Relevance of neutron excess in nuclear matter to proton-induced composite-particle pre-equilibrium emission

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Outline

- some general ideas about the equation of state (EOS)
- relevance of light clusters in formulation of EOS
- α–cluster trend with mass asymmetry in Sn isotopes
- pre-equilibrium reactions and relevance of neutron asymmetry
- experiment to verify influence α–clustering variation in Sn isotopes

Equation of State of Nuclear Matter

$$e(\rho,\delta) = e(\rho,0) + S(\rho)\delta^2 + \mathcal{O}(\delta^4)$$

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

symmetry energy

$$S(\rho) = \frac{1}{2}\frac{\partial^2 e(\rho,\delta)}{\partial \delta^2}\bigg|_{\delta=0}$$

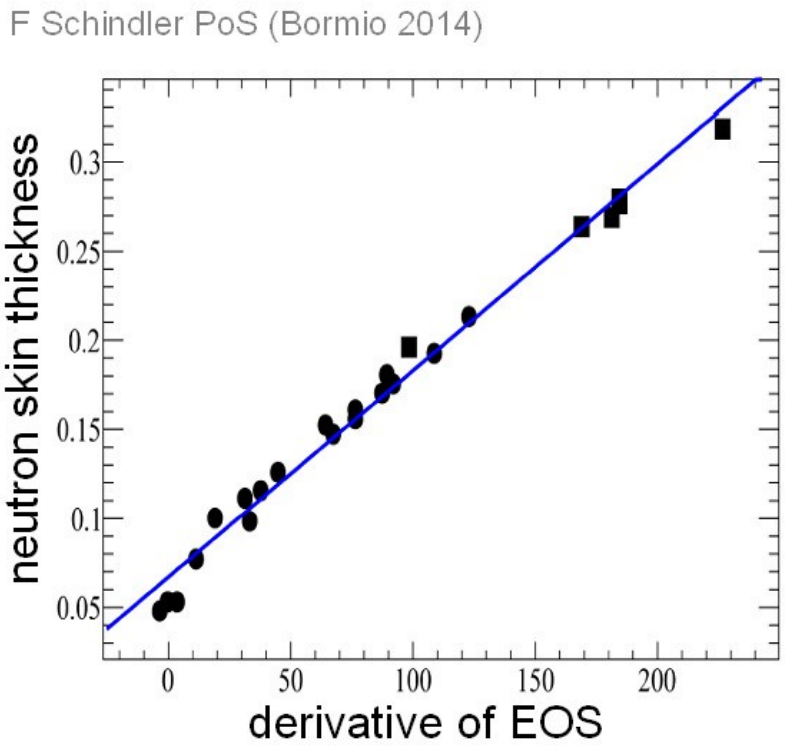
range of interest

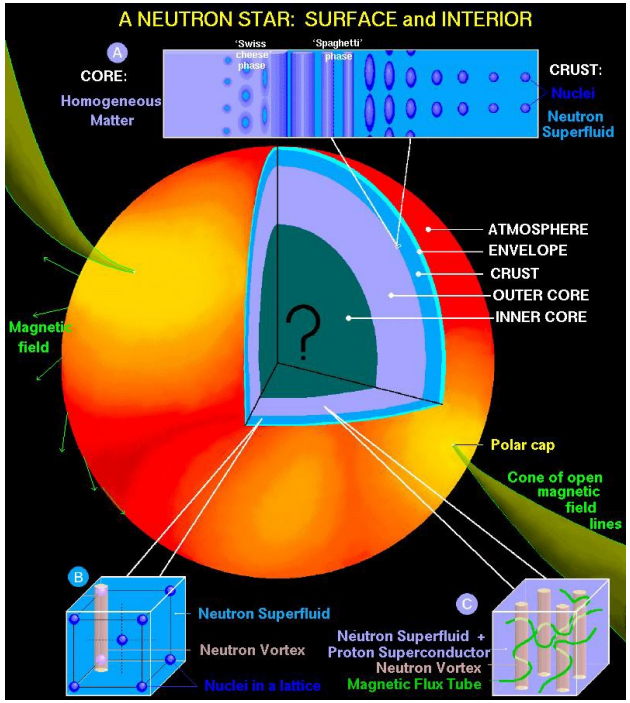
$10^{-8} \le \rho/\rho_0 \le 10$

$0 \le T \le 100 MeV$

$0 \le Y_p \le 0.6$ proton fraction

Symmetry energy vs neutron skin thickness





neutron skin thickness of, for example, ^{208}Pb has implications for properties of neutron star !!

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PHYSICAL REVIEW C **81**, 015803 (2010)

Composition and thermodynamics of nuclear matter with light clusters

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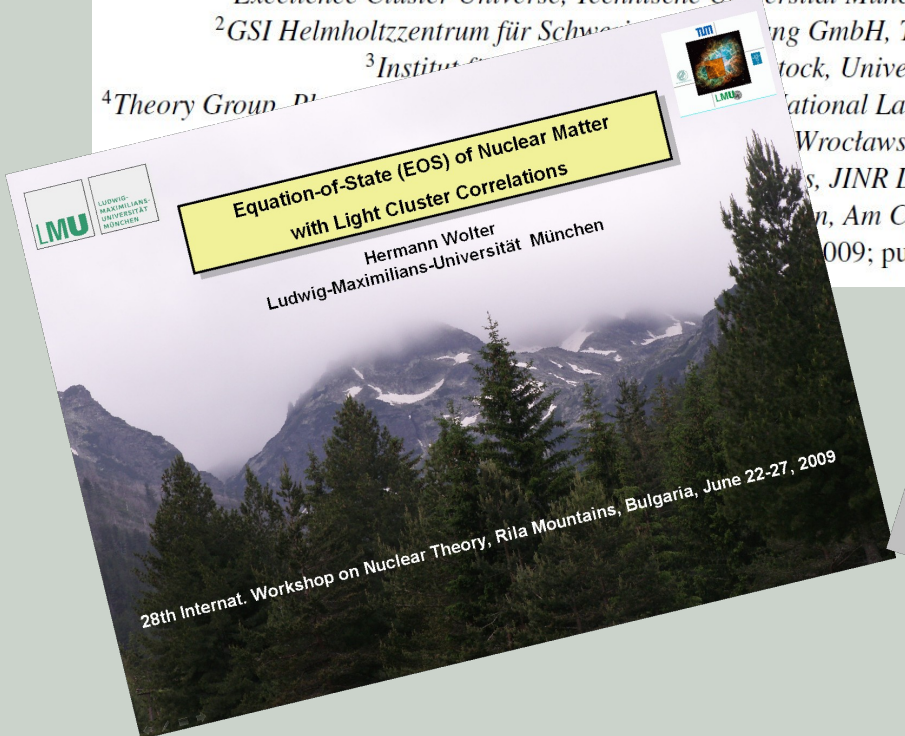
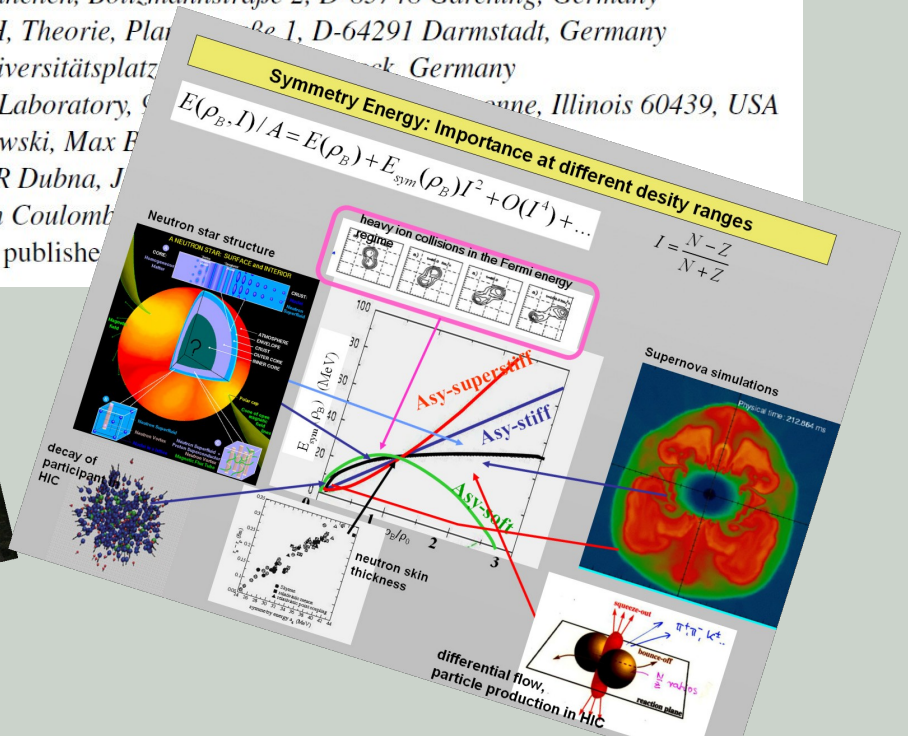
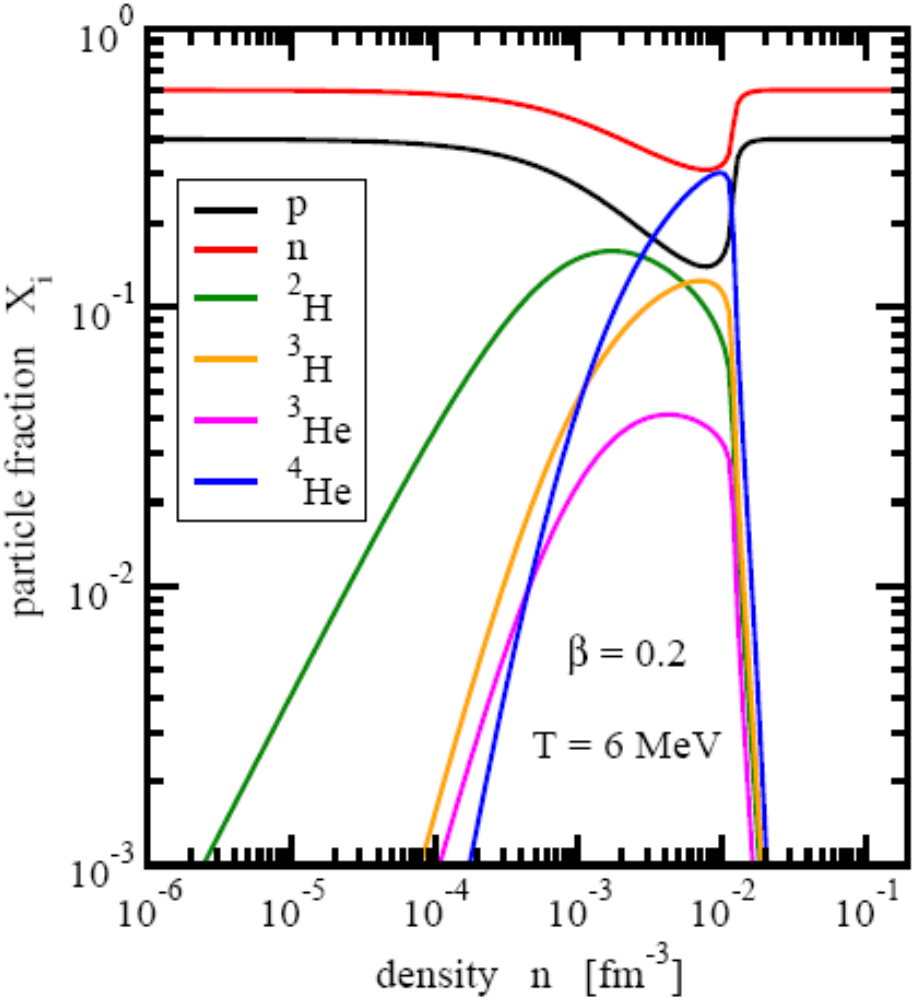


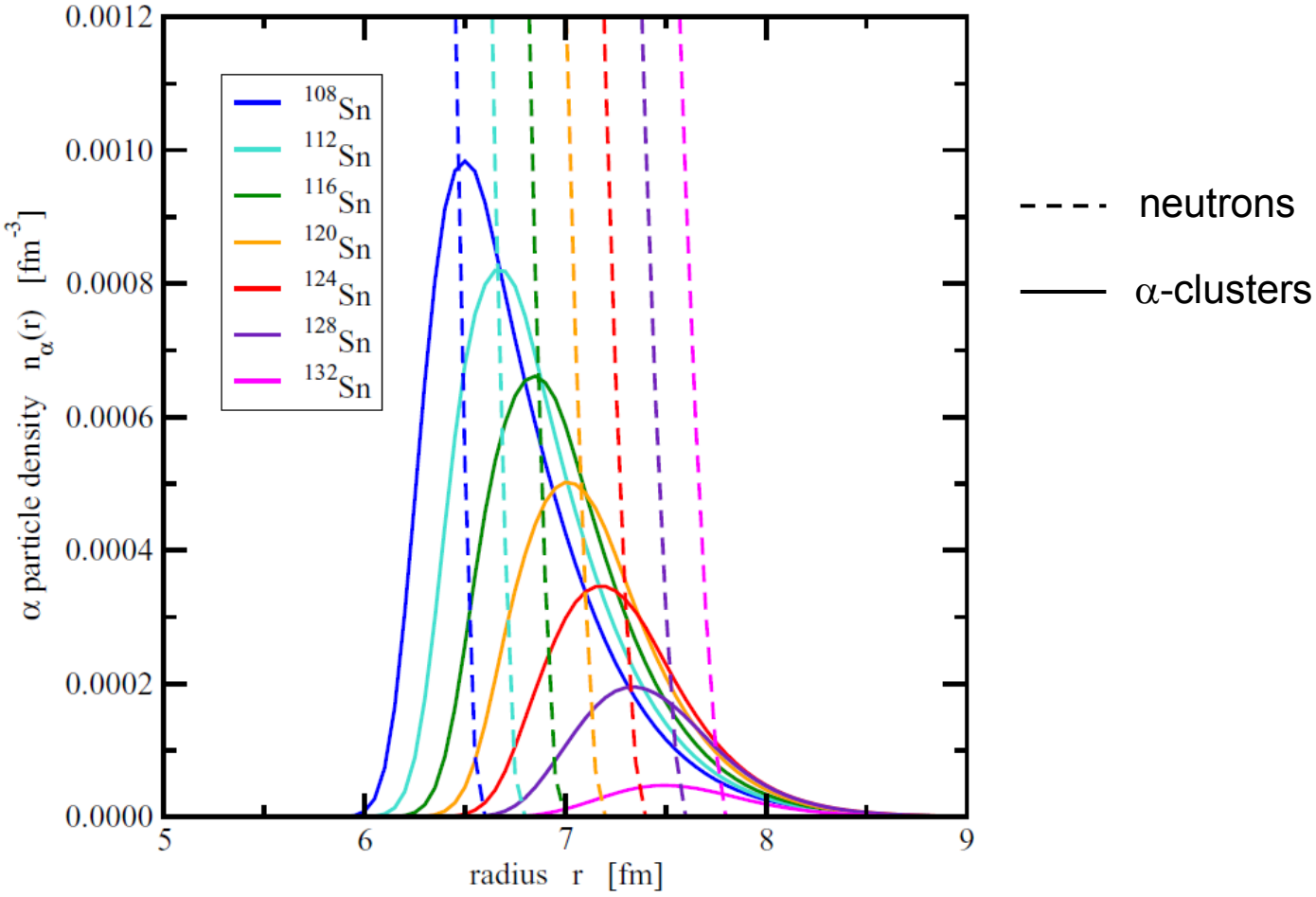


Light Cluster Correlations



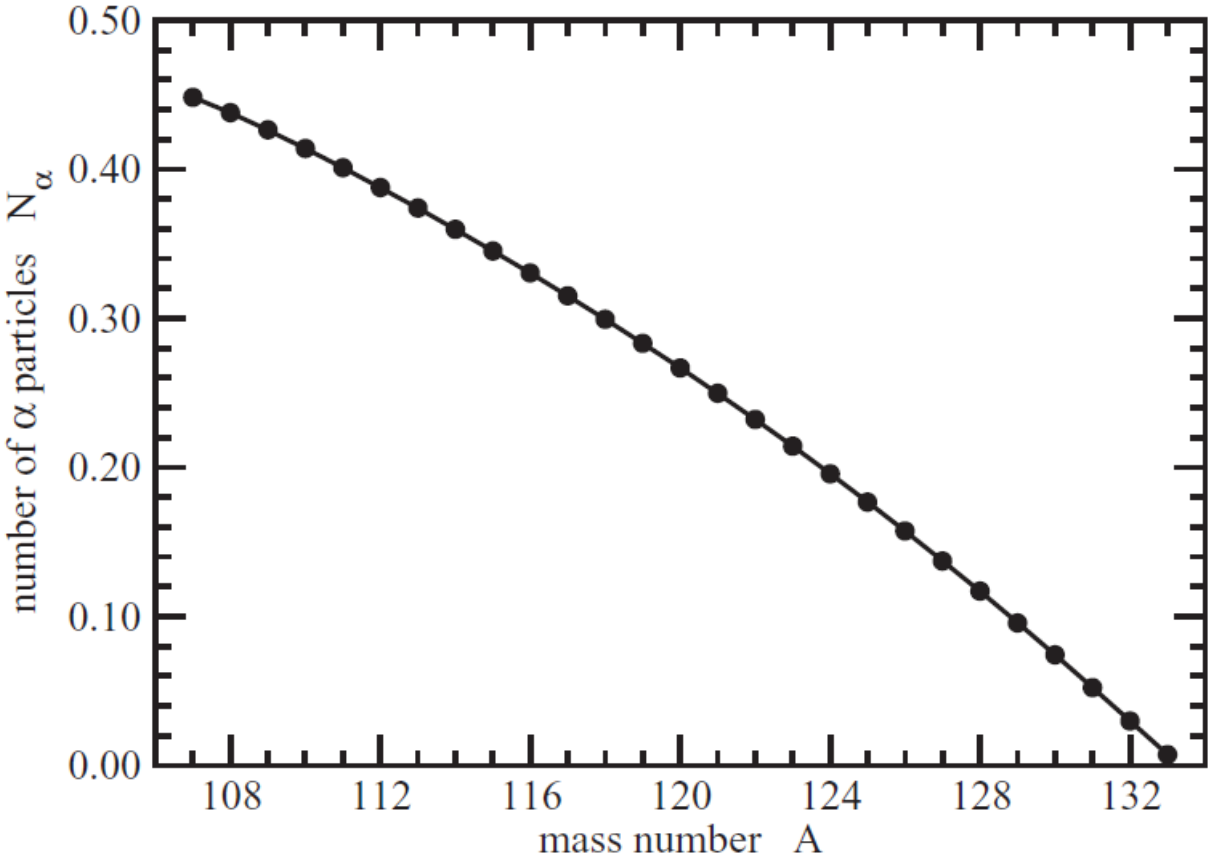
Hermann Wolter 28th Int. Workshop on Nuclear Theory, Rila Mountains, Bulgaria, June 2009

Predicted α-clustering with different mass asymmetry



S Typel Phys Rev C **89** (2014) 064321

Total number of α-cluster variation with Sn target mass



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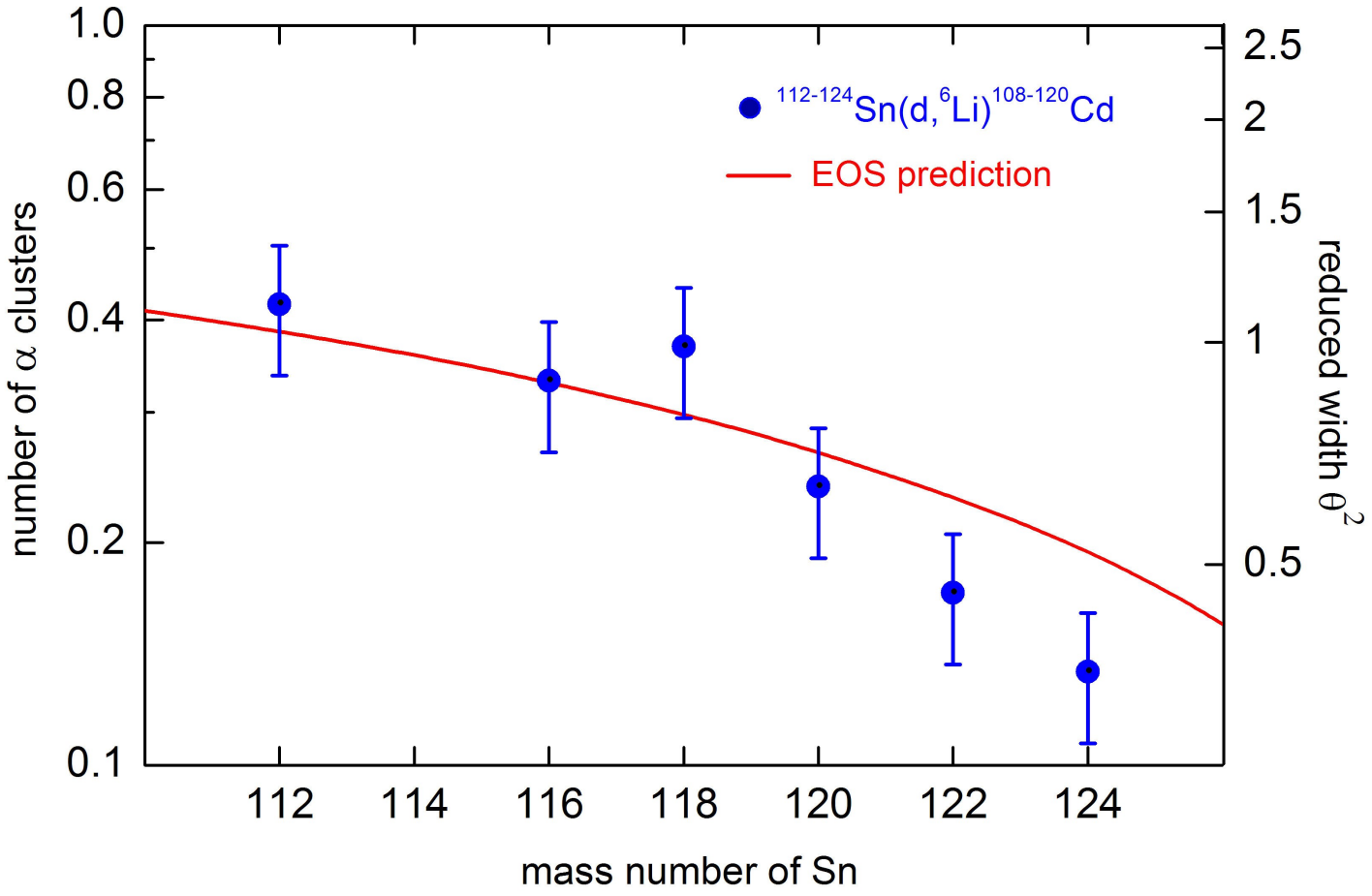
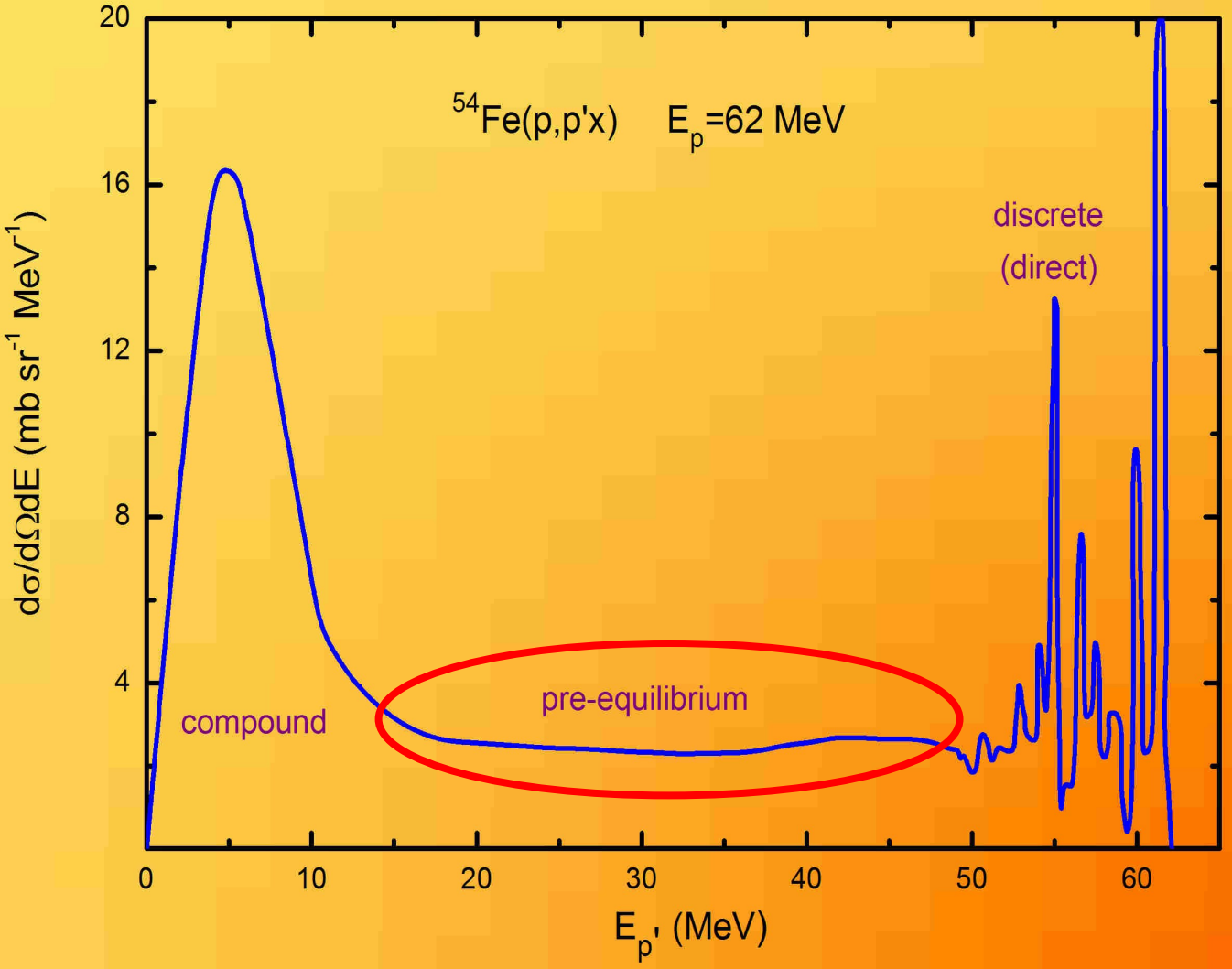
α – cluster pickup vs equation – of –state prediction



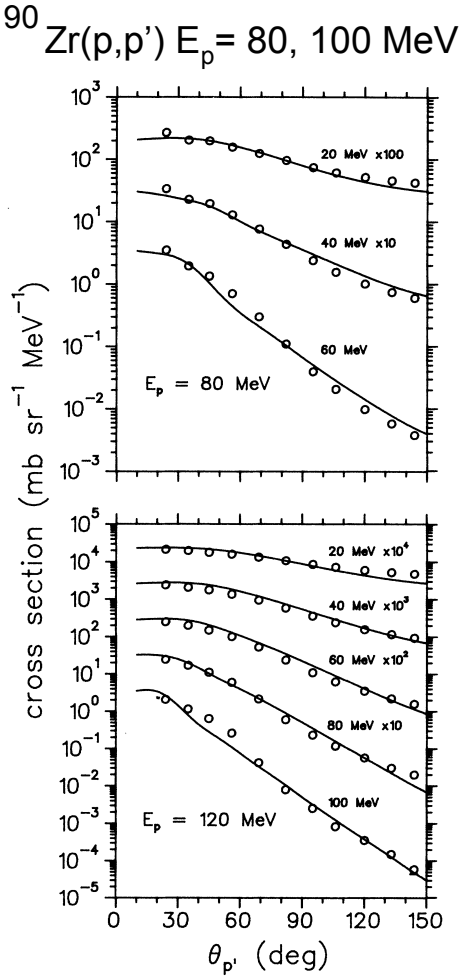
AAC Phys Rev C **93** (2016) 054329

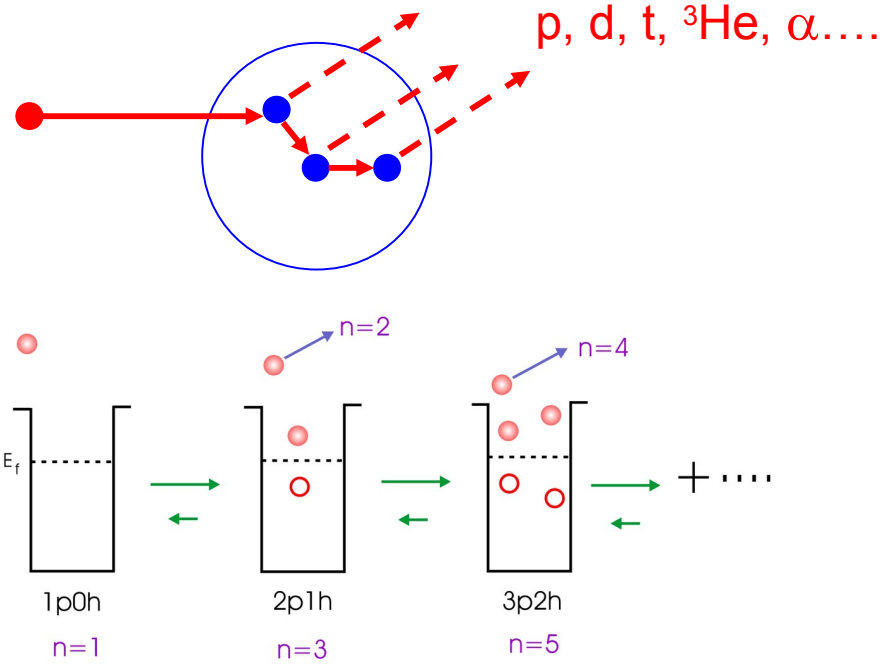
Pre-equilibrium (inclusive) reactions

Bertrand & Peele Phys Rev C **8** (1973) 1045



Mechanism pre-equilibrium (inclusive) reactions





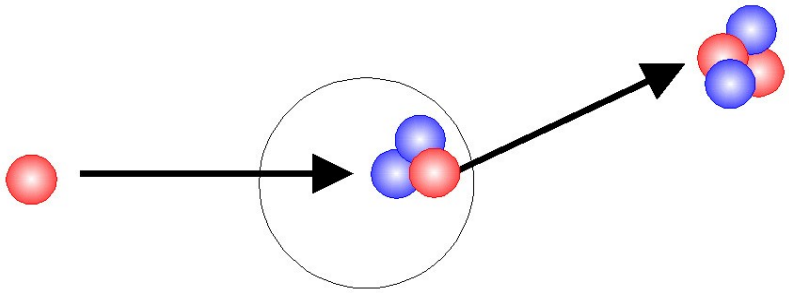
$$\left.\frac{d^2\sigma}{dE\,d\Omega}\right|_{\text{multistep}} = \sum_{n=2}^{n_{max}} \sum_{m=n-1}^{n+1} \int d\mathbf{k}_1 \cdots \int d\mathbf{k}_n \left[\frac{d^2W_{m,n}(\mathbf{k}_f,\mathbf{k}_n)}{dE_f\,d\Omega_f}\right] \left[\frac{d^2W_{n,n-1}(\mathbf{k}_n,\mathbf{k}_{n-1})}{dE_n\,d\Omega_n}\right]$$

$$\times \cdots \times \left[\frac{d^2W_{2,1}(\mathbf{k}_2,\mathbf{k}_1)}{dE_2\,d\Omega_2}\right] \left[\frac{d^2\sigma_{1,i}(\mathbf{k}_1,\mathbf{k}_i)}{dE_1\,d\Omega_1}\right]$$

Curves: Predictions of statistical multistep direct reaction mechanism (Feshbach, Kerman, and Koonin)

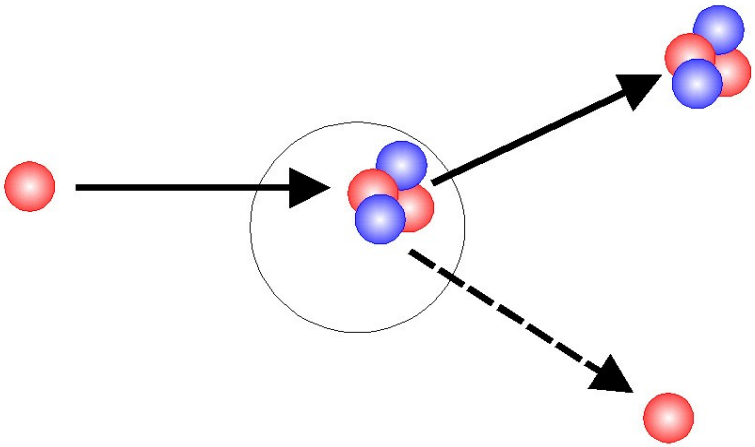
(p,α) pre-equilibrium reaction

- competition between knockout and pickup



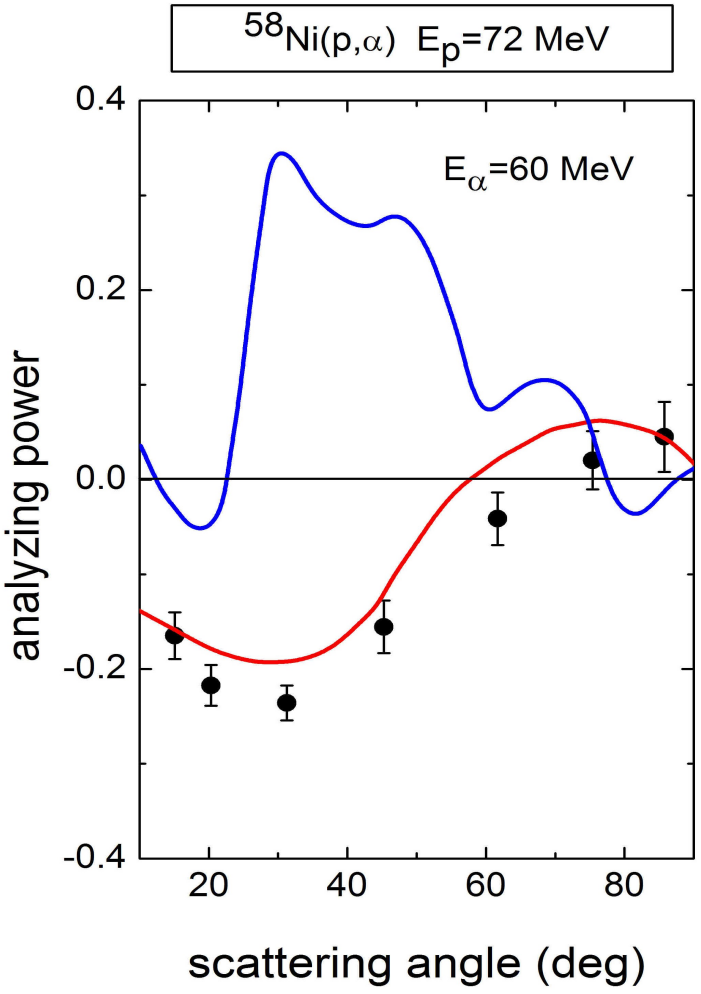
pick-up (1 step)

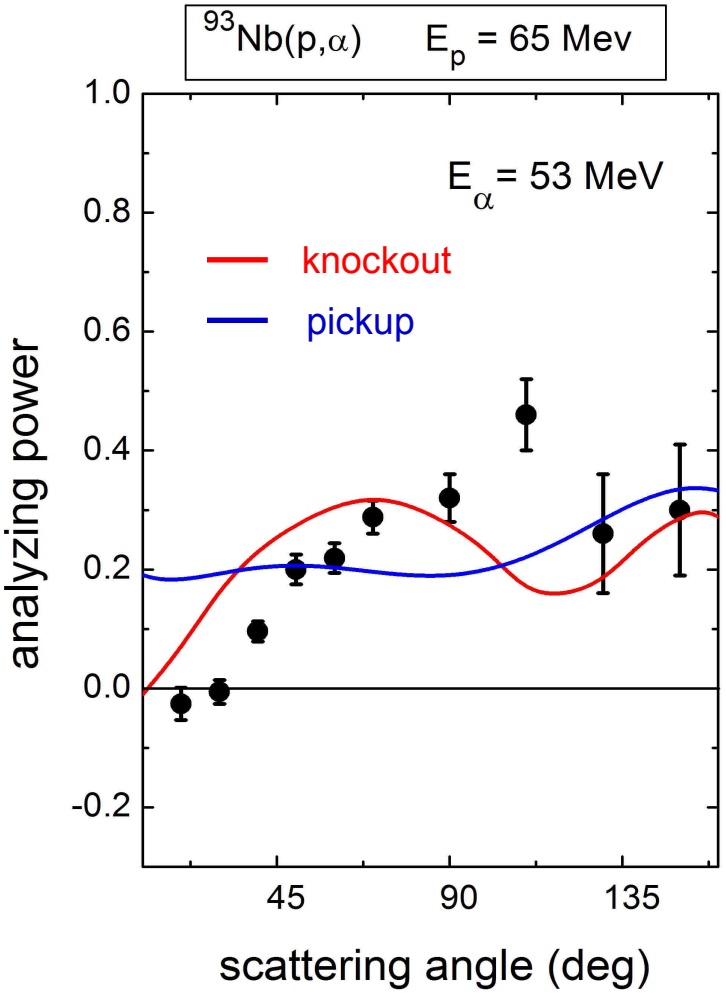
and



α–knockout (1 step)

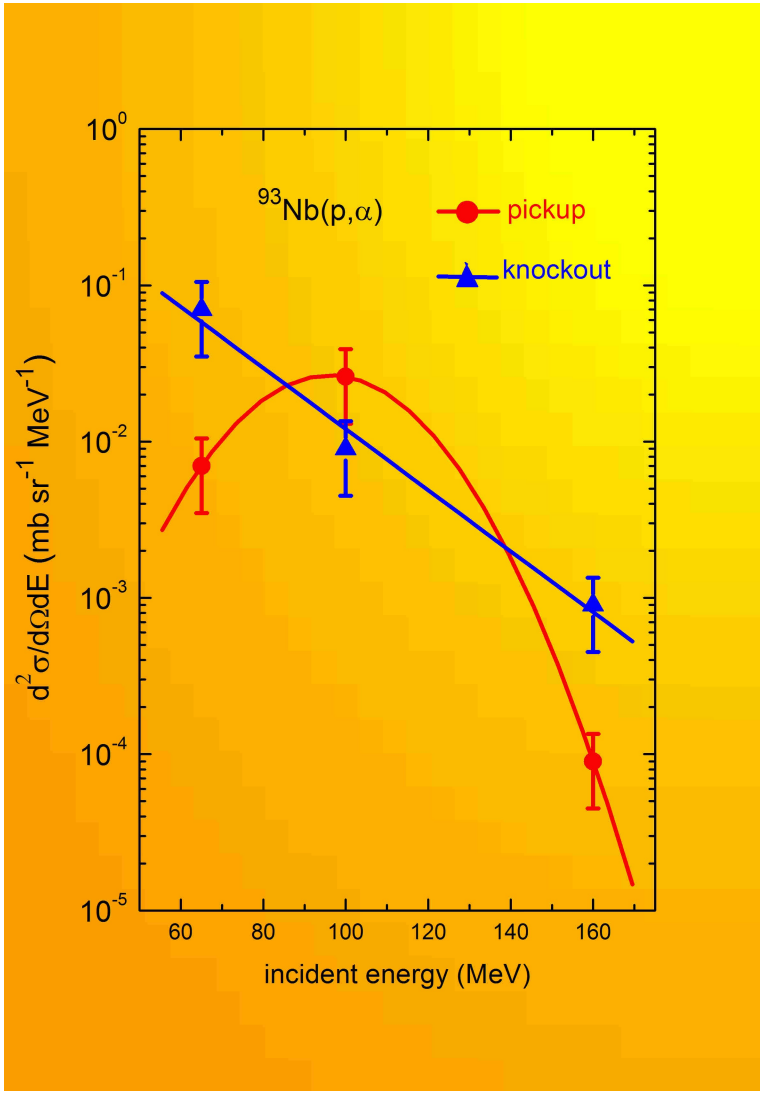
Sensitivity to reaction mechanism





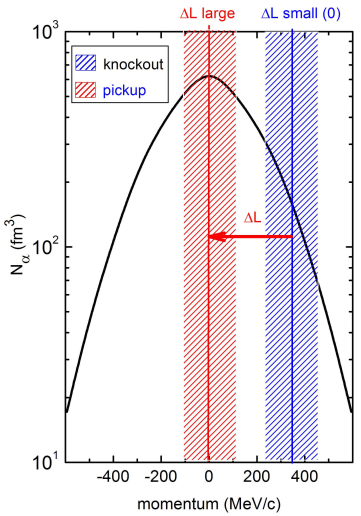
Change of dominant mechanism with incident energy

^{93}Nb(p,α) E_p= 65 → 160 MeV



Reasons for incident-energy trend

- target structure
- kinematics
- DWBA sensitivity to the above



RADIAL INTEGRAL I where $\frac{\sim\sim}{d\Omega}(DWBA) \sim |I|^2$

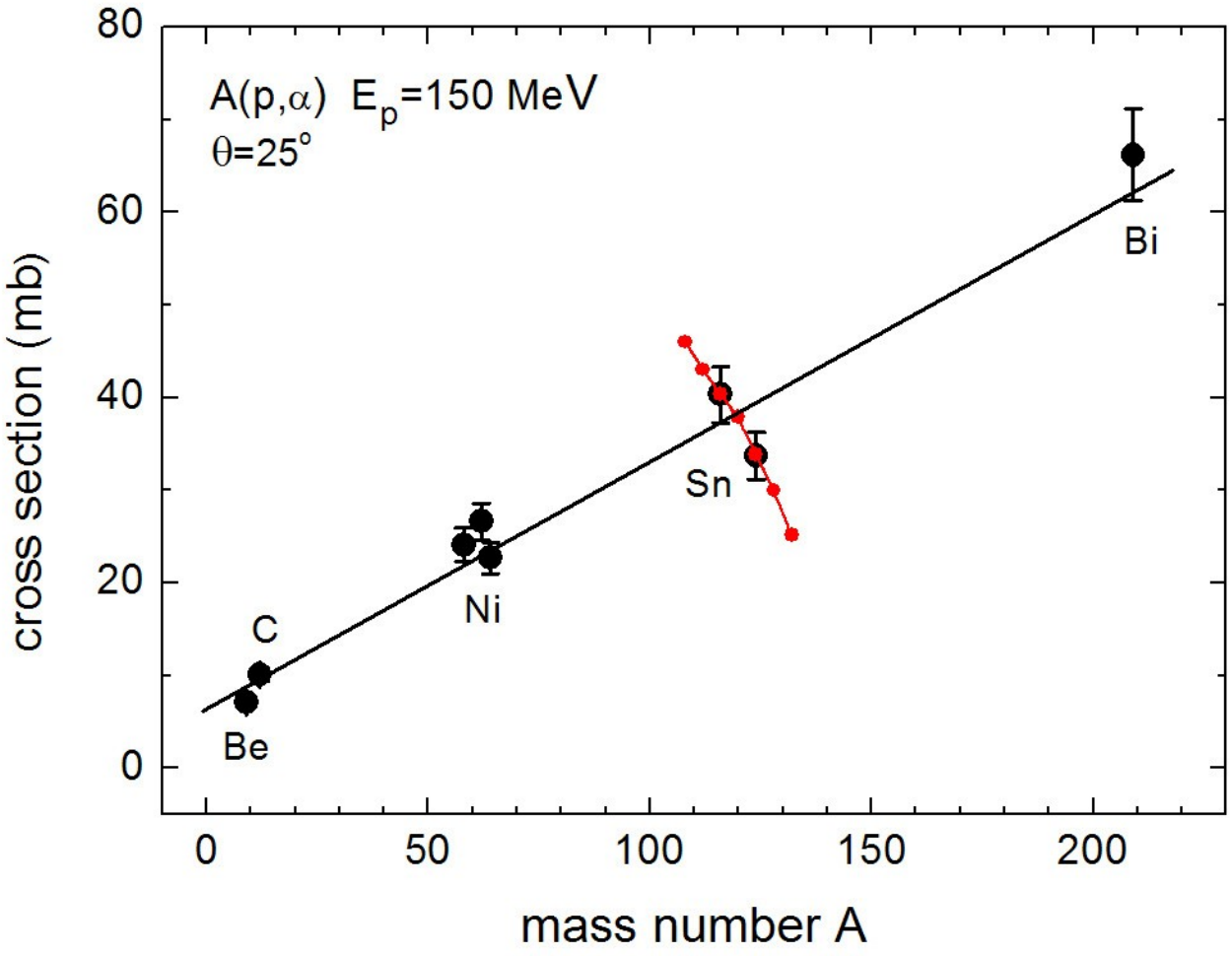
reaction: A(a,b)B

$$I = \int dr_c\, \chi^{(-)(k_b, \frac{B}{A} r_a)}\, \phi_{_C}(r_c)\, \chi^{(+)(k_a, r_a)} \quad \text{distorted-wave expression}$$

$$\approx \int dr\, e^{-i(k_b - k_a)r} \phi_{_C}(r) \quad \text{plane waves; B} \approx \text{A}$$

$$\equiv \psi_{_C}(k_b - k_a) \quad \text{Bound state Fourier transformation}$$

Sensitivity of pre-equilibrium cross section to clustering?



Summary

- light ion clustering is probably a crucial component of the EOS
- (d,^{6}Li) pickup consistent with predicted α–clustering trend in Sn isotopes
- decreasing α–clustering on the surface of Sn with growing mass asymmetry is predicted to have a prominent influence on pre-equilibrium reactions

Acknowledgement

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Thank you