Exploring the medium anisotropy in p–O and p–C collisions at the LHC energy with exotic α-clusters

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Introduction

In ultra-relativistic heavy-ion collisions at the LHC, the signatures of quark-gluon plasma (QGP) are studied considering proton-proton (pp) collisions as the baseline, where the formation of QGP is usually not anticipated. But the recently observed heavy-ion like features in high multiplicity pp and p–Pb collisions have motivated collider physicists to explore small collision systems in detail, one of the interests being the small system collectivity [1]. Anisotropic flow, which develops mainly due to the initial spatial asymmetry during non-central nuclear collisions, can be quantified via the anisotropy in the momentum distribution of the final state particles and can provide strong evidence of collectivity in the medium formed during the ultra-relativistic collisions, if any.

As a timely reward, the Run 3 data taking at the LHC has planned to inject oxygen (^{16}O) beams for the first time to make p–O and O-O collisions possible. These collision systems are apt in their system size as they bridge the multiplicity gap between pp, p–Pb and Pb–Pb collisions. They can also aid to comprehend the observed collective phenomena in asymmetric systems like p–Pb which serves as a baseline for cold nuclear effects. The p–O collisions, in particular, closely resemble the interaction of cosmic rays with atmospheric oxygen, thus helping us constrain various theoretical models dealing with cosmic air showers. Apart from these, the possibility for the nucleons inside ^{16}O and ^{12}C nuclei to arrange themselves into α-clusters, gives us a unique opportunity to investigate the effects of α-clustering on the final state anisotropic flow coefficients viz. v_2 and v_3, as they are known to be sensitive to the initial nuclear distributions, fluctuations and deformations [2].

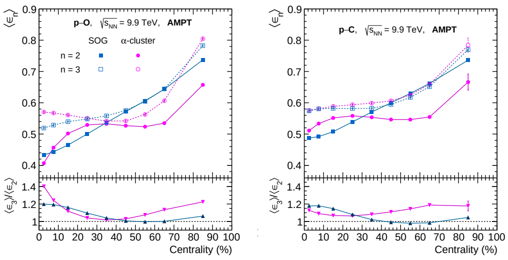

FIG. 1: Centrality dependence of $\langle\epsilon_2\rangle$ and $\langle\epsilon_3\rangle$ for p–O (left) and p–C (right) collisions at $\sqrt{s_{\rm NN}}$ = 9.9 TeV using AMPT for SOG and α–cluster nuclear density profiles. Ratio $\langle\epsilon_3\rangle/\langle\epsilon_2\rangle$ as a function of centrality is plotted in the lower panel [3].

Thus, with a specific interest to probe the effects of exotic α-clusters on the final state momentum anisotropy, for the first time, we perform p–O and p–C collisions at $\sqrt{s_{\rm NN}}$ = 9.9 TeV within a multiphase transport model framework. This study implements two different nuclear density profiles: the sum-of-Gaussians (SOG) and the α-cluster type density profiles, for the nuclei. We use the two-particle-Q-cumulant method to extract the flow coefficients, which deals with removing the non-flow effects by introducing a pseudorapidity gap. The details of nuclear density profile implementation, event generation, and flow estimation methodology can be found in Ref. [3].

Results and Discussions

The initial spatial anisotropy, quantified by eccentricity ($\langle\epsilon_2\rangle$) and triangularity ($\langle\epsilon_3\rangle$) are studied in Fig. 1 as a function of centrality

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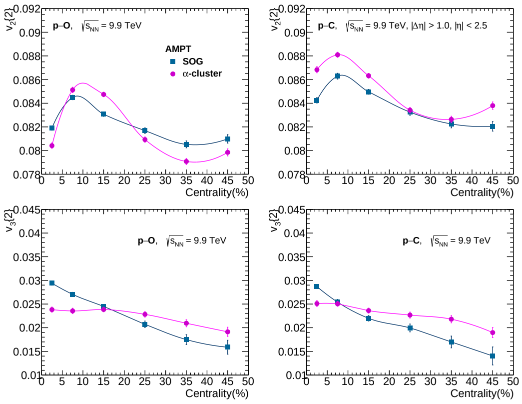

FIG. 2: v_2 and v_3 as a function of centrality for SOG and α-cluster density profiles in p–O and p–C collisions at $\sqrt{s_{\rm NN}} = 9.9$ TeV [3].

for two density profiles namely, SOG and α-cluster in p–O and p–C collisions, at $\sqrt{s_{\rm NN}}$ = 9.9 TeV using AMPT. While $\langle\epsilon_2\rangle$ increases steadily with collision centrality for the SOG profile in both p–O and p–C collisions, the α-cluster density profile maintains a unique wavy trend. The SOG distribution has a dense core with matter density decreasing gradually towards the periphery of the nucleus but α-cluster profile has nucleons concentrated at certain distances, leading to a nuclear-profile-dependent behavior of $\langle\epsilon_2\rangle$. $\langle\epsilon_3\rangle$ for both the density profiles in p–C collisions show very similar increments with centrality while for p–O collisions, α-cluster profile shows a trend complementary to that shown by $\langle\epsilon_2\rangle$. This is reflected in the $\langle\epsilon_3\rangle/\langle\epsilon_2\rangle$ ratio, where we see a hike in the ratio for the most central p–O collisions. On the other hand, such a central hike is absent in p–C collisions and could be attributed to the presence of an extra α-cluster in ^{16}O nucleus. Thus, even when the collision species remain the same, a difference in nuclear density profile leads to differences in the initial anisotropies.

Figure 2 shows the centrality dependence of elliptic (v_2) and triangular (v_3) flow for SOG and α-cluster density profiles in p–O and p–C collisions. We see that the centrality dependence of $\langle\epsilon_2\rangle$ is not well-reflected in the values of v_2 for both p–O and p–C collision systems in mid-central and peripheral collisions due to a smaller number of participants. Still, the uniqueness of the α-cluster profile is evidently visible. In the case of triangular flow that decreases with collision centrality, v_3 from α-cluster case dominates over that of SOG trend after central collisions. When compared in magnitude, the collision centrality dependence shown by v_2 is smaller than the corresponding v_3. It is also observed that both $\langle\epsilon_2\rangle$ and v_2 have higher magnitudes in p–C than in p–O collisions, owing to a smaller system with larger density fluctuations.

In addition to these, we also study the ratios that characterize the response of the formed medium to the evolution of anisotropic flow viz. $v_2/\langle\epsilon_2\rangle$, $v_3/\langle\epsilon_3\rangle$ and v_3/v_2 which can be found in Ref [3].

Summary

In summary, this study reports the effect of the initial eccentricity and triangularity on the final-state azimuthal anisotropy in small collision systems like p–O and p–C at $\sqrt{s_{\rm NN}} = 9.9$ TeV, using AMPT. It employs the two-particle cumulant method which can reduce substantial non-flow effects from the calculation. It is found that the choice of the nuclear density profile affects not only the initial eccentricities but also the production yield and the final-state anisotropic flow coefficients. This study thus serves as a transport model-based prediction for the future O–O and p–O collisions planned at the LHC in the coming years, connecting nuclear structure with observables in TeV heavy-ion collisions.

References

[1] V. Khachatryan *et al.* [CMS], Phys. Lett. B **765**, 193 (2017).

[2] D. Behera, S. Prasad, N. Mallick and R. Sahoo, Phys. Rev. D **108**, 054022 (2023).

[3] Aswathy Menon K.R., S. Prasad, N. Mallick and R. Sahoo, [arXiv:2407.03823 [nucl-th]] and the references therein.