

## ULTRA-RELATIVISTIC LIGHT-HEAVY NUCLEAR COLLISIONS AND COLLECTIVITY\*

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We briefly review highlights for ultra-relativistic light-heavy collisions ( $p$ -Pb,  $d$ -Au,  $^3\text{He}$ -Au,  $^{12}\text{C}$ -Au) which display collective evolution, with the same very characteristic features as in the  $A$ - $A$  systems.

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This paper is based on Refs. [1–8] where more details and complete references may be found.

Collectivity of the evolution in the intermediate phase of ultra-relativistic nuclear reactions leads to specific, very characteristic signatures. Due to very large density of the initial fireball, collective flow of the medium is generated, which determines many features found in experiments as well as in modeling based on hydrodynamics of transport models. The most vivid hallmarks are:

1. The ridge structure in two-particle correlations in relative azimuth and pseudorapidity. In particular, the collimation of flow at distant pseudorapidities yields the away-side ridge. Observation of this phenomenon in  $p$ -Pb collisions, as well as in the highest multiplicity  $p$ - $p$  collisions, have changed our view on the dynamics of light-heavy reactions [9–13].

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2. Mass ordering of such observables as the mean transverse momentum or the harmonic flow coefficients. Due to emission from fluid elements moving with large collective velocity, heavier hadrons acquire more momentum than the lighter ones. In particular, collective modeling of  $p$ -Pb collisions [4] reproduces the data seen in proton-nucleus collisions [14].
3. The near-equality of higher-order cumulants (involving 4, 6, 8, *etc.*, particles) for the harmonic flow coefficients. The phenomenon is caused by the collective nature of correlations, and holds also for  $p$ -Pb reactions [15].
4. The fall-off of the HBT correlation radii with the transverse momentum of the pair also indicates flow in heavy-light systems [2, 7]. It has recently been observed in  $p$ -Pb collisions [16].
5. Transverse-momentum fluctuations, as generated by the mechanism of Ref. [17].
6. Long-range event-plane correlations in pseudorapidity and the torque effect [18–20].

Effects which involve harmonic flow rely on the shape-flow transmutation, thus are sensitive to the modeling of the initial state and fluctuations therein. Investigations of small systems serve to set the limits on applicability of hydrodynamics or transport theory, and differentiation with other approaches, for instance those based on the QCD saturation phenomena [21].

Results for the  $p$ - $A$  and  $d$ - $A$  [22] systems have been extensively presented in the cited literature, hence we do not discuss them here. In Figs. 1 and 2, we show an outcome of a recent study [7] for  $^3\text{He}$ -Au collisions, plotting the correlation function

$$C(\Delta\eta, \Delta\phi) = \frac{S(\Delta\eta, \Delta\phi)}{B(\Delta\eta, \Delta\phi)}, \quad (1)$$

where the signal  $S$  is constructed from pairs of particles with the relative pseudorapidity  $\Delta\eta$  and the relative azimuth  $\Delta\phi$ , while the background  $B$  is evaluated with the mixed events. The kinematic cuts indicated in Fig. 2 correspond to the PHENIX experiment [23]. We note the formation of the ridges, both on the Au and  $^3\text{He}$  sides, clearly indicating the collectivity of the dynamics. We note that the model based on hydrodynamics is in very good agreement with the data, as can be seen from Fig. 2.

The shape-flow transmutation has, to a good accuracy, the approximate feature that the distribution of scaled (*i.e.*, divided by the average) eccentricities in the initial state is equal to the distribution of the scaled harmonic flow [5]. The property holds as long as the response of the system to small eccentric perturbations is linear. Then, one finds corresponding equalities

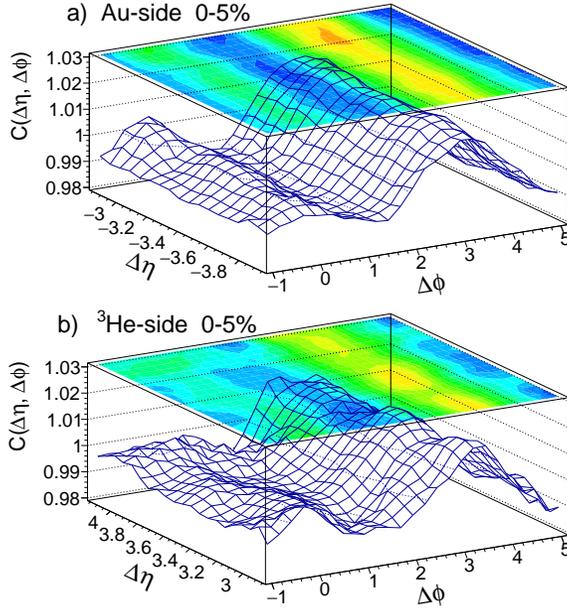


Fig. 1. The ridge effect in  ${}^3\text{He}$ -Au collisions, seen in the two-particle correlation function in relative azimuth and pseudorapidity (taken from Ref. [7]).

for scaled statistical event-by-event measures for  $n = 2, 3$  (higher-order harmonics have nonlinear response)

$$\frac{\sigma(\epsilon_n)}{\langle \epsilon_n \rangle} = \frac{\sigma(v_n)}{\langle v_n \rangle}, \quad \frac{\epsilon_n\{4\}}{\epsilon_n\{2\}} = \frac{v_n\{4\}}{v_n\{2\}}, \quad \text{etc.}, \quad (2)$$

where  $\{m\}$  indicates quantities obtained from  $m$ -particle cumulants. Formulas (2) have important practical significance, as they allow for making predictions for the measurable flow coefficients solely by modeling the eccentricities in the initial state, without the costly hydrodynamic simulations and hadronization.

In Ref. [8], a new methodology of studying the ground-state correlations in nuclear distributions has been proposed. It is based on the shape-flow transmutation, which carries over the initial eccentricities to the flow coefficients. As an interesting example, the  ${}^{12}\text{C}$  nucleus, due to strong  $\alpha$  clusterization, may be viewed as a small triangle. A collision at ultra-relativistic energy proceeds in a time much shorter from any characteristic nuclear time scale, hence a frozen ground-state configuration is seen. The collision forms a triangular fireball, which upon evolution leads to increased triangular flow. The picture is blurred to some extent with the fluctuations and averaging over orientations, nevertheless a substantial effect persists.

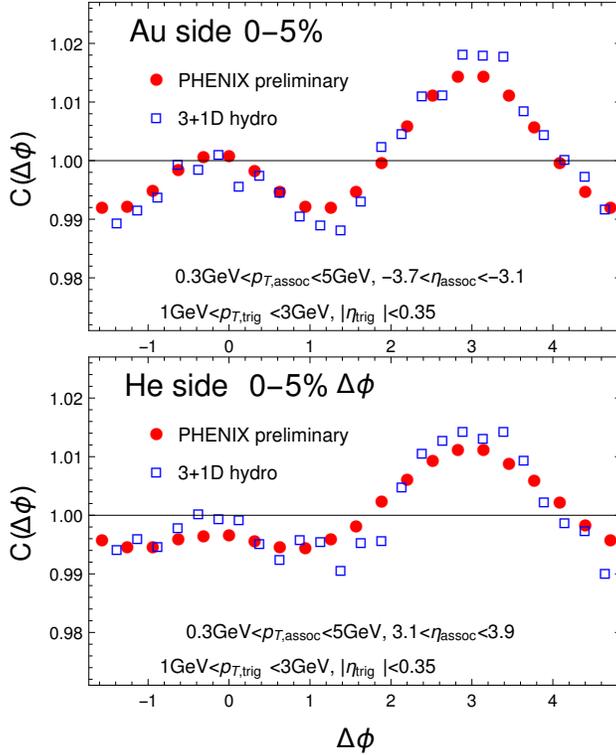


Fig. 2. Projected two-particle correlation function in relative azimuth. The PHENIX data come from Ref. [23] (taken from Ref. [7]).

In Fig. 3, we show the Glauber model predictions for the  $^{12}\text{C}-^{208}\text{Pb}$  collisions. We compare the clustered wave function (thick lines) to uniform distribution (thin lines). We note large effects, especially at low centralities. We note that the curves for the triangular flow coefficients change character at  $c \sim 10\%$ , where the clustered and uniform cases depart from each other: the scaled standard deviation of Fig. 3 (a) decreases with  $N_W$  for the clustered case, whereas for the uniform case it remains almost constant. The origin of this behavior is geometric. As  $N_W$  increases, the  $^{12}\text{C}$  triangle is oriented more and more face-on with respect to the reaction plane, hence average triangularity increases and the ratio  $\sigma(\epsilon_n)/\langle\epsilon_n\rangle$  decreases. The behavior for the ellipticity is opposite. Similarly, the cumulant ratios of Fig. 3 (b) change behavior around  $c = 10\%$ . These results, showing qualitative and quantitative sensitivity of the harmonic flow to specific features of the ground-state wave function, prove the feasibility of the proposed new method of studying low-energy nuclear structure with techniques developed for ultra-relativistic heavy-ion collisions.

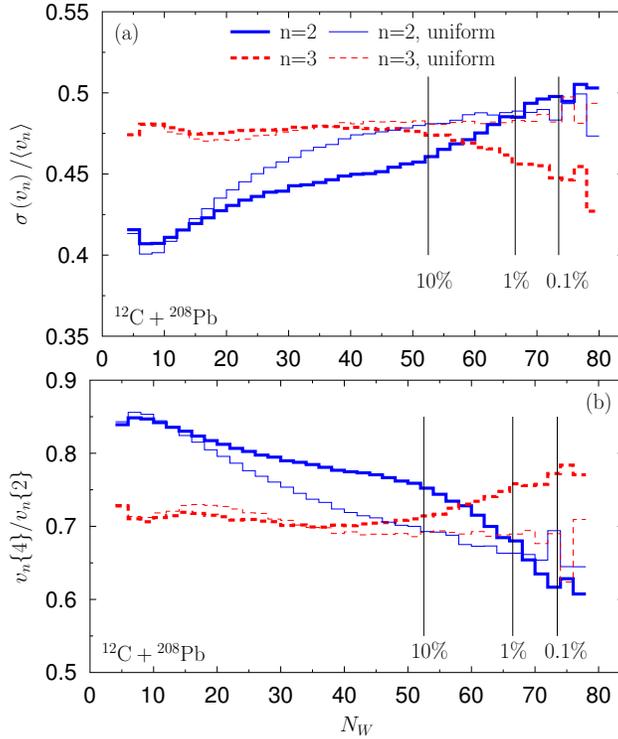


Fig. 3. Ratios (2) vs. the number of wounded nucleons for the  $^{12}\text{C}$ – $^{208}\text{Pb}$  collisions computed from the mixed Glauber model simulations [24] at the SPS energies, with the nucleon–nucleon inelastic cross section  $\sigma_{NN}^{\text{inel}} = 32$  mb. Centralities are indicated by vertical lines.

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## REFERENCES

- [1] P. Bożek, W. Broniowski, *Phys. Lett. B* **718**, 1557 (2013) [arXiv:1211.0845 [nucl-th]].
- [2] P. Bożek, W. Broniowski, *Phys. Lett. B* **720**, 250 (2013) [arXiv:1301.3314 [nucl-th]].
- [3] P. Bożek, W. Broniowski, *Phys. Rev. C* **88**, 014903 (2013) [arXiv:1304.3044 [nucl-th]].

- [4] P. Bożek, W. Broniowski, G. Torrieri, *Phys. Rev. Lett.* **111**, 172303 (2013) [arXiv:1307.5060 [nucl-th]].
- [5] P. Bożek, W. Broniowski, *Phys. Lett. B* **739**, 308 (2014) [arXiv:1409.2160 [nucl-th]].
- [6] P. Bożek *et al.*, *Phys. Rev. C* **90**, 064902 (2014) [arXiv:1410.7434 [nucl-th]].
- [7] P. Bożek, W. Broniowski, *Phys. Lett. B* **747**, 135 (2015) [arXiv:1503.00468 [nucl-th]].
- [8] W. Broniowski, E. Ruiz Arriola, *Phys. Rev. Lett.* **112**, 112501 (2014) [arXiv:1312.0289 [nucl-th]].
- [9] V. Khachatryan *et al.* [CMS Collaboration], *J. High Energy Phys.* **1009**, 091 (2010) [arXiv:1009.4122 [hep-ex]].
- [10] A. Adare *et al.* [PHENIX Collaboration], *Phys. Rev. Lett.* **111**, 212301 (2013) [arXiv:1303.1794 [nucl-ex]].
- [11] G. Aad *et al.* [ATLAS Collaboration], *Phys. Rev. Lett.* **110**, 182302 (2013) [arXiv:1212.5198 [hep-ex]].
- [12] S. Chatrchyan *et al.* [CMS Collaboration], *Phys. Lett. B* **724**, 213 (2013) [arXiv:1305.0609 [nucl-ex]].
- [13] B. Abelev *et al.* [ALICE Collaboration], *Phys. Lett. B* **719**, 29 (2013) [arXiv:1212.2001 [nucl-ex]].
- [14] B. Abelev *et al.* [ALICE Collaboration], *Phys. Lett. B* **727**, 371 (2013) [arXiv:1307.1094 [nucl-ex]].
- [15] A. Bzdak, P. Bożek, L. McLerran, *Nucl. Phys. A* **927**, 15 (2014) [arXiv:1311.7325 [hep-ph]].
- [16] J. Adam *et al.* [ALICE Collaboration], *Phys. Lett. B* **746**, 1 (2015) [arXiv:1502.01689 [nucl-ex]].
- [17] W. Broniowski, M. Chojnacki, L. Obara, *Phys. Rev. C* **80**, 051902 (2009) [arXiv:0907.3216 [nucl-th]].
- [18] P. Bożek, W. Broniowski, J. Moreira, *Phys. Rev. C* **83**, 034911 (2011) [arXiv:1011.3354 [nucl-th]].
- [19] J. Jia, P. Huo, *Phys. Rev. C* **90**, 034915 (2014) [arXiv:1403.6077 [nucl-th]].
- [20] P. Bożek, W. Broniowski, arXiv:1506.02817 [nucl-th].
- [21] K. Dusling, R. Venugopalan, *Phys. Rev. D* **87**, 051502 (2013) [arXiv:1210.3890 [hep-ph]].
- [22] P. Bożek, *Phys. Rev. C* **85**, 014911 (2012) [arXiv:1112.0915 [hep-ph]].
- [23] S. Huang [PHENIX Collaboration], talk given at the Workshop on Initial Stages of High Energy Nuclear Collision, Napa, CA, December 3–7, 2014.
- [24] M. Rybczyński *et al.*, *Comput. Phys. Commun.* **185**, 1759 (2014) [arXiv:1310.5475 [nucl-th]].