Cluster production in AMD model

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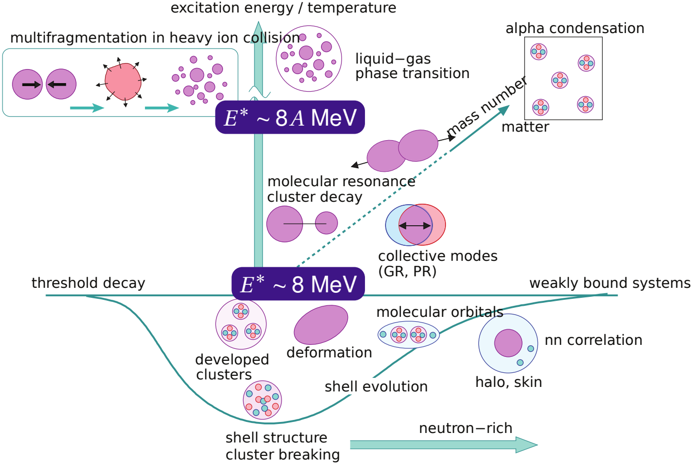
Clustering phenomena in excited states of nuclear systems

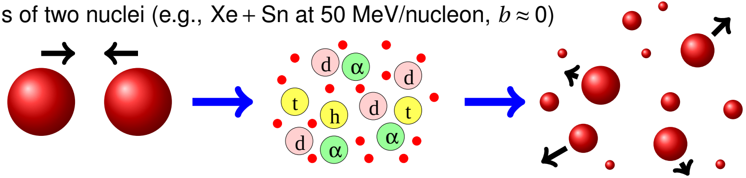
$E^* \sim 80A$ MeV Gas of clusters at higher energies



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, $b \approx 0$)



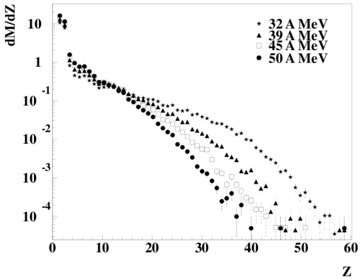
Light-cluster correlations

Partitioning of protons

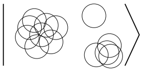
	Xe + Sn 50 MeV/u	Au + Au 250 MeV/u
p	≈10%	21%
α	≈20%	20%
d, t, ^{3}He	≈10%	40%
$A > 4$	≈60%	18%

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

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



Light-cluster correlations may be important at relatively early times.



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

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

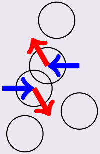
$\{\mathbf{Z}_i, \mathscr{H}\}_{\text{PB}}$: Motion in the mean field

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

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.

Antisymmetrized Molecular Dynamics (very basic version)

Wigner function for the AMD wave function

$$f_\alpha(\mathbf{r},\mathbf{p}) = 8\sum_{i\in\alpha}\sum_{j\in\alpha} e^{-2\nu(\mathbf{r}-\mathbf{R}_{ij})^2} e^{-(\mathbf{p}-\mathbf{P}_{ij})^2/2\hbar^2\nu} B_{ij} B^{-1}_{ji}, \qquad \alpha = p\uparrow, p\downarrow, n\uparrow, n\downarrow$$

$$\mathbf{R}_{ij} = \frac{1}{2\sqrt{\nu}}(\mathbf{Z}_i^* + \mathbf{Z}_j), \quad \mathbf{P}_{ij} = i\hbar\sqrt{\nu}(\mathbf{Z}_i^* - \mathbf{Z}_j), \quad B_{ij} = e^{-\frac{1}{2}(\mathbf{Z}_i^* - \mathbf{Z}_j)^2}$$

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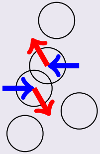


- $|V|^2$ or σ_{NN} (in medium)
- Pauli blocking

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

Zero-range effective interaction

Skyrme force

$$v_{ij} = t_0(1 + x_0 P_\sigma)\delta(\mathbf{r}) + \tfrac{1}{2} t_1(1 + x_1 P_\sigma)[\delta(\mathbf{r})\mathbf{k}^2 + \mathbf{k}^2\delta(\mathbf{r})] \qquad \mathbf{r} = \mathbf{r}_i - \mathbf{r}_j$$

$$+ t_2(1 + x_2 P_\sigma)\mathbf{k}\cdot\delta(\mathbf{r})\mathbf{k} + t_3(1 + x_3 P_\sigma)[\rho(\mathbf{r}_i)]^\alpha \delta(\mathbf{r}) \qquad \mathbf{k} = \tfrac{1}{2\hbar}(\mathbf{p}_i - \mathbf{p}_j)$$

Spacial integration of the potential energy density which is a function of several kind of densities.

$$\langle V\rangle = \int \mathcal{V}\Big(\rho(\mathbf{r}), \tau(\mathbf{r}), \triangle\rho(\mathbf{r}), \mathbf{j}(\mathbf{r})\Big) d\mathbf{r} \qquad \sim A^2 \times \text{Volume}$$

$$\rho_\alpha(\mathbf{r}) = \int f_\alpha(\mathbf{r},\mathbf{p}) \frac{d\mathbf{p}}{(2\pi\hbar)^3} = \left(\tfrac{2\nu}{\pi}\right)^{\frac{3}{2}} \sum_{i\in\alpha}\sum_{j\in\alpha} e^{-2\nu(\mathbf{r}-\mathbf{R}_{ij})^2} B_{ij}B^{-1}_{ji}, \qquad \mathbf{R}_{ij} = \frac{1}{2\sqrt{\nu}}(\mathbf{Z}_i^* + \mathbf{Z}_j)$$

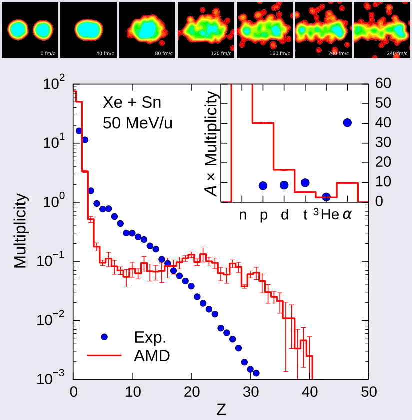
$$\mathbf{j}_\alpha(\mathbf{r}) = \int \frac{\mathbf{p}}{M} f_\alpha(\mathbf{r},\mathbf{p}) \frac{d\mathbf{p}}{(2\pi\hbar)^3} = \left(\tfrac{2\nu}{\pi}\right)^{\frac{3}{2}} \sum_{i\in\alpha}\sum_{j\in\alpha} \frac{\mathbf{P}_{ij}}{M} e^{-2\nu(\mathbf{r}-\mathbf{R}_{ij})^2} B_{ij}B^{-1}_{ji}, \qquad \mathbf{P}_{ij} = i\hbar\sqrt{\nu}(\mathbf{Z}_i^* - \mathbf{Z}_j)$$

$$\tau_\alpha(\mathbf{r}) = \int \frac{\mathbf{p}^2}{M^2} f_\alpha(\mathbf{r},\mathbf{p}) \frac{d\mathbf{p}}{(2\pi\hbar)^3} = \left(\tfrac{2\nu}{\pi}\right)^{\frac{3}{2}} \sum_{i\in\alpha}\sum_{j\in\alpha} \frac{\mathbf{P}_{ij}^2 + 3\hbar^2\nu}{M^2} e^{-2\nu(\mathbf{r}-\mathbf{R}_{ij})^2} B_{ij}B^{-1}_{ji}$$

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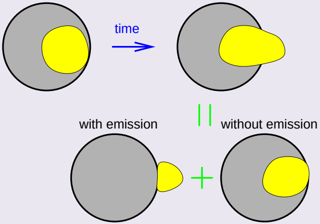
INDRA data, Hudan et al., PRC67 (2003) 064613.

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

Two directions of extension of AMD



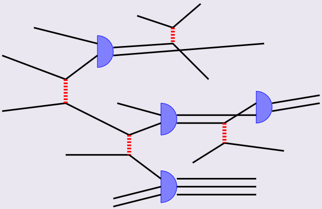
Wave-packet splitting: Give fluctuation to each wave packet centroid, based on the **single-particle motion**.

$$\frac{d}{dt}Z = \{Z, \mathscr{H}\}_{\mathrm{PB}} + \text{(NN Collision)}$$

$$+ \text{(W.P. Splitting)} + \text{(E. Conservation)}$$

Ono, Hudan, Chibihi, Frankland, PRC66 (2002) 014603

Ono and Horiuchi, PPNP53 (2004) 501



At each two-nucleon collision, **cluster formation** is considered for the final state.

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

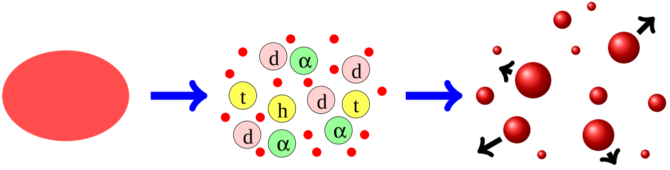
$$W_{i\to f} = \frac{2\pi}{\hbar}|\langle \mathrm{CC}|V_{NN}|\mathrm{NBNB}\rangle|^2\delta(\mathscr{H} - E)$$

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

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

Interacting and reacting clusters in heavy-ion collisions

- The system may be composed of many clusters.
- Clusters are not only created but also broken by reactions.



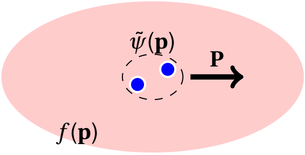
Transport models with clusters

+decay

I want a transport model which can describe the dynamics for a sufficiently long time (e.g., $t \sim 1000$ fm/c).

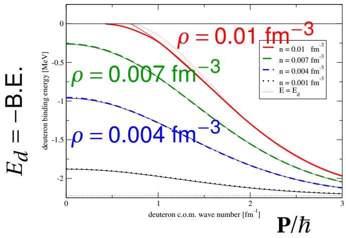
The decays of the excited fragments at the end of the dynamical calculation are calculated by a statistical decay code.

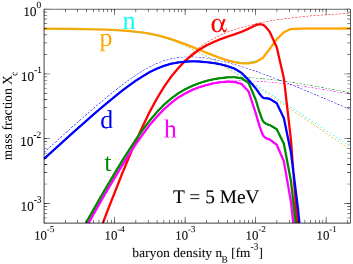
- $n+p+X \leftrightarrow d+X'$
- $d+n+X \leftrightarrow t+X'$
- $d+p+X \leftrightarrow h+X'$
- $t+p+X \leftrightarrow \alpha+X'$
- $h+n+X \leftrightarrow \alpha+X'$
- $d+d+X \leftrightarrow \alpha+X'$
- $2n+p+X \leftrightarrow t+X'$
- $n+2p+X \leftrightarrow h+X'$
- $d+n+p+X \leftrightarrow \alpha+X'$
- $2n+2p+X \leftrightarrow \alpha+X'$
- $d+d \leftrightarrow p+t$
- $d+d \leftrightarrow n+h$
- $p+t \leftrightarrow n+h$
- $d+t \leftrightarrow n+\alpha$
- $d+h \leftrightarrow p+\alpha$
- $d+t \leftrightarrow 2n+h$
- $d+h \leftrightarrow 2p+t$
- $d+\alpha \leftrightarrow t+h$



Equation for a deuteron in uncorrelated medium

$$
\Big[e(\tfrac{1}{2}\mathbf{P}+\mathbf{p})+e(\tfrac{1}{2}\mathbf{P}-\mathbf{p})\Big]\tilde{\psi}(\mathbf{p})
$$
$$
+\Big[1-f(\tfrac{1}{2}\mathbf{P}+\mathbf{p})-f(\tfrac{1}{2}\mathbf{P}-\mathbf{p})\Big]\int\frac{d\mathbf{p}'}{(2\pi)^3}\langle\mathbf{p}|v|\mathbf{p}'\rangle\tilde{\psi}(\mathbf{p}')
$$
$$
=E\tilde{\psi}(\mathbf{p})
$$





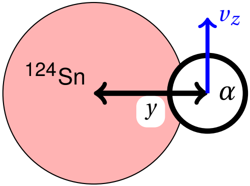
Momentum ($\mathbf{P}$) dependence of B.E.

Röpke, NPA867 (2011) 66.

QS for symmetric nuclear matter

Röpke, PRC 92 (2015) 054001.

A cluster put into a nucleus in AMD



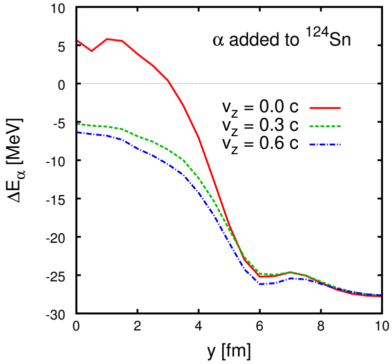
α cluster $|\alpha,\mathbf{Z}\rangle$: Four wave packets with different spins and isospins at the same phase space point $\mathbf{Z}$.

$$E_\alpha : \quad \mathscr{A}\, |\alpha,\mathbf{Z}\rangle|^{124}\mathrm{Sn}\rangle$$

$$E_\mathrm{N} : \quad \mathscr{A}\, |\mathbf{Z}\rangle|^{124}\mathrm{Sn}\rangle \quad (\mathrm{N} = p\uparrow, p\downarrow, n\uparrow, n\downarrow)$$

$$-B_\alpha = \Delta E_\alpha = E_\alpha - (E_{p\uparrow} + E_{p\downarrow} + E_{n\uparrow} + E_{n\downarrow})$$

(Energies are defined relative to $|^{124}\mathrm{Sn}\rangle$.)



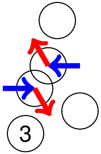
$$\frac{\mathrm{Re}\,\mathbf{Z}}{\sqrt{\nu}} = (0, y, 0), \quad \frac{2\hbar\sqrt{\nu}\,\mathrm{Im}\,\mathbf{Z}}{M} = (0, 0, v_z)$$

- Distance from the center: y
  $\approx$ Dependence on density
- Dendence on $P_\alpha = M_\alpha v_z$
- Due to the density dependence of the Skyrme force, the interaction between nucleons in the α cluster is weakened in the nucleus.

Energy is OK, but dynamics is . . .

NN collisions without or with cluster correlations

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

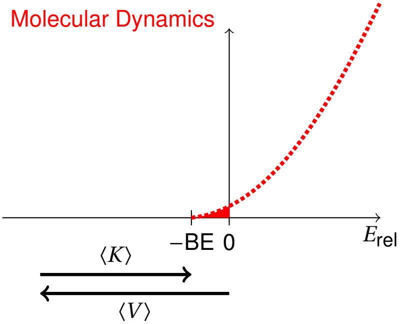


In the usual way of NN collision, only the two wave packets are changed.

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

(ignoring antisymmetrization for simplicity of presentation.)

Phase space or the density of states for two nucleon system



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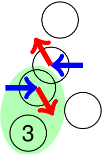

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$$\{|\Psi_f\rangle\} = \{|\varphi_{k_1}(1)\varphi_{k_2}(2)\Psi(3,4,\ldots)\rangle\}$$

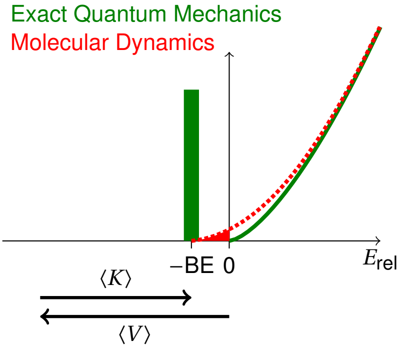
(ignoring antisymmetrization for simplicity of presentation.)

Extension for cluster correlations

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

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

Phase space or the density of states for two nucleon system

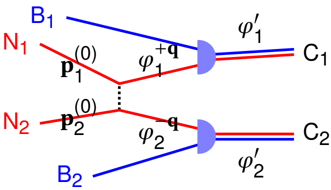


NN collisions with cluster correlations

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

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

- N_1, N_2 : Colliding nucleons
- B_1, B_2 : Spectator nucleons/clusters
- C_1, C_2 : N, $(2N)$, $(3N)$, $(4N)$ (up to α cluster)



Transition probability

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

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

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

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

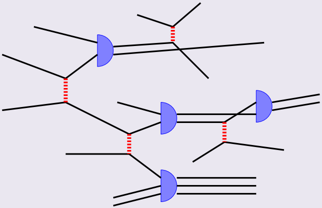
$$\varphi_1^{+\mathbf{q}} = \exp(+i\mathbf{q}\cdot\mathbf{r}_{\mathrm{N}_1})\varphi_1^{(0)}$$

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

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

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

NN collisions with cluster correlations (more explanations)



For each NN collision, cluster formation is considered.

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

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

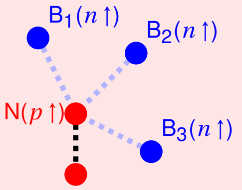
Ono, J. Phys. Conf. Ser. 420 (2013) 012103

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. But the cluster formation may be artificially weakened (nnchange_gamma).
- There are many possibilities to from clusters in the final states. Non-orthogonality of the final states should be carefully handled.

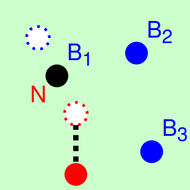
Construction of Final States

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



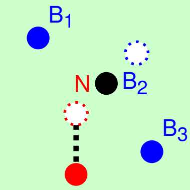
$|\Phi^{\mathbf{q}}\rangle$

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



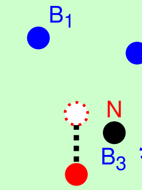
$|\Phi'_1\rangle$

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



$|\Phi'_2\rangle$

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



$|\Phi'_3\rangle$

$\mathrm{N} + \mathrm{B}_3 \to \mathrm{C}$

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:

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

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

An algorithm to decide cluster formation

decide to do a collision based on $(d\sigma/d\Omega)_{\mathrm{NN}}$

C = N

do for species in $p\uparrow$, $p\downarrow$, $n\uparrow$, $n\downarrow$ (in a random order)

P = probability that C forms a cluster with a nucleon of species

- taking care of the non-orthogonality
- taking care of the p_{rel}-dependence of the phase space factors and the overlap probabilities

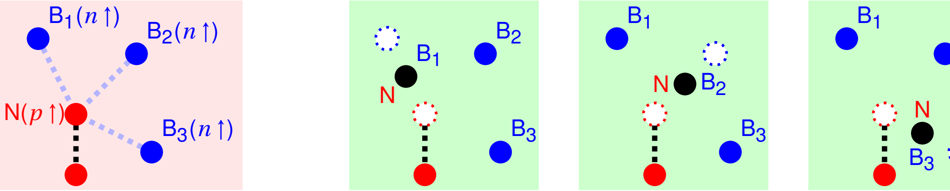
if rand() $< P$ then

choose a nucleon B of species

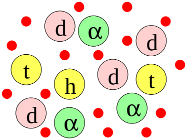
C = C + B ! put the wave packets at the same phase space point

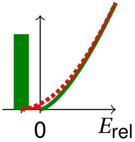
endif

enddo



Correlations to bind several clusters

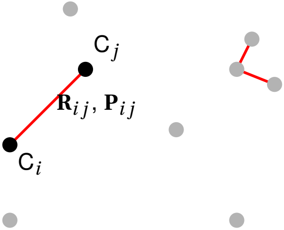




Clusters may form a loosely bound state.

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

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



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

- if C_i is one of the 3 clusters closest to C_j, and $(i \leftrightarrow j)$,
- and if the distance is 1 fm $< |\mathbf{R}_{ij}| < 7$ fm,
- and if they are slowly moving away, $\mathbf{P}_{ij}^2/2\mu_{ij} <$ 10 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 $6 \le A \le 9$ or $19 \le A \le 23$.

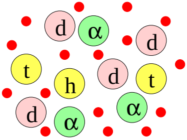
Step 3 *Transition* of the internal state of CC by eliminating the (radial component of) internal momentum

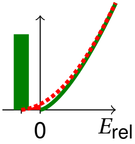
$$\mathbf{P}_i \to 0 \quad \text{for } i \in \text{CC in the c.m. of CC}$$

with some care of the momentum conservation.

Next *Energy conservation*.

Correlations to bind several clusters

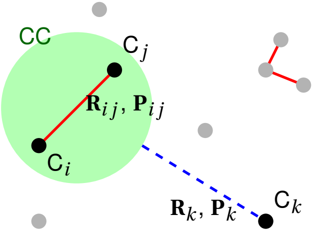




Clusters may form a loosely bound state.

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

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



Step 4 Search a third particle for E-conservation

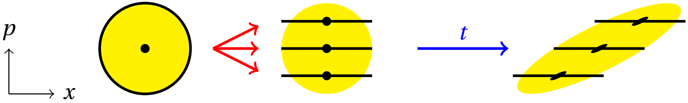
- A cluster C_k is selected, depending on the distance and momentum ($|\mathbf{R}_k|$ and $|\mathbf{P}_k|$) relative to CC.
- If the selected C_k already belongs to a CC′, this whole CC′ is treated as the third particle for E-conservation.

Step 5 Scale the radial component of the relative momentum between CC and C_k for the total energy conservation.

$$\mathbf{P}_k = \mathbf{P}_{k\parallel} + \mathbf{P}_{k\perp} \to \beta \mathbf{P}_{k\parallel} + \mathbf{P}_{k\perp}$$

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.



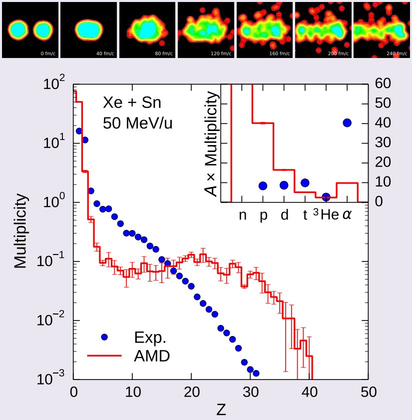
$f(p) = Ne^{-(p-P)^2/2\Delta p^2}$ $\qquad$ $p = P + \Delta p$

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].

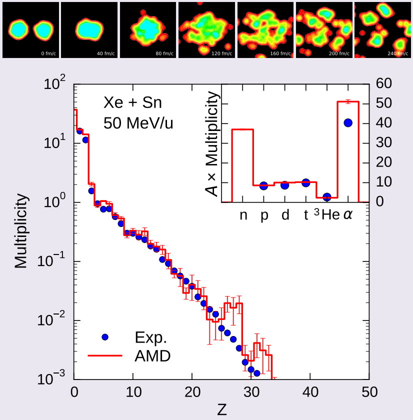
- For a formed cluster, the momentum fluctuation is given to its center-of-mass motion.
- Total momentum and energy conservation.
- A particle is regarded as **'emitted'** when there is no other particles around it in phase space within the radius $(\Delta r, \Delta v) = (3.5\ \mathrm{fm}, 0.25c)$.
-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

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

Without clusters

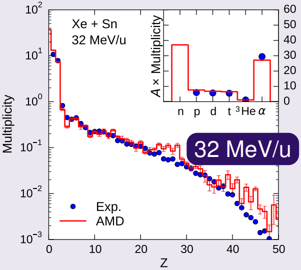


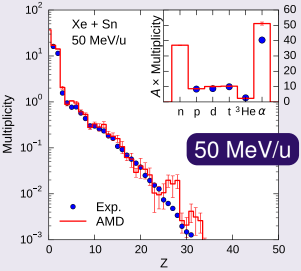
With clusters



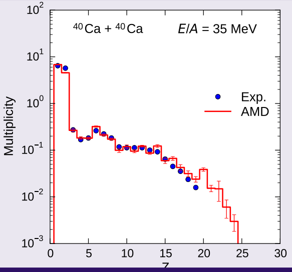
Results for multifragmentation in central collisions

Xe + Sn

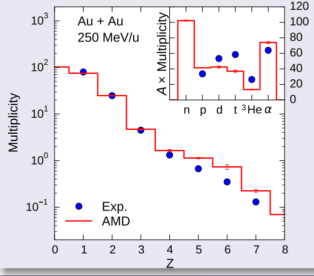




Ca + Ca at 35 MeV/u



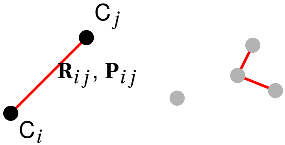
Au + Au at 250 MeV/u



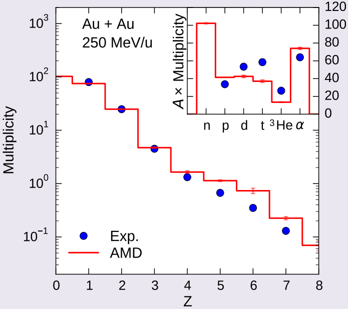
Data:
Hudan et al., PRC 67 (2003) 064613.
Hagel et al., PRC 50 (1994) 2017.
Reisdorf et al., NPA 848 (2010) 366.

Changes:

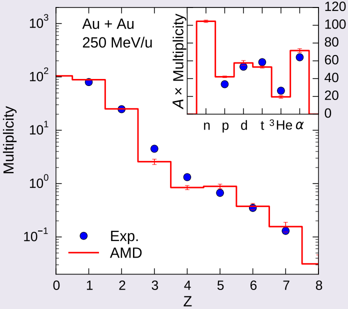
- Link two clusters only if at least one of them is α.
- Don't produce α clusters at high densities $\rho > \rho_0$.



Old

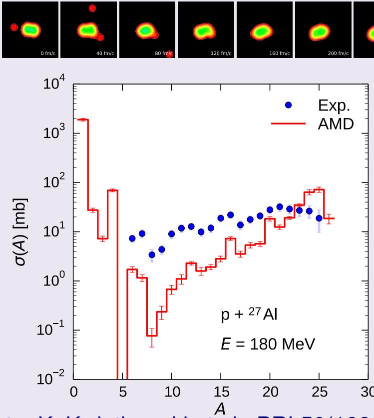


New

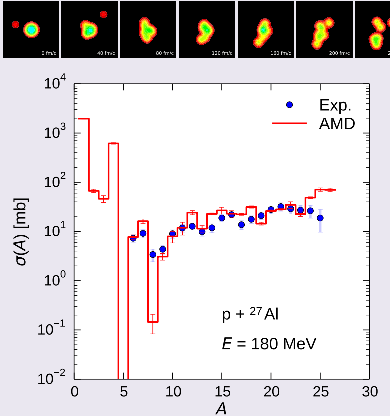


Effect of cluster correlations: $p + \mathrm{Al}$ at 180 MeV

Without clusters



With clusters



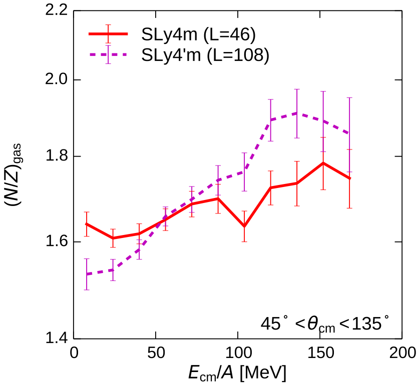
Data: K. Kwiatkowski et al., PRL50(1983)1648.

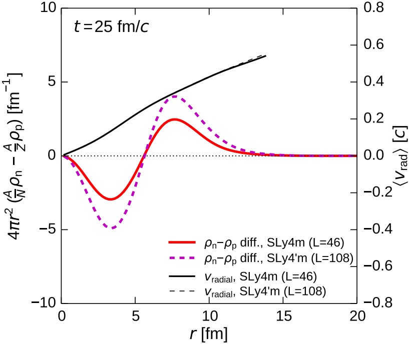
The result is sensitive to the inmedium two-nucleon cross sections.

$$\sigma_{\mathrm{NN}} = \sigma_0 \tanh(\sigma_{\mathrm{free}}/\sigma_0), \quad \sigma_0 = y\rho^{-2/3}, \quad y = 4.$$

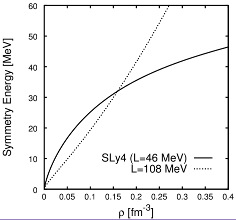
c.f. Coupland et al., PRC84(2011)054603

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



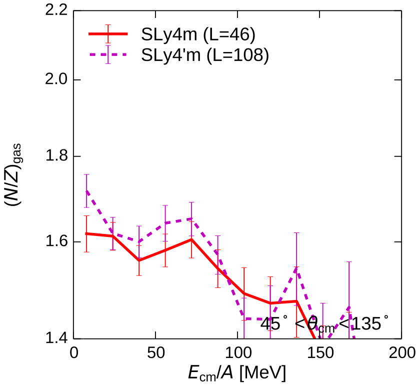


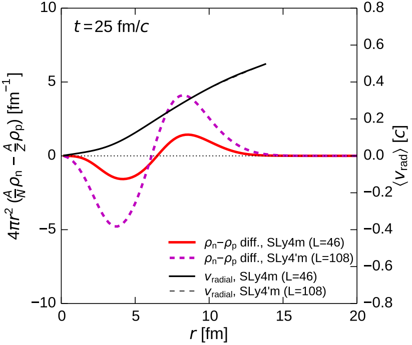
$$\left(\frac{N}{Z}\right)_{\rm gas} = \frac{Y_n(v) + Y_d(v) + 2Y_t(v) + Y_h(v) + 2Y_\alpha(v)}{Y_p(v) + Y_d(v) + Y_t(v) + 2Y_h(v) + 2Y_\alpha(v)}$$



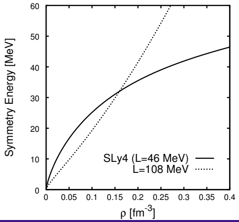
N/Z of spectrum of emitted particles is similar to the neutron-proton density difference at the compression stage.

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



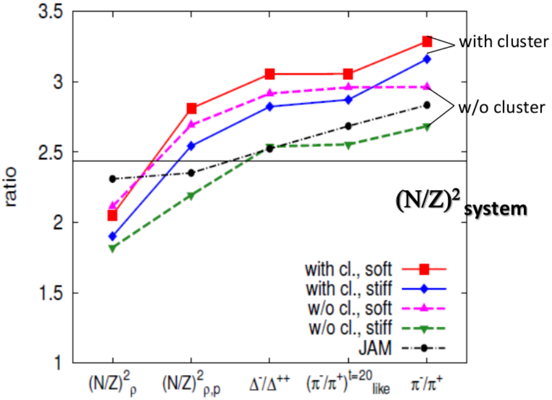


$$\left(\frac{N}{Z}\right)_{\text{gas}} = \frac{Y_n(v) + Y_d(v) + 2Y_t(v) + Y_h(v) + 2Y_\alpha(v)}{Y_p(v) + Y_d(v) + Y_t(v) + 2Y_h(v) + 2Y_\alpha(v)}$$



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

Ikeno's talk; Ikeno, Ono, Nara, Ohnishi, PRC 93 (2016) 044612



Summary

Recent developments of AMD

- Cluster correlations in the final states of NN collisions
- Binding of several clusters (production of Li, Be,. . .)
- Treatment of the wave-packet momentum width
- Test particles sampled from $f(\mathbf{r},\mathbf{p})$ of AMD
  - Comparison with other models
  - Combining with another model (pion production)
  - Improvement of NN collision procedure