XXVIIIth International Conference on Ultrarelativistic Nucleus-Nucleus Collisions
(Quark Matter 2019)

Flow in collisions of light nuclei[☆]

Wojciech Broniowski[a,b], Piotr Bożek[c], Maciej Rybczyński[a], Enrique Ruiz Arriola[d]

[a]*Institute of Physics, Jan Kochanowski University, 25-406 Kielce, Poland*
[b]*H. Niewodniczański Institute of Nuclear Physics, Polish Academy of Sciences, 31-342 Cracow, Poland*
[c]*AGH University of Science and Technology, Faculty of Physics and Applied Computer Science, 30-059 Cracow, Poland*
[d]*Departamento de Física Atómica, Molecular y Nuclear and Instituto Carlos I de Física Teórica y Computacional,
Universidad de Granada, E-18071 Granada, Spain*

Abstract

In this talk we discuss several interesting aspects of collective flow in small systems in reference to planned future experiments. First, we bring in the novel possibility of exploring elliptic flow with heavy nuclei collisions on polarized deuteron targets, accessible in AFTER@LHC program after Long Shutdown 3. Then we discuss the Glauber model predictions for the presently considered ^{16}O – ^{16}O program at RHIC and the LHC. Finally, we turn to our previous proposal concerning specific flow signatures of intrinsic correlations (such as the predicted α clusterization) in the structure of light nuclei in collisions with heavy nuclei. In particular, ^{12}C–heavy nucleus ultrarelativistic reactions would provide insight into the ground-state ^{12}C structure, complementary to traditional nuclear structure measures.

Keywords: ultrarelativistic light-heavy collisions, harmonic flow, collisions with polarized deuteron, nuclear clustering

1. Collisions on polarized deuteron targets

The deuteron, being a spin $j = 1$ nucleus, can be polarized in an external magnetic field *B*. The admixture of the *D*-wave in its ground-state wave function leads to an intrinsic deformation of the nucleon matter distribution; it is prolate for $j_3 = \pm 1$ and oblate for for $j_3 = 0$, where j_3 is the projection of spin along the polarization axis *B*, see Fig. 1 (left). When such a polarized deuteron target is hit with an ultrarelativistic heavy nucleus, the deformation of the formed fireball in the transverse plane reflects, to a large degree, the intrinsic deformation of the deuteron. The following collective evolution produces, via the shape–flow transmutation mechanism, elliptic flow which can be quantified with respect to the (fixed) polarization axis in terms of a *one-body* quantity, which would be straightforward to measure experimentally [1, 2].

[☆]Talk by WB at parallel session *Small systems*, Quark Matter 2019, 4-9 Nov. 2019, Wuhan, China
    Email addresses: Wojciech.Broniowski@ujk.edu.pl (Wojciech Broniowski), Piotr.Bozek@fis.agh.edu.pl (Piotr Bożek), Maciej.Rybczynski@ujk.edu.pl (Maciej Rybczyński), earriola@ugr.es (Enrique Ruiz Arriola)
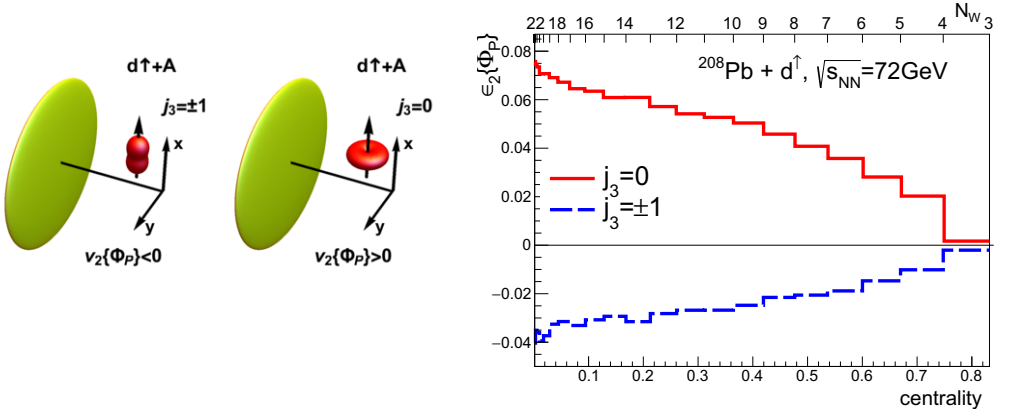
Fig. 1. Left: A schematic view of the ultra-relativistic collision of a heavy nucleus on the deuteron target polarized along ($j_3 = \pm1$) and perpendicular ($j_3 = 0$) to the fixed polarization axis $\{\Phi_P\}$. The deformation of the created fireball in the transverse plane reflects the intrinsic deformation of the polarized deuteron. The collective *shape-flow transmutation* mechanism results in the *one body* elliptic flow coefficient with respect to the polarization axis, $v_2\{\Phi_P\}$, with the signs as labeled in the figure. Right: Ellipticities of the initial condition in the fireball, evaluated with respect to the fixed polarization axis, $\epsilon_2\{\Phi_P\}$, for Pb collisions on a polarized deuteron target at $\sqrt{s_{NN}} = 72$ GeV. The lower-axis coordinate is the centrality determined from the initial entropy S, whereas the top-axis coordinate is the corresponding number of the wounded nucleons, N_W. (Graphics from [2])

The planned fixed target AFTER@LHC experiments, in particular SMOG2@LHCb [3, 4, 5, 6], will be able to study collisions of a 2.76A TeV Pb beam on fixed targets, with a possibility of using in the future polarized hydrogen and deuterium targets [7], which can be installed during the LHC Long Shutdown 3 in the years 2023-2025. We note that the proposed method requires a measurement of a one-body distribution and, with a very high beam intensity, could be simply performed with minimum bias events and without event plane reconstruction or pile-up corrections. Precise estimates, including hydrodynamic simulations, error estimates, etc., are provided in [2].

An analogous effect is present for collisions on other light targets with $j \geq 1$, such as ^{7}Li, ^{9}Be, or ^{10}B. Interestingly, the magnitude of the elliptic flow can be estimated from their known mean square radii and quadrupole moments, and is sizable, even larger that for the case of the deuteron. The estimate for the elliptic flow coefficient evaluated with respect to the polarization axis is [2]

$$v_2\{\Phi_P\} \simeq -k \frac{3Q_2}{4Z(\langle r^2 \rangle + \frac{3}{2}\langle b^2 \rangle)} \frac{3j_3^2 - j(j+1)}{j(2j-1)},$$

where $k \sim 0.1$ is the hydrodynamic response coefficient, Q_2 is the quadrupole moment, Z is the atomic number, and $\langle r^2 \rangle$ is that mean squared charge radius of the light nucleus. The quantity $\langle b^2 \rangle \sim 1$ fm^2 is the average impact parameter squared in inelastic NN collisions. The formula holds for perfect polarization, sufficiently central collisions, and $j \geq 1$.

If the effect of the elliptic flow in polarized heavy–light collisions is indeed confirmed, it would corroborate the scenario of the late-stage generation of collectivity. Other interesting opportunities emerging from such collisions involve studies of hard probes as well as femtoscopic correlations, with appropriate measures defined with respect to the polarization axis.

2. ^{16}O − ^{16}O collisions

Proposals to study collisions with ^{16}O beams at the LHC [8] and at RHIC [9] are presently under serious consideration. In this regard we have carried out an analysis of the initial state in ^{16}O-^{16}O in the Monte Carlo Glauber approach [10]. Similar results in other models were presented earlier in [11, 12, 13]. The results can
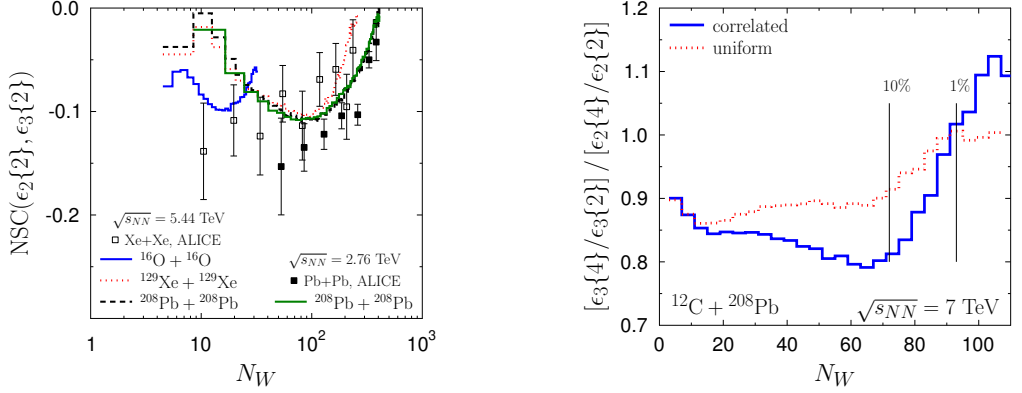
Fig. 2. Left: GLISSANDO [14] results for symmetric cumulants for various collisions systems indicated in the legend, plotted as a function of N_w. Large systems are compared to the available data. The solid line represents predictions for $^{16}O - ^{16}O$ collisions. Right: Double eccentricity ratio for $^{12}C - ^{208}Pb$ collisions from GLISSANDO for the correlated (clustered) and uniform ^{12}C structure, plotted as a function of N_w. The observed non-monotonicity of the solid line is a hallmark of clusterization. (Graphics in the left panel from [10])

be summarized with a statement that they are qualitatively similar to the effects found in heavier collision systems, with a natural scaling towards the smaller number of participants. A typical result is shown in the left panel of Fig. 2, where we plot the normalized symmetric cumulant, measuring correlations between the elliptic and triangular deformations. We note a similar behavior in ^{16}O-^{16}O as in Pb-Pb or Xe-Xe, albeit, as expected, moved to lower values of the number of wounded nucleon, N_W. Further results are given in [10].

3. Signature of intrinsic correlations

Over the past few years we have been pursuing the idea [15, 16, 17, 18] that clustering in light nuclei may produce specific signals in harmonic flow correlations in reactions with heavy nuclei. The issue is fundamentally interesting, as in collisions at the highest available energies the reaction time is so short that the existing nucleon cluster structures (such as the α particles present in the ground state) are effectively frozen when the nuclear wave function collapses. As a result, the shape of the formed fireball in the transverse plane is, event-by-event, revealing information on the lowest-energy ground-state of the light nucleus colliding with a "wall" of a heavy nucleus.

Most promising signals for the cluster effects would originate from ^{12}C - heavy nucleus collisions, since the ^{12}C nucleus is believed to have a prominent cluster structure (for a review, see [19]), with three α particles in configuration of an equilateral triangle. In our GLISSANDO [14] simulations we have used configurations from state-of-the-art cluster Variational Monte Carlo simulations [20], as supplied in files in [21]. Similar studies were reported in [11]. We stress that the dynamically generated distributions used here contain realistic nuclear correlations.

An example of a measure sensitive to the cluster correlations in the light nucleus is the double ratio of triangular and elliptic eccentricities evaluated with cumulants with 2 and 4 particles, $[\epsilon_3\{4\}/\epsilon_3\{2\}]/[\epsilon_2\{4\}/\epsilon_2\{2\}]$. It is plotted in the right panel of Fig. 2 as a function of the number of wounded nucleons. We note a characteristic non-monotonic behavior for the case where the ^{12}C nucleus is clustered (solid line), as opposed to the case of a uniform distribution (dotted line). An analogous behavior is expected for the corresponding double ratio of the elliptic and triangular flow coefficients. More details can be found in [15, 16, 17, 18].

To summarize, various intriguing and hitherto unexplored physical effects may be explored in future heavy-light ultrarelativistic nuclear collisions, which may further probe the origin of collectivity in the fireball dynamics and its limits, as well as investigate the nuclear structure correlation effects in the initial

state. The observation of the discussed effects would confirm the scenario of the late stage generation of collective flow in small systems, which, while plausible, needs independent and unique tests.

References

[1] P. Bożek, W. Broniowski, Elliptic Flow in Ultrarelativistic Collisions with Polarized Deuterons, Phys. Rev. Lett. 121 (20) (2018) 202301. arXiv:1808.09840, doi:10.1103/PhysRevLett.121.202301.

[2] W. Broniowski, P. Bożek, Elliptic flow in ultra-relativistic collisions with light polarized nucleiarXiv:1906.09045.

[3] C. Barschel, Precision luminosity measurement at LHCb with beam-gas imaging, Ph.D. thesis, RWTH Aachen U. (2014).

[4] R. Aaij, et al., Precision luminosity measurements at LHCb, JINST 9 (12) (2014) P12005. arXiv:1410.0149, doi:10.1088/1748-0221/9/12/P12005.

[5] LHCb Collaboration, LHCb SMOG Upgrade, Tech. Rep. CERN-LHCC-2019-005. LHCB-TDR-020, CERN, Geneva (May 2019).
URL http://cds.cern.ch/record/2673690

[6] A. Bursche, H. P. Dembinski, P. Di Nezza, M. Ferro-Luzzi, F. Fleuret, G. Graziani, G. Manca, E. A. Maurice, N. Neri, L. L. Pappalardo, P. Robbe, M. Schmelling, M. A. Winn, V. Zhukov, Physics opportunities with the xed-target program of the LHCb experiment using an unpolarized gas target, Tech. Rep. LHCb-PUB-2018-015. CERN-LHCb-PUB-2018-015, CERN, Geneva (Dec 2018).
URL https://cds.cern.ch/record/2649878

[7] C. A. Aidala, et al., The LHCSpin ProjectarXiv:1901.08002.

[8] Z. Citron, et al., Report from Working Group 5, in: A. Dainese, M. Mangano, A. B. Meyer, A. Nisati, G. Salam, M. A. Vesterinen (Eds.), Report on the Physics at the HL-LHC,and Perspectives for the HE-LHC, 2019, pp. 1159–1410. arXiv:1812.06772, doi:10.23731/CYRM-2019-007.1159.

[9] STAR Collaboration, The star beam use request for run-20 and run-21 (2019).
URL https://drupal.star.bnl.gov/STAR/system/files/BUR2019_final_0.pdf

[10] M. Rybczyński, W. Broniowski, Glauber Monte Carlo predictions for ultra-relativistic collisions with ^{16}O, Phys. Rev. C100 (6) (2019) 064912. arXiv:1910.09489, doi:10.1103/PhysRevC.100.064912.

[11] S. H. Lim, J. Carlson, C. Loizides, D. Lonardoni, J. E. Lynn, J. L. Nagle, J. D. Orjuela Koop, J. Ouellette, Exploring New Small System Geometries in Heavy Ion Collisions, Phys. Rev. C99 (4) (2019) 044904. arXiv:1812.08096, doi:10.1103/PhysRevC.99.044904.

[12] M. D. Sievert, J. Noronha-Hostler, CERN Large Hadron Collider system size scan predictions for PbPb, XeXe, ArAr, and OO with relativistic hydrodynamics, Phys. Rev. C100 (2) (2019) 024904. arXiv:1901.01319, doi:10.1103/PhysRevC.100.024904.

[13] S. Huang, Z. Chen, J. Jia, W. Li, Disentangle contributions to small-system collectivity via scans of light nucleus-nucleus collisionsarXiv:1904.10415.

[14] P. Bożek, W. Broniowski, M. Rybczyński, G. Stefanek, GLISSANDO 3: GLauber Initial-State Simulation AND mOre..., ver. 3, Comput. Phys. Commun. 245 (2019) 106850. arXiv:1901.04484, doi:10.1016/j.cpc.2019.07.014.

[15] W. Broniowski, E. Ruiz Arriola, Signatures of alpha clustering in light nuclei from relativistic nuclear collisions, Phys. Rev. Lett. 112 (2014) 112501. arXiv:1312.0289, doi:10.1103/PhysRevLett.112.112501.

[16] E. Ruiz Arriola, W. Broniowski, Low Energy Nuclear Structure from Ultra-relativistic Heavy-Light Ion collisions, J. Phys. Conf. Ser. 630 (1) (2015) 012060. arXiv:1411.5807, doi:10.1088/1742-6596/630/1/012060.

[17] P. Bożek, W. Broniowski, E. Ruiz Arriola, M. Rybczyński, α clusters and collective flow in ultrarelativistic carbon – heavy-nucleus collisions, Phys.Rev. C90 (6) (2014) 064902. arXiv:1410.7434, doi:10.1103/PhysRevC.90.064902.

[18] M. Rybczyński, M. Piotrowska, W. Broniowski, Signatures of α clustering in ultrarelativistic collisions with light nuclei, Phys. Rev. C97 (3) (2018) 034912. arXiv:1711.00438, doi:10.1103/PhysRevC.97.034912.

[19] M. Freer, H. Horiuchi, Y. Kanada-En'yo, D. Lee, U.-G. Meißner, Microscopic Clustering in Light Nuclei, Rev. Mod. Phys. 90 (3) (2018) 035004. arXiv:1705.06192, doi:10.1103/RevModPhys.90.035004.

[20] D. Lonardoni, A. Lovato, S. C. Pieper, R. B. Wiringa, Variational calculation of the ground state of closed-shell nuclei up to $A = 40$, Phys. Rev. C96 (2) (2017) 024326. arXiv:1705.04337, doi:10.1103/PhysRevC.96.024326.

[21] C. Loizides, J. Nagle, P. Steinberg, Improved version of the PHOBOS Glauber Monte Carlo, SoftwareX 1-2 (2015) 13–18. arXiv:1408.2549, doi:10.1016/j.softx.2015.05.001.