Light clusters in transport models of heavy-ion collisions

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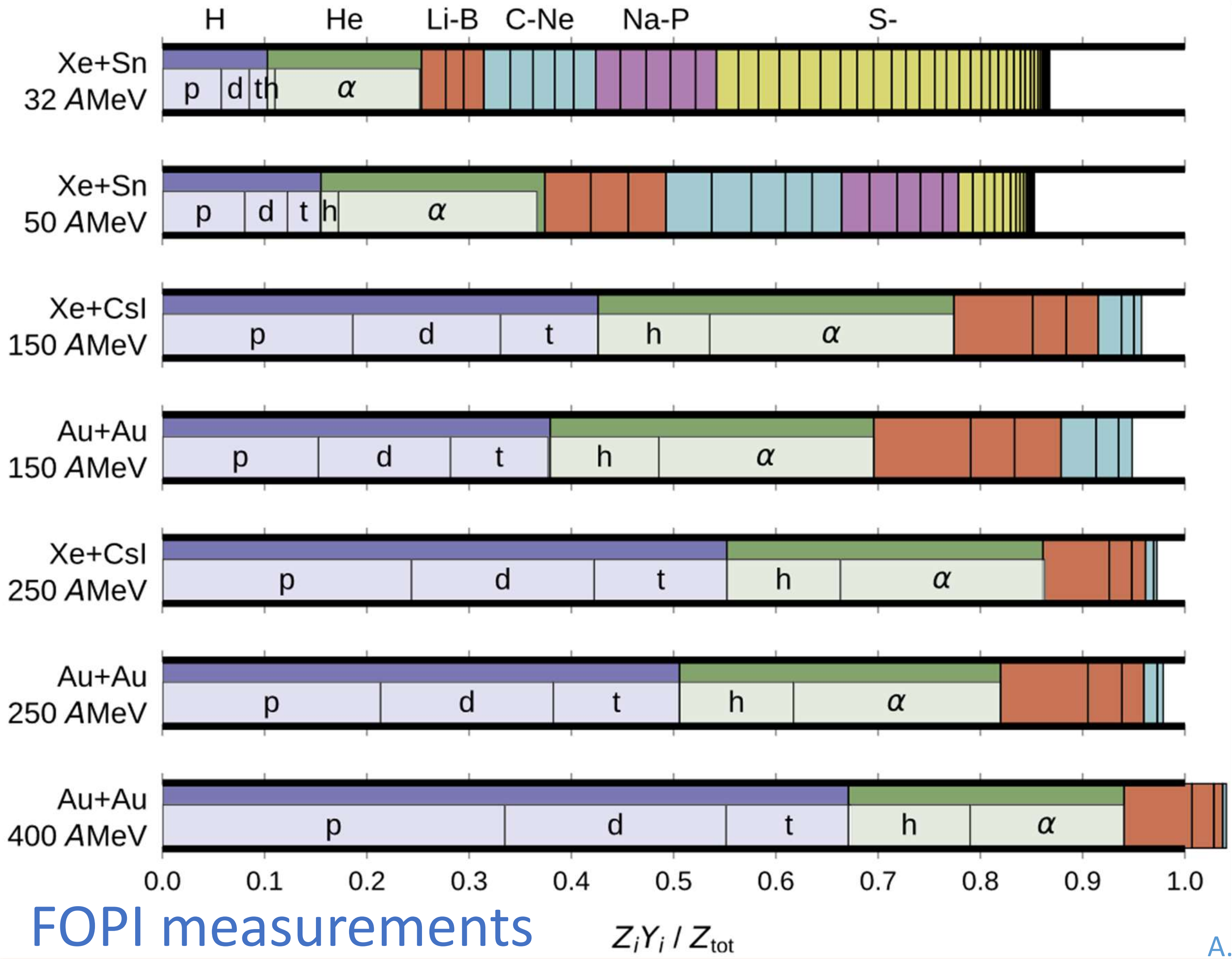
Fragments in heavy-ion collisions



FOPI measurements

Light nuclei (mass number ≤4) and large fragments (mass number>4) account for a large portion of the measured final-state charged particles

- Their production mechanism
- Their effects on the reaction dynamics and then on nucleon/pion observables

FOPI Collaboration, Nuclear Physics A 848 (2010) 366–427

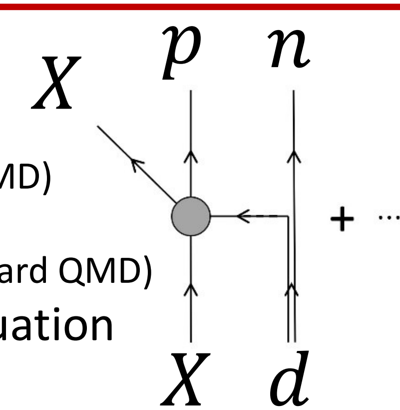
A. Ono, Progress in Particle and Nuclear Physics 105 (2019) 139–179

Clusters in heavy-ion collisions

Mean fields (potential) versus few-body correlation between nucleons

- Spinodal instability
  (Intermediate mass fragments, IMF)
  Fluctuations, SMF, Boltzmann-Langevin
  Talk by Maria
- Spectator nuclei

- Many-body scatterings like $NNN \leftrightarrow Nd$
  - Quantum/antisymmetrized molecular dynamics
    A. Ono, Journal of Physics: Conference Series 420 (2013) 012103 (AMD)
    G. Coci, et. al, Physical Review C108, 014902 (2023) (PHQMD)
    H.-G. Cheng and Z.-Q. Feng, Phys. Rev. C 109, L021602 (2024) (standard QMD)
  - Kinetic approach/Boltzmann–Uehling–Uhlenbeck equation
    Light nuclei d, t, ^{3}He, ^{4}He have been included.
    P. Danielewicz and G. F. Bertsch, Nuclear Physics A533, (1991) 712-748 (pioneer work)
    D. Oliinychenko, et. al, Physical Review C99, 044907 (2019) (SMASH)
    R. Wang, Y.-G. Ma, L.-W. Chen, et.al, Physical Review C108, L031601 (2023) (up to α)
    K.-J. Sun, R. Wang, et. al, Nature Communication 15, 1074, (2024) (hadronic afterburner)

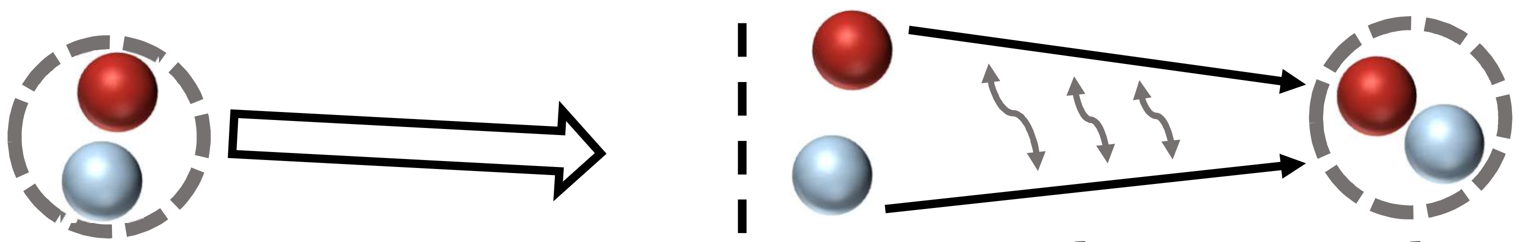


- Particle recognition
  - Minimum spanning tree
    J. Aichelin, Physics Reports202, (1991) 233-360
  - Simulated Annealing Clusterization Algorithm, FRIGA (binding energies)
    R. K. Puri, et. al, Physical Review C54, R28 (1996)
    A. Le Fèvre, et. al, Physical Review C100, 034904 (2019)

Heavy fragments can decay to light cluster (SMM or GEMINI)

- Final-state interactions? Coalescence? Femtoscopy?

Clusters form before kinetic freeze-out, or form after kinetic freeze-out?

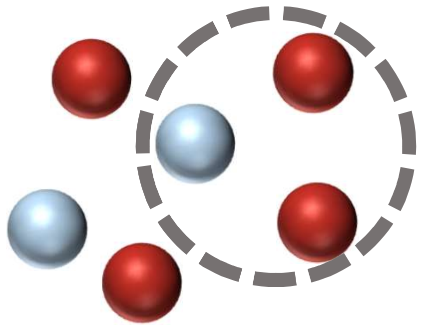


$np \rightarrow d\gamma$ or $np \rightarrow d\pi$?

Light nuclei in kinetic approach

BUU-like

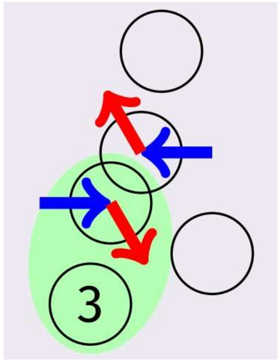
1. Find possible groups of test particles in a given cell



2. Calculate the scattering possibility based on the σ_{X-LN}, the impulse approximation and the detailed balance relation

AMD/QMD-like

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



2. Scattering possibility based on σ_{NN} and the overlap between nucleon and correlated states

3. Check whether the produced cluster is allowed in the sense of the medium (Mott) effect

$$\langle f_N \rangle_i(\vec{P}) \equiv \int f_N^{\mathrm{tot}}\left(\frac{\vec{P}}{A_i} + \vec{p}\right) |\phi_i(\vec{p})|^2 \mathrm{d}\vec{p} \leqslant F_{A=A_i}^{\mathrm{cut}}$$

light-nuclei internal wave function

A larger $F_{A=A_i}^{\mathrm{cut}}$ corresponds to a weaker Mott effect

Phase-space density $\rho_i < \rho_c$

$$\rho_i'^{(\mathrm{ini/fin})} = \left(\frac{2\nu}{\pi}\right)^{\frac{3}{2}} \sum_{k(\neq i)} \theta\left(p_{\mathrm{cut}} > |\boldsymbol{P}_i^{(\mathrm{ini/fin})} - \boldsymbol{P}_k|\right) e^{-2\nu(\boldsymbol{R}_i - \boldsymbol{R}_k)^2}$$

$$p_{\mathrm{cut}} = (375\ \mathrm{MeV}/c)\, e^{-\epsilon_{\mathrm{cm}}/(225\ \mathrm{MeV})}$$

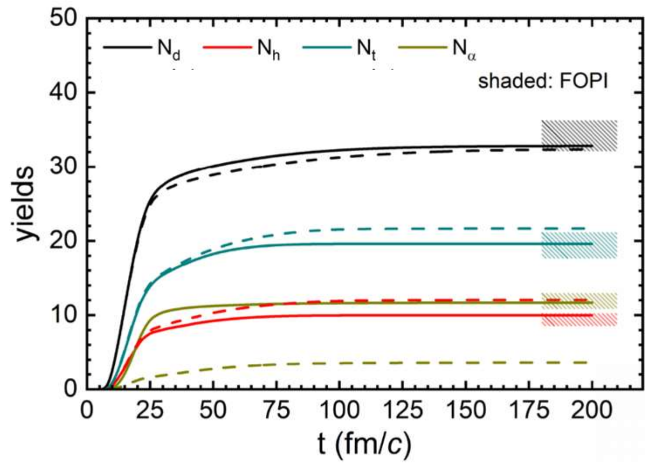
Potential homework

1. Box calculation of free Boltzmann gas consisted by nucleons and light nuclei. Compare with the thermal distribution.

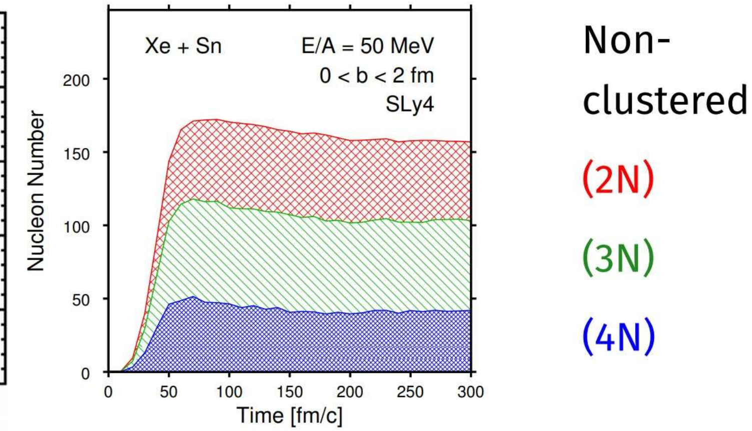
2. Box calculation with Mott effect, compare the results from BUU-type and AMD/QMD-type.

3. Check the sensitivity of certain quantities in terms of different treatments of the Mott effect (e.g., in-medium binding energy, light-nuclei internal wave function)

4. ……



RW, Y.-G. Ma, L.-W. Chen, et.al, Physical Review C108, L031601 (2023)



A. Ono, Journal of Physics: Conference Series 420 (2013) 012103

- Both AMD/QMD-type and BUU-type calculations show that light nuclei or correlation states are formed starting from the early stage of the reaction. Their impact on the reaction dynamics and nucleon/pion observables need to be tested.

N. Ikeno, A. Ono, Y. Nara, et. al, Physical Review C93, 044612 (2016) (Pion yields)
R. Wang, S. Burrello, M. Colonna, et.al., arXiv:2405.02157 (Unstable mode growth)

Potential contributors:

1. Akria (AMD)
2. Pawel? (BUU-type)
3. Rui Wang & Zhen Zhang (BUU-type)
4. Hui-Gan Cheng and Zhao-Qing Feng (QMD-type)