重イオン衝突で探る核物質

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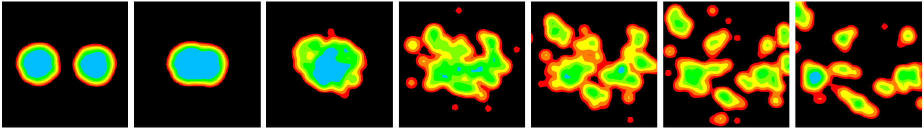
新学術領域「実験と観測で解き明かす中性子星の核物質」キックオフシンポジウム
2012 年 10 月 26 日〜27 日，理化学研究所

- ほぼ一様密度で理解できる現象
- 密度の濃淡が重要になる現象　　⇔ 理論研究の戦略
- クラスター相関の重要性

Nuclear Matter during Nuclear Collisions

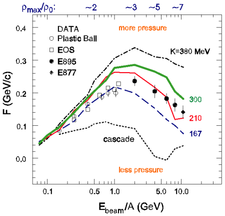


An event of central collision of Xe + Sn at 50 MeV/nucleon (AMD calculation)

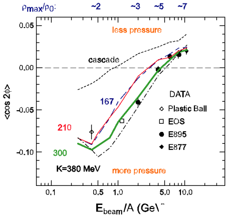
- A large number of nucleons are participating.
  $\approx$ Information of bulk.
- Wide range of density:
  $\rho_0 \rightarrow \sim 2\rho_0 \rightarrow 0.5\rho_0 \rightarrow 0$
- Excitation energy (finite temperature):
  12.5 MeV/nucleon ($\approx$ B.E.) $\rightarrow$ 2 MeV/nucleon $\rightarrow$ 0
- Density fluctuation and/or cluster correlations

EOS of Symmetric Nuclear Matter from Flow

Transverse Flow



Eliptic Flow

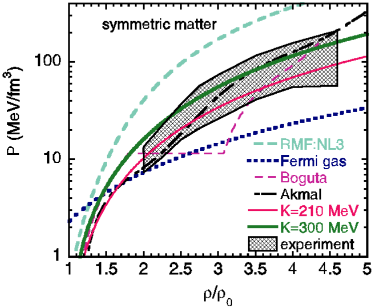


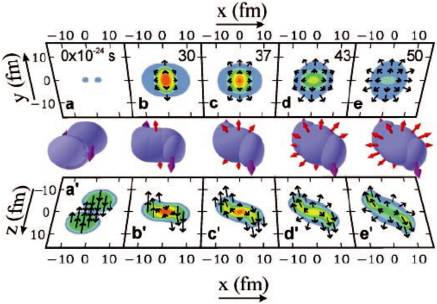
Danielewicz et al.,

Science 298(2002)1592.

⇓

Equation of State



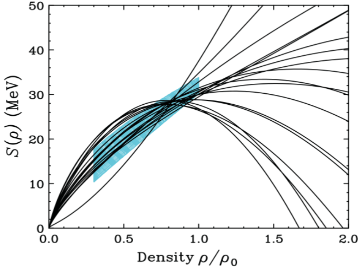


Symmetry Energy at High and Low Densities

Nuclear EOS (at $T = 0$)

$$(E/A)(\rho_p, \rho_n) = (E/A)_0(\rho) + E_{\text{sym}}(\rho)\delta^2$$

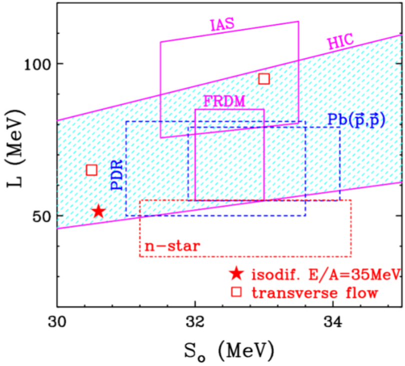
$$\rho = \rho_p + \rho_n, \quad \delta = \frac{\rho_n - \rho_p}{\rho_n + \rho_p}$$



$E_{\text{sym}}(\rho)$ for Skyrme interactions

- $S_0 = E_{\text{sym}}(\rho_0)$ at the saturation density
- $L = 3\rho_0(dE_{\text{sym}}/d\rho)_{\rho=\rho_0}$

Tsang et al., PRC86(2012)015803



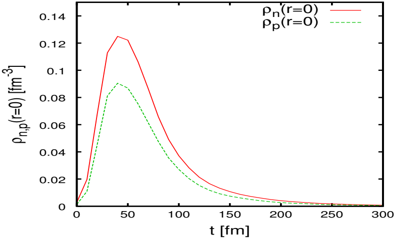
- Nuclear structure
- Heavy-ion collisions
- Neutron stars

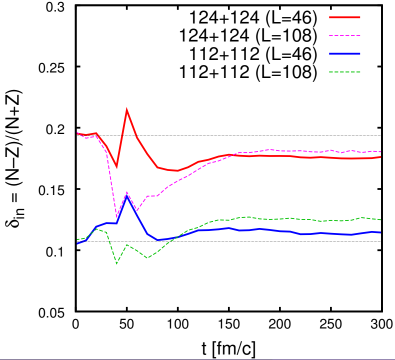
Model ambiguities should be reduced.

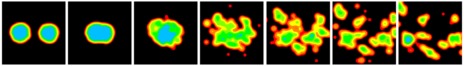
Outline

1. ほぼ一様密度で理解できる現象 — 反応初期・中期
2. 密度の濃淡が重要な現象 — 反応中期・後期
3. クラスター相関の重要性

Dynamics of Neutrons and Protons at Compression State





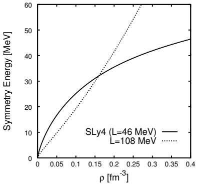


Sn + Sn central collisions at E/A = 50 MeV

- ^{124}Sn + ^{124}Sn
- ^{112}Sn + ^{112}Sn

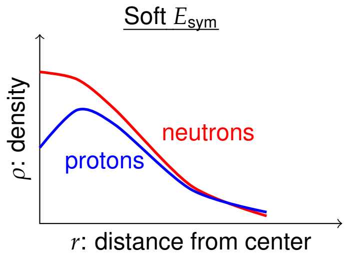
Skyrme force

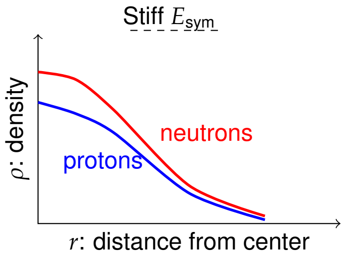
- SLy4 (L = 46 MeV)
- L = 108 MeV

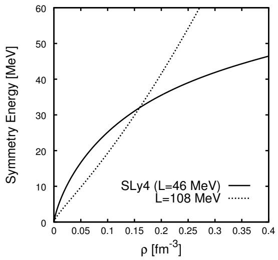


Densities and asymmetry were calculated for an inner part of the system around the center of mass.

Neutron-Proton Densities at Compression





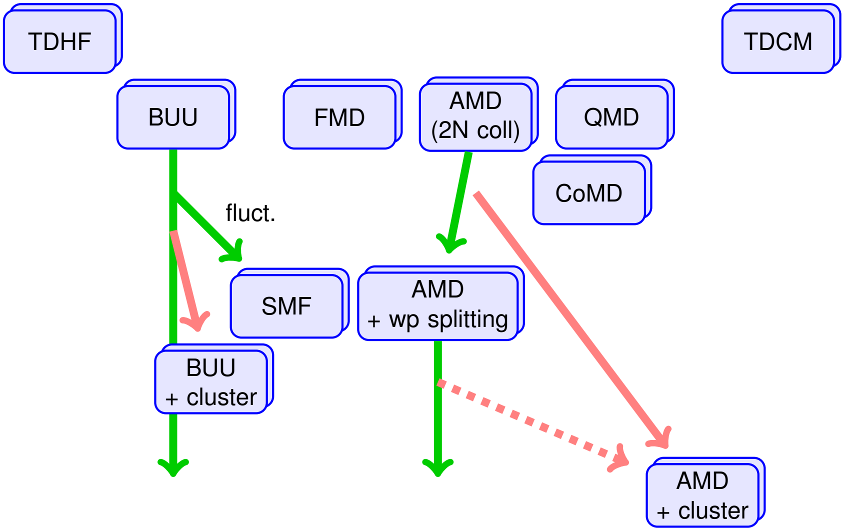


The difference of the motions of neutrons and protons is reflecting the density dependence of the symmetry energy.

Observables

- π^-/π^+ yield ratio
- Neutrons and protons (or tritons and ^{3}He)

Various Microscopic Approaches



Dynamical Approaches

Single-Particle Dynamics $\Leftarrow$ Effective interaction $\cdots ? \cdots$ EOS

- TDHF (quantum)

$$i\hbar \frac{\partial}{\partial t}\varphi_i(\mathbf{r},t) = \left(-\frac{\hbar^2}{2M}\frac{\partial^2}{\partial \mathbf{r}^2} + U[\Phi]\right)\varphi_i(\mathbf{r},t)$$

- Vlasov equation (semiclassical)

$$\frac{\partial f(\mathbf{r},\mathbf{p},t)}{\partial t} = \frac{\partial h}{\partial \mathbf{r}}\cdot\frac{\partial f}{\partial \mathbf{p}} - \frac{\partial h}{\partial \mathbf{p}}\cdot\frac{\partial f}{\partial \mathbf{r}}$$

- Molecular Dynamics (AMD, QMD)

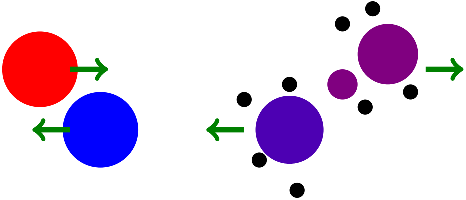
$$\varphi_i(\mathbf{r}) = e^{-\nu(\mathbf{r}-\mathbf{R}_i)^2} e^{(i/\hbar)\mathbf{P}_i\cdot\mathbf{r}}, \qquad \frac{d}{dt}\mathbf{P}_i = \{\mathbf{P}_i, \mathcal{H}\}_{\mathrm{PB}}, \quad \frac{d}{dt}\mathbf{R}_i = \{\mathbf{R}_i, \mathcal{H}\}_{\mathrm{PB}}$$

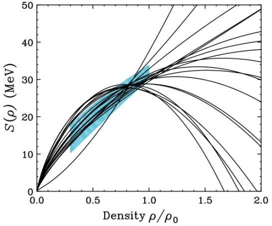
Nucleon-Nucleon Collisions (residual interaction, two-body correlations)

- Not yet done: TDHF
- Taken into account: VUU, BUU, QMD, AMD

Isospin Diffusion

Isospin diffusion through the neck between projectile and target





Comparison of different models

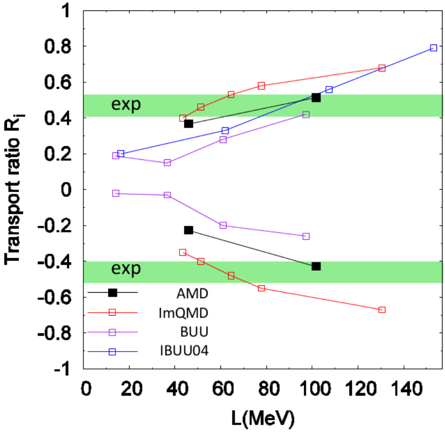


Figure by T. Akaishi

Mechanism of Isospin Diffusion

Isospin diffusion through the neck between projectile and target

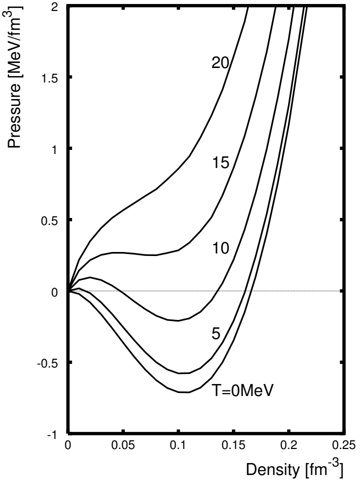
- Diffusion. (depends on single-particle motion and σ_{NN})
- Symmetry potential. (depends on low-density E_{sym})
- ······
- Reaction dynamics. (e.g. reaction time, Rizzo et al., NPA806(2008)79)

Link with low-energy collisions (DIC) should be made clearer.

- Semiclassical approaches (such as BUU and QMD) at medium energies.
- More quantum mechanical approaches (such as TDHF) at lower energies. (charge equilibration, nucleon transfer)

Outline

EOS for finite temperature



Nuclear Matter EOS for Gogny force
(mean field approximation)

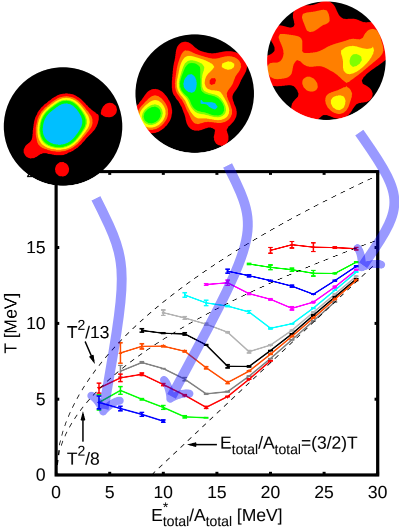
($N = Z$ system)

Similarity to Van der Waals EOS

$$\left(P + \frac{a}{v^2}\right)(v - b) = RT, \quad v = V/N$$

Liquid-gas phase transition is expected.

Caloric Curves and Liquid-Gas Phase Transition



Constant-pressure caloric curves calculated with AMD

Equilibrium Simulation

Solve long-time evolution for given (V, E).

$\Rightarrow$ Microcanonical ensemble

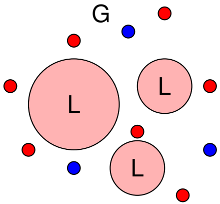
$\Rightarrow$ (T, P)

$$\frac{1}{T} = \frac{\partial S(E)}{\partial E} = \left\langle \frac{\partial S_{\text{gas}}(E_{\text{gas}})}{\partial E_{\text{gas}}} \right\rangle_E$$

$$= \left\langle \frac{\frac{3}{2}N_{\text{gas}} - 1}{E_{\text{gas}}} \right\rangle_E \approx \frac{3}{2} \left\langle \frac{E_{\text{gas}}}{N_{\text{gas}}} \right\rangle_E^{-1}$$

Furuta and Ono, PRC79 (2009) 014608; PRC74 (2006) 014612.

Liquid-Gas Separation in Neutron-Rich System

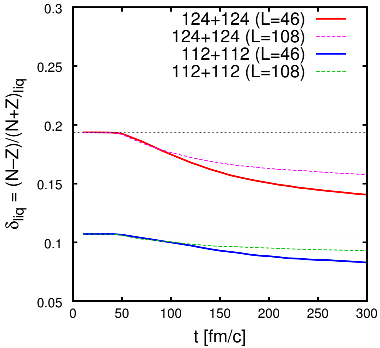


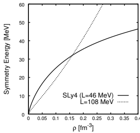
Fractionation/Distillation

δ(liquid) < δ(gas)

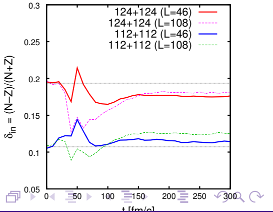
- Gas = $\sum(A \leq 4$ particles)
- Liquid = $\sum(A > 4$ fragments)

Neutron-proton asymmetry of liquid part



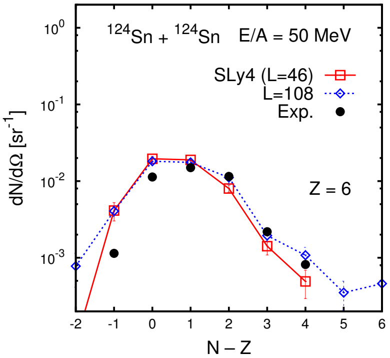


Neutron-proton asymmetry of central part

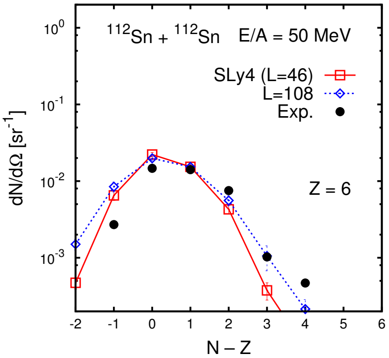


MSU Data: T.X. Liu et al., PRC 014603 (2004).

Calculation: AMD



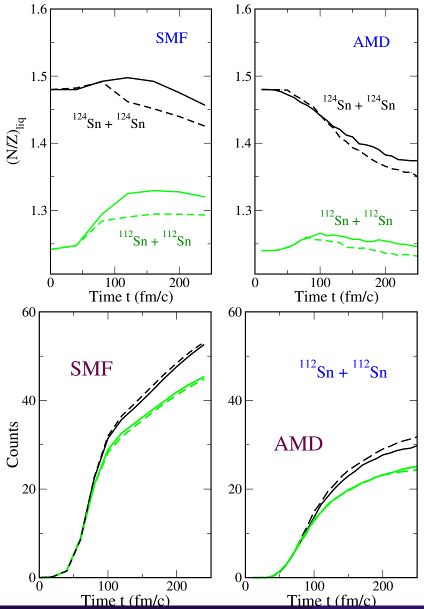
$\langle N - Z \rangle$ = 0.75 and 0.99



$\langle N - Z \rangle$ = 0.36 and 0.53

- The average asymmetry and the width are sensitive to the symmetry energy.
- Compared to data, $Z \geq N$ fragments are overproduced.

Comparison of AMD and SMF



Colonna, Ono, Rizzo, PRC82 (2010) 054613.

Neutron-Proton Ratio of Liquid

$N_{\text{liq}} = N_{\text{tot}} - N_{\text{gas}}, \quad Z_{\text{liq}} = Z_{\text{tot}} - Z_{\text{gas}}$

- Dependence on the symmetry energy $E_{\text{sym}}(\rho)$ (soft or stiff)
- Dependence on models

$N_{\text{gas}}, Z_{\text{gas}}$: Number of Nucleons in Gas

(Emitted nucleons and clusters with $A \leq 4$)

- Black line: neutrons
- Green line: protons

Emission of light particles should be described properly!

General strategy to obtain EOS from HIC

Optimistic:

$$f(\text{model, EOS, other parameters}\ldots) = \text{Observable (exp data)}$$

$$\text{Would be happy if} \quad \frac{\partial f}{\partial\ \text{others}} = 0 \quad \text{and} \quad \frac{\partial f}{\partial\ \text{model}} = 0.$$

Real life:

$$\begin{cases} f_1(\text{model, EOS, other parameters}\ldots) & = & \text{Obs}_1 & (N/Z)_{\text{liquid}} \\ f_2(\text{model, EOS, other parameters}\ldots) & = & \text{Obs}_2 & \text{Gas/Liquid fraction} \\ f_3(\text{model, EOS, other parameters}\ldots) & = & \text{Obs}_3 & \alpha\text{-particle multiplicity} \\ & \cdots\cdots & & \end{cases}$$

What to do?

- Choose suitable observables $\{\text{Obs}_i\}$.
- Check whether a model can describe $\{\text{Obs}_i\}$ by assuming an EOS.
- Improve models.

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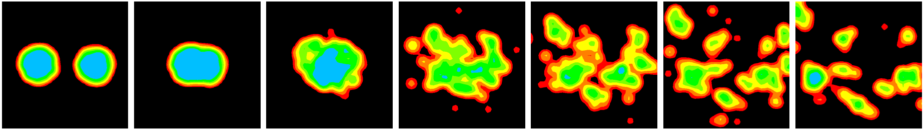
Bulk Properties and Correlations



An event of central collision of Xe + Sn at 50 MeV/nucleon (AMD calculation)

Bulk properties and dynamics
e.g. EOS $E(\rho)$

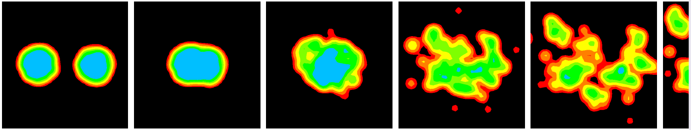
$\Longleftarrow\Longrightarrow$
interplay

Correlations
e.g. clusters and fragments

$\Downarrow$ $\Downarrow$

Isospin dynamics, Symmetry energy
$\rho_n - \rho_p, \quad n/p, \quad t/^3\text{He}, \ldots$

Bulk Properties and Correlations



An event of central collision of Xe + Sn at 50 MeV/nucleon (AMD

Partitioning of protons	
p	≈10%
α	≈20%
d, t, ^{3}He	≈10%
$A > 4$	≈60%

Exp. data (INDRA etc.)

Bulk properties and dynamics
e.g. EOS $E(\rho)$

$\Longleftarrow\Longrightarrow$ interplay

Correlations
e.g. clusters and fragments

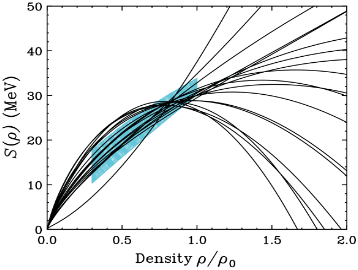
$\Downarrow$ $\Downarrow$

Isospin dynamics, Symmetry energy
$\rho_n - \rho_p$, n/p, $t/^3$He, ...

Nuclear EOS (at $T = 0$)

$$(E/A)(\rho_p, \rho_n) = (E/A)_0(\rho) + E_{\text{sym}}(\rho)\delta^2$$

$$\rho = \rho_p + \rho_n, \quad \delta = \frac{\rho_n - \rho_p}{\rho_n + \rho_p}$$

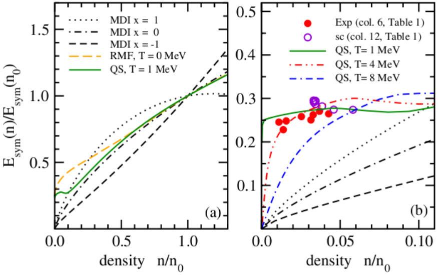


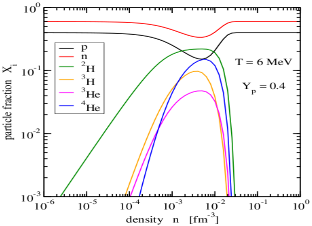
$E_{\text{sym}}(\rho)$ under mean-field approximation

EOS ≠ Skyrme parameters

With clusters

Natowitz et al., PRL104 (2010) 202501.





Generalized RMF by Typel

Why Clusters? — some theoretical background

Two-nucleon collision:

$$W_{i\to f} = \frac{2\pi}{\hbar}|\langle\Psi_f|V|\Psi_i\rangle|^2\delta(E_f - E_i)$$

$$\sum_f |\Psi_f\rangle\langle\Psi_f| = 1$$

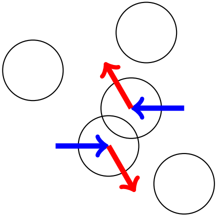
What is a suitable complete basis set for the final states of a two-nucleon scattering?

- A usual choice is to change only the two.

$$\sum_{k_1,k_2}\left|\varphi_{k_1}(1)\varphi_{k_2}(2)\Psi(3,4,\ldots)\right\rangle\left\langle\varphi_{k_1}(1)\varphi_{k_2}(2)\Psi(3,4,\ldots)\right|$$

- If a deuteron will propagate stably in medium, a more suitable basis will include

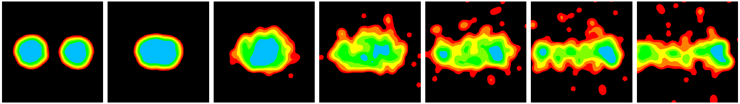
$$\left|\varphi_{k_1}(1)\psi_{\mathrm{d}}(2,3)\Psi(4,\ldots)\right\rangle\left\langle\varphi_{k_1}(1)\psi_{\mathrm{d}}(2,3)\Psi(4,\ldots)\right| + \cdots$$



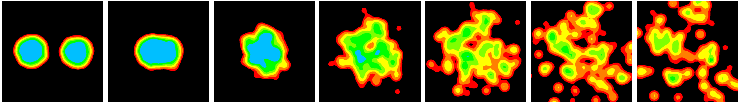
Consider cluster formation up to α-particles.

Effect of Clusters on the Density Evolution

Without cluster correlations (AMD with NN collisions)

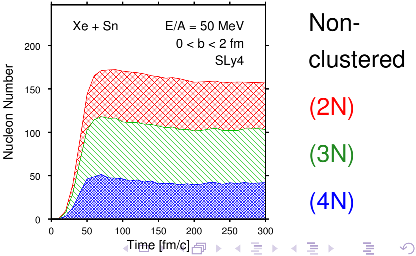


With cluster correlations

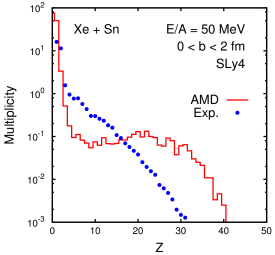


During the time evolution, clusters are . . .

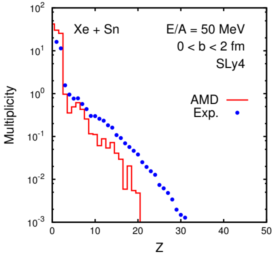
- formed at NN collisions.
- propagated by AMD equation. (nothing special)
- broken by NN collisions. (nothing special)



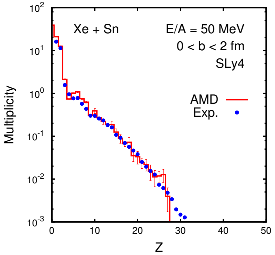
Usual NN collisions



With Clusters



With C & C-C

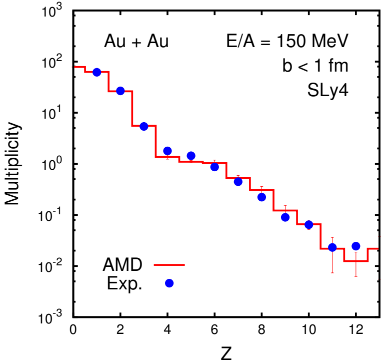


	w/o C	with C	C & C-C	INDRA
$M(p)$	40.2	10.9	10.8	8.4
$M(\alpha)$	2.5	23.2	10.7	10.1
$Z_{\text{gas}}/Z_{\text{tot}}$	55%	78%	43%	(40-50%)

- Gas = $\sum$ (particles of $A \leq 4$)
- Liquid = $\sum$ (heavier fragments)

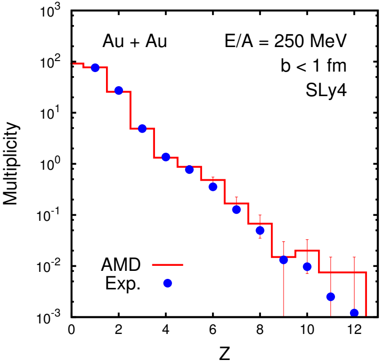
Au + Au Central Collisions at Higher Energies

E/A = 150 MeV



	with C & C-C	FOPI
$M(p)$	32.8	26.1
$M(\alpha)$	20.1	21.0
$Z_{\text{gas}}/Z_{\text{tot}}$	71%	73%

E/A = 250 MeV



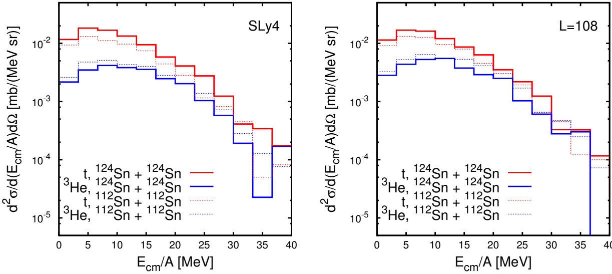
	with C & C-C	FOPI
$M(p)$	42.0	31.9
$M(\alpha)$	19.4	18.2
$Z_{\text{gas}}/Z_{\text{tot}}$	80%	83%

FOPI data: Reisdorf et al., NPA 612 (1997) 493.

Energy Spectra of Clusters

^{124}Sn + ^{124}Sn and ^{112}Sn + ^{112}Sn central collisions at 50 MeV/nucleon

⇒ Energy spectra of tritons and ^{3}He emitted to transverse directions



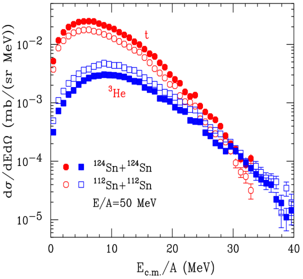
SLy4 (L = 46 MeV) L = 108 MeV

- Triton/^{3}He difference is consistent with fractionation and is sensitive to the symmetry energy at low density.

Energy Spectra of Clusters

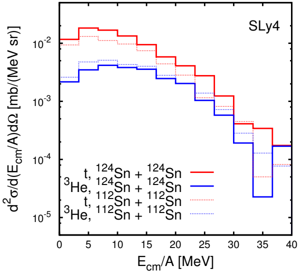
^{124}Sn + ^{124}Sn and ^{112}Sn + ^{112}Sn central collisions at 50 MeV/nucleon

⇒ Energy spectra of tritons and ^{3}He emitted to transverse directions

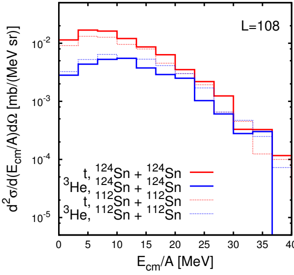


Data @NSCL/MSU

Liu et al., arXiv:1208.3108



SLy4 (L = 46 MeV)

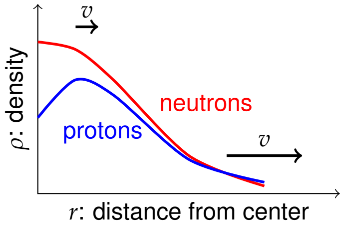


L = 108 MeV

- Triton/^{3}He difference is consistent with fractionation and is sensitive to the symmetry energy at low density.
- To reproduce data, there should be more low-energy tritons and less high-energy tritons, and low-energy ^{3}He particles (or protons) should be less.

Compression and Expansion Dynamics of Neutrons and Protons?

Both liquid and gas (low energy part) should be more neutron rich.
(⇒ It is not an issue of fractionation in fragmentation.)



Compared to the current AMD results, neutrons should have lower energies in order to explain the data for

- the triton spectrum
- the small yield of proton-rich nuclei
- the large energy of proton-rich nuclei

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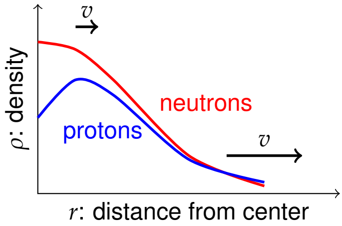

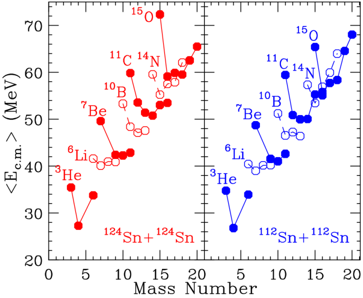

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Kinetic energies of proton-rich fragments are anomalously large.
(Yields of low-energy proton-rich fragments are anomalously small.)

Summary

- 重イオン衝突での多くの観測量は $E_{\mathrm{sym}}(\rho)$ を反映している．($\rho > \rho_0$, $\rho < \rho_0$)
- モデルを仮定すれば結論が得られるが，結論はモデルに依存する．
- モデルによる不定性を減らす努力が必要．
  - モデルに依らない物理量を探す．
  - 特定の観測量だけでなく，反応の大局的様相に注意が必要．
  - モデルを改良する．
- 重イオン衝突では（思ったよりも）クラスター相関が強い．（数百 MeV/u でも）