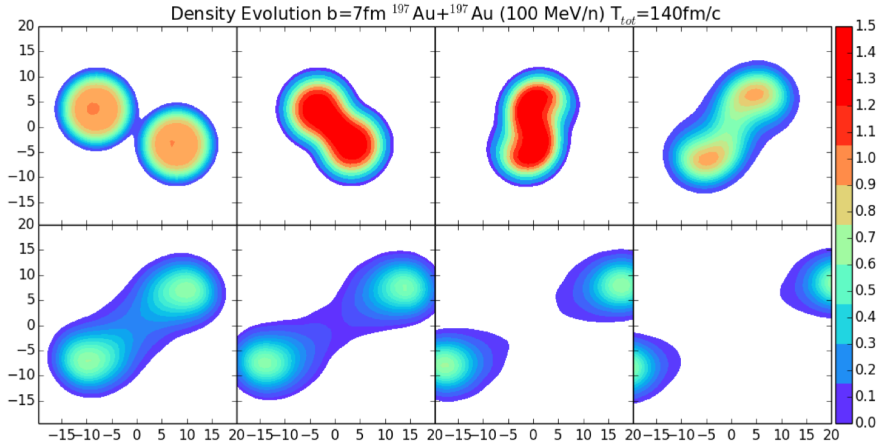
<u>Boltzmann-Uehling-Uhlenbeck(BUU)</u>

- ✓ Less fluctuation, Good to study EOS
- ✓ Not good for event generator
  - ➢ Code(DjBUU) developed by external experts: ***S. Jeon*** *(McGill Univ), C.-H. Lee(Pusan Nat'l Univ.)*

<u>Quantum Molecular Dynamics (QMD)</u>

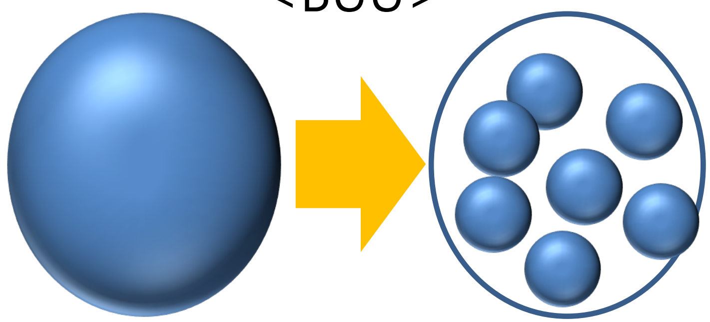
- ✓ Good for event generator (event by event analysis)
- ✓ More fluctuation, More CPU time
  - ➢ Code development mainly by KK with *K.S. Lee(Chonnam Nat'l Univ)*

Simulation sample by QMD
$^{197}Au+^{197}Au$ at b=7fm
with the beam energy 100MeV/n
(averaging 1000 events)



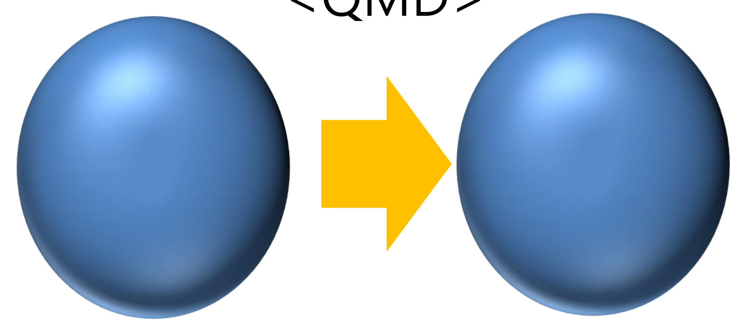
BUU vs QMD

<BUU>

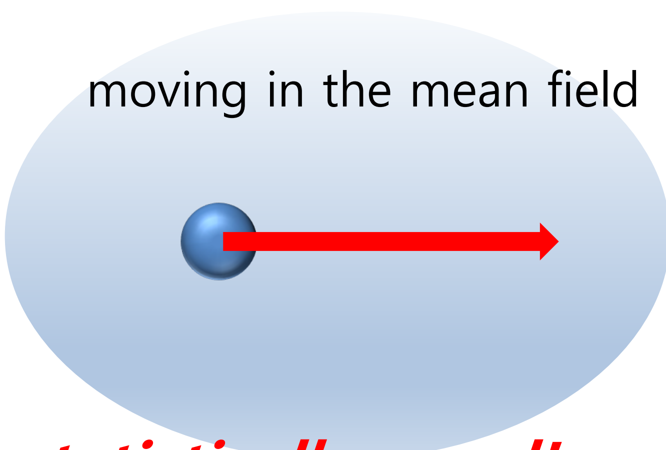


One nucleon N test particles

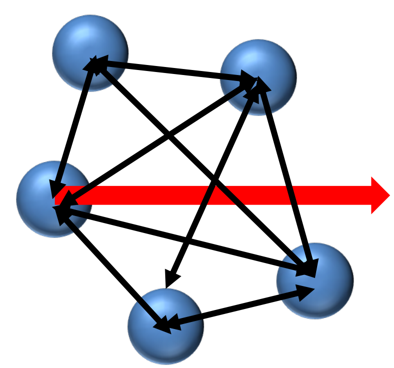
<QMD>



One nucleon One nucleon



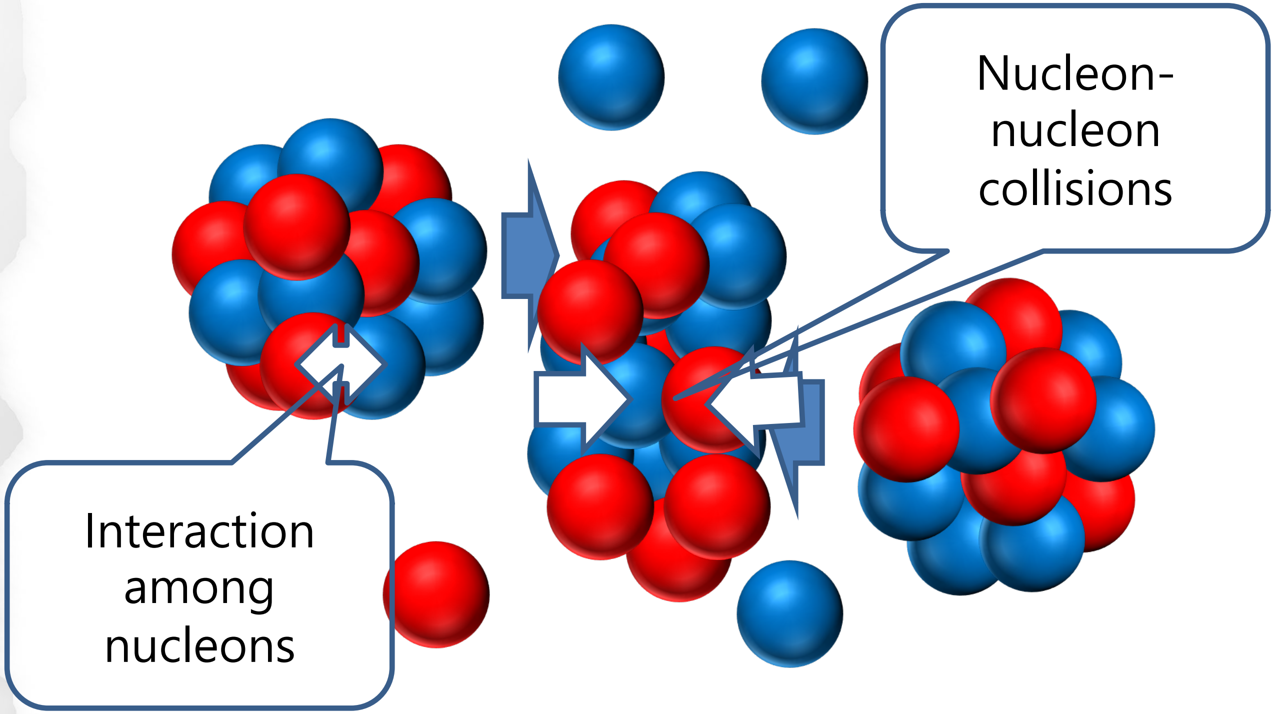
statistically good!



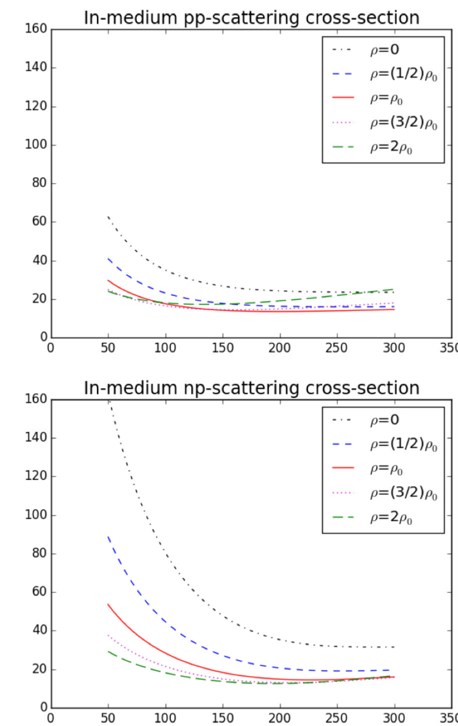
n-body Hamiltonian based

event by event analysis!

Transport Model



In-medium cross-section :



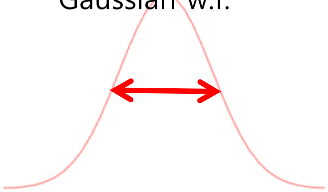
Wavefunction : $\psi_i(\vec{r},t) = \frac{1}{(2\pi\sigma_r^2)^{3/4}} \exp\left(-\frac{(\vec{r}-\vec{r_i})^2}{4\sigma_r^2} + \frac{i}{\hbar}(\vec{p_i}\cdot\vec{r})\right)$

Potential : $H = \sum_i \frac{\vec{p_i}^2}{2m} + U^{2body} + U^{3body} + U^{surf} + U^{sym} + U^{Coul}$

QMD Model - Potential

Nucleon -> Gaussian wave packet

$$\psi_i(\vec{r},t) = \frac{1}{(2\pi\sigma_r^2)^{3/4}} \exp\left(-\frac{(\vec{r}-\vec{r_i})^2}{4\sigma_r^2} + \frac{i}{\hbar}(\vec{p_i}\cdot\vec{r})\right)$$



$$H = \sum_i \frac{\vec{p_i}^2}{2m} + U^{2body} + U^{3body} + U^{surf} + U^{sym} + U^{Coul}$$

Skyrme parametrization for NN potential

$$U^{2body} = \frac{\alpha}{2\rho_0}\sum_{i,j\neq i}\rho_{ij},$$

$$U^{3body} = \frac{\beta}{\gamma+1}\sum_i\left(\sum_{j\neq i}\frac{\rho_{ij}}{\rho_0}\right)^\gamma,$$

$$U^{surf} = \frac{g_{surf}}{2\rho_0}\sum_{i,j\neq i}\nabla_{r_i}^2(\rho_{ij}),$$

$$U^{sym} = \frac{g_{sym}}{2\rho_0}\sum_{i,j\neq i}[2\delta_{\tau_i\tau_j}-1]\rho_{ij},$$

$$U^{Coul} = \frac{e^2}{2}\sum_{i,j\neq i}\frac{1}{|\vec{r_i}-\vec{r_j}|}\mathrm{erf}\left(\frac{|\vec{r_i}-\vec{r_j}|}{2\sigma_r}\right) \quad (i,j \text{ for protons})$$

K(MeV)	α (MeV)	β(MeV)	γ	EOS
200	-356	303	7/6	Soft
380	-124	70.5	2	Hard

Ref.) M. Papa PRC 64(2010)024612

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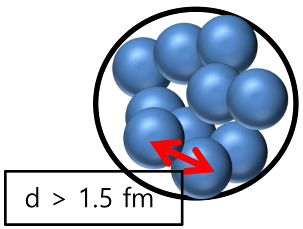
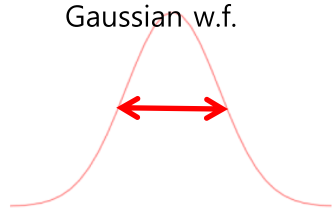
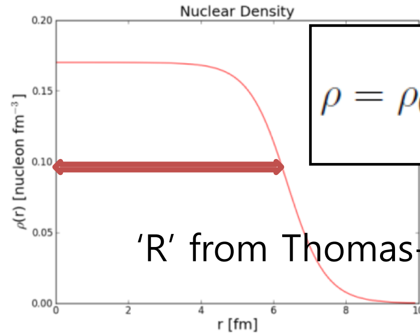
QMD Model - Initialization

<Initialization>







$$\rho = \rho_0 \left[1 + \exp\left\{ \frac{r - R}{a} \right\} \right]^{-1}$$

'R' from Thomas-Fermi model

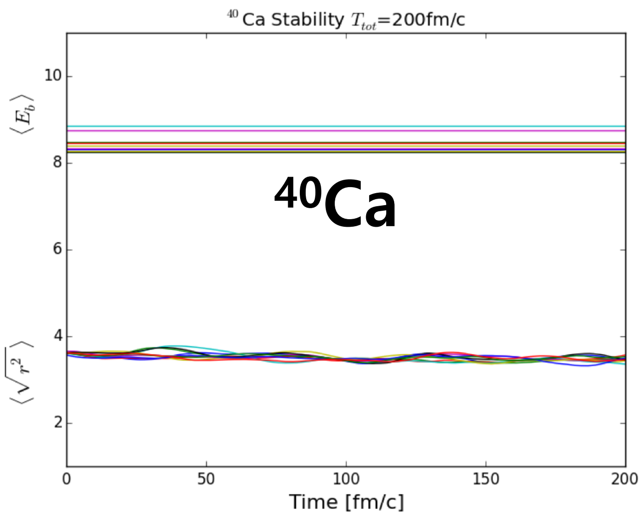
$$f_i = \frac{1}{(2\pi\sigma_r\sigma_p)^3} \exp\left[-\frac{(\vec{r} - \vec{r_i})^2}{2\sigma_r^2} - \frac{(\vec{p} - \vec{p_i})^2}{2\sigma_p^2} \right]$$

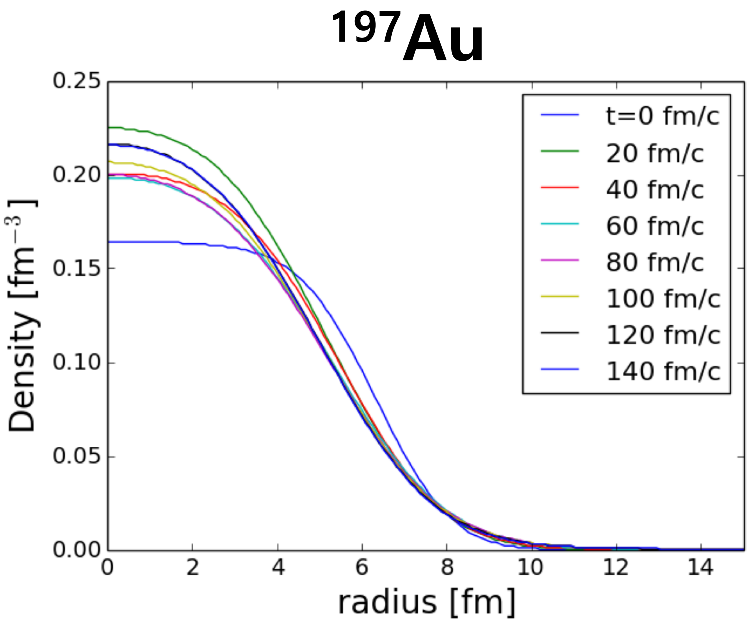
momentum of a nucleon is also chosen in the range of 0~ $k_f = \sqrt{2 m_i U_{tot}^i}$,

Only the set which gives the binding energy within 5% difference with experimental (or theoretical) data will be selected.

QMD Model - Initialization

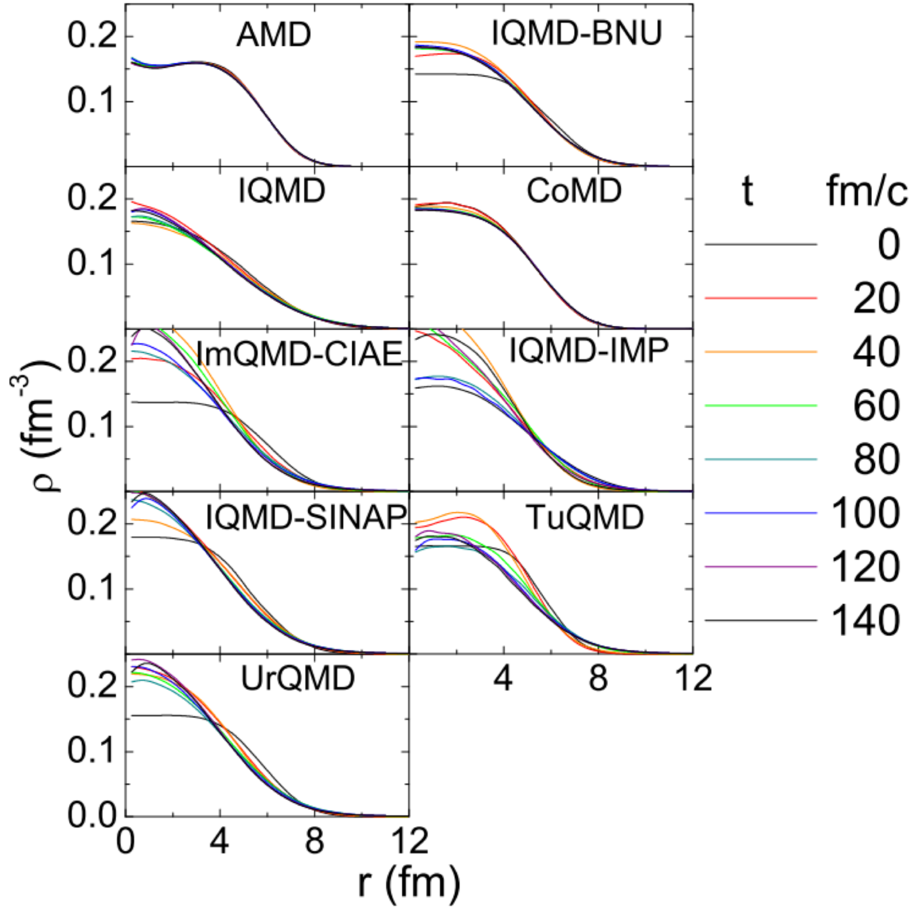
<Stability check>



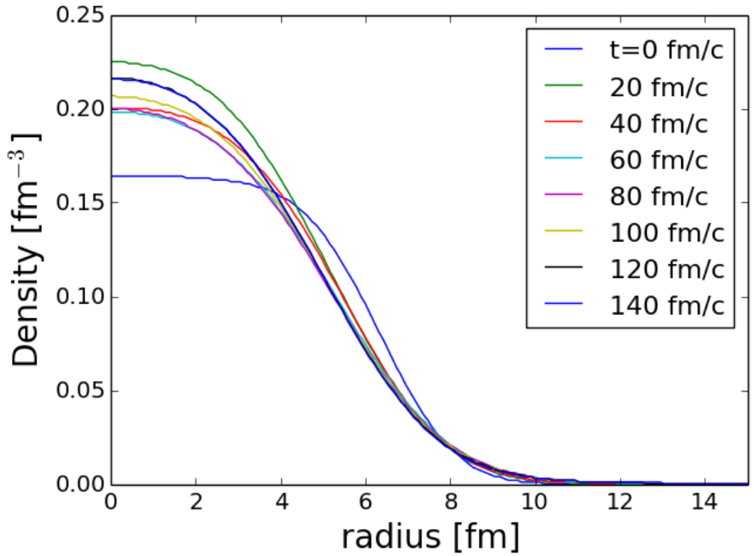


QMD Model - Comparison

ref. J. Xu, et al. PRC 93 (2016) 044609



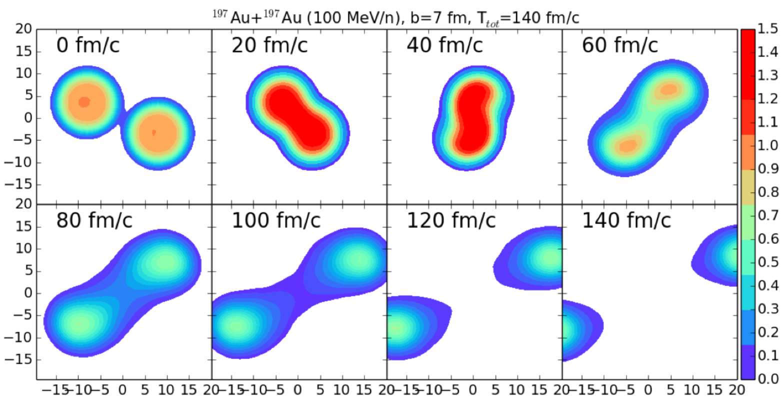
Our QMD

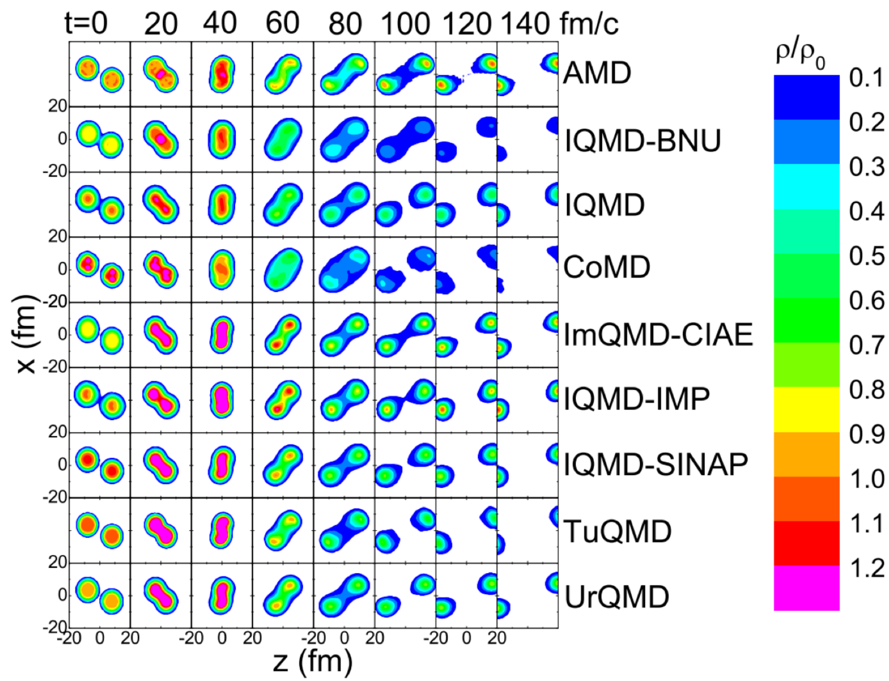


QMD Model - Propagation

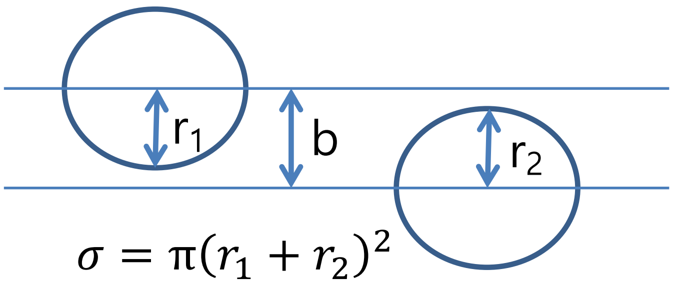
<Equation of Motion>

$$\frac{d\vec{r}_i}{dt} = \frac{\vec{p}_i}{\mu} \qquad \frac{d\vec{p}_i}{dt} = -\nabla_{r_i} U$$





QMD Model - Collisions



$$\sigma = \pi(r_1 + r_2)^2$$

In classical scattering,

$$b < r_1 + r_2$$

→ *Two particles are always scattered.*

In our model,

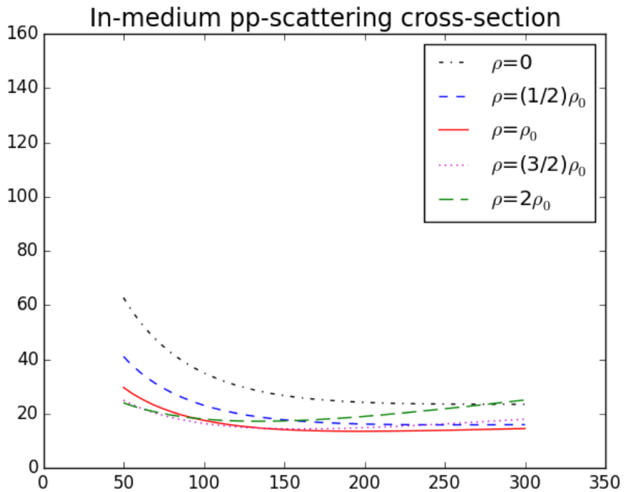
$$b = \sqrt{\sigma_{tot}/(10 \times \pi)}, \qquad (b\text{: [fm]}, \sigma\text{: [mb]})$$

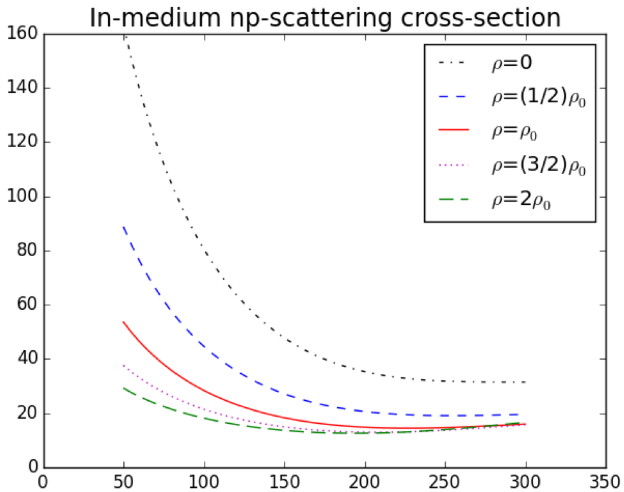
→ **If a distance, d, between two nucleons is smaller than b, d<b, a collision is always tried.**

Here, σ_{tot} is in-medium cross-section.

$$\left| \frac{\Delta\vec{r} \cdot \vec{p}}{p} \right| < \left(\frac{p}{2m_1} + \frac{p}{2m_2} \right) \frac{\delta t}{2}$$

QMD Model - Collisions





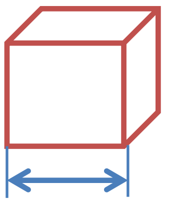
Ref.) G.Li and R.Machleidt PRC 48, 1702, PRC 49, 566

$$\sigma_{pp-tot}(E_{lab},\rho) = [23.5 + 0.00256(18.2 - E_{lab}^{0.5})^{4.0}] \times \frac{1.0 + 0.1667 E_{lab}^{1.05}\rho^3}{1.0 + 9.704\rho^{1.2}}$$

$$\sigma_{np-tot}(E_{lab},\rho) = [31.5 + 0.092|20.2 - E_{lab}^{0.53}|^{2.9}] \times \frac{1.0 + 0.0034 E_{lab}^{1.51}\rho^2}{1.0 + 21.55\rho^{1.34}},$$

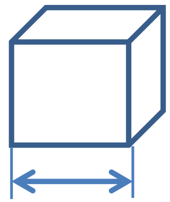
QMD Model – Pauli Blocking

<x-space>



$\sqrt{2\pi\hbar\sigma_r/\sigma_p}$

<p-space>

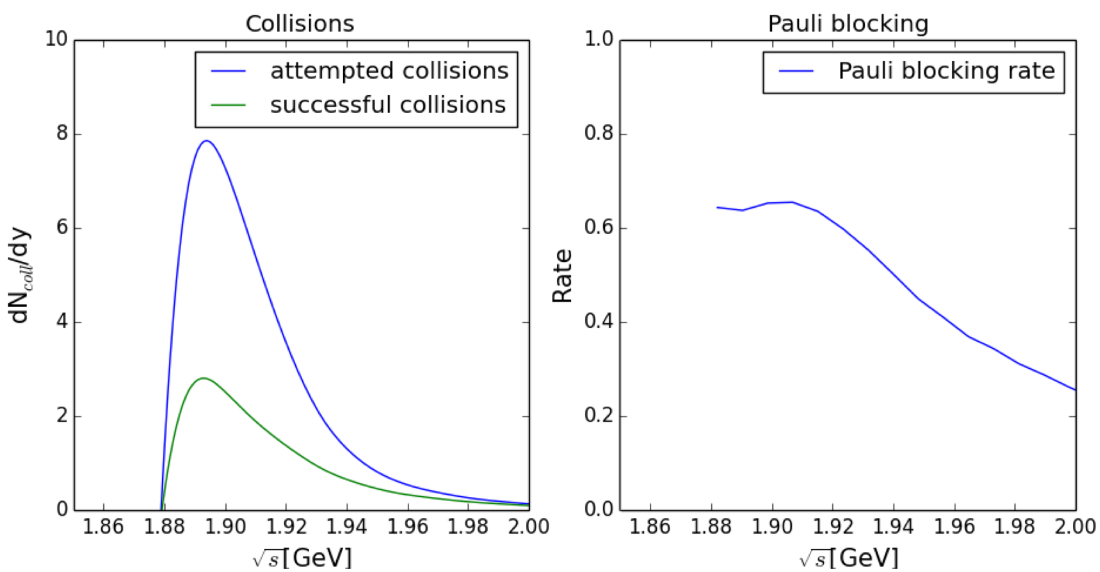


$\sqrt{2\pi\hbar\sigma_p/\sigma_r}$

<Phase space density for *i* th particle>

$$\bar{f}_i \equiv \sum_j \delta_{\tau_i,\tau_j}\delta_{s_i,s_j} \int_{h^3} f_i(\vec{r},\vec{p})\; d^3r d^3p$$

Occupation number



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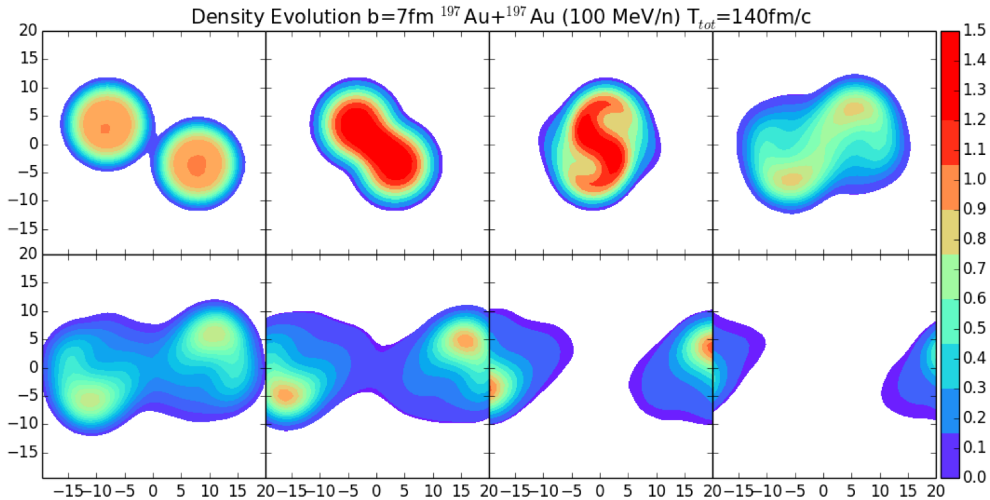
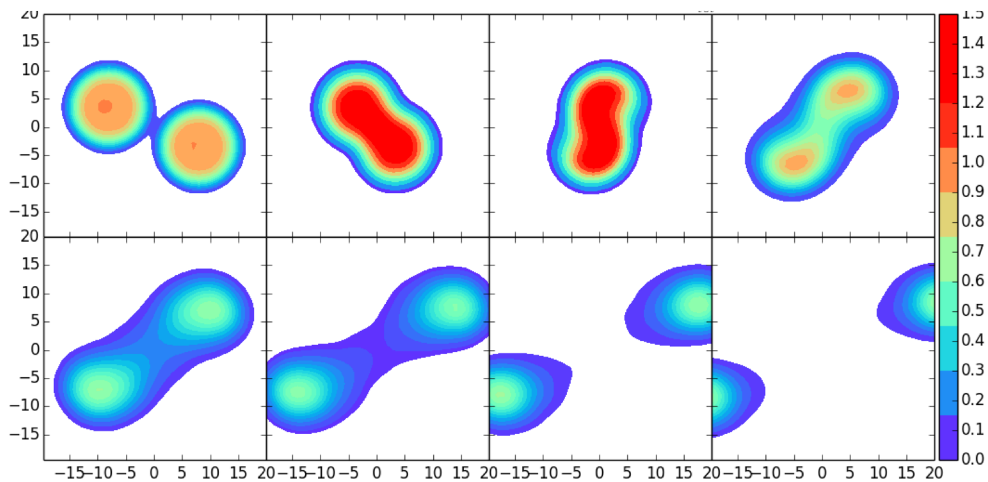
Role of NN Collision



w/o collisions



w/ collisions

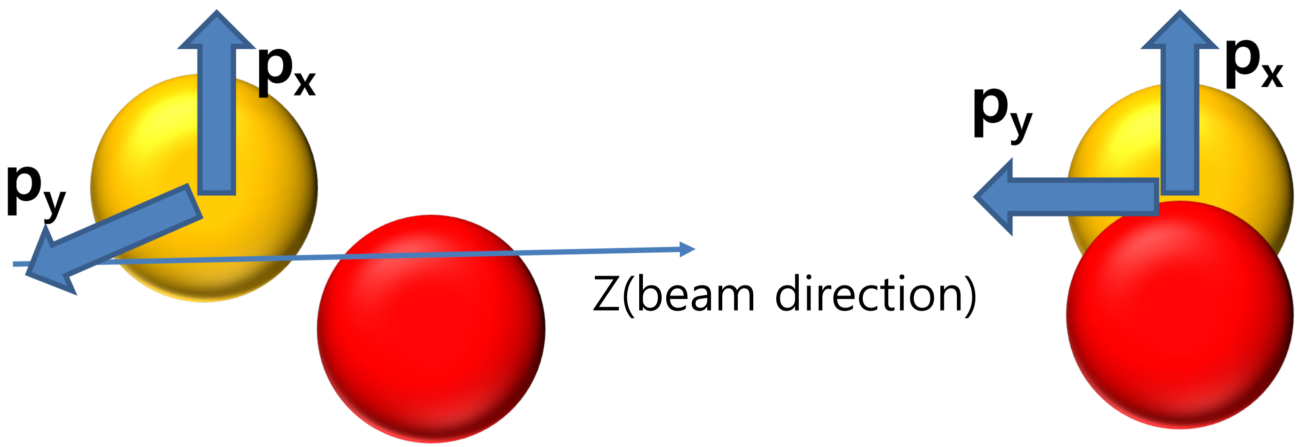
Differential Flow

$$u = (\gamma, \vec{\beta}\gamma); \qquad u_t = \beta_t \gamma$$

$$\frac{dN}{u_t\, du_t\, dy\, d\phi} = v_0[1 + 2v_1 \cos(\phi) + 2v_2 \cos(2\phi)]$$

$$v_0 = v_0(y, u_t); \qquad v_1 = v_1(y, u_t); \qquad v_2 = v_2(y, u_t)$$

$$v_1 = \left\langle \frac{p_x}{p_t} \right\rangle = \langle \cos(\phi) \rangle; \qquad v_2 = \left\langle \left(\frac{p_x}{p_t}\right)^2 - \left(\frac{p_y}{p_t}\right)^2 \right\rangle = \langle \cos(2\phi) \rangle$$



Sn+Sn Simulation

- $^{112}Sn + ^{112}Sn$ and $^{132}Sn + ^{124}Sn$ at E_{lab} = 200 MeV/n
- impact parameter, b = 5 fm
- number of total event = 20,000
- asy-soft (**σ**=0.5) and asy-stiff (**σ**=2) EOS

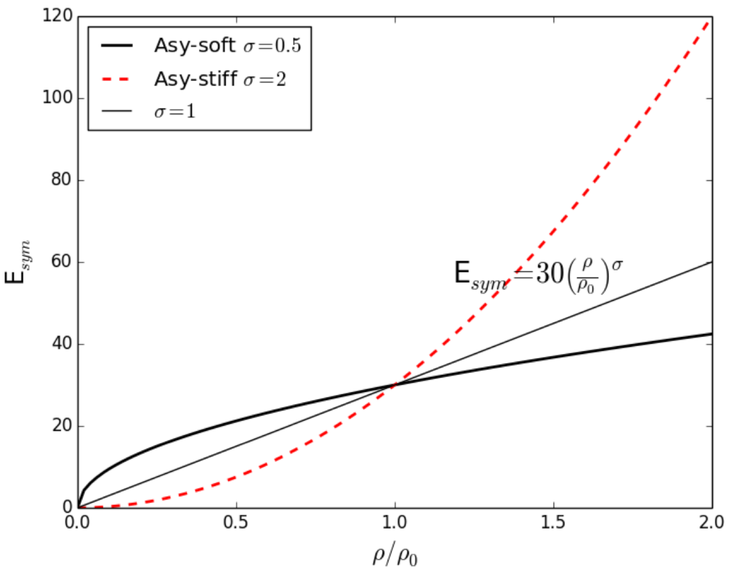
$$E_{sym} = 30 \left(\frac{\rho}{\rho_0}\right)^{\sigma}$$

- under the pion threshold energy

$$U = \alpha \left(\frac{\rho}{\rho_0}\right) + \beta \left(\frac{\rho}{\rho_0}\right)^{\gamma},$$

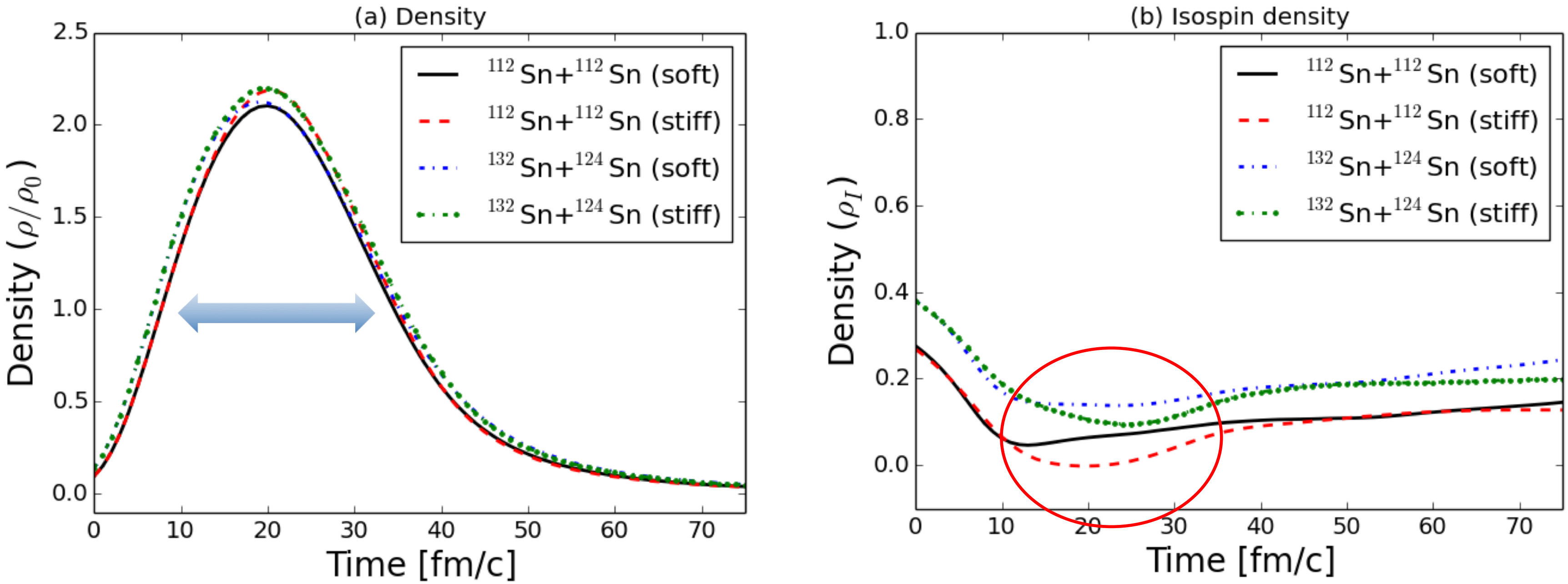
when $\alpha = -218$ MeV, $\beta = 164$ MeV and $\gamma = 4/3$.

$$E_{sym} = 30 \left(\frac{\rho}{\rho_0}\right)^{\sigma}$$



Density and Isospin Density

Density (left) and isospin density (right) at the center of the Sn+Sn system



- The duration time for the supra-saturation density is ~20 fm/c.
- The isospin density when the asy-soft EOS is used is larger.

cf.) $\rho_I = \dfrac{\rho_n - \rho_p}{\rho_n + \rho_p}.$

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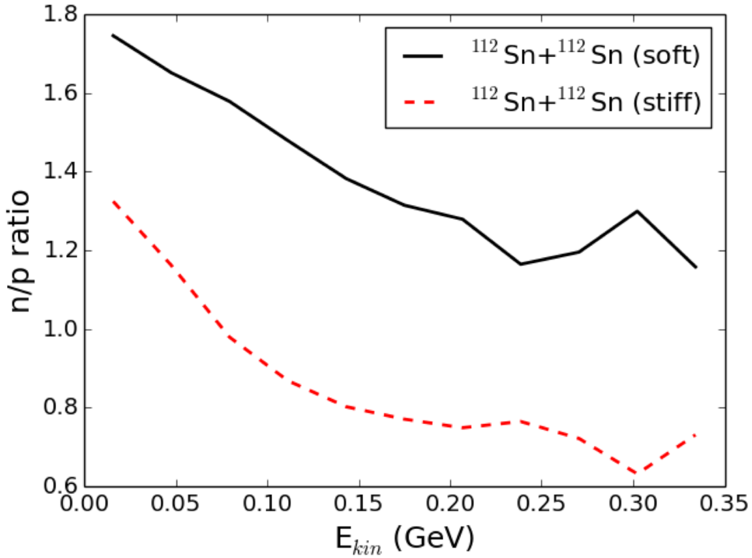
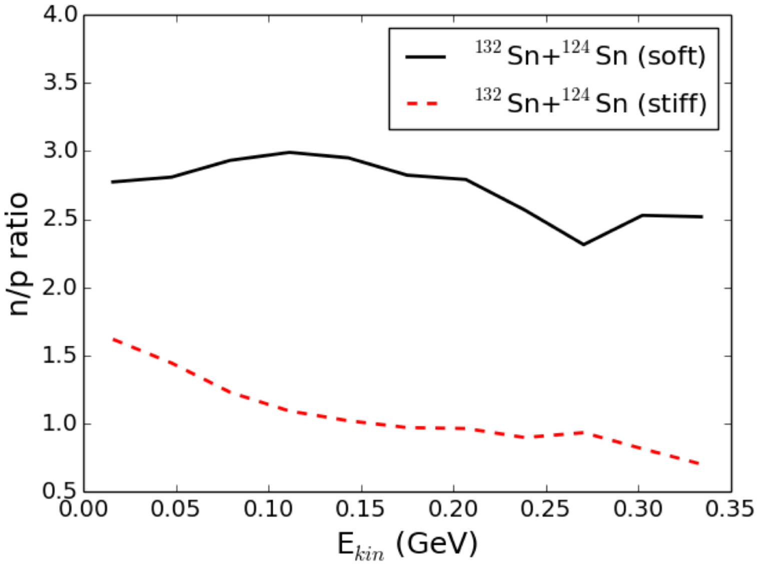
Observables – n/p Ratio

<n/p ratio – ^{112}Sn+^{112}Sn>



<n/p ratio – ^{132}Sn+^{124}Sn>



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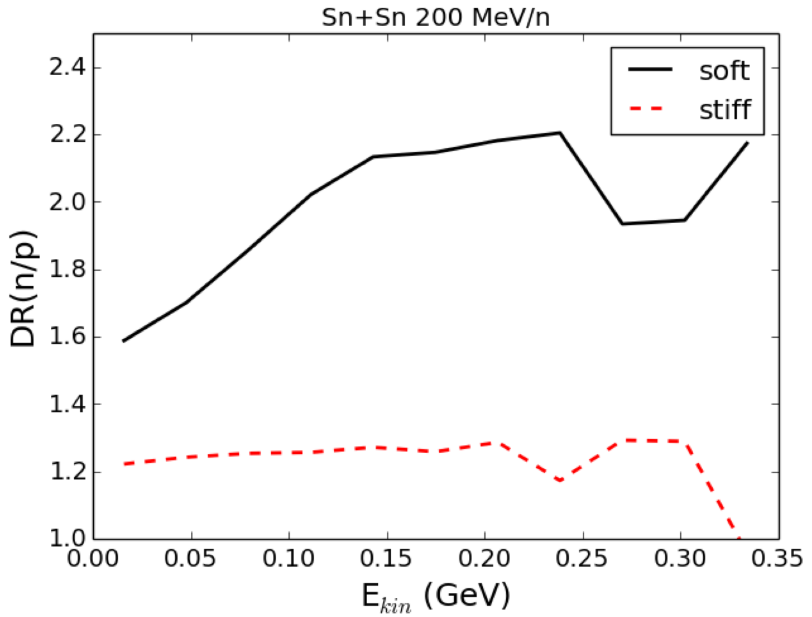
Observables – Double n/p Ratio

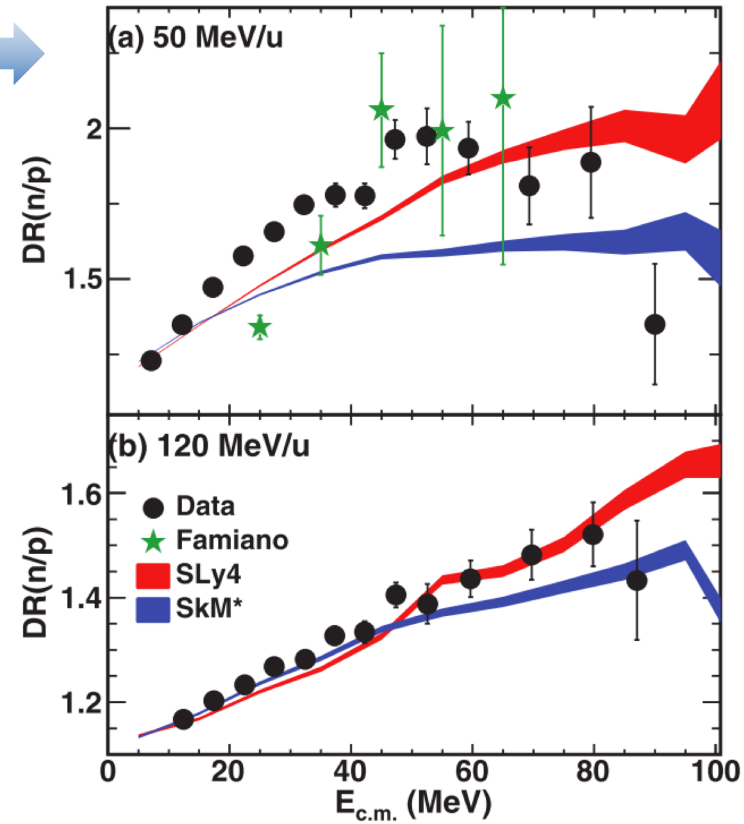
$$DR(n/p) = \frac{n/p(^{124}Sn + ^{124}Sn)}{n/p(^{112}Sn + ^{112}Sn)}$$

$$DR(n/p) = \frac{n/p(^{132}Sn + ^{124}Sn)}{n/p(^{112}Sn + ^{112}Sn)}$$



QMD simulation

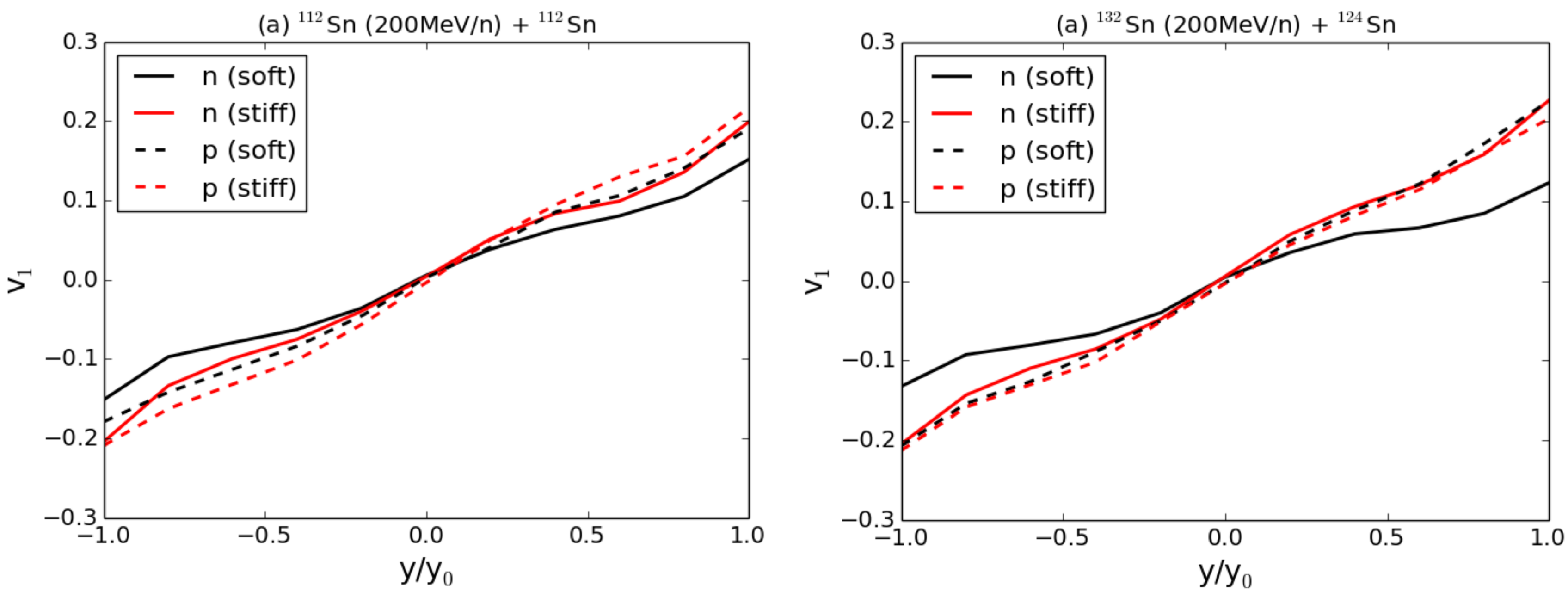
Double neutron-to-proton ratio from NSCL data



ref. D. D. S. Coupland, et al. PRC 94 (2016) 011601

Observables – v_1

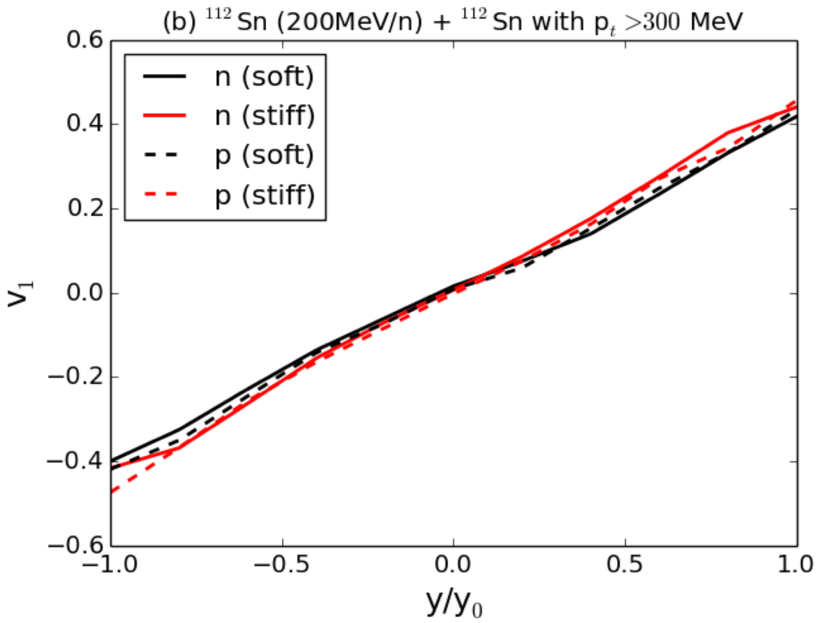
v_1 of the emitted nucleons from Sn+Sn collisions

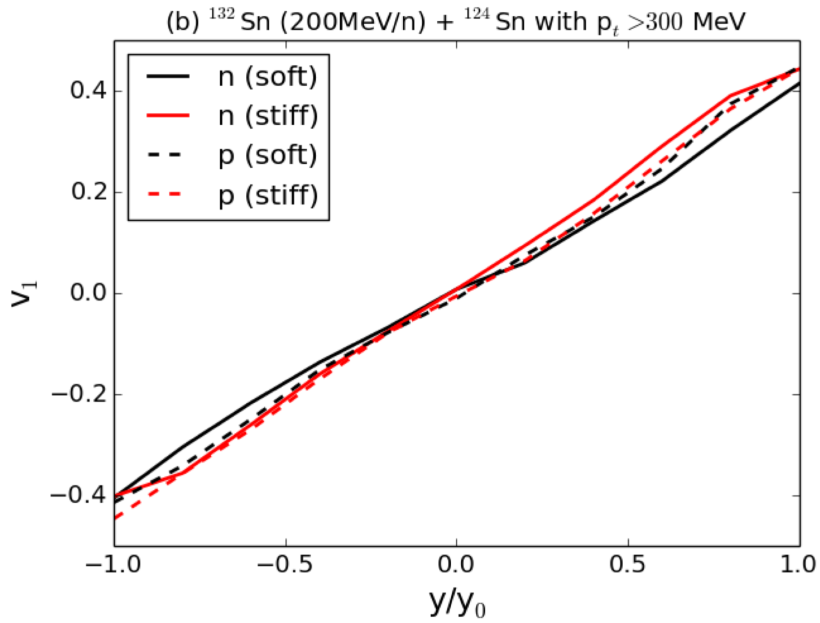


Here, y_0 is the rapidity of a nucleon of projectile in the center of mass frame.

Observables – v_1 with p_t cut

v_1 of the emitted nucleons from Sn+Sn collisions with p_t > 300 MeV





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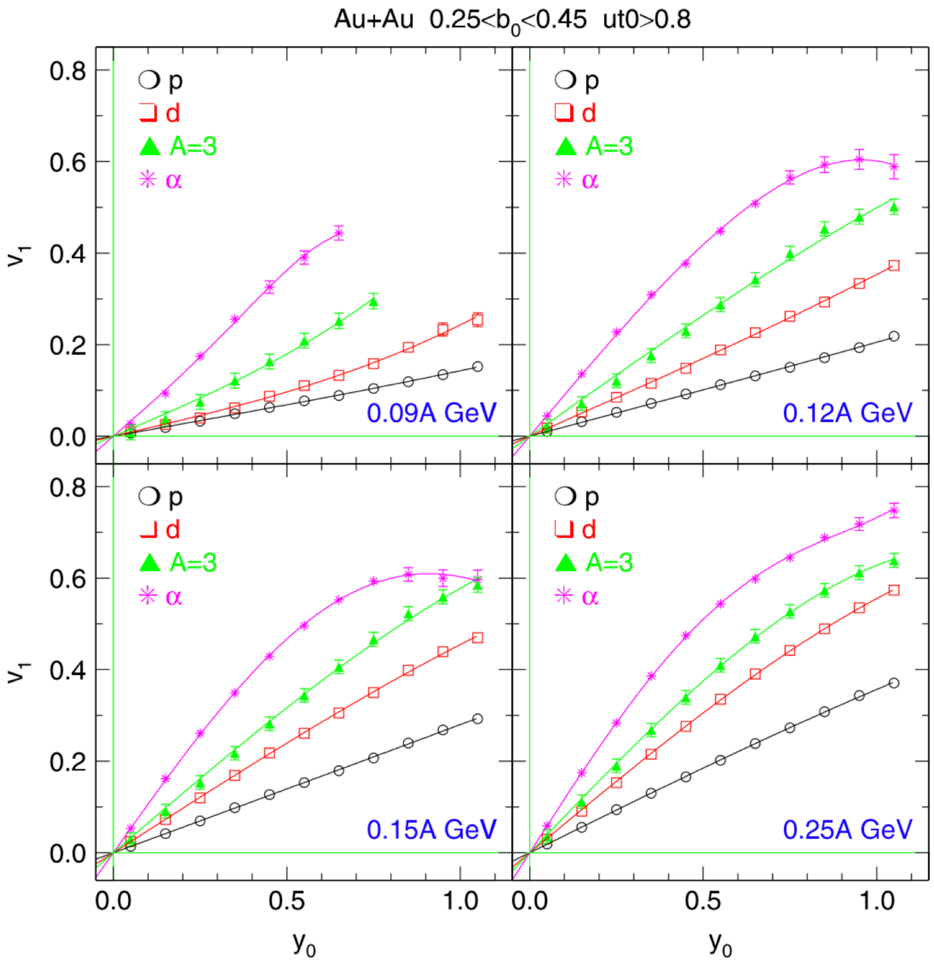
Observables – v1 from FOPI Data



- v_1 of light particles of ^{197}Au+^{197}Au collision from FOPI data
- 3.3 fm < b < 6 fm with p_t cut

ref. Reisdorf, et al. NPA 876 (2012) 1

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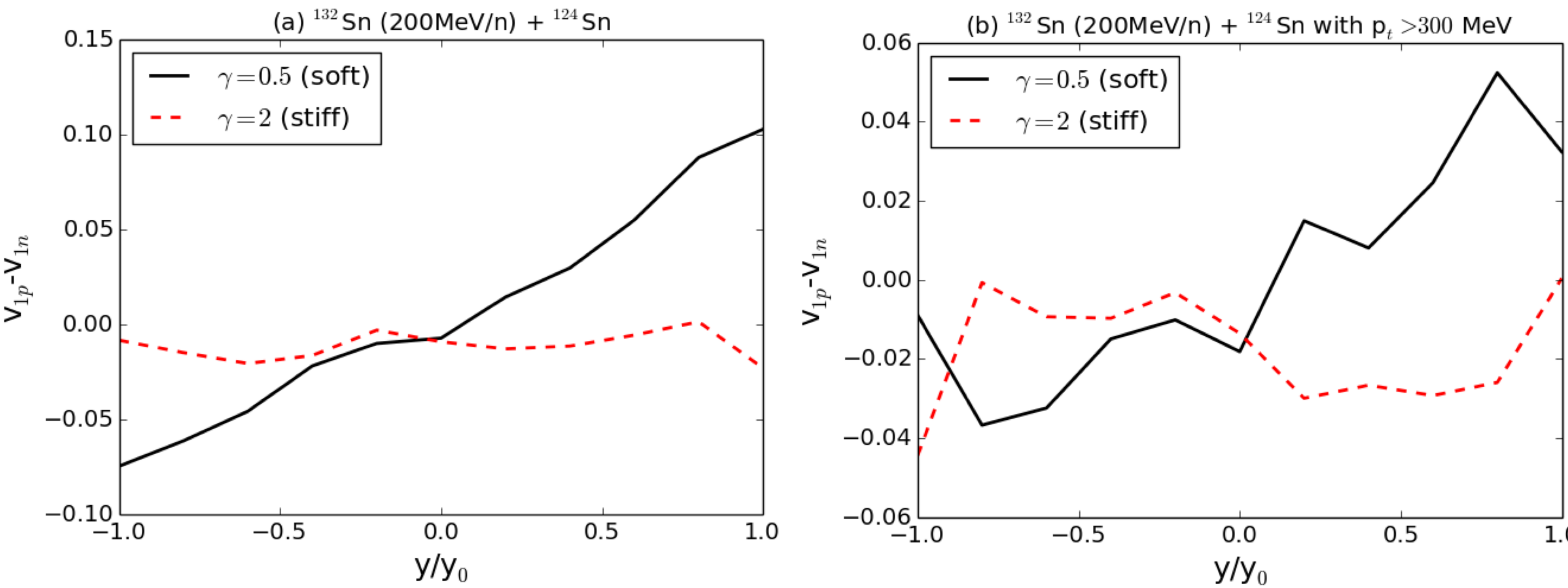
Observables – v_{1p}-v_{1n}

The difference of v_1 between protons and neutrons



When the asy-soft EOS is used, the difference is larger.

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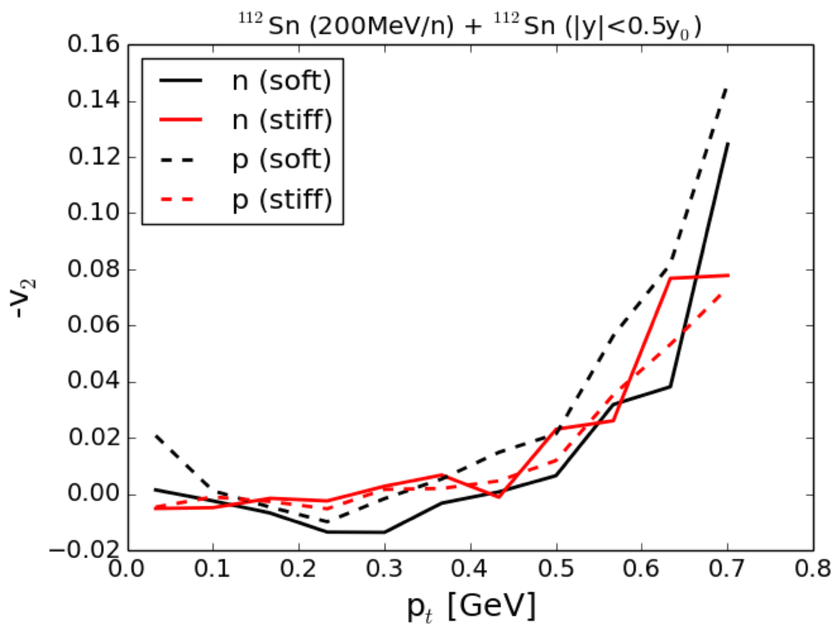
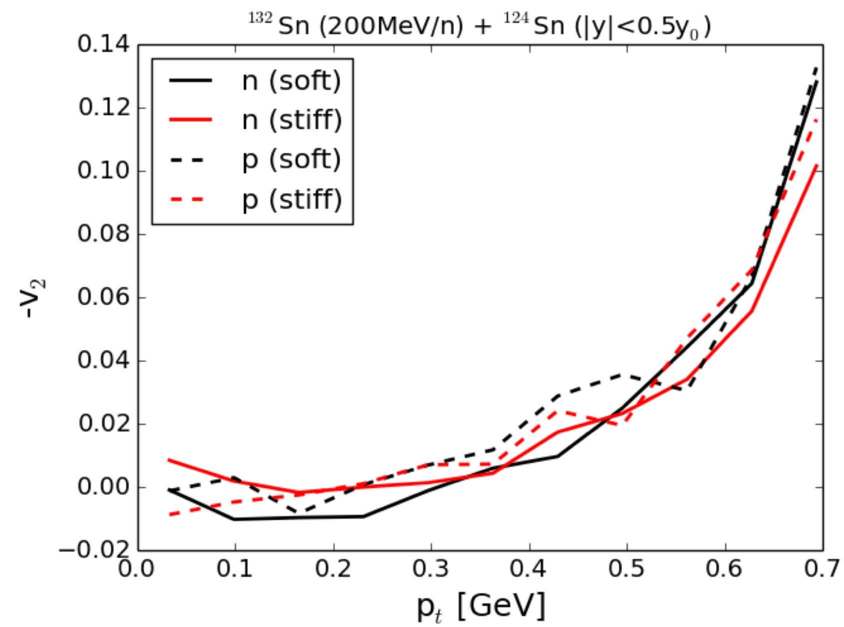
Observables – v_2





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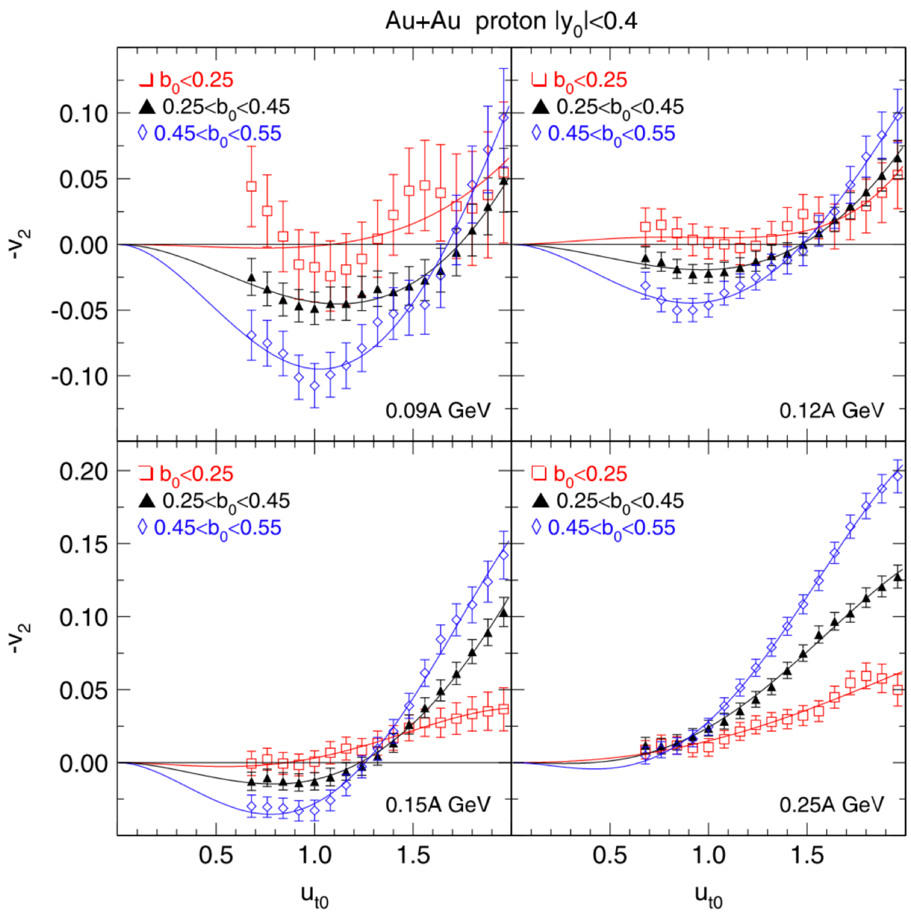
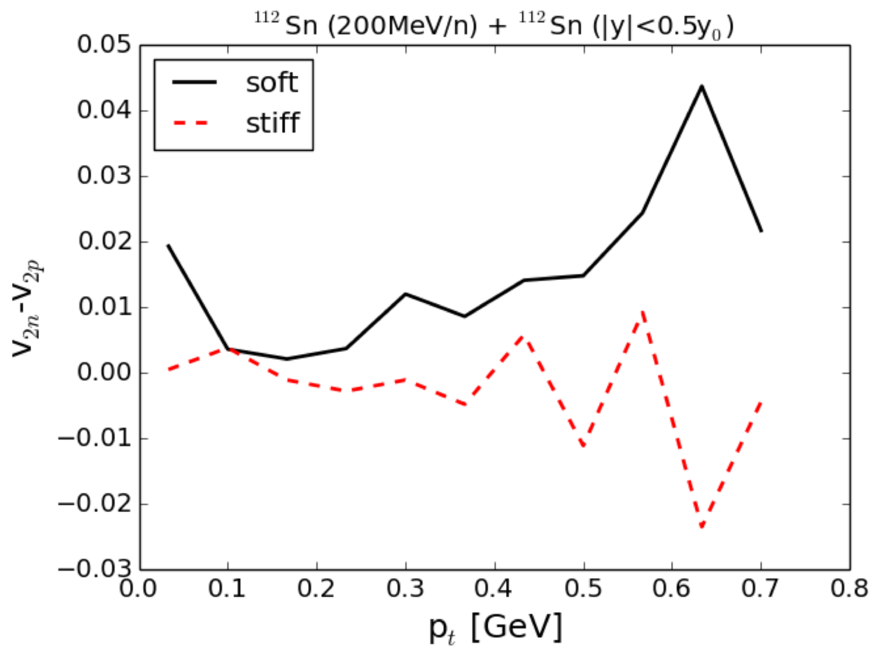
Observables – v2 from FOPI Data

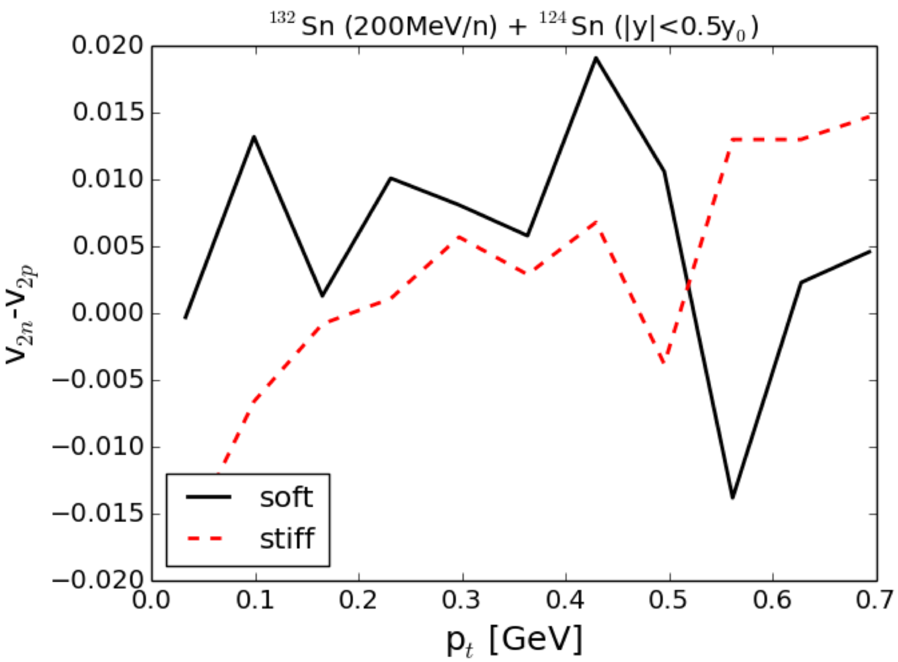


ref. Reisdorf, et al. NPA 876 (2012) 1

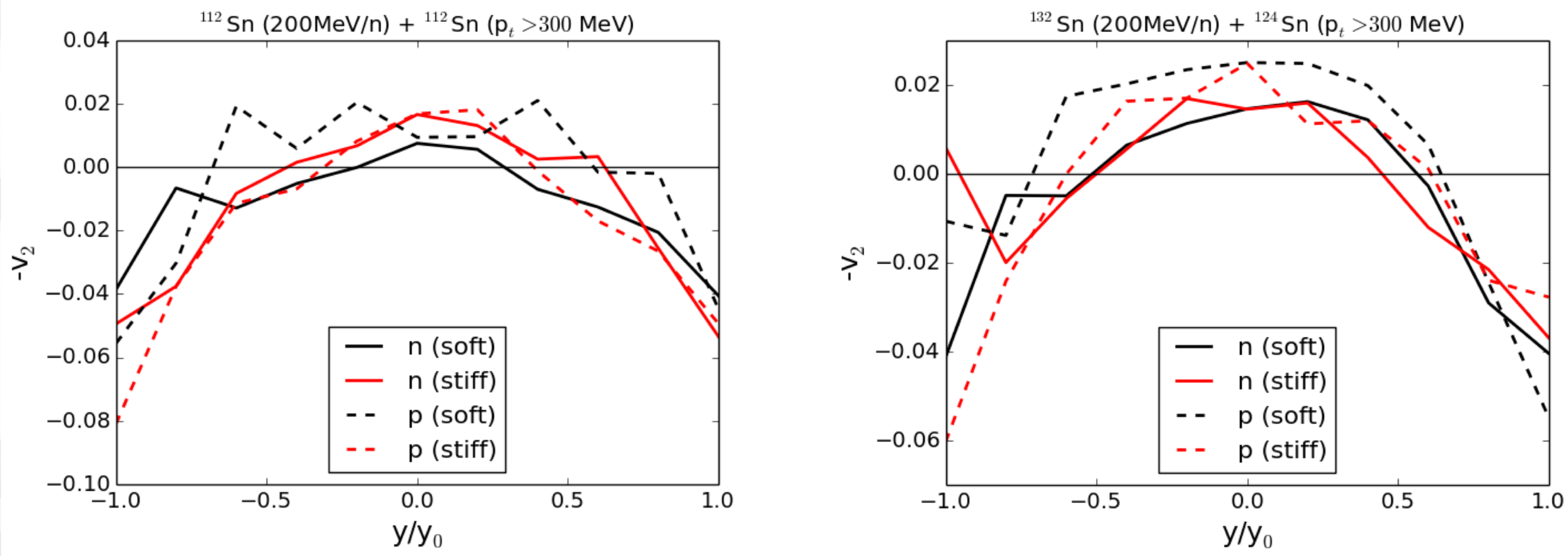
- v_2 of the emitted protons of $^{197}Au+^{197}Au$ collision from FOPI data with y_0 range

Observables – v_{2n}-v_{2p}





Observables – v_2



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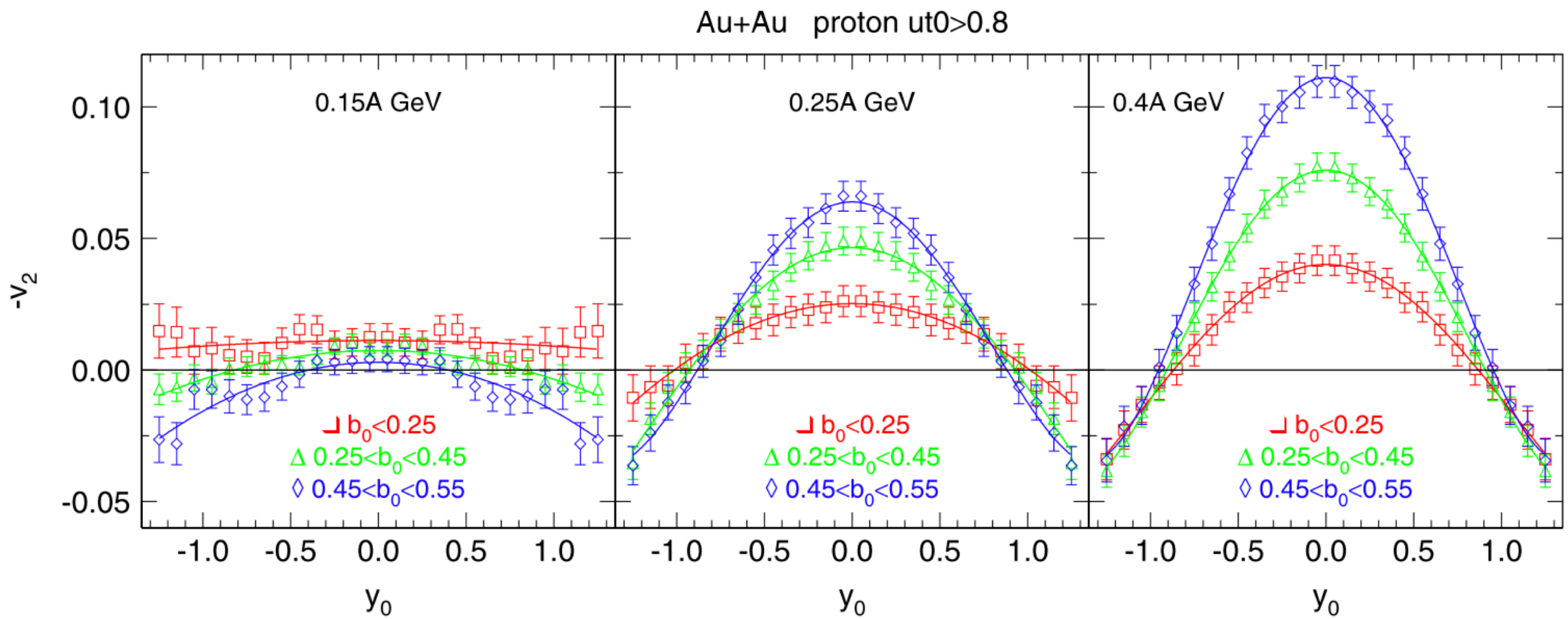
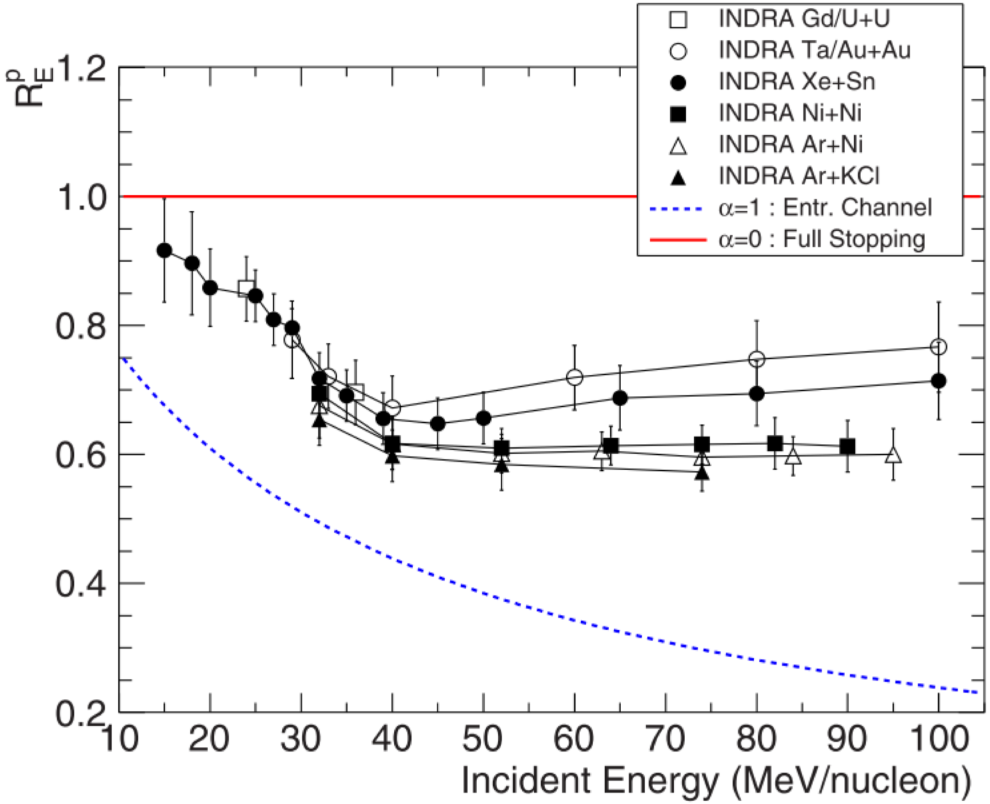
Observables – v_2 from FOPI Data



ref. Reisdorf, et al. NPA 876 (2012) 1

Stopping Ratio

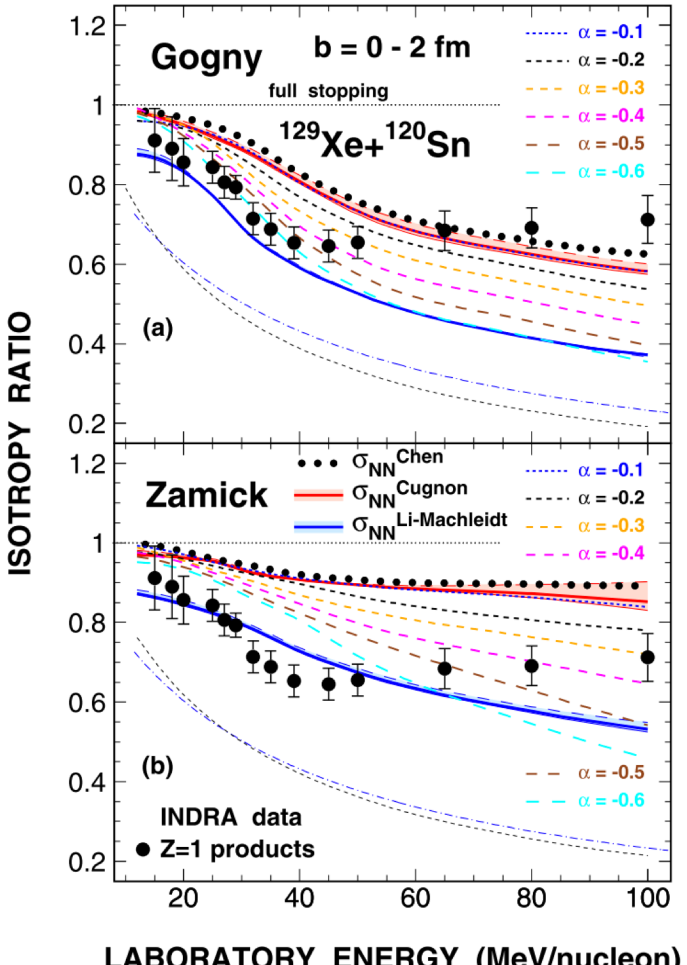


O. Lopez et al. PRC 90, 064602 (2014)

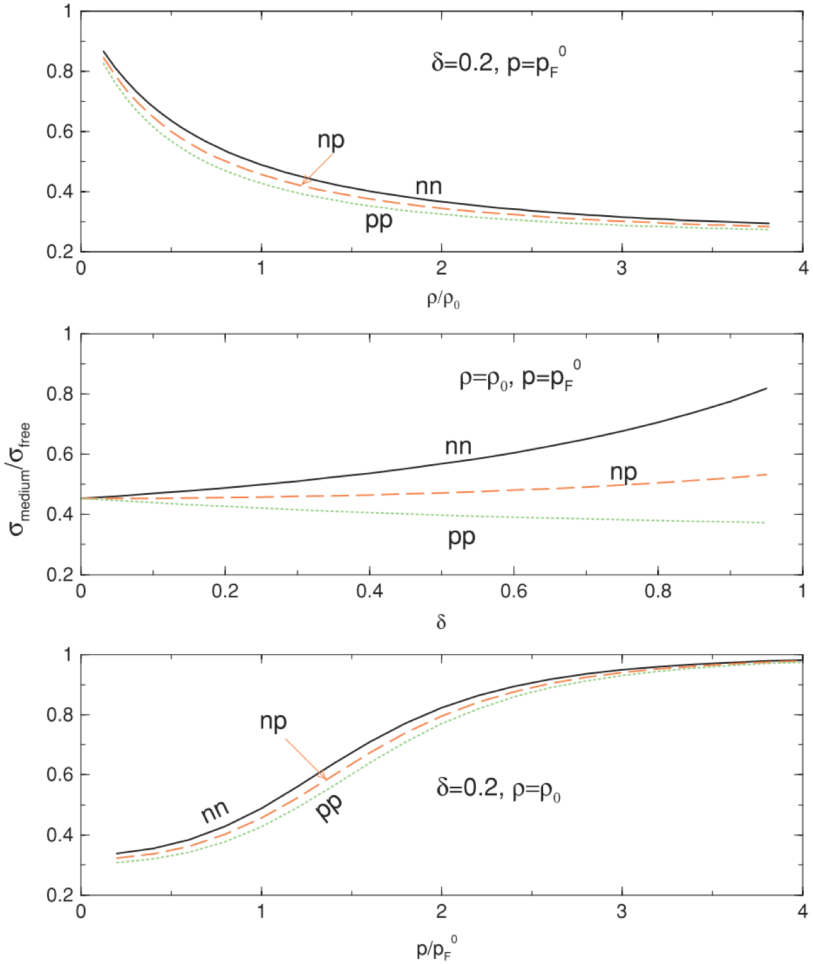
<Energy-based isotropy ratio>

$$R_E = \frac{\sum E^i_{trans}}{2\sum E^i_{long}}$$

NN Cross Section in Medium



Z. Basrak, P. Eudes, and V. de la Mota
PRC 93, 054609 (2016)



L.Chen and B.Li PRC 72, 064611 (2005)

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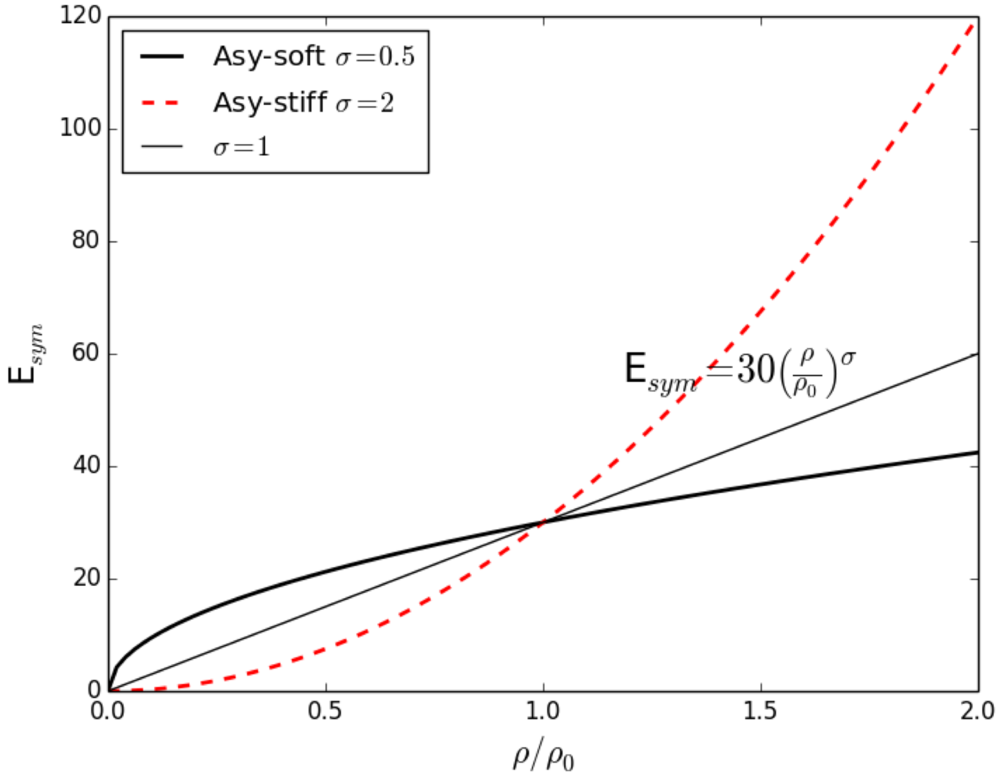
^{129}Xe+^{120}Sn Simulation

$$U = \alpha\left(\frac{\rho}{\rho_0}\right) + \beta\left(\frac{\rho}{\rho_0}\right)^{\gamma},$$ when $\alpha = -218$ MeV, $\beta = 164$ MeV and $\gamma = 4/3$.

$$E_{sym} = 30\left(\frac{\rho}{\rho_0}\right)^{\sigma}$$



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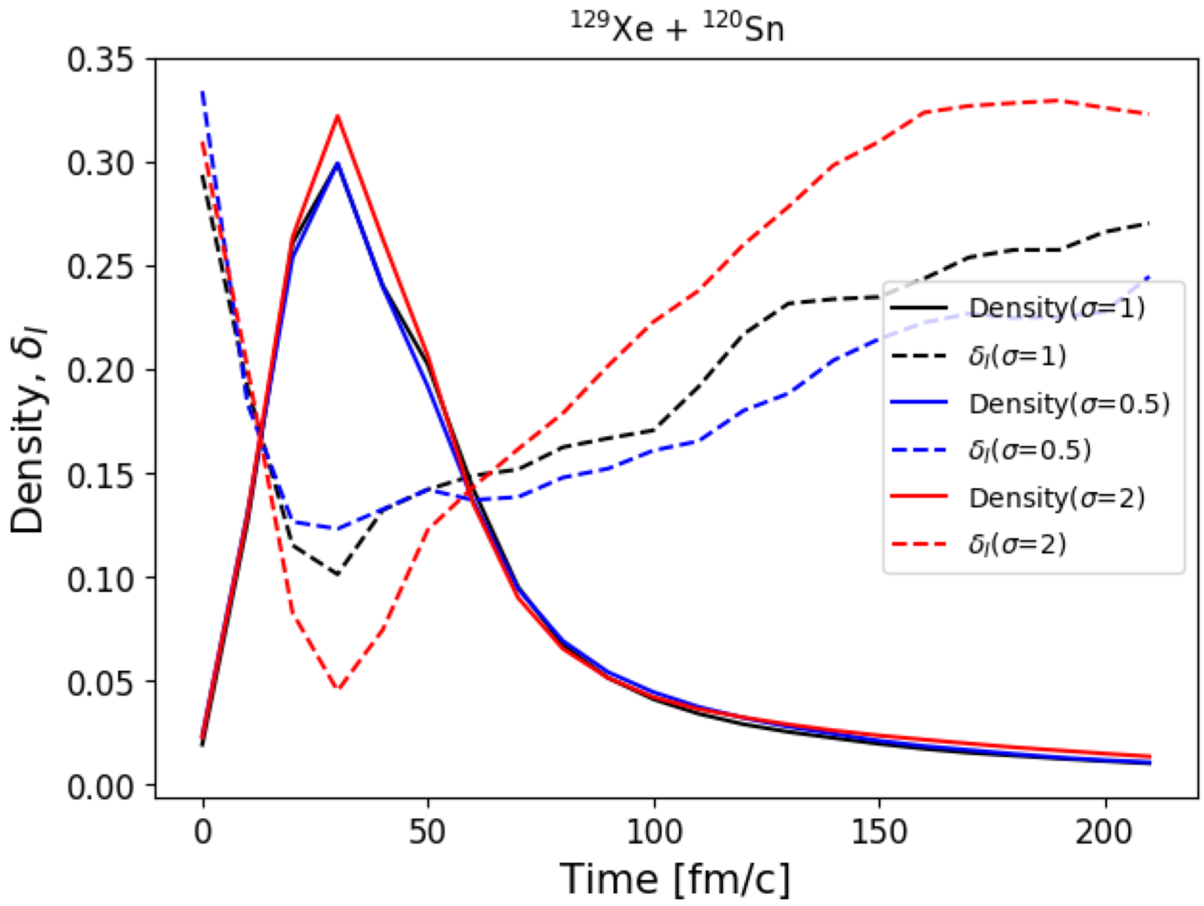
Density



$$\delta_I = \frac{\rho_n - \rho_p}{\rho_n + \rho_p}$$

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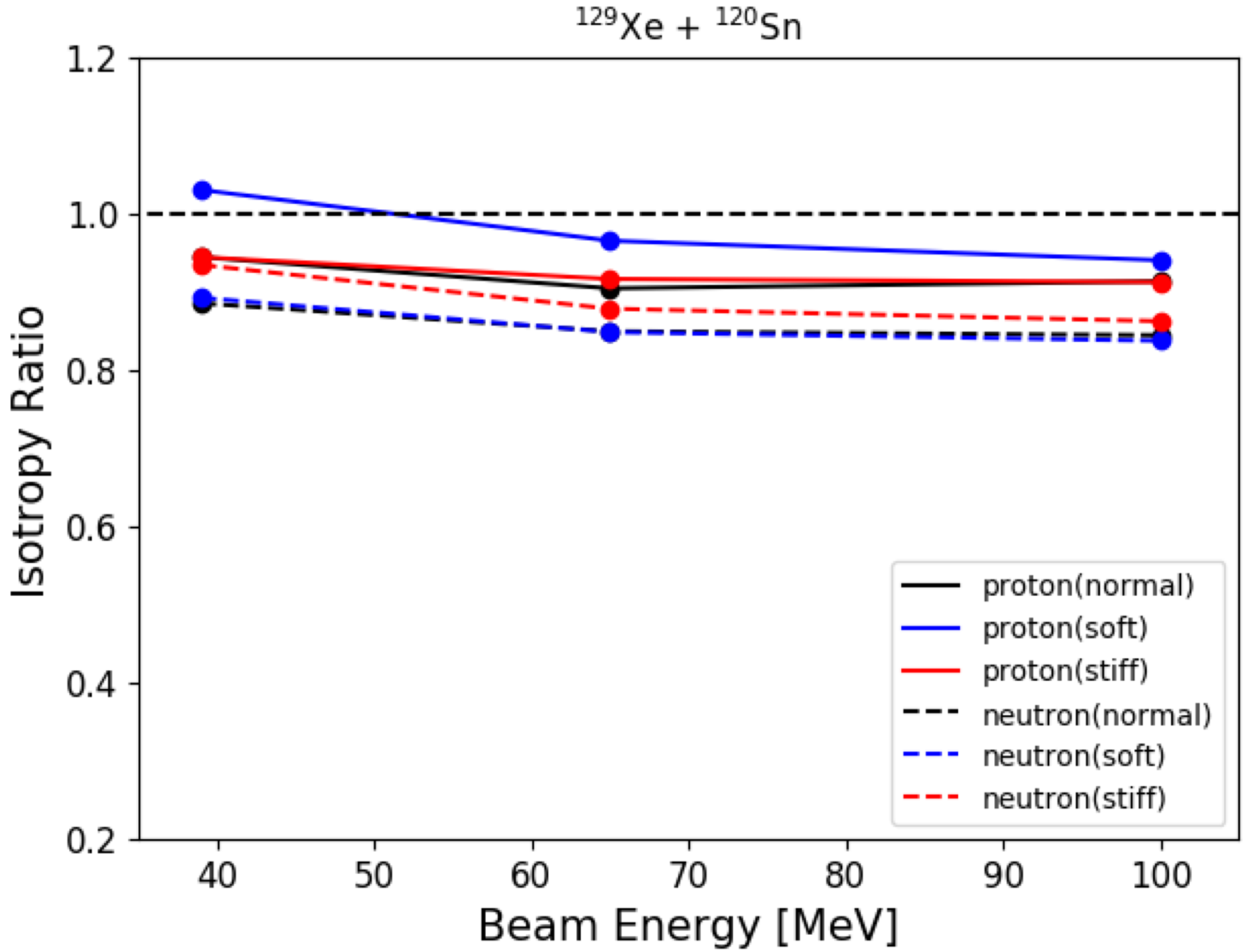
Results



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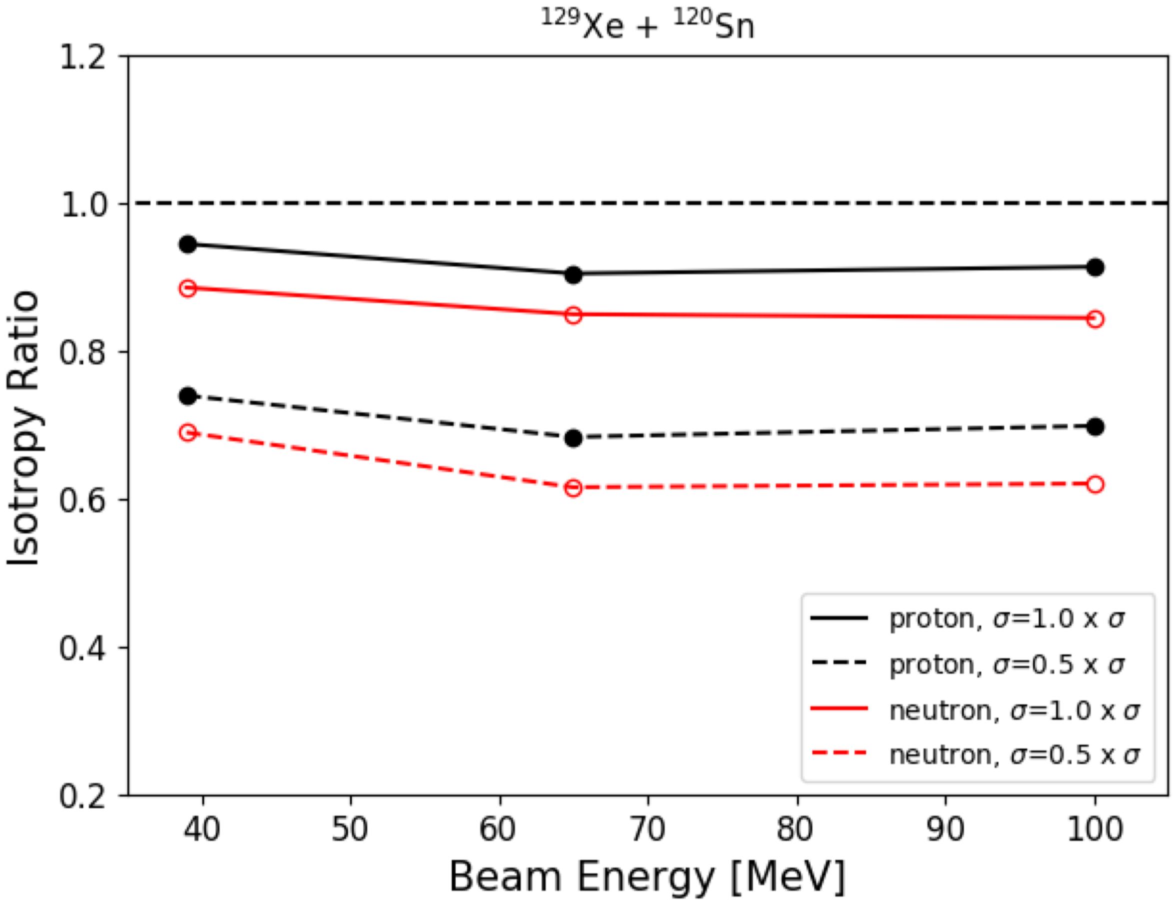
Results



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Summary

- We investigate the energy-based isotropy ratios of protons and neutrons in $^{129}Xe+^{120}Sn$ with our QMD code.
- These ratios have a dependence of symmetry energy.
- As well as the potential, the in-medium NN cross-section gives large effect on the ratio.
- We have a plan to investigate the effect of nn- and pp-cross section splitting in asymmetric matter to the ratio.

Thank you for your attention!!