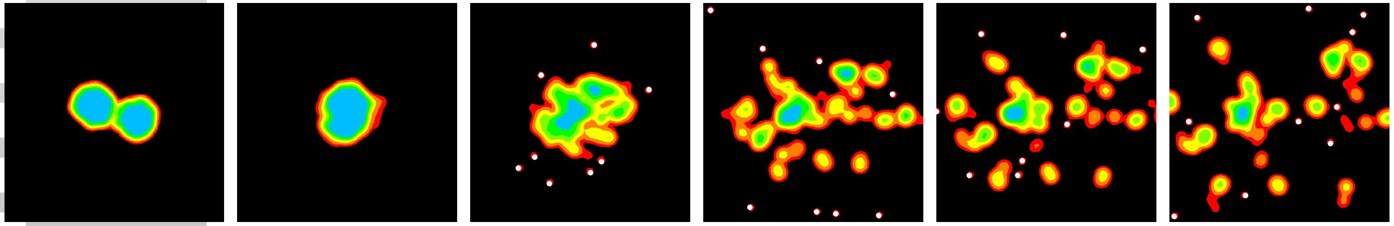
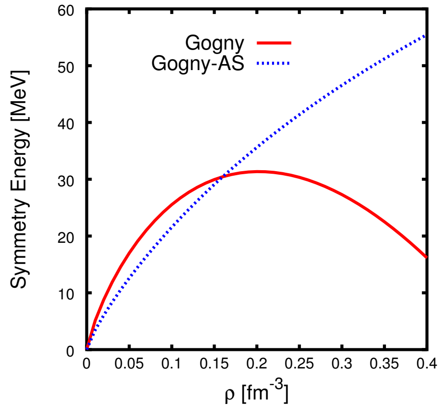
Dynamical aspects of multifragmentation

Akira Ono (Tohoku University)





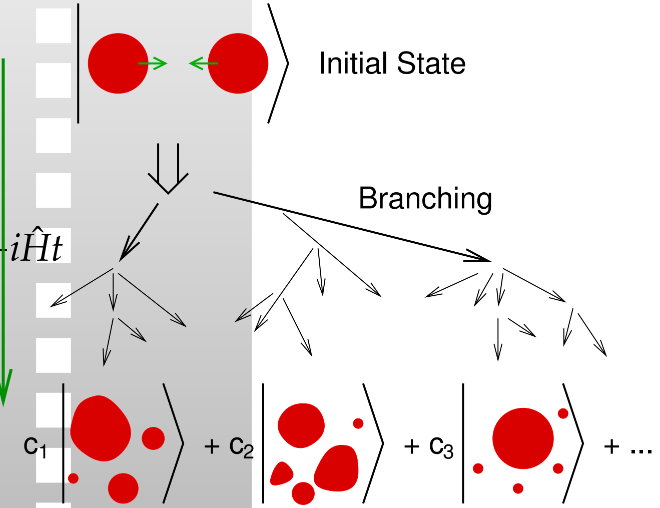
- **Mean field (one-body) effects**
  - How does fragments reflect EOS?
  - Fragmentation mechanism.
- **Cluster (many-body) correlations**
  - Why is the nucleon multiplicity so small?
  - Effects on fragmentation.
- **Statistical aspects** ⇒ Poster by Furuta and Ono

  Equailibrium, L-G phase transition

	Mult.	% of p
p	8.4	8%
d, t, ^{3}He	8.6	9%
α	10.1	19%
$A > 5$	6.6	63%
		100%

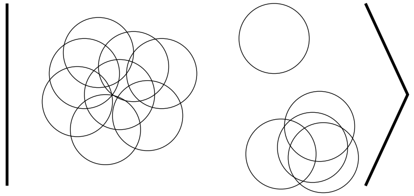
Xe+Sn, 50 MeV/nucleon, INDRA

Antisymmetrized Molecular Dynamics



AMD wave function

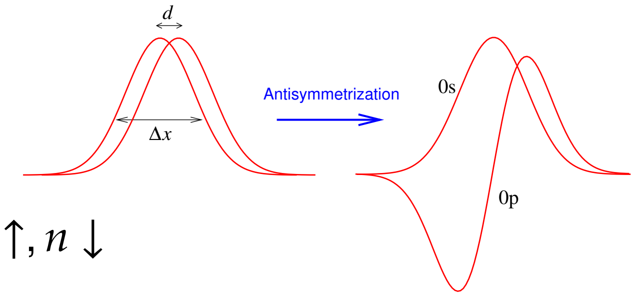
$$|\Phi(Z)\rangle = \det_{ij}\Big[\exp\Big\{-\nu\Big(\mathbf{r}_j - \frac{\mathbf{Z}_i}{\sqrt{\nu}}\Big)^2\Big\}\chi_{\alpha_i}(j)\Big]$$



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

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:

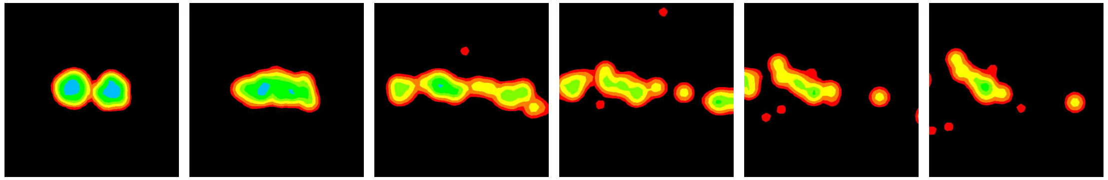
$$\frac{d}{dt}\mathbf{Z}_i = \{\mathbf{Z}_i, \mathcal{H}\}_{\text{PB}} + \Delta\mathbf{Z}_i(t) + (\text{NN collisions})$$

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

Energy is conserved. No temperature in the equation.

Quantum effects are included.

Fragment yields in AMD simulations



AMD simulations for ^{60}Ca + ^{60}Ca, ^{48}Ca + ^{48}Ca, ^{40}Ca + ^{40}Ca

($b = 0$, $E/A = 35$ MeV, $t = 300$ fm/c)

$\boxed{Y_i(N,Z)}$ The yield of fragment nucleus (N,Z) in reaction i

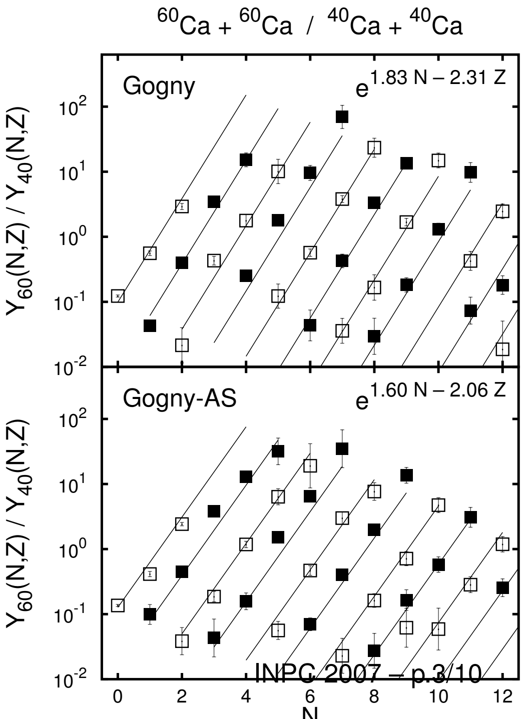
The AMD results are fitted well by

AO et al., PRC68(2003)051601(R); PRC70(2004)041604(R)

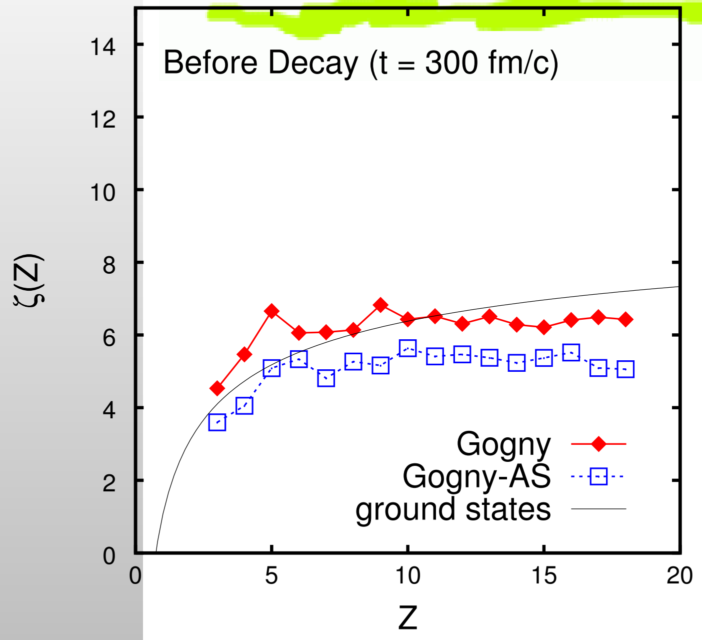
$$Y_i(N,Z) = \exp\Big[-K(N,Z) + \alpha_i N + \beta_i Z\Big]$$

$$K(N,Z) = \xi(Z)N + \eta(Z) + \zeta(Z)\frac{(N-Z)^2}{N+Z}$$

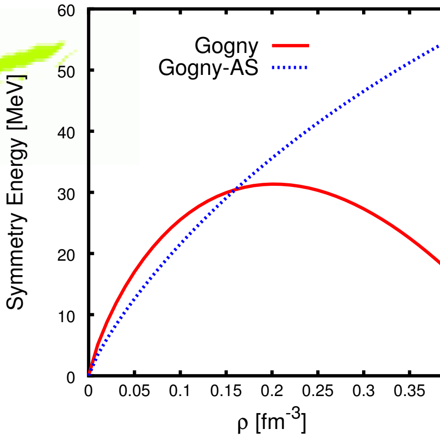
- Isoscaling: $\dfrac{Y_i(N,Z)}{Y_j(N,Z)} = e^{(\alpha_i-\alpha_j)N+(\beta_i-\beta_j)Z}$
- $\alpha_i - \alpha_j = 4\zeta(Z)\times\Big[(Z/\bar{A})_j^2 - (Z/\bar{A})_i^2\Big]$
- $\zeta(Z) \sim \dfrac{C_{\text{sym}}}{T}$ in equilibrium



What can we learn from $\zeta(Z)$?



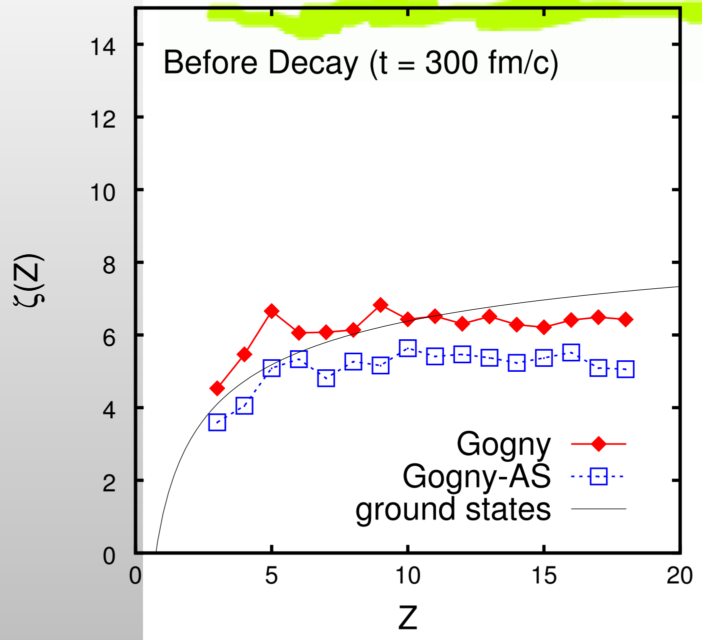
- Dependence on the symmetry energy term (Gogny and Gogny-AS).

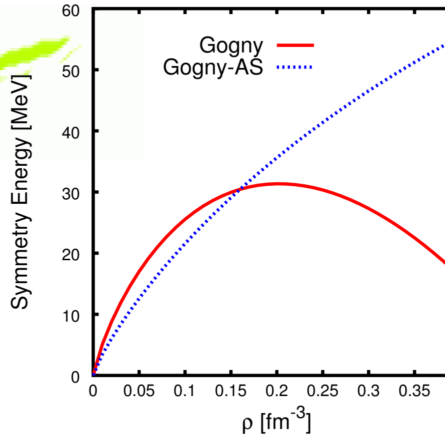


- Z-dependence of $\zeta(Z)$ is very weak compared to the surface symmetry energy term for the ground state nuclei.

$$\Rightarrow \quad \zeta \approx C_{\mathrm{sym}}(\rho \approx \tfrac{1}{2}\rho_0)/T, \quad T \approx 3.4\ \mathrm{MeV}$$

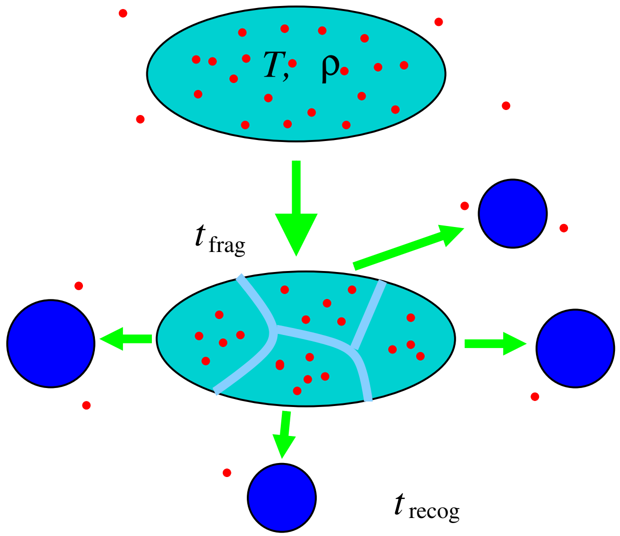
What can we learn from $\zeta(Z)$?



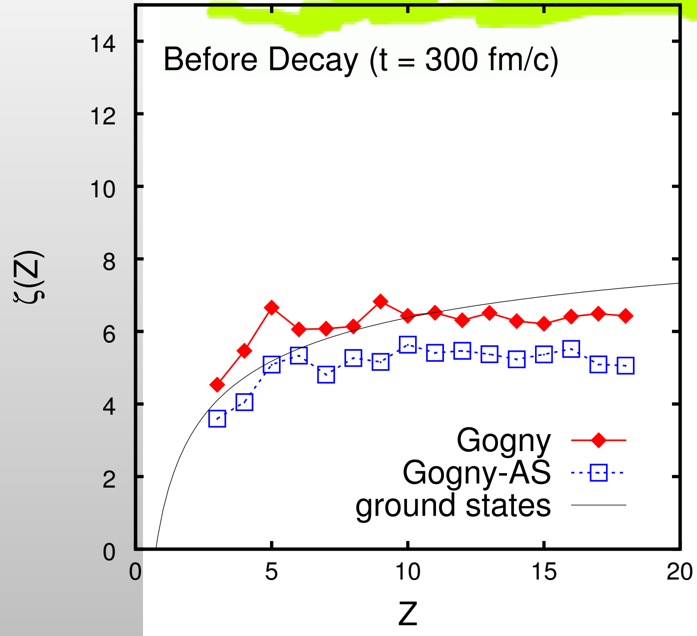


- Dependence on the symmetry energy term (Gogny and Gogny-AS).
- Z-dependence of $\zeta(Z)$ is very weak compared to the surface symmetry energy term for the ground state nuclei.

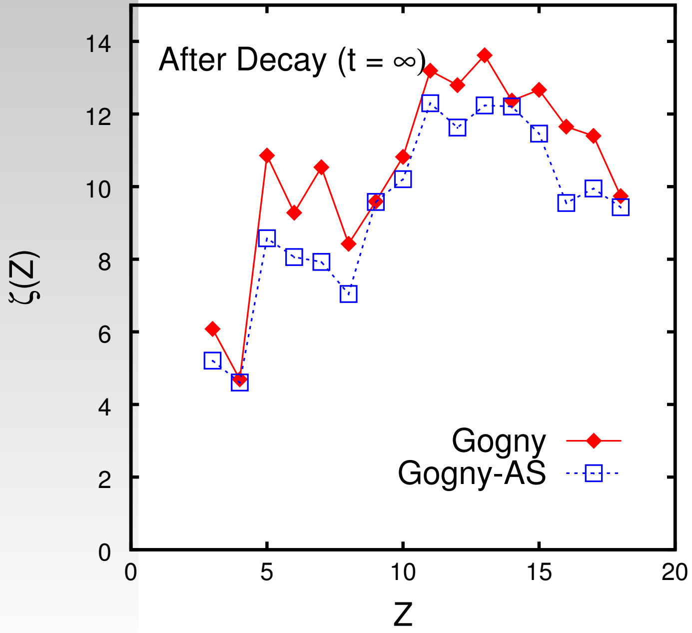
$$\Rightarrow \quad \zeta \approx C_{\mathrm{sym}}(\rho \approx \tfrac{1}{2}\rho_0)/T, \quad T \approx 3.4 \text{ MeV}$$

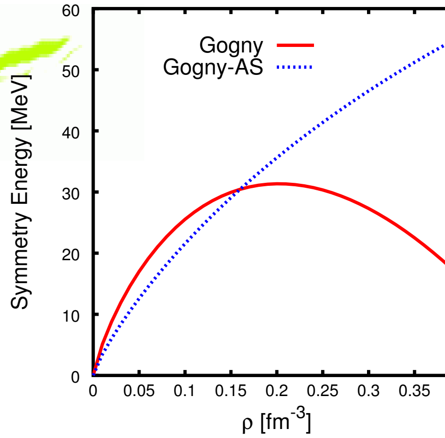


What can we learn from $\zeta(Z)$?



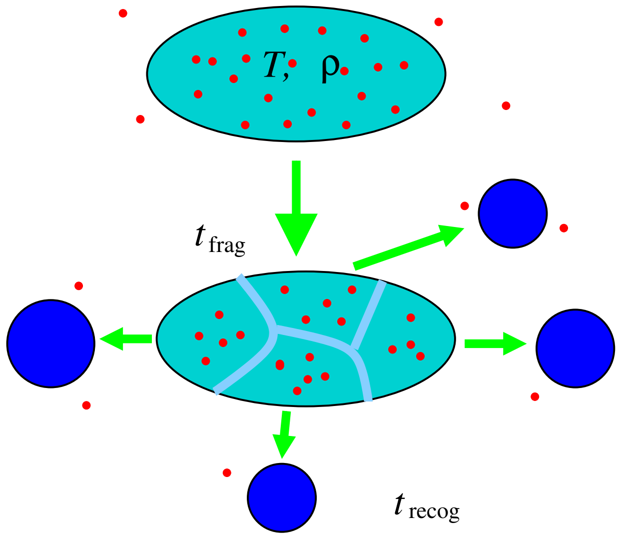
⇓ Statistical decay



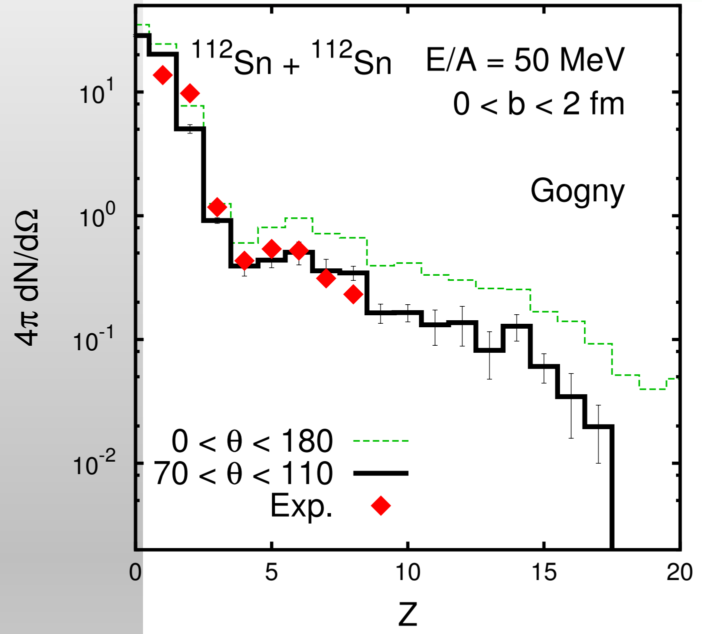


- Dependence on the symmetry energy term (Gogny and Gogny-AS).
- Z-dependence of $\zeta(Z)$ is very weak compared to the surface symmetry energy term for the ground state nuclei.

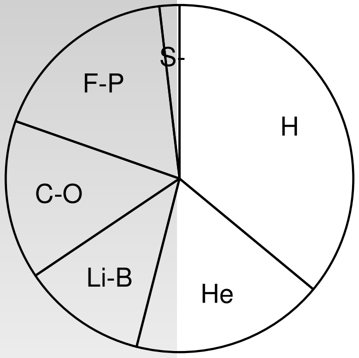
$$\Rightarrow \quad \zeta \approx C_{\mathrm{sym}}(\rho \approx \tfrac{1}{2}\rho_0)/T, \quad T \approx 3.4 \text{ MeV}$$



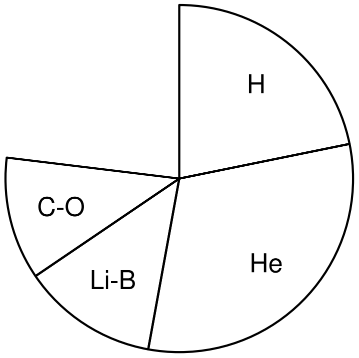
The problem of too large proton multiplicity



Exp.: MSU data ($70^\circ \lesssim \theta_{\rm cm} \lesssim 110^\circ$)



AMD (70°–110°)



Exp.
(Arbitrary normalization)

^{112}Sn + ^{112}Sn at 50 MeV/nucleon, $b \sim 0$

- Gogny Force
- NN cross sections

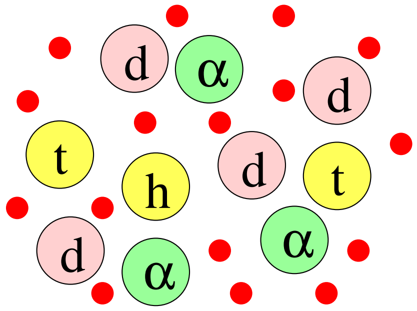
  $\sigma_{NN} = \min\left(\sigma_{NN}^{\rm free}(E_{NN}),\ 150\ {\rm mb}\right) \times 0.5$

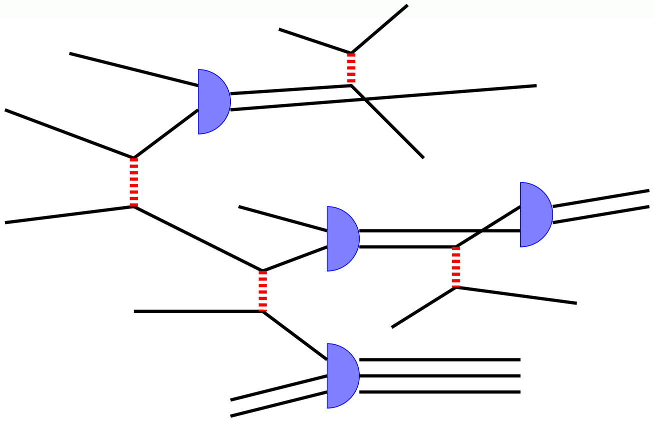
  - Emission to transverse directions
  - Number of emitted nucleons

	AMD (0°–180°)	Exp.
p	(14) 18%	8%
d,t,h	(6) 7%	9%
α	(5) 14%	19%
$A \geq 5$	(75) 61%	63%

(at $t = 600$ fm/c)
Exp.: Xe+Sn, INDRA data

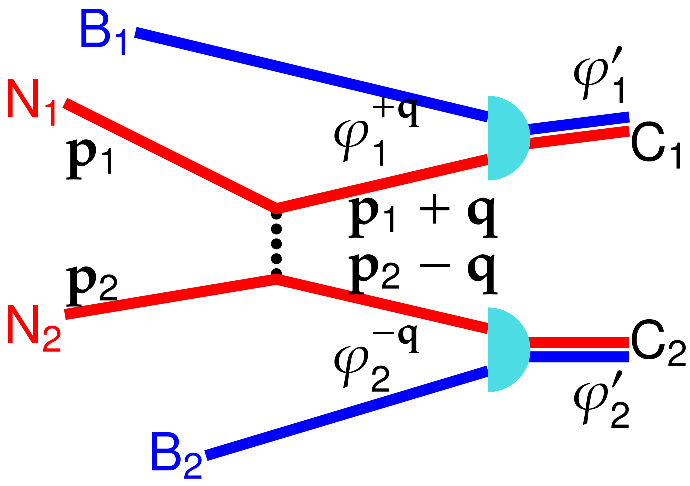
Cluster formation cross sections





$$N_1 + B_1 + N_2 + B_2 \rightarrow C_1 + C_2$$

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



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

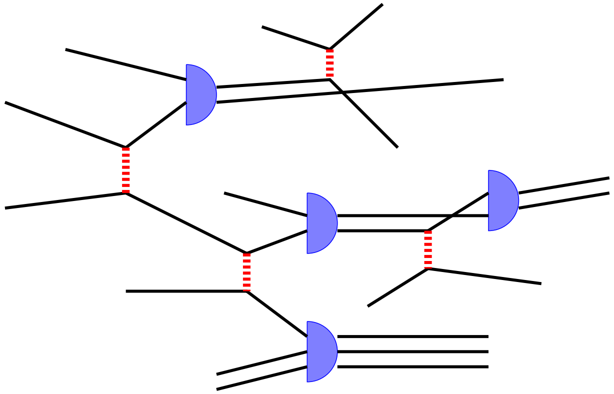
c.f. Danielewicz et al., NPA533(1991)712.

The details of cluster correlations

- **Formation**
  - $(d\sigma/d\Omega)_{NN} \Rightarrow$ Cluster formation cross section
  - Clusters: N, $2N$, $3N$, $4N = (0\text{s})^n$ & α-$(0\text{s})^{n>1}$
  - Pauli-blocking factor: $\prod_{i\in\text{C}}(1-f_i)$
  - Avoid double countings of final states
  - Take care of the non-orthogonality of final states
- **Propagation**

  Nucleons i in a cluster C are propagated as usual, except that the internal fluctuations are turned off:

$$\frac{d}{dt}\mathbf{Z}_i = \{\mathbf{Z}_i, \mathcal{H}\}_{\text{PB}} + \Delta\mathbf{Z}_i(t), \quad \Delta\mathbf{Z}_i(t) := \frac{1}{\text{C}}\sum_{j\in\text{C}}\Delta\mathbf{Z}_j(t)$$

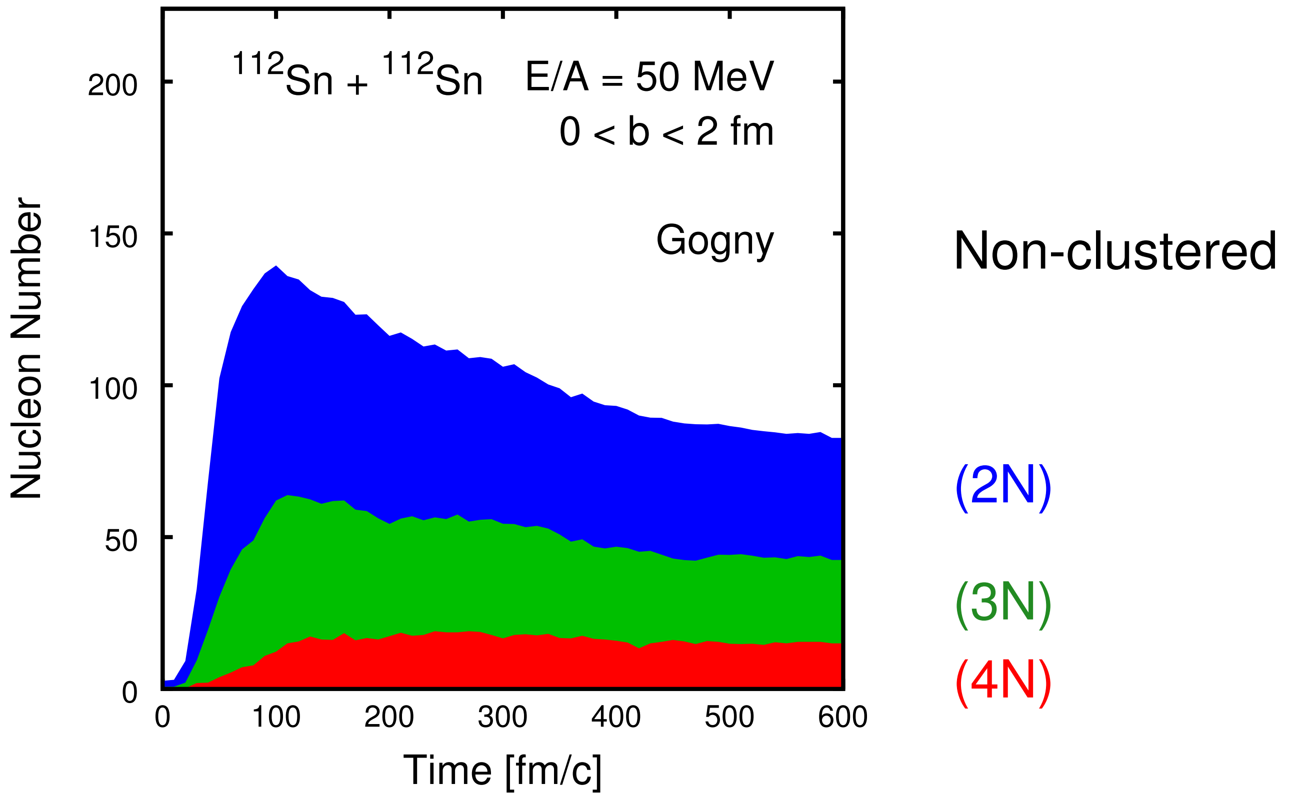


- **Breakup**

  A cluster C is broken when a nucleon in C collides with another nucleon.

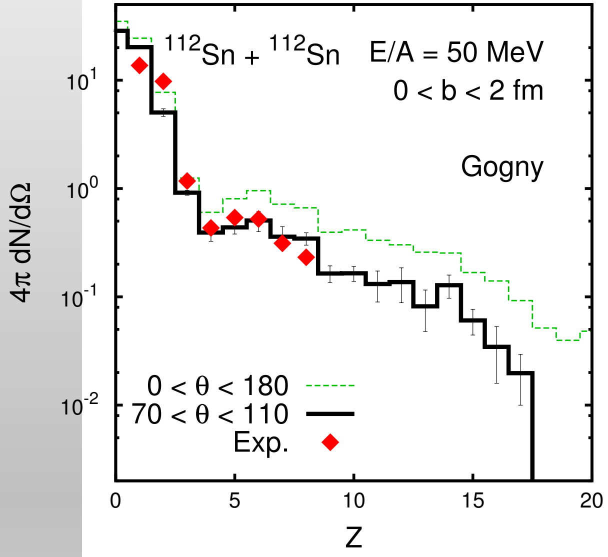
Time evolution of number of clusters

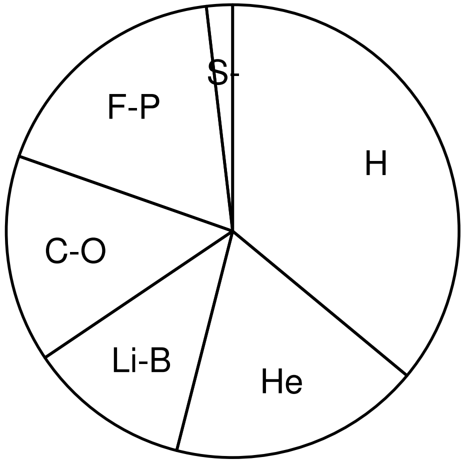
Number of nucleons in correlated clusters



Effects of cluster correlations

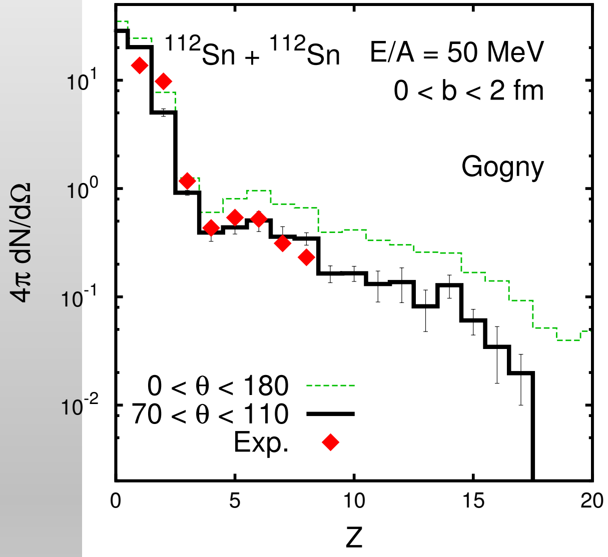
Without cluster correlations $\Sigma Z(70^\circ < \theta < 110^\circ) = 19$

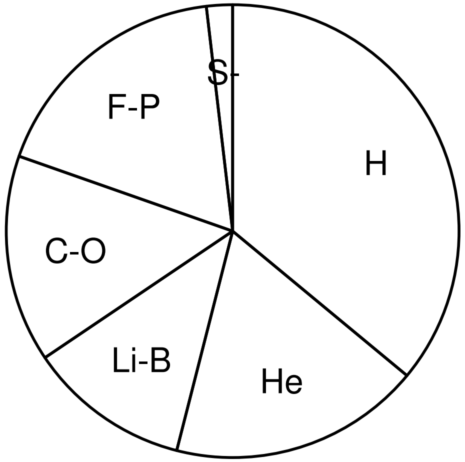




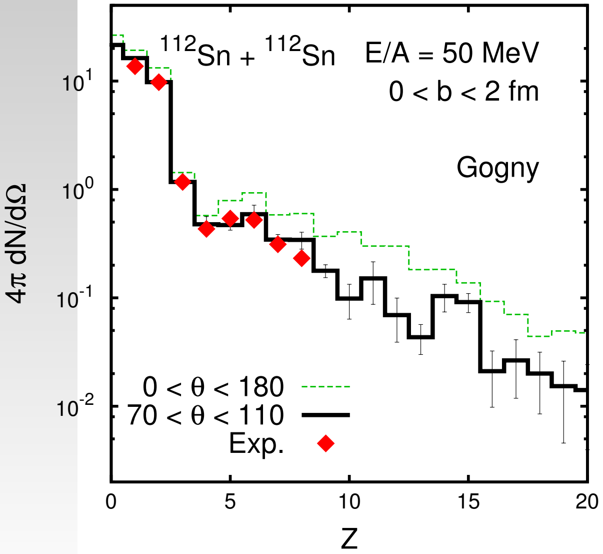
Effects of cluster correlations

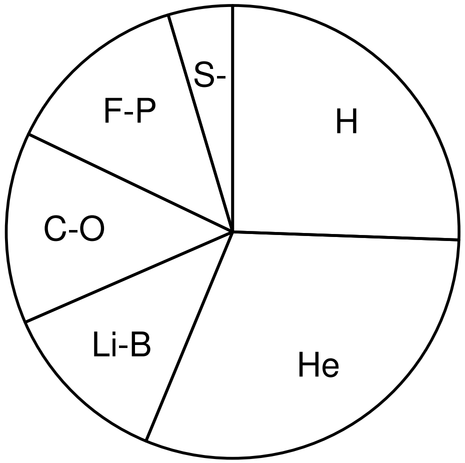
Without cluster correlations $\Sigma Z(70^\circ < \theta < 110^\circ) = 19$





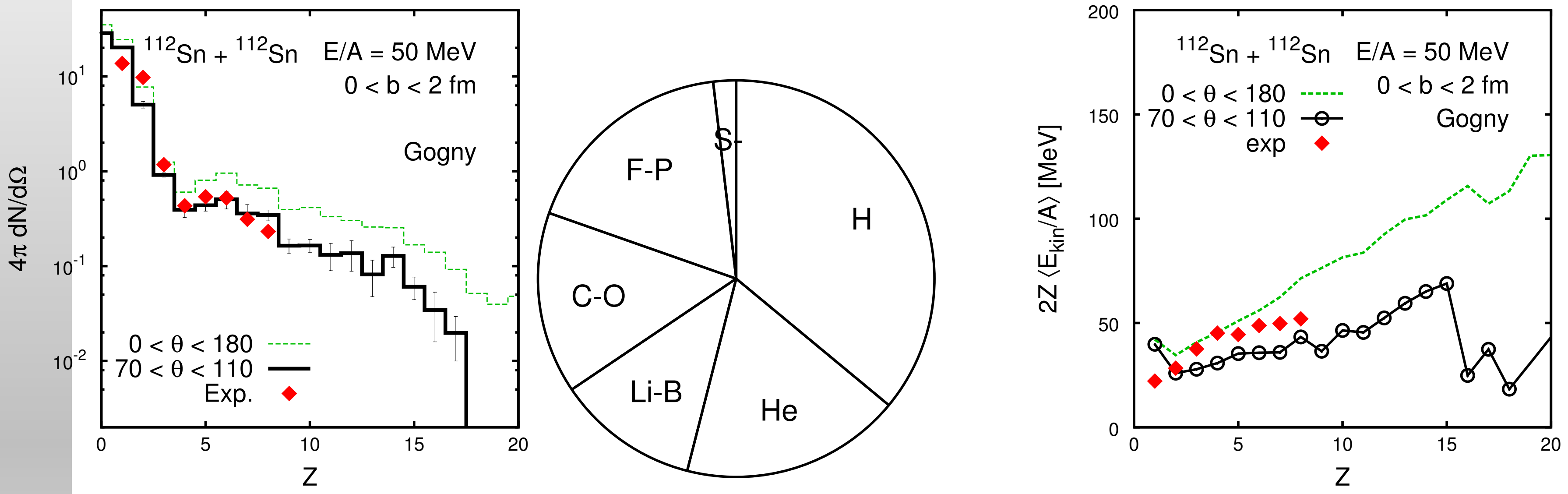
With cluster correlations $\Sigma Z(70^\circ < \theta < 110^\circ) = 22$



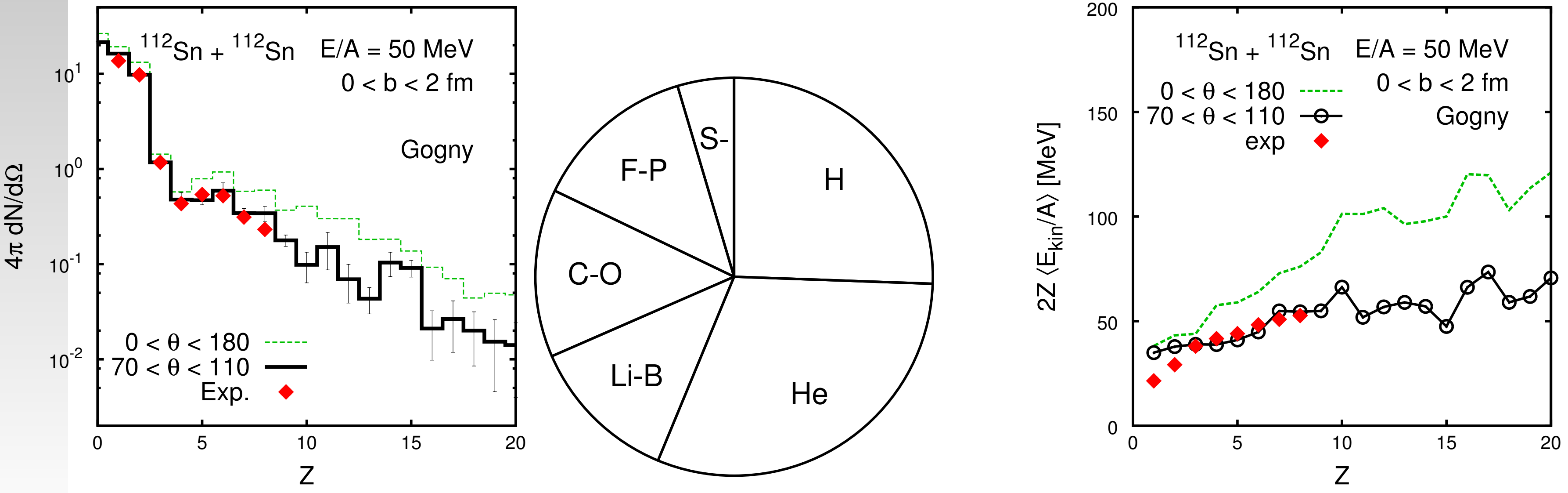


Effects of cluster correlations

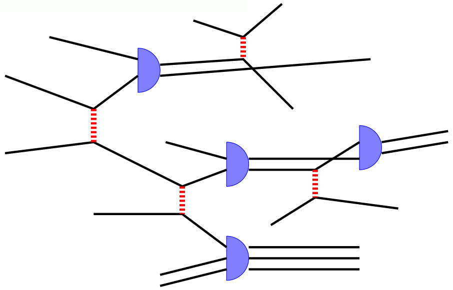
Without cluster correlations $\Sigma Z(70^\circ < \theta < 110^\circ) = 19$



With cluster correlations $\Sigma Z(70^\circ < \theta < 110^\circ) = 22$

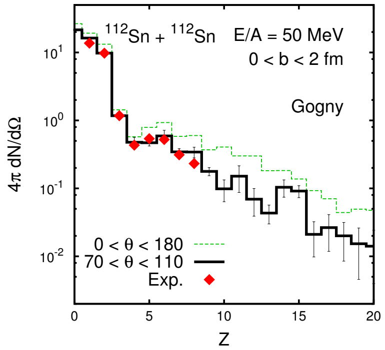


Summary

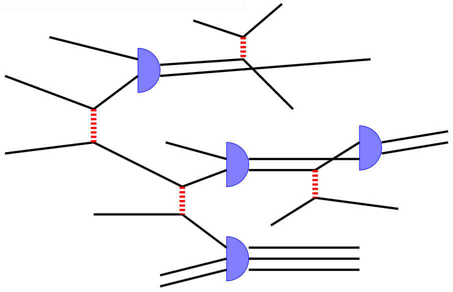


Cluster correlations

- $N_1 + B_1 \;+\; N_2 + B_2 \;\rightarrow C_1 + C_2,$ based on $(d\sigma/d\Omega)_{NN}$
- Cluster correlations improve the consistent reproduction of
  - M_p, M_α, and ΣZ_{IMF}
  - $\Sigma Z_{\text{transverse}}$ and $E_{\text{kin}}(A)$

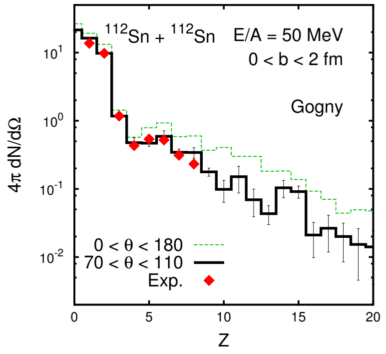


Summary



Cluster correlations

- $\mathrm{N}_1 + \mathrm{B}_1 \; + \; \mathrm{N}_2 + \mathrm{B}_2 \; \rightarrow \mathrm{C}_1 + \mathrm{C}_2$, based on $(d\sigma/d\Omega)_{NN}$
- Cluster correlations improve the consistent reproduction of
  - M_p, M_α, and ΣZ_{IMF}
  - $\Sigma Z_{\mathrm{transverse}}$ and $E_{\mathrm{kin}}(A)$



Mean field effects

- Fragment isospin composition seems to be governed by the symmetry energy of uniform nuclear matter at $\rho \sim \frac{1}{2}\rho_0$.
- The statistical decay does not always destroy the effects.