Scientific Programming Centre

Simulation of the momentum distributions of the spectator fragments in ^{124}Xe+CsI Collisions at the BM@N with accounting for pre-equilibrium clusterization

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Outline

- Simulation of spectator fragment creation, decay, and momentum distributions using AAMCC, Goldhaber models, and MST clustering
- Validation of modeling results with KLMM data
- Incorporating Coulomb repulsion between charged fragments
- Validation of modeling results with KLMM data with and without Coulomb repulsion
- Momentum distributions of spectator H, He, Li fragments for BM@N

Motivation

- FHCal and ScWall are capable of detecting spectator nucleons and at least some spectator fragments[1]
- Modelling the momentum distributions of spectator fragments in relativistic nuclear collisions, such as those in the BM@N experiment (NICA), is crucial for estimating their acceptance.
- Analyzing this detector performance requires a model that accurately reflects the momentum distributions of spectator fragments

1) M. Kapishin et al., "Studies of baryonic matter at the BM@N experiment (JINR)," Nuclear Physics A, vol. 982, pp. 967-970, 2019.

Our model Abrasion-Ablation Monte Carlo for Colliders

Simulation stages in AAMCC[1]:

- The Glauber Monte Carlo model simulates nucleus-nucleus collisions[2], where spectator matter (prefragment) is formed by non-participating nucleons.
- The excitation energy of the prefragment can be estimated as follows:
  - The Ericson formula based on the particle-hole model[3].
  - The ALADIN parabolic approximation[4] for light and heavy nuclei.
  - A hybrid method: Ericson formula for peripheral collisions and ALADIN otherwise.
- MST clustering
- Deexcitation follows Geant4 decay models[5]:
  - Fermi break-up model[5].
  - Statistical Multifragmentation Model (SMM)[5].
  - Weisskopf-Ewing evaporation model[5].

1) R. Nepeivoda et al., "Pre-Equilibrium Clustering in Production of Spectator Fragments in Collisions of Relativistic Nuclei," Particles, vol. 5, pp. 40-51, 2022. *2)* S. Loizides, J. Kamin, D. d'Enterria, "Phys. Rev. C," vol. 97, p. 054910, 2018.

3) T. Ericson, "Advances in Physics," vol. 9, p. 737, 1960.

4) A. Botvina et al., "Nuclear Physics A," vol. 584, 1995.

5) J. Alison et al., "Nucl. Inst. A," vol. 835, p. 186, 2016.

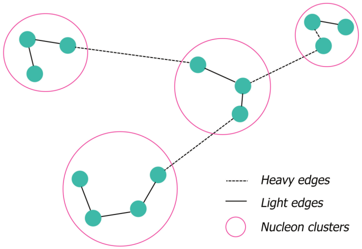
MST clustering

The MST-clustering algorithm[1] models pre-equilibrium fragmentation. Graph vertices represent nucleons, and edge weights represent distances between them.

- A minimum spanning tree is selected from the complete graph.
- Nucleons i, j are clustered if their distance r_{ij} satisfies

$$r_{ij} < d$$

- Connectivity components form separate prefragments



Following Kopylov's method[2], the excitation energy attributed to the free spectator nucleons is converted into the kinetic energy of the prefragments.

1) R. Nepeivoda et al., "Pre-Equilibrium Clustering in Production of Spectator Fragments in Collisions of Relativistic Nuclei," Particles, vol. 5, pp. 40-51, 2022.

2) G. I. Kopylov and M. I. Podgoretsky, "Correlations of Identical Particles Emitted by Highly Excited Nuclei," in Proceedings of the International Conference on Nuclear Physics, 1972

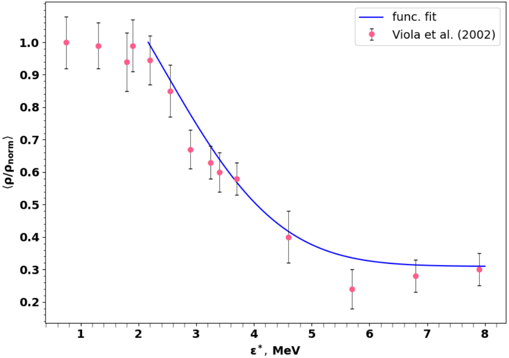
Prefragment expansion

- As the prefragment expands, the average nucleon distance also increases.
- In MST-clustering, instead of increasing all distances, d is decreased to emulate this effect.

$$d \propto \rho^{\frac{1}{3}}$$

- The density parametrization is a piecewise function, with parameters from experimental data.

$$d = \begin{cases} d_0, & \text{if } \epsilon^* \\ d_0 \cdot \left(\gamma \cdot \exp\left(-\left(\frac{\epsilon^*}{\beta}\right)^{\alpha}\right) + \delta\right)^{1/3}, & \text{if } \epsilon^* \end{cases}$$



$$d_0 = 2.7\,fm, \quad \alpha = 2.24, \quad \beta = 3.18\,\text{MeV}, \quad \gamma = 0.99, \quad \delta = 0.29$$

1) R. Nepeivoda et al., "Pre-Equilibrium Clustering in Production of Spectator Fragments in Collisions of Relativistic Nuclei," Particles, vol. 5, pp. 40-51, 2022.

Goldhaber model and spectator momentums of fragments

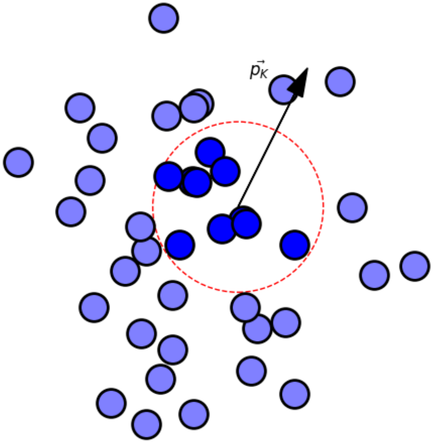
To account for the intranuclear motion of the removed nucleons and define momentums of spectator nucleons right after collision, we use the Goldhaber statistical model[1]:

- momentums distribution is Gaussian

$$\sigma^2 = \sigma_0^2 \cdot \frac{N_{\mathrm{specA}} \cdot N_{\mathrm{partA}}}{A - 1}, \ \sigma_0 = 193\,\mathrm{MeV}$$

- distribution in angles is uniform

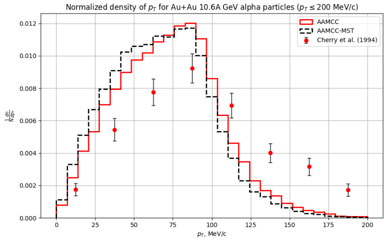
A – mass of colliding nuclei.

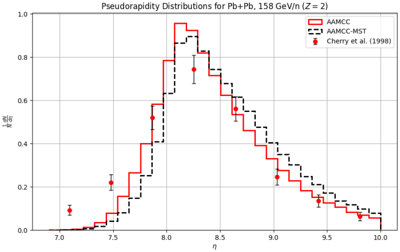


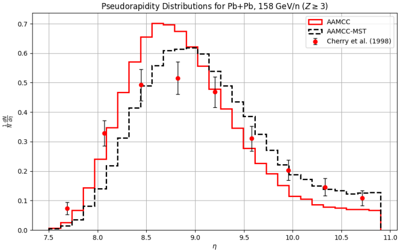
1) A.S. Goldhaber, "Statistical models of fragmentation processes," *Physics Letters B*, vol. 53, pp.

Comparisons with KLMM data

- Pseudorapidity distribution of spectator fragments in Pb + Pb 158A GeV collision:
  - $Z = 2$ AAAMCC-MST results fit better
- Transverse momentum p_T distribution of spectator fragments in Au + Au 10.6A GeV collision :
  - Spectator fragments are overestimated for $p_T \leq 100$ MeV/c, underestimated for $p_T \geq 100$ MeV/c
  - fragments distribution $Z \geq 3$ is well described by AAMCC-MST.







Accounting for Coloumb repulsion

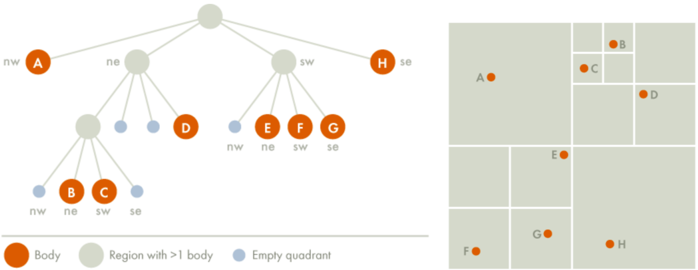
- The excited prefragments after MST-clustering repel each other due to Coloumb repulsion.
- Repulsion additionally accelerates charged prefragments
- Mean pseudorapidity η and mean transverse momentum p_T over all prefragments should increase

How to estimate this effect efficiently in calculations?

Barnes-Hut Algorithm[1)]

Idea: Group nearby protons and approximate them as a single body.

- **Building Octree:**
  - — Recursively subdivide the space into 8 octants until each subdivision contains 0 or 1 proton.
  - — Nodes - boxes, child nodes represent 8 subspaces.
  - — Node keeps: total charge in the box, size of the box s, center $\vec{a}$, center of charges of internal protons $\vec{r_c}$
  - — Protons – leaf nodes



1) X. Gan et al., "An efficient Barnes-Hut algorithm for approximate nearest neighbor search on the GPU," *Journal of Parallel and Distributed Computing*, vol. 73, pp. 86-100, 2013.

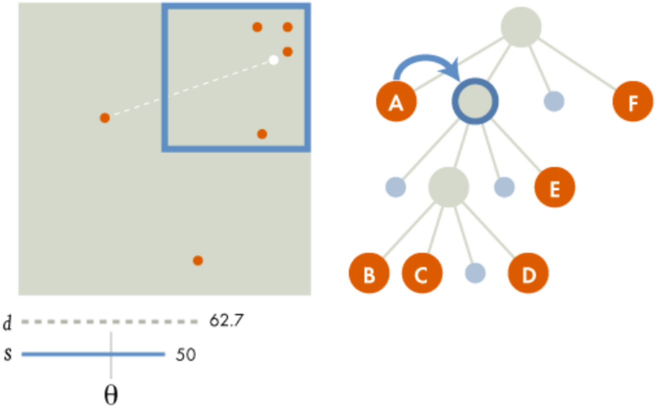
Barnes-Hut Algorithm

Calculating the force on a nucleon at $\vec{r}$:
Traverse the octree. If the current node is:

- leaf: calculate particle-particle force $\vec{F}$
- internal:

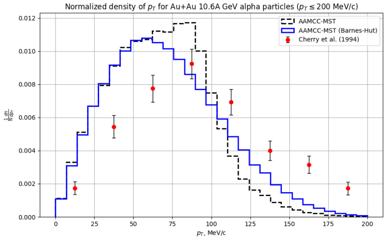
$$\frac{s}{|\vec{a}-\vec{r}|} < \theta \rightarrow \text{treat as a single charge}$$

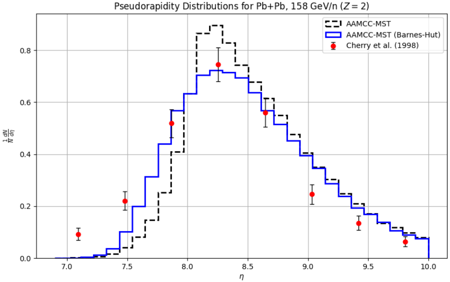
else $\rightarrow$ continue traversing

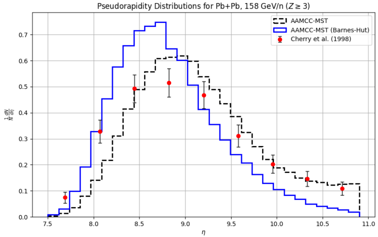


Comparisons with KLMM data with Coloumb repulsion

- Pseudorapidity distribution of spectator fragments in Pb + Pb 158A GeV collision:
  - — η distribution for $Z = 2$ is described better with accounting for Coloumb repulsion
- Transverse momentum p_T distribution of spectator fragments in Au + Au 10.6A GeV collision :
  - — Underestimation for $p_T \geq 100$ MeV/c decreases

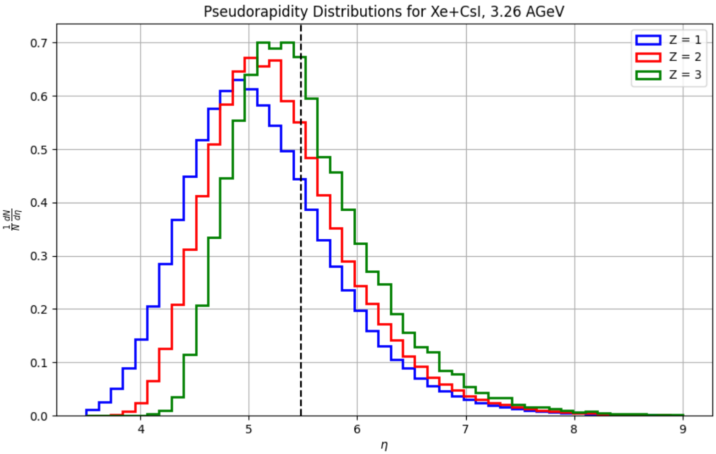






Spectator fragments momentums distributions for BM@N.

- SciWall can detect spectator nucleons and spectator fragments with $Z \leq 3$, but has a hole in the center ($\eta > 5.48$).
- Pseudorapidity distribution of spectator fragments in Xe + Cs 3.26A GeV collision with centrality $\geq 60\%$ for $Z = 1, Z = 2, Z = 3$ in AAMCC-MST with accounting for Coloumb repulsion
- The estimated fraction of spectator fragments with $\eta > 5.48$:
  — 27%, $Z = 1$
  — 34%, $Z = 2$
  — 45%, $Z = 3$



Summary

- Accounting for pre-equilibrium fragmentation and Coloumb repulsion increases the mean transverse momentum p_T of the spectator fragments and improves agreement with the experimental data
- The estimated percentage of spectator fragments with $1 \leq Z \leq 3$ recorded in the BM@N ScWall during Xe+Cs collisions at 3.26 A GeV is 27%, 34% and 45%.