Exploring nuclear fragmentation at heavy-ion colliders

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Outline

• Can we evaluate the role of nuclear fragmentation at heavy-ion colliders?

• Our model: Abrasion-Ablation Monte Carlo for Colliders (AMCC)

• Universality of nuclear fragmentation: from SPS to LHC

• Characteristics of nuclear fragmentation at colliders can be predicted as functions of collision centrality:
  - total charge bound in fragments $Z_{\text{bound}}$
  - multiplicity of fragments with a given charge $N_{Z=1}, N_{Z=2}, \ldots$
  - n/p-ratio for free spectator nucleons
  - multiplicity of spectator neutrons
Nuclear fragmentation at heavy-ion colliders?

- Presently only spectator neutrons and protons can be detected in forward calorimeters at RHIC\textsuperscript{1)} and LHC\textsuperscript{2,3)}.

- Nuclear spectator fragments remain undetected.

- There is a proposal to install a detector of spectator fragments at RHIC\textsuperscript{4)} to study fragmentation directly, but its status is not yet defined.

- However, one can use the information on the number of nucleon-nucleon collisions $N_{NN}$ extracted from multiplicity of produced particles to estimate the collision centrality\textsuperscript{3)}.

- Within a fragmentation model $N_{NN}$ or centrality can be related to multiplicity of spectator fragments, $Z_{\text{bound}}$ and other characteristics of spectator matter in each event.

\textsuperscript{1)} C. Adler et al., NIM A 499 (2003) 433-436
\textsuperscript{2)} G. Puddu et al., NIM A 581, 1-2 (2007)
\textsuperscript{3)} B. Abelev et al., PRC 88, 044909 (2013)
\textsuperscript{4)} S. Tarafdar et al., NIM A 768 170-178 (2014)
AAMCC

- Our model **Abrasion-Ablation Monte Carlo for Colliders (AAMCC)**\(^1\) written in C++ is based on the famous Glauber Monte Carlo v.3.0\(^2\) and models of decays of excited nuclei from Geant4 toolkit\(^3\) (G4Evaporation, G4SMM, G4FermiBreakUp).

- A difference in proton and neutron density distributions in colliding nuclei is taken into account in GlauberMC v3.0.

- We tested and improved\(^4\) G4SMM (E*/A\(_{pf}\) > 3 MeV) and G4FermiBreakUp (the latter is for explosive decays of Z < 9, A < 19 nuclei).


\(^2\) C. Loizides, J. Kamin, D. d’Enterria, PRC **97** (2018) 054910


\(^4\) I. Pshenichnov., A.S. Botvina, I. Mishustin, W. Greiner, NIMB **268** (2010) 604
Two kinds of correlation between excitation energy and prefragment volume are implemented in AAMCC

\[ \rho_e(E_x, a) = \frac{g_0^a}{a!(a-1)!} E_x^{a-1} \]

Level density in the particle-hole model: Ericson formula


\[ 1 - \frac{a}{A} = 1 - 0.015 \left( \frac{E_x}{(A - a)} \right)^2 \]

Empirical approximation by ALADIN collaboration


\( E_x \) – excitation energy
\( a \) – number of removed nucleons
\( A \) – mass number of the initial nucleus

Level density parameter \( g_0 \approx 16 \text{ MeV}^{-1} \)
AAMCC: comparison with experiment

Good description of these data in general with ALADIN approximation

EMU-01/12 collaboration – ZPA 359, 277 (1997)
Universality of fragmentation

Only slight changes of fragmentation from SPS to LHC in central collisions
Charge bound in fragments as a function of $N_{NN}$

Could be obtained via $N_{part}$, neutron and proton multiplicities

$Z_{bn} = \sum_{Z_i \geq n} Z_i$

$Z_{bound}, Z_{b2}, Z_{b3}, Z_{b7}$ decrease as $N_{NN}$ increases because the volume of spectator matter decreases and prefragment becomes hotter.
Multiplicity of fragments with given charge

Several fragments are produced in events with $400 < N_{NN} < 1000$

Indication of multifragment decays in semi-peripheral events
Multiplicity of nuclear fragments as a function of $N_{NN}$

The famous rise and fall of multifragmentation is evident in peripheral events. Several neutrons, deuterons, tritons and alpha-particles are produced via evaporation from heavy nuclei.

$$\langle M_F \rangle = 7.920$$

$$\langle M_{IMF} \rangle = 1.434$$

The famous rise and fall of multifragmentation is evident.
n/p-ratio as a function of $N_{NN}$

Significant increase in peripheral events with small $N_{NN}$.

Indicates the dominance of evaporation.
n/p-ratio for free nucleons

Central collision

Peripheral collision

n/p-ratio is close to the ratio for the initial nucleus.

Mostly neutrons are evaporated from heavy nuclei at low excitations.
Significant rise of neutron yield in peripheral events. A huge rise of n/p-ratio as a consequence.
Neutrons vs. $N_{NN}$

Can be measured by ALICE, STAR or other collider experiments

Results are very sensitive to the method to calculate excitation energy of prefragments
Neutrons vs. $Z_{\text{bound}}$

While the general shape of the correlation is preserved at the LHC, a higher yield of central events with small $Z_{\text{bound}}$ is predicted due to a larger $\sigma_{\text{NN}}$ at the LHC.

A subject of further studies
Summary

- By means of AAMCC model the number of NN-collisions in a PbPb event can be correlated with characteristics of spectator fragmentation, in particular with multiplicities of spectator neutrons and protons and their n/p-ratio.

- Such correlations can be measured at the LHC or elsewhere.

- According to AAMCC spectator fragmentation is quite violent. Average fragment multiplicities in minimum bias events are:
  \[ \langle M_F \rangle = 7.920 \quad \langle M_{IMF} \rangle = 1.434 \]

- \( Z_{\text{bound}} \) is decreasing monotonically with the number of NN-collisions.

- While the characteristics of nuclear fragmentation as functions of \( Z_{\text{bound}} \) very similar at SPS and LHC, some interesting deviations are predicted in very central events due to changes in \( \sigma_{\text{NN}} \).
Thank you for attention!

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