Light clusters and light nuclei in collision dynamics

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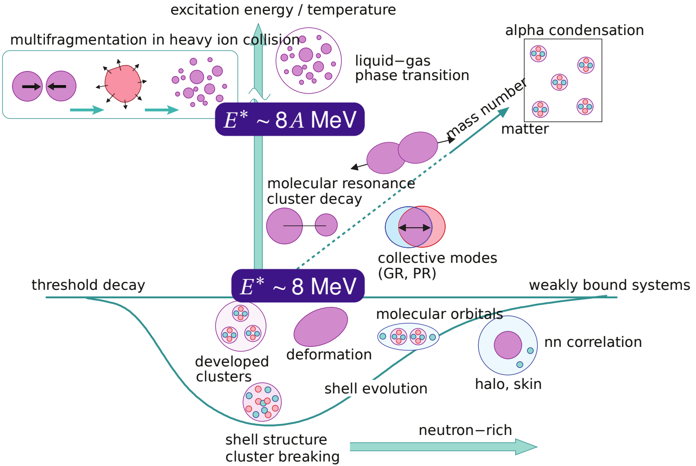
Clustering phenomena in excited states of nuclear systems

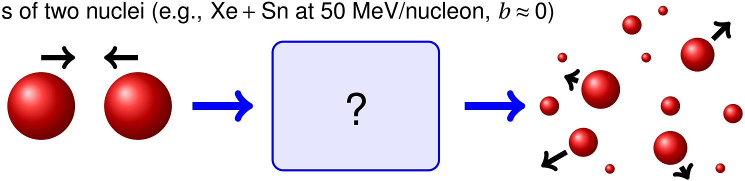
$E^* \sim 80A$ MeV Gas of clusters at higher energies



Kanada-En'yo, Kimura, Ono, Prog. Theor. Exp. Phys. 2012 01A202 (2012)

Importance of clusters in heavy-ion collisions

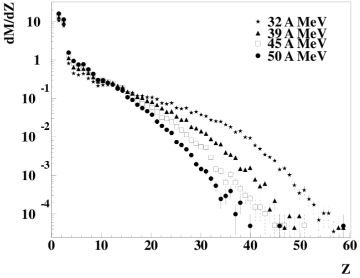
Collisions of two nuclei (e.g., Xe + Sn at 50 MeV/nucleon, $b \approx 0$)



Partitioning of protons		
	Xe + Sn 50 MeV/u	Au + Au 250 MeV/u
p	≈10%	21%
α	≈20%	20%
d, t, ^{3}He	≈10%	40%
$A > 4$	≈60%	18%

INDRA data, Hudan et al., PRC67 (2003) 064613.

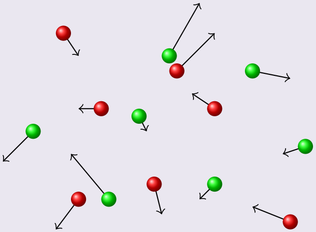
FOPI data, Reisdorf et al., NPA 848 (2010) 366.



Light-cluster correlations are important in late times, at least.

Cluster production in transport models

Transport models ≈ Nucleons move almost independently in the mean field.



Description by $f_n(\mathbf{r},\mathbf{p})$ and $f_p(\mathbf{r},\mathbf{p})$, ignoring correlations.

Probability to find a cluster in a snapshot:

$$|\langle\Psi_d|\psi_n\psi_p\rangle|^2 = \iiiint F_d(\mathbf{r}_1,\mathbf{p}_1,\mathbf{r}_2,\mathbf{p}_2) f_n(\mathbf{r}_1,\mathbf{p}_1) f_p(\mathbf{r}_2,\mathbf{p}_2) \frac{d\mathbf{r}_1\, d\mathbf{p}_1\, d\mathbf{r}_2\, d\mathbf{p}_2}{(2\pi\hbar)^6}$$

$$\Psi_d(\mathbf{r}_1,\mathbf{r}_2) = \psi_d^{\text{int}}\Big(\mathbf{r}_1-\mathbf{r}_2\Big)\psi_d^{\text{cm}}\Big(\tfrac{1}{2}(\mathbf{r}_1+\mathbf{r}_2)\Big)$$

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Unfortunately, $|\langle\Psi_d|\psi_n\psi_p\rangle|^2$ is time dependent.

- Coalescence prescription: Assume that the transport calculation is correct until “freeze out”, and then clusters are suddenly emitted with these probabilities.

  e.g. L.W. Chen, et al., NPA 729 (2003) 809.

- More dynamical approaches with cluster correlations:
  - Should predict when each cluster is formed.
  - Should calculate the fate of formed clusters.

Cluster production in transport models

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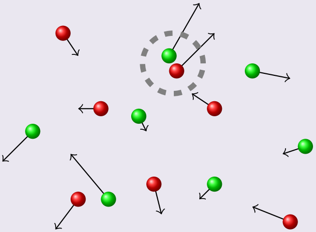

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BUU with clusters

Danielewicz and Bertsch, NPA 533 (1991) 712.

Coupled equations for $f_n(\mathbf{r},\mathbf{p},t)$, $f_p(\mathbf{r},\mathbf{p},t)$, $f_d(\mathbf{r},\mathbf{p},t)$, $f_t(\mathbf{r},\mathbf{p},t)$, $f_h(\mathbf{r},\mathbf{p},t)$ are solved by the test particle method.

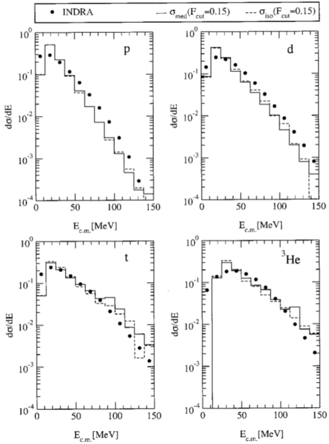
$$\frac{\partial f_n}{\partial t}+\mathbf{v}\cdot\frac{\partial f_n}{\partial \mathbf{r}}-\frac{\partial U_n}{\partial \mathbf{r}}\cdot\frac{\partial f_n}{\partial \mathbf{p}}=I_n^{\text{coll}}[f_n,f_p,f_d,f_t,f_h]$$

$$\frac{\partial f_p}{\partial t}+\mathbf{v}\cdot\frac{\partial f_p}{\partial \mathbf{r}}-\frac{\partial U_p}{\partial \mathbf{r}}\cdot\frac{\partial f_p}{\partial \mathbf{p}}=I_p^{\text{coll}}[f_n,f_p,f_d,f_t,f_h]$$

$$\frac{\partial f_d}{\partial t}+\mathbf{v}\cdot\frac{\partial f_d}{\partial \mathbf{r}}-\frac{\partial U_d}{\partial \mathbf{r}}\cdot\frac{\partial f_d}{\partial \mathbf{p}}=I_d^{\text{coll}}[f_n,f_p,f_d,f_t,f_h]$$

$$\frac{\partial f_t}{\partial t}+\mathbf{v}\cdot\frac{\partial f_t}{\partial \mathbf{r}}-\frac{\partial U_t}{\partial \mathbf{r}}\cdot\frac{\partial f_t}{\partial \mathbf{p}}=I_t^{\text{coll}}[f_n,f_p,f_d,f_t,f_h]$$

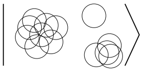
$$\frac{\partial f_h}{\partial t}+\mathbf{v}\cdot\frac{\partial f_h}{\partial \mathbf{r}}-\frac{\partial U_h}{\partial \mathbf{r}}\cdot\frac{\partial f_h}{\partial \mathbf{p}}=I_h^{\text{coll}}[f_n,f_p,f_d,f_t,f_h]$$



Renormalized cluster spectra

Kuhrts et al., PRC63(2001)034605.

Antisymmetrized Molecular Dynamics (very basic version)



AMD wave function

$$|\Phi(Z)\rangle = \det_{ij}\left[\exp\left\{-\nu\left(\mathbf{r}_j - \frac{\mathbf{Z}_i}{\sqrt{\nu}}\right)^2\right\}\chi_{\alpha_i}(j)\right]$$

$$\mathbf{Z}_i = \sqrt{\nu}\mathbf{D}_i + \frac{i}{2\hbar\sqrt{\nu}}\mathbf{K}_i$$

ν : Width parameter = (2.5 fm)$^{-2}$

χ_{α_i} : Spin-isospin states = $p\uparrow, p\downarrow, n\uparrow, n\downarrow$

Equation of motion for the wave packet centroids Z

$$\frac{d}{dt}\mathbf{Z}_i = \{\mathbf{Z}_i, \mathscr{H}\}_{\text{PB}} \quad + \quad \text{(NN collisions)}$$

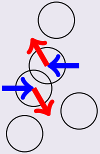
$\{\mathbf{Z}_i, \mathscr{H}\}_{\text{PB}}$: Motion in the mean field

$$\mathscr{H} = \frac{\langle\Phi(Z)|H|\Phi(Z)\rangle}{\langle\Phi(Z)|\Phi(Z)\rangle} + \text{(c.m. correction)}$$

H: Effective interaction (e.g. Skyrme force)

NN collisions

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



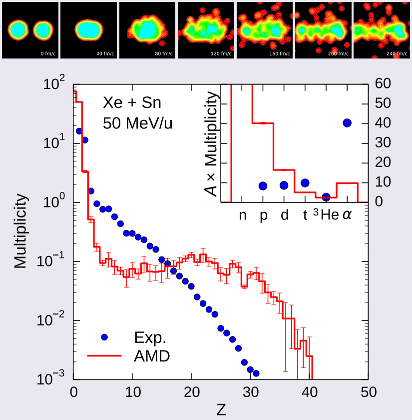
- $|V|^2$ or σ_{NN} (in medium)
- Pauli blocking

Ono, Horiuchi et al., Prog. Theor. Phys. 87 (1992) 1185.

Failure of fragmentation and cluster production

AMD with usual NN collisions (very basic version)

Central Xe + Sn at 50 MeV/u



Partitioning of protons

(experimental data)

	Xe + Sn 50 MeV/u	Au + Au 250 MeV/u
p	≈10%	21%
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$A > 4$	≈60%	18%

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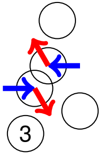
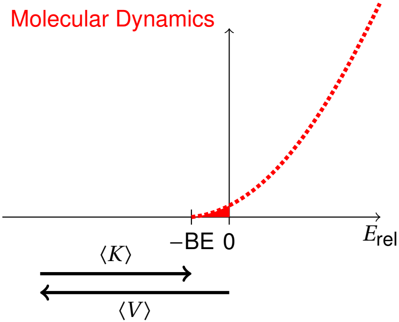


In the usual way of NN collision, only the two wave packets are changed.

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

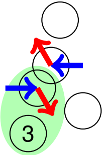
(ignoring antisymmetrization for simplicity of presentation.)

Phase space or the density of states for two nucleon system



NN collisions without or with cluster correlations

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



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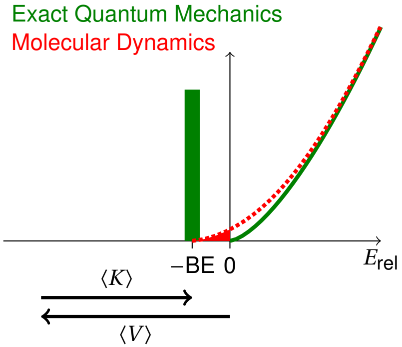
Extension for cluster correlations

Include correlated states in the set of the final states of each NN collision.

$$\Big\{|\Psi_f\rangle\Big\} \ni |\varphi_{k_1}(1)\psi_d(2,3)\Psi(4,\ldots)\rangle, \ \ldots$$

Phase space or the density of states for two nucleon system

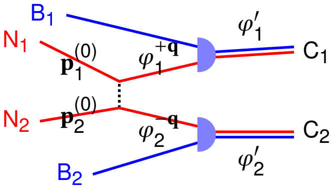


NN collisions with cluster correlations

Similar to Danielewicz et al., NPA533 (1991) 712.

$$\mathrm{N}_1 + \mathrm{B}_1 + \mathrm{N}_2 + \mathrm{B}_2 \to \mathrm{C}_1 + \mathrm{C}_2$$

- $\mathrm{N}_1, \mathrm{N}_2$: Colliding nucleons
- $\mathrm{B}_1, \mathrm{B}_2$: Spectator nucleons/clusters
- $\mathrm{C}_1, \mathrm{C}_2$: N, $(2N)$, $(3N)$, $(4N)$ (up to α cluster)



Transition probability

$$W(\mathrm{NBNB} \to \mathrm{CC}) = \frac{2\pi}{\hbar} |\langle \mathrm{CC}|V|\mathrm{NBNB}\rangle|^2 \delta(E_f - E_i)$$

$$v\,d\sigma \propto |\langle \varphi_1' | \varphi_1^{+\mathbf{q}} \rangle|^2 |\langle \varphi_2' | \varphi_2^{-\mathbf{q}} \rangle|^2 |M|^2 \delta(E_f - E_i) p_{\mathrm{rel}}^2 \, dp_{\mathrm{rel}} \, d\Omega$$

$|M|^2 = |\langle \mathrm{NN}|V|\mathrm{NN}\rangle|^2$: Matrix elements of NN scattering

$\Leftarrow (d\sigma/d\Omega)_{\mathrm{NN}}$ in medium (or in free space)

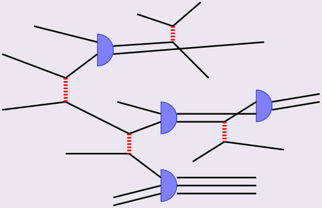
$$\mathbf{p}_{\mathrm{rel}} = \tfrac{1}{2}(\mathbf{p}_1 - \mathbf{p}_2) = p_{\mathrm{rel}} \hat{\boldsymbol{\Omega}}$$

$$\mathbf{q} = \mathbf{p}_1 - \mathbf{p}_1^{(0)} = \mathbf{p}_2^{(0)} - \mathbf{p}_2$$

$$\varphi_1^{+\mathbf{q}} = \exp(+i\mathbf{q}\cdot\mathbf{r}_{\mathrm{N}_1})\varphi_1^{(0)}$$

$$\varphi_2^{-\mathbf{q}} = \exp(-i\mathbf{q}\cdot\mathbf{r}_{\mathrm{N}_2})\varphi_2^{(0)}$$

NN collisions with cluster correlations (more explanations)



For each NN collision, cluster formation is considered.

$$\mathrm{N}_1 + \mathrm{B}_1 + \mathrm{N}_2 + \mathrm{B}_2 \to \mathrm{C}_1 + \mathrm{C}_2$$

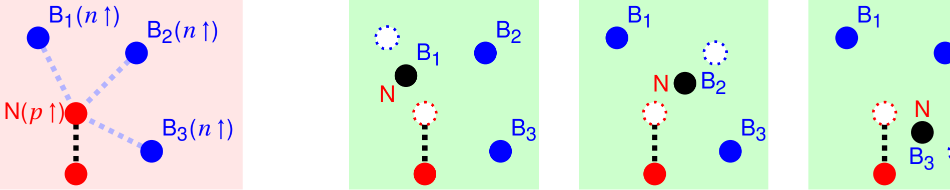
$$W_{i\to f} = \frac{2\pi}{\hbar} |\langle \mathrm{CC}| V_{NN} |\mathrm{NBNB}\rangle|^2 \delta(E_f - E_i)$$

Ono, J. Phys. Conf. Ser. 420 (2013) 012103

Ikeno, Ono et al., PRC 93 (2016) 044612

- We always have a Slater determinant of nucleon wave packets. A cluster in the final states is represented by placing wave packets at the same phase space point.
- Consequently the processes such as $d + X \to n + p + X'$ and $d + X \to d + X'$ are automatically taken into account.
- No parameters have been introduced to adjust individual reactions.
- There is an option to suppress clusters depending on the medium.
- There are many possibilities to from clusters in the final states. Non-orthogonality of the final states should be carefully handled.

Clusters (in the final states) are assumed to have $(0s)^N$ configuration.



$|\Phi^{\mathbf{q}}\rangle$ After $\mathbf{p}^{(0)} \to \mathbf{p}^{(0)} + \mathbf{q}$

$|\Phi'_1\rangle$ $\mathrm{N} + \mathrm{B}_1 \to \mathrm{C}_1$

$|\Phi'_2\rangle$ $\mathrm{N} + \mathrm{B}_2 \to \mathrm{C}_2$

$|\Phi'_3\rangle$ $\mathrm{N} + \mathrm{B}_3 \to \mathrm{C}$

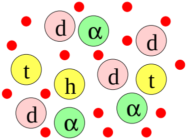
Final states are not orthogonal: $N_{ij} \equiv \langle\Phi'_i|\Phi'_j\rangle \neq \delta_{ij}$

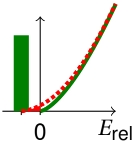
The probability of cluster formation with one of B's:

$$\hat{P} = \sum_{ij} |\Phi'_i\rangle N^{-1}_{ij} \langle\Phi'_j|, \qquad P = \langle\Phi^{\mathbf{q}}|\hat{P}|\Phi^{\mathbf{q}}\rangle \qquad \neq \sum_i |\langle\Phi'_i|\Phi^{\mathbf{q}}\rangle|^2$$

$$\begin{cases} P & \Rightarrow \text{Choose one of the candidates and make a cluster.} \\ 1-P & \Rightarrow \text{Don't make a cluster (with any n}\uparrow\text{).} \end{cases}$$

Correlations to bind several clusters

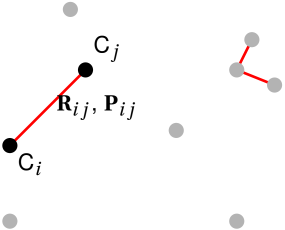




Clusters may form a loosely bound state.

e.g., $^7\text{Li} = \alpha + t - 2.5$ MeV

Need more probability of $|\alpha + t\rangle \to |^7\text{Li}\rangle$



Step 1 Clusters (and nucleons) C_i and C_j are *linked*,

- if C_i is one of the 4 clusters closest to C_j, and $(i \leftrightarrow j)$,
- and if the distance is 1 fm $< |\mathbf{R}_{ij}| <$ 5 fm,
- and if they are slowly moving away, $\mathbf{P}_{ij}^2/2\mu_{ij} <$ 8 MeV and $\mathbf{R}_{ij} \cdot \mathbf{P}_{ij} > 0$.

Step 2 Linked clusters (CC) are identified. Following steps are taken only for CC with mass number $6 \le A \le 9$.

Step 3 *Transition* of the internal state of CC by eliminating the internal momentum

$$\mathbf{P}_i \to 0 \quad \text{for } i \in \text{CC in the c.m. of CC}$$

Step 4 *Energy conservation.*

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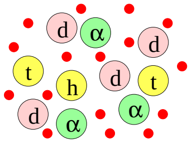

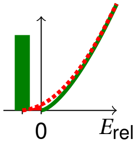

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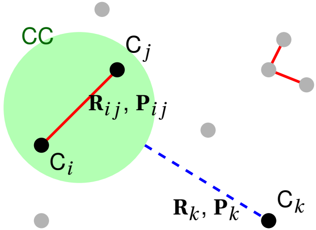

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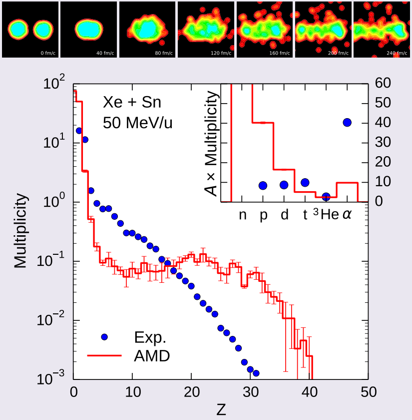
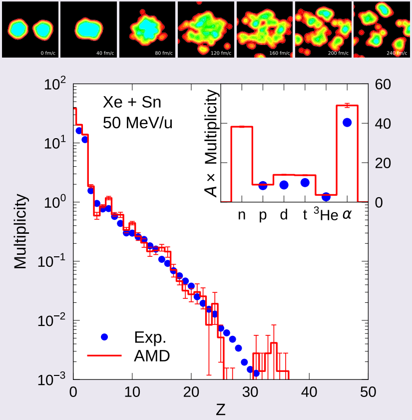
Effect of cluster correlations: central Xe + Sn at 50 MeV/u

Without clusters

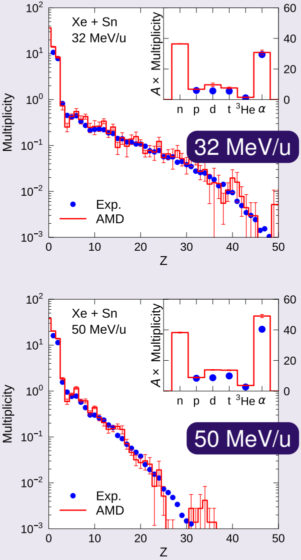


With clusters

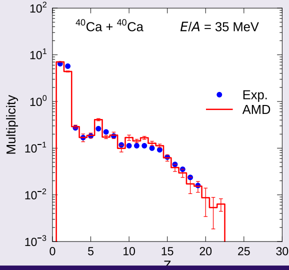


Results for multifragmentation in central collisions

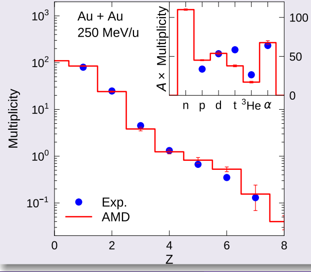
Xe + Sn



Ca + Ca at 35 MeV/u



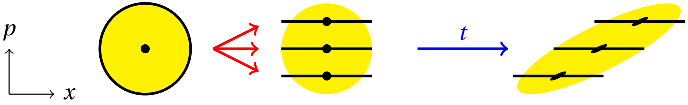
Au + Au at 250 MeV/u



Data:
Hudan et al., PRC 67 (2003) 064613.
Hagel et al., PRC 50 (1994) 2017.
Reisdorf et al., NPA 848 (2010) 366.

Transition from a wave packet to a plane wave

Each wave packet has a momentum width. E.g., it is an important part of the Fermi motion.

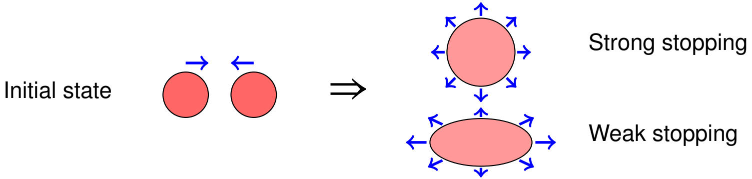


$f(p) = Ne^{-(p-P)^2/2\Delta p^2}$ $\qquad$ $p = P + \Delta p$

The momentum fluctuation Δp is given to a wave packet when it is **'emitted'**, following Ono and Horiuchi, PRC53 (1996) 845 [a simple version of wp splitting].

- For a formed cluster, the momentum fluctuation is given to its center-of-mass motion.
- Total momentum and energy conservation.
- A particle is regarded as **'emitted'** when there is no other particles around it in phase space within the radius $(\Delta r, \Delta v) = (3.5\text{ fm}, 0.25c)$.
- Consistency with the method of the zero-point energy correction.

Stopping



A quantity to represent stopping

$$R_E = \frac{\sum(E_x + E_y)}{2\sum E_z},$$

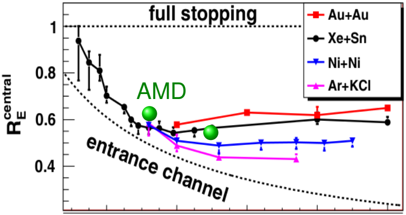
$\sum$ for all charged products ($Z \geq 1$)

Stopping should depend on

- Inmedium NN cross sections
- Treatment of Pauli blocking
- Effective interaction
- How to select events

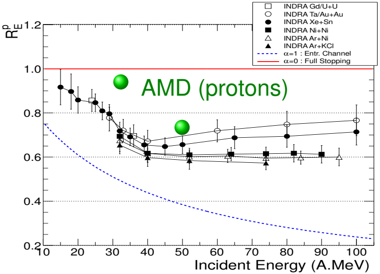
$$R_E = \frac{\sum(E_x+E_y)}{2\sum E_z}, \qquad \sum \text{ for all } (Z \geq 1)$$

Data: Lehaut et al., PRL104 (2010) 232701.



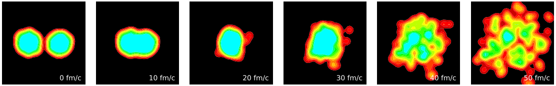
$$R_E^p = \frac{\sum(E_x+E_y)}{2\sum E_z}, \qquad \sum \text{ for protons}$$

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



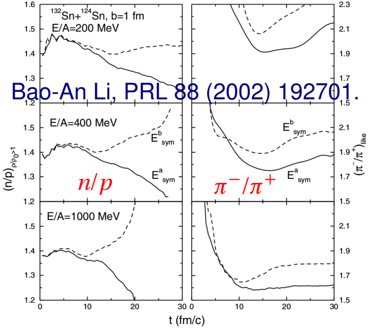
Collisions at ~ 300 MeV/nucleon

- High density ($\sim 2\rho_0$)
- Pion produciton



^{132}Sn + ^{124}Sn, $E/A = 300$ MeV, $b \sim 0$, AMD calculation

Neutron rich system ($N = 156$, $Z = 100$)



Bao-An Li, PRL 88 (2002) 192701.

Simple picture

$$\text{Symmetry Energy } S(\rho) \iff n/p \overset{NN\leftrightarrow N\Delta}{\iff} \Delta^-/\Delta^0/\Delta^+/\Delta^{++} \overset{\Delta\leftrightarrow N\pi}{\iff} \pi^-/\pi^+$$

Is the simple expectation $(n/p)^2 \approx \pi^-/\pi^+$ valid in HIC?

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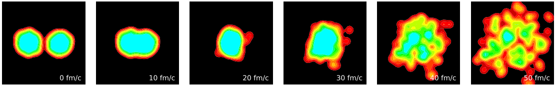

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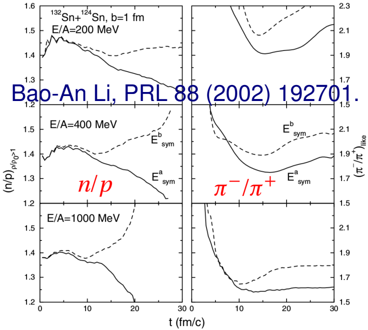


Bao-An Li, PRL 88 (2002) 192701.

More complicated picture

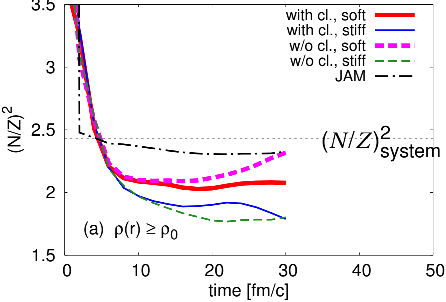
Equation of State NN cross sections Cluster correlations	$\Bigg\}$	$\Longleftrightarrow \quad n/p \quad \overset{NN \leftrightarrow N\Delta}{\Longleftrightarrow} \quad \Delta^-/\Delta^0/\Delta^+/\Delta^{++} \quad \overset{\Delta \leftrightarrow N\pi}{\Longleftrightarrow} \quad \pi^-/\pi^+$ other observables

Is the simple expectation $(n/p)^2 \approx \pi^-/\pi^+$ valid in HIC?

Does Δ production agree with n/p dynamics?

Ikeno, Ono, Nara, Ohnishi, PRC 93 (2016) 044612. (updated)

$(N/Z)^2$ @ high density



Different n/p dynamics ⇐ different $E_{\text{sym}}(\rho)$ **and** cluster correlations

Four AMD+JAM calculations and a JAM calculation

- Solid lines: with clusters; **Soft** ($L = 46$ MeV) and Stiff ($L = 108$ MeV)
- Dashed lines: without clusters; **Soft** ($L = 46$ MeV) and Stiff ($L = 108$ MeV)
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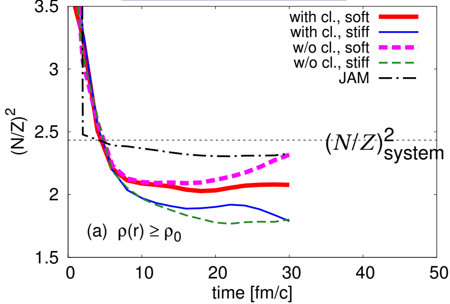
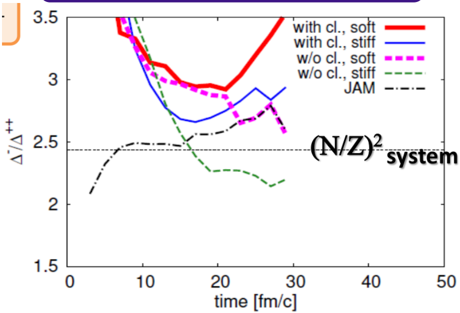


Rate($nn \to p\Delta^-$) / Rate($pp \to n\Delta^{++}$)



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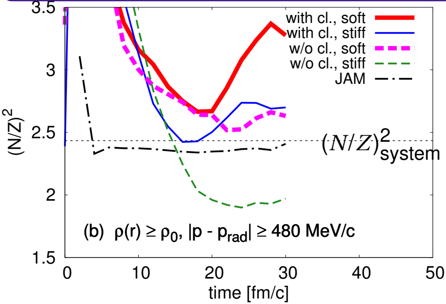

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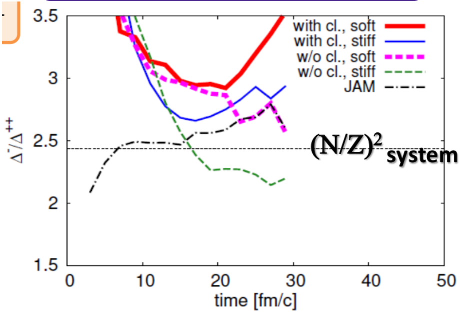

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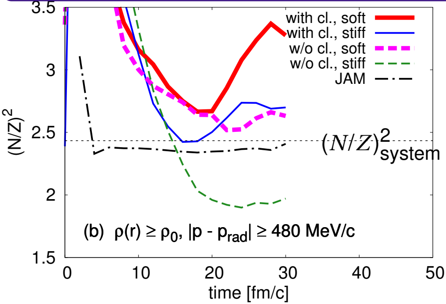

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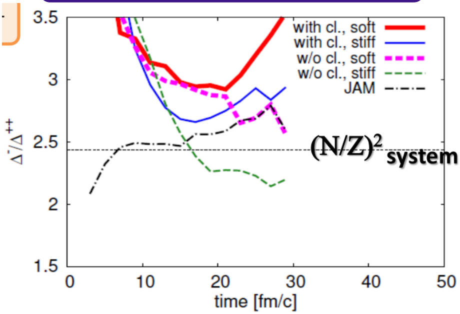
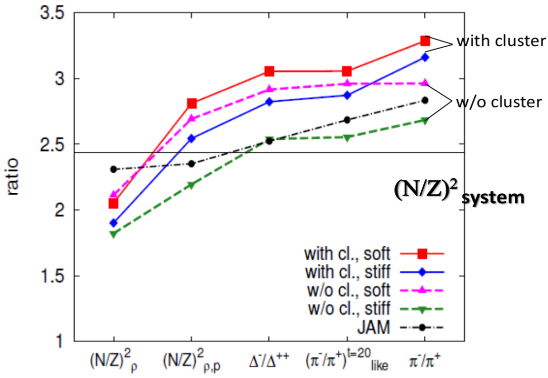


Nucleons ⇒ Δ production

- Δ production sees the nucleons in the **high-density and high-momentum** region of phase space.
- Δ production is also affected by the nucleons in the **low-momentum** region of phase space. ⇒ Ikeno's talk on Wednesday.

Summary of ratios, for ^{132}Sn + ^{124}Sn at 300 MeV/nucleon



Ikeno, Ono, Nara, Ohnishi, PRC 93 (2016) 044612 (updated)

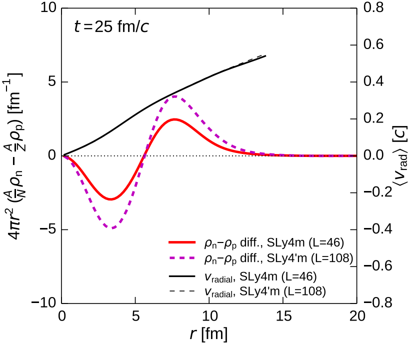
$(N/Z)^2_\rho$, $(N/Z)^2_{\rho,p}$, Δ^-/Δ^{++}: representative values integrated (or averaged) over time.

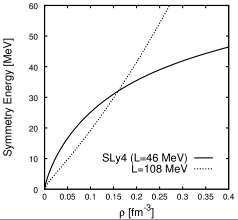
- $(N/Z)^2$ in high-ρ and high-p region $\approx$ $(\pi^-/\pi^+)_{\text{like}}$ at $t = 20$ fm/c $\cdots$ Final π^-/π^+

  ~30% reduction of E_{sym} effect

- Effects of clusters: Larger ratios, and weaker dependence on E_{sym}

N/Z Ratio in ^{132}Sn + ^{124}Sn at 300 MeV/u (AMD with clusters)

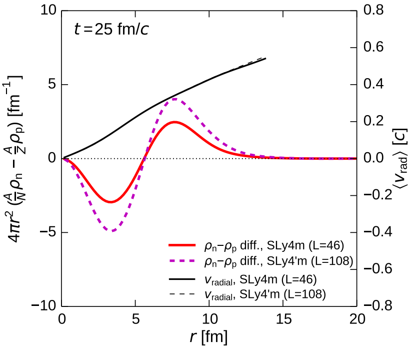


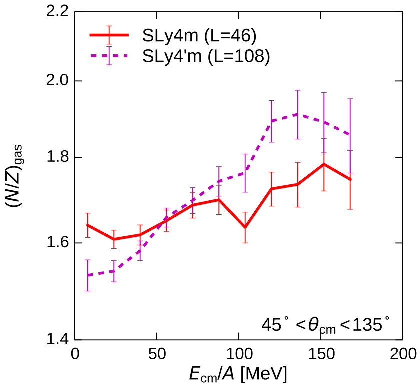


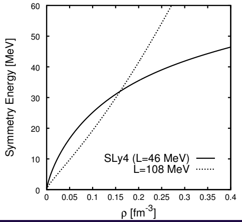
Pions have to go through the exterior region of the expanding system.

- For stiff symmetry energy,
  - The interior region is less neutron rich.
    π^-/π^+ ↘↘↘
  - The exterior region is more neutron rich.
    π^-/π^+ ↗

N/Z Ratio in ^{132}Sn + ^{124}Sn at 300 MeV/u (AMD with clusters)



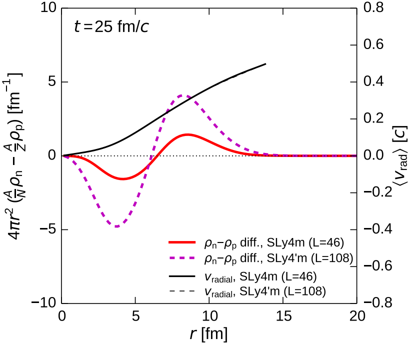


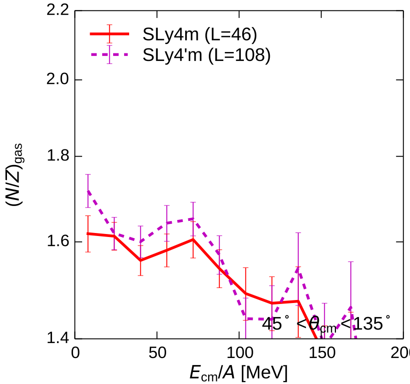


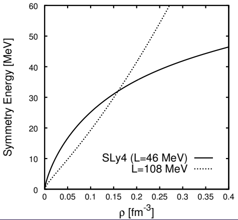
$$\left(\frac{N}{Z}\right)_{\text{gas}} = \frac{Y_n(v)+Y_d(v)+2Y_t(v)+Y_h(v)+2Y_\alpha(v)}{Y_p(v)+Y_d(v)+Y_t(v)+2Y_h(v)+2Y_\alpha(v)}$$

N/Z of spectrum of emitted particles is similar to the neutron-proton density difference at the compression stage.

N/Z Ratio in ^{132}Sn + ^{124}Sn at 300 MeV/u (AMD without clusters)







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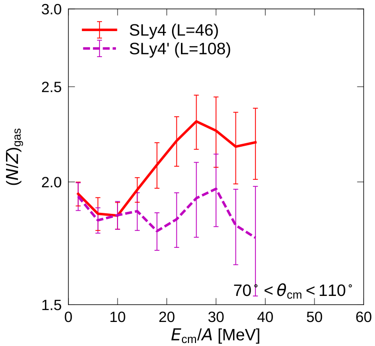
N/Z of spectrum of emitted particles is NOT similar to the neutron-proton density difference at the compression stage.

Central collisions calculated by AMD with clusters

^{124}Sn + ^{124}Sn at $E/A = 50$ MeV



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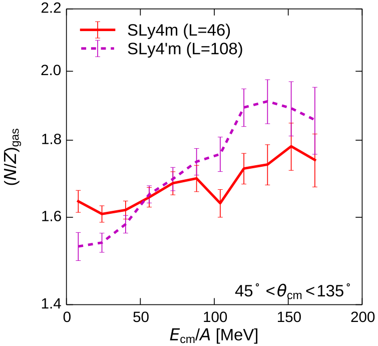

Low density effect $\Longleftrightarrow$ High density effect

N/Z Ratio at 50 and 300 MeV/u

Central collisions calculated by AMD with clusters

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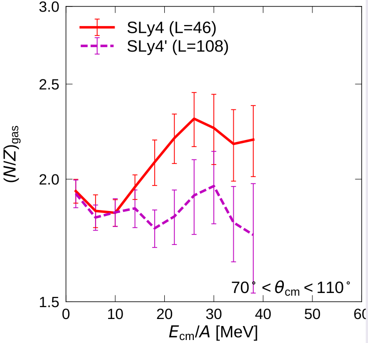
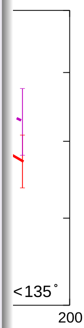
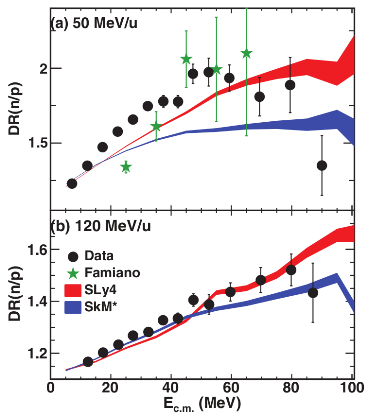


Low density effect

) MeV



ImQMD result



Coupland et al., PRC94(2016)011601(R)

"Probing effective nucleon masses. . . "

Summary

- Recent extensions of AMD
  - Light clusters, produced at NN collisions
  - Correlations between light clusters, to produce light nuclei
  - Momentum fluctuation in Gaussian wave packet
- Fragment size distributions in various collisions can be reproduced reasonably well.
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- The effects are reflected in some observables, such as the π^-/π^+ ratio and the n/p spectral ratio.

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- The effects are reflected in some observables, such as the π^-/π^+ ratio and the n/p spectral ratio.
- TODO: More consistent description of various reactions and observables, such as the energy dependence of stopping observables and the particle spectra.