核破砕反応・シミュレーション計算

小野章

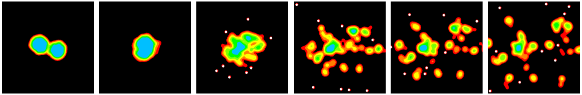
東北大・理

理研ミニワークショップ「核データと核理論」2009 年 3 月 25–26 日

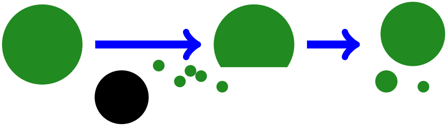
- 種々の破砕反応の微視的・動力学的記述
    - 重イオン衝突（中心衝突）
    - 入射核破砕反応
    - 核子入射
- AMD の最近の進展
    - 計算の高速化（Skyrme 力）
    - クラスター相関
    - 熱化学平衡の記述

様々な破砕反応

- 重イオン衝突（中心衝突）



- 入射核破砕反応



- 核子入射反応での破砕片生成

核物質の動的過程

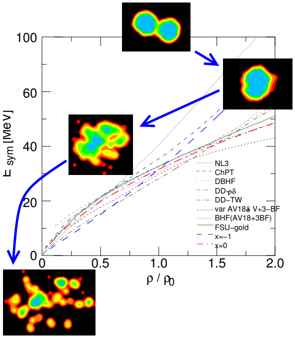
- 平均場・状態方程式
- フロー・膨張
- 液相気相相転移

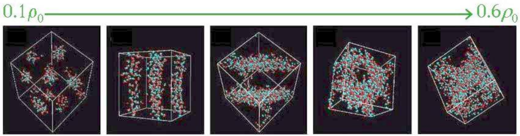
$\Updownarrow$

カスケード＋統計計算　(?)

応用上重要

Nuclear Matter in Nuclear Collisions and Neutron Stars



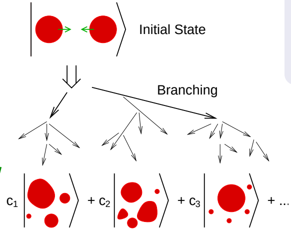


QMD simulation of nuclear pasta. G. Watanabe et al.

- Inhomogeneous. (fragments, clusters, pasta)
- Excited. (finite temperature and/or dynamic)
- Liquid-gas phase transition.

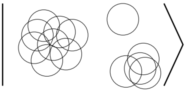
- Statistical calculations with AMD for finite systems
  ⇒ Relevance of equilibrium in nuclear collisions (Furuta, Ono)
- Extension of AMD for cluster correlations (Ono)
- AMD study of neutron star (Hasnaoui, Ono, Furuta, Gulminelli, Chomaz)
  - Implementation of Skyrme force in AMD
- Isospin effects etc in heavy-ion collisions

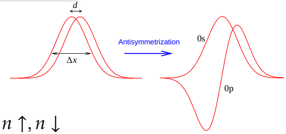
Antisymmetrized Molecular Dynamics



AMD wave function

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





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

ν : Width parameter = $(2.5\text{ fm})^{-2}$

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

Stochastic equation of motion for the wave packet centroids Z:

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

- Mean field (Time evolution of single-particle wave functions)
- Nucleon-nucleon collisions (as the residual interaction)

Energy is conserved. No temperature in the equation.

Quantum effects are included.

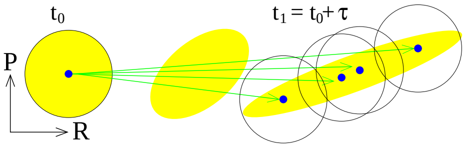
Mean field + Qauntum branching

At each time t_0, for each wave packet k, . . .

Mean field propagation $t_0 \to t_0 + \tau$ + **Branching at $t_0 + \tau$** τ: Coherence time

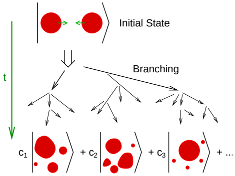
$t = t_0$ $t = t_0 + \tau$

$$|\mathbf{Z}_k\rangle\langle\mathbf{Z}_k| \xrightarrow[\text{Mean field}]{} |\psi_k\rangle\langle\psi_k| \xrightarrow[\text{Branching}]{} \int |\mathbf{z}\rangle\langle\mathbf{z}|\, w_k(\mathbf{z})d\mathbf{z} \qquad \text{for } k = 1, \ldots, A$$



$$i\hbar\frac{d}{dt}|\psi_k(t)\rangle = h^{\mathrm{HF}}|\psi_k(t)\rangle \quad \text{or} \quad \frac{\partial f_k}{\partial t} = -\frac{\partial h^{\mathrm{HF}}}{\partial \mathbf{p}}\cdot\frac{\partial f_k}{\partial \mathbf{r}} + \frac{\partial h^{\mathrm{HF}}}{\partial \mathbf{r}}\cdot\frac{\partial f_k}{\partial \mathbf{p}}$$

- $\tau \to 0$ (Strongest branching)
- $\tau = \tau(\rho)$ (Density-dependent)
- $\tau = \tau_{\text{NN-coll}}$ (Decoherence at NN collisions)



AMD and FMD with Skyrme force

So far AMD calculations are done with the Gogny force.

$$v_{ij} = \sum_{k=1,2} (W_k + B_k P_\sigma - H_k P_\tau - M_k P_\sigma P_\tau) e^{-(\mathbf{r}_i-\mathbf{r}_j)^2/a_k^2} + \ t_\rho (1 + P_\sigma) \rho(\mathbf{r}_i)^\sigma \delta(\mathbf{r}_i - \mathbf{r}_j)$$

$$\langle V \rangle = \frac{1}{2} \sum_{i=1}^{A} \sum_{j=1}^{A} \sum_{k=1}^{A} \sum_{l=1}^{A} \langle ij|v|kl - lk \rangle B_{ki}^{-1} B_{lj}^{-1} \qquad \sim A^4$$

Skyrme can be flexible and faster.

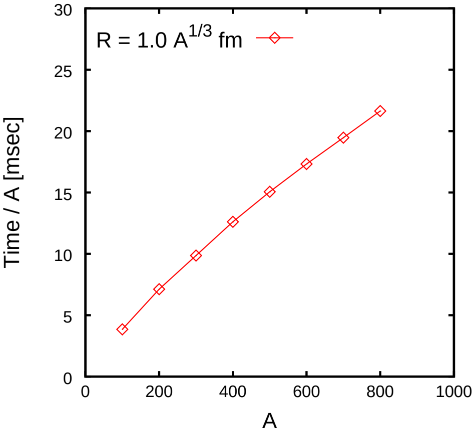
⇒ Applications to heavy systems and stellar matter

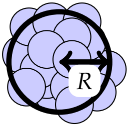
$$\langle V \rangle = \int \mathcal{V}\Big(\rho(\mathbf{r}), \tau(\mathbf{r}), \triangle\rho(\mathbf{r}), \mathbf{j}(\mathbf{r})\Big) d\mathbf{r} \qquad \sim A^2 V \quad (+\epsilon A^3)$$

$$\rho(\mathbf{r}) = \left(\frac{2\nu}{\pi}\right)^{3/2} \sum_{i=1}^{A} \sum_{j=1}^{A} e^{-2\nu(\mathbf{r}-\mathbf{R}_{ij})^2} B_{ij} B_{ji}^{-1}, \qquad \mathbf{R}_{ij} = \frac{1}{2\sqrt{\nu}} (\mathbf{Z}_i^* + \mathbf{Z}_j)$$

重い系に使えるか？

System size dependence of the CPU time for an evaluation of $\left\{ \frac{\partial}{\partial \mathbf{Z}_k^*}\langle V\rangle;\ k = 1, 2, \ldots A \right\}$





$\Leftrightarrow$ Naive expectation $\sim A^2V$

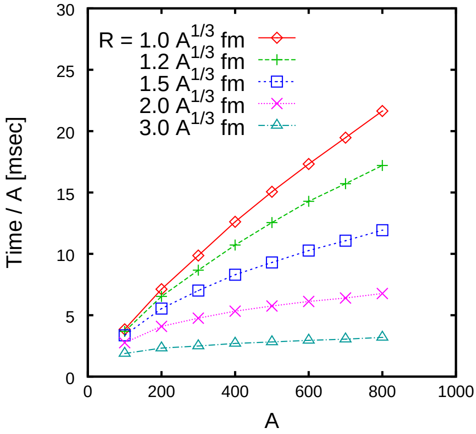
$$\langle V\rangle = \int d\mathbf{r}\,\mathcal{V}\Big(\rho(\mathbf{r}), \tau(\mathbf{r}), \triangle\rho(\mathbf{r}), \mathbf{j}(\mathbf{r})\Big)$$

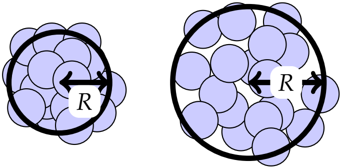
$$\rho(\mathbf{r}) = \left(\frac{2\nu}{\pi}\right)^{3/2} \sum_{i=1}^{A}\sum_{j=1}^{A} e^{-(\mathbf{r}-\mathbf{R}_{ij})^2} B_{ij} B_{ji}^{-1}$$

- Mesh size $\Delta r = 0.75$ fm, $Z_\uparrow = Z_\downarrow = N_\uparrow = N_\downarrow$
- Xeon E5430 Harpertown 2.66 GHz, Using 1 of 8 cores, Almost no load by other processes

重い系に使えるか？

System size dependence of the CPU time for an evaluation of $\left\{\frac{\partial}{\partial \mathbf{Z}_k^*}\langle V\rangle;\ k = 1, 2, \ldots A\right\}$





⇔ Naive expectation $\sim A^2 V$

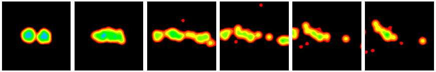
$$\langle V\rangle = \int d\mathbf{r}\ \mathcal{V}\Big(\rho(\mathbf{r}), \tau(\mathbf{r}), \triangle\rho(\mathbf{r}), \mathbf{j}(\mathbf{r})\Big)$$

$$\rho(\mathbf{r}) = \left(\frac{2\nu}{\pi}\right)^{3/2} \sum_{i=1}^{A}\sum_{j=1}^{A} e^{-(\mathbf{r}-\mathbf{R}_{ij})^2} B_{ij} B^{-1}_{ji}$$

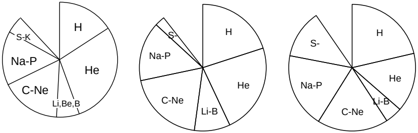
- Mesh size $\Delta r = 0.75$ fm, $\quad Z_\uparrow = Z_\downarrow = N_\uparrow = N_\downarrow$
- Xeon E5430 Harpertown 2.66 GHz, Using 1 of 8 cores, Almost no load by other processes

AMD results for multifragmentation (central collisions)

^{40}Ca + ^{40}Ca at 35 MeV/u, $b = 0$



Experiment AMD AMD



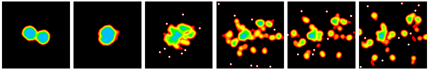
Hagel et al.

PRC50(1994)2017

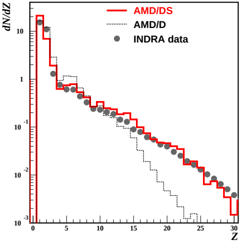
$\tau(\rho)$

$\tau_{\text{NN-coll}}$

Xe + Sn at 50 MeV/u, $0 \le b \le 4$ fm



Charge distribution



- AMD ($\tau \to 0$)
- AMD ($\tau_{\text{NN-coll}}$)

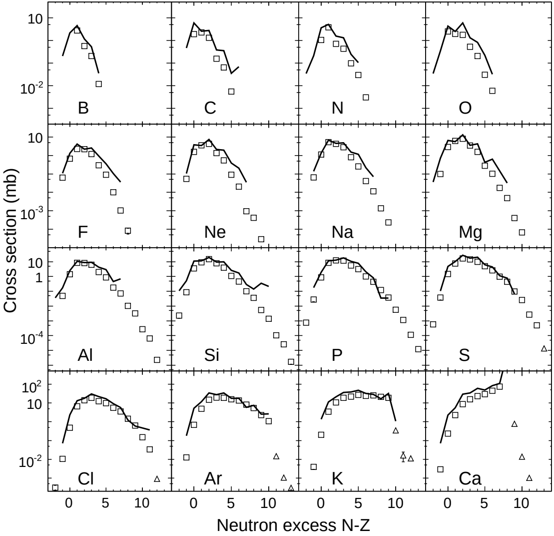
Can we reproduce different data with the same model of branching?

(Cluster correlations?)

Rare isotope production by projectile fragmentation

Mocko, Tsang, AO et al., PRC78(2008)024612.

^{48}Ca + ^{9}Be at 140 MeV/nucleon



AMD（反対称化分子動力学）

核子波束の運動を解くことによる反応のシミュレーション

- **平均場の効果**
- **二核子衝突（確率的）**
- **励起したフラグメントの統計崩壊**

- AMD calc: 17,000 events

  ⇒ 40 CPU · days

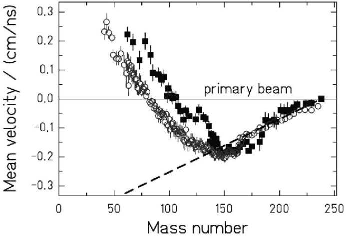
  (HPC Center at MSU)
- Experiment: $\sim 10^7$ events

Experimental data of velocity shift

Ricciardi et al., PRL 90 (2003) 212302.

^{238}U + Pb and ^{238}U + Ti

at 1 GeV/nucleon



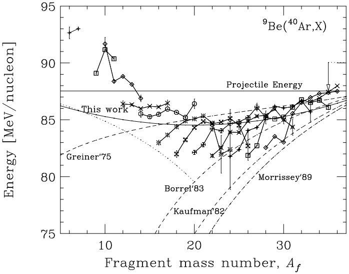
Dashed line: Morrissey systematics

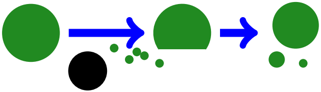
$$\Delta v_{\parallel} \propto \Delta A$$

Notani et al., PRC 76 (2007) 044605.

^{40}Ar + ^{9}Be

about 90A MeV



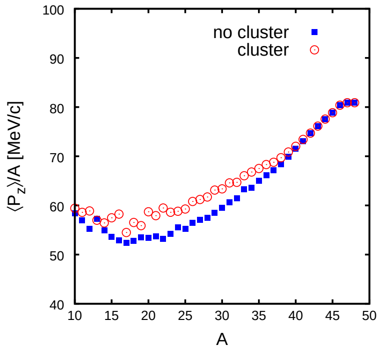


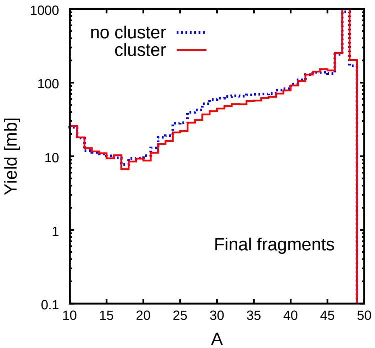
v_{beam}

$\langle v\rangle = v_{\text{beam}} + \Delta v$

Fragment mean velocity and yield

フラグメントの速度（運動量）の平均値　　**フラグメントの質量数分布**



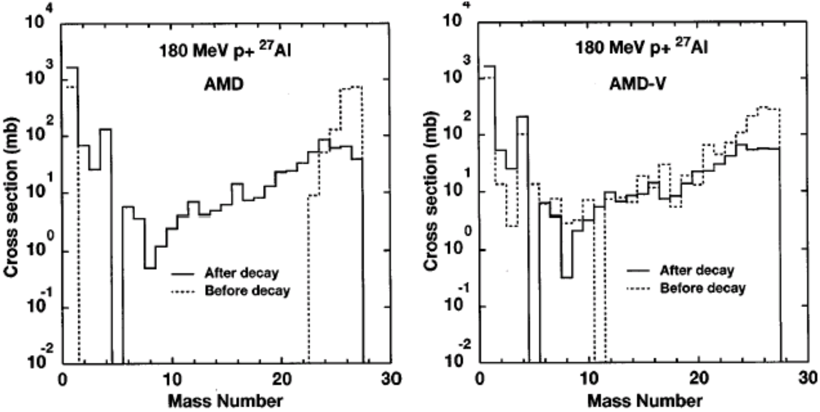


なぜ，フラグメントの速度のピークががビームより速くなり得るのか，計算では説明できていない．

核子による標的核破砕

$p+{}^{27}$Al at 180 MeV　　Y. Tosaka, A. Ono, H. Horiuchi, PRC60 (1999) 064613.

ゆらぎ ΔZ **なし**　　**強力なゆらぎ** ΔZ ($\tau_{\text{coherence}} \to 0$)



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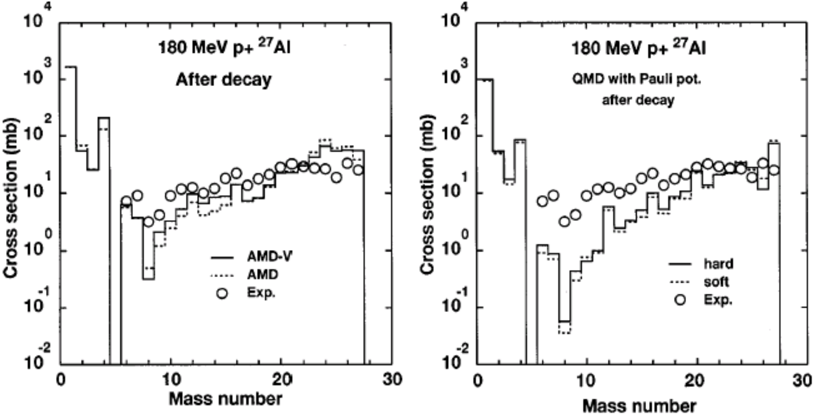
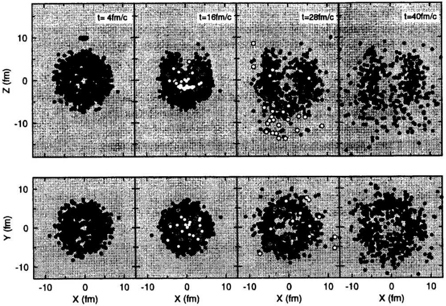


AMD も QMD も $A\sim\frac{1}{2}A_{\text{projectile}}$ のフラグメントを過小評価している.

高エネルギー p, α による標的核破砕

フラグメントの角度分布に側方ピーク



シミュレーション計算の実状：

- α (5 GeV/u) + Au

  Tomoyuki Maruyama et al, PTP 97 (1997) 579.

  ⇒ QMD では，幅の狭い波束を使って，相互作用のレンジを小さくする必要がある．
- p (11.5 GeV) + Au

  Y. Hirata et al, NPA 707 (2002) 193.

  ⇒ 微視的な計算 (JAM/MF) に，パーコレーション模型を組み合わせる必要がある．

少し励起した原子核（膨張が弱い）の崩壊を微視的に記述するのは難しいのか？

Excited low-density system

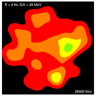
Gas

(nucleons + clusters)

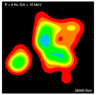
Liquid-gas

phase transition

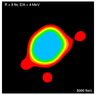
$W(E) \approx e^{2\sqrt{aE^*}}$



$E^* = 28A$ MeV



$E^* = 10A$ MeV



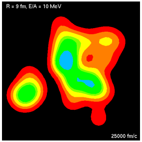
$E^* = 4A$ MeV

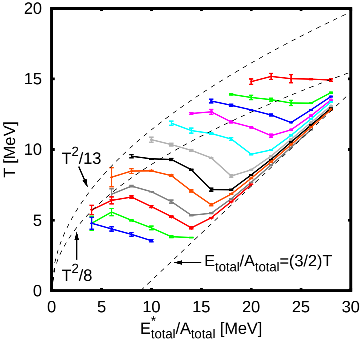
Volume $V = \frac{4}{3}\pi(9\text{ fm})^3$

Equilibrium ensembles and caloric curves

分子動力学は励起した核子多体系（熱平衡）を適切に記述できるのか？

- Ono & Horiuchi
- Ohnishi & Randrup
- Schnack & Feldmeier
- Sugawa & Horiuchi
- Furuta & Ono
- Hasnaoui et al.

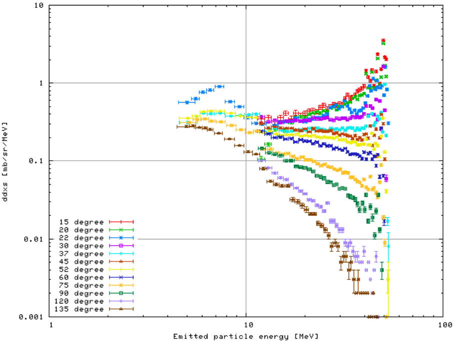




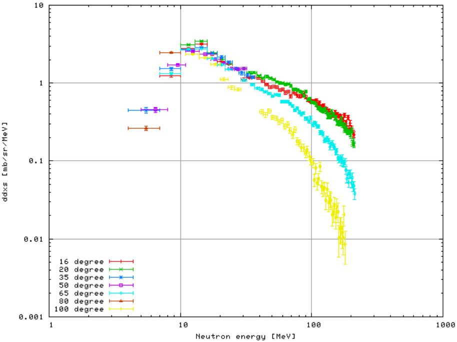
Furuta and Ono,
PRC79 (2009) 014608;
PRC74 (2006) 014612.

Production of light charged particles

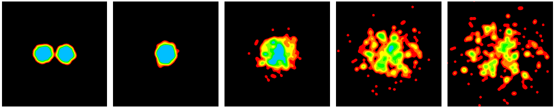
p(62 MeV) + Fe $\rightarrow d$



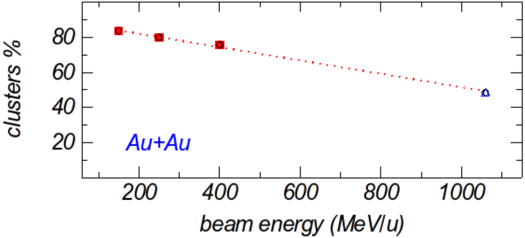
p(1200 MeV) + Au $\rightarrow d$

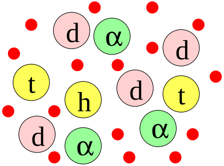


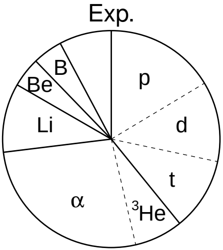
Cluster correlations in heavy-ion collisions

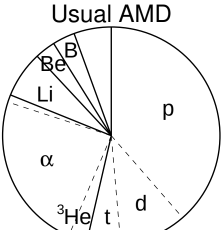


^{197}Au + ^{197}Au at 150 MeV/u





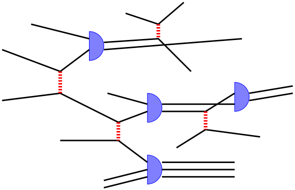




Cluster formation

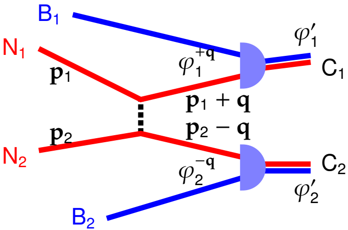
During the time evolution of AMD,

- Cluster formation
- Propagation
- Breakup



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

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

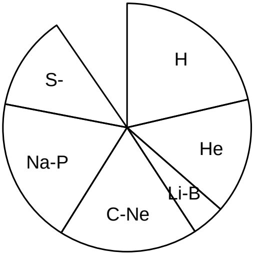


$$\frac{d\sigma}{d\Omega} = F_{\mathrm{kin}} \, |\langle \varphi_1' | \varphi_1^{+\mathbf{q}} \rangle|^2 \, |\langle \varphi_2' | \varphi_2^{-\mathbf{q}} \rangle|^2 \left(\frac{d\sigma}{d\Omega} \right)_{\mathrm{NN}}$$

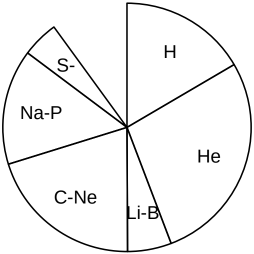
Effects of cluster correlations

^{40}Ca + ^{40}Ca, E/A = 35 MeV, filtered violent collisions

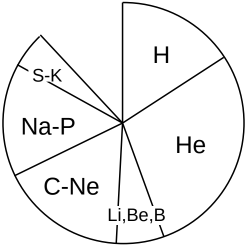
w/o cluster correlations



with cluster correlations



experiment



p	6.7
d	1.5
t	0.3
^{3}He	0.3
α	2.7

p	4.4
d	1.8
t	0.5
^{3}He	0.6
α	5.0

Effects of clusters

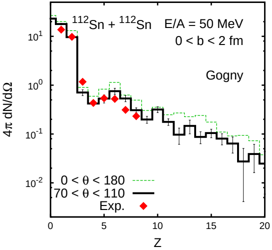
- M_p ↓
- M_α ↑
- $\sum_{\text{IMF}} Z$ ↓

Coherence time: $\tau_{\text{NN-coll}}$

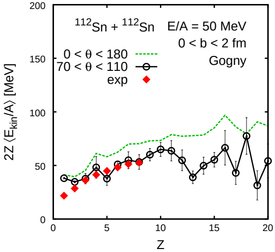
Results for Sn + Sn system

^{112}Sn + ^{112}Sn at E/A = 50 MeV/nucleon, $0 < b < 2$ fm

With cluster correlations $\Sigma Z(70^\circ < \theta < 110^\circ) = 22.6$



n	27.3
p	10.4
d	6.4
t	3.0
^{3}He	1.2
α	12.2



Xe+Sn, INDRA data

p	8.4
d	4.4
t	3.3
^{3}He	0.9
α	10.1

multiplicities of detected particles

まとめ

AMD 計算の最近の進展

- 熱平衡（液相気相相転移）の記述の確認　動力学と熱力学の統一的記述へ
- Skyrme 力の場合の計算の高速化　核物質・中性子星の計算へ
- クラスター相関の導入　粒子ベース ⇔ クラスター相関

破砕反応の微視的記述（AMD）

- 重イオン衝突（中心衝突）での多重破砕　破砕しすぎる傾向
- 入射核破砕反応
- 核子入射による標的核破砕　破砕が足りない傾向