Elucidating cluster structure in ^{16}O nucleus with O-AgBr collisions at 60 AGeV

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Introduction

The primary goal of relativistic heavy-ion collisions is to create and characterize quark-gluon plasma (QGP), a medium of strongly interacting deconfined quarks and gluons. It has been recently realized that such collisions can also be used to probe into the inner structures of the atomic nuclei. For example, data from the isobar collisions at RHIC have revealed a hint of octupole deformation in Zirconium (^{96}Zr) nucleus and Xe-Xe collisions at LHC indicate triaxial deformation in ^{129}Xe nucleus [1, 2]. In 2025, collisions of Oxygen (^{16}O) nuclei have been proposed at LHC. It is known since long that ^{16}O nucleus may have a novel cluster configuration whereby four ^{4}He nuclei (α particle) are arranged in a tetrahedral shape.

Currently several studies are being done to speculate the outcome of having such exotic structures in the atomic nuclei on the final state observables, which are measured quite often in heavy-ion collisions. Of particular interest are the measurements of anistropic flow coefficients v_n, that carry an imprint of the shape of the initial matter distribution in the collision region, where two nuclei overlap, to the final stage. If ^{16}O nucleus possesses such cluster structure, the initial shape of the collision region is likely to be different from the one without cluster structure. This difference is expected to be captured by the measurements of anistropic flow coefficients and manifested in the final stage.

Implementation of α-cluster in ^{16}O

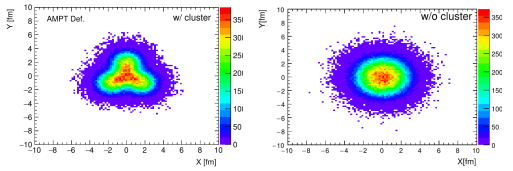

FIG. 1: Spatial distribution of nucleons in x-y plane for ^{16}O (left) with cluster and (right) without cluster configuration.

In this work, we simulate the cluster configuration of ^{16}O nucleus within the framework of Glauber Monte Carlo (GMC) with a tetrahedral geometry, where 4 α-particles occupy vertices of a regular tetrahedron. The distributions of nucleons within the α-particles are sampled from a three parameter (3pF) Woods-Saxon density profile,

$$\rho(r) = \frac{\rho_0(1+\omega(r/r_0)^2)}{1+\mathrm{Exp}(\frac{r-r_0}{a})}. \qquad (1)$$

The parameters in Eq. 1 have their usual meanings and for ^{4}He nucleus their values are, r_0 = 0.964 fm, ω = 0.517 and a = 0.322 fm. For reference we also simulate unclustered ^{16}O nucleus by sampling the spatial distributions of nucleons from Eq. 1 with the parameter values as follows, r_0 = 2.608 fm, ω = -0.051 and a = 0.513. Figure 1 shows the spatial distribution of nucleons in x-y plane for cluster (left) and non-cluster (right) configurations. The initial nucleon distribution for the clustered configuration of ^{16}O exhibits a triangular shape in x-y plane when sampled over

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many events. In reality this triangular shape will not be so prominent because the orientation of the nucleus would be random from event to event.

Analysis

We implement this cluster configuration for ^{16}O in A Multiphase Transport Model (AMPT) and simulate particle production using its default version. To constrain the free parameters in the AMPT model namely, the **a** and **b** parameters of Lund String fragmentation function, strong coupling constant α_s and gluon screening mass μ, we use the data from emulsion stacks exposed to ^{16}O beam at 60 AGeV at CERN SPS [3].

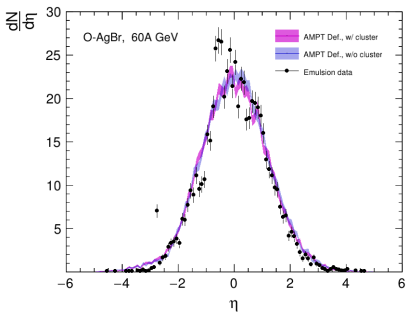

FIG. 2: η-distribution of charged particles produced in O-AgBr collisions at 60 AGeV

Figure 2 shows the pseudorapidity (η) distribution of charged particles produced in O-AgBr collisions at 60 AGeV in nuclear emulsion experiment and its comparison with AMPT model calculation. It is to be noted that the chemical composition of nuclear emulsion medium is mainly silver bromide (AgBr). So, ^{16}O beam interacts with both Ag and Br. As a result the final outcome is always a mix between the two. In AMPT, we replicate this situation by simulating events independently for O-Ag and O-Br collisions at 60 AGeV and then mix them in exact proportions. As can be seen from Fig. 2, AMPT predictions for O-AgBr collisions are in good agreement with nuclear emulsion data for both clustered and unclustered initial configurations of ^{16}O nucleus. Also it is to be mentioned that the η-distributions are shifted to zero both in data and model calculation.

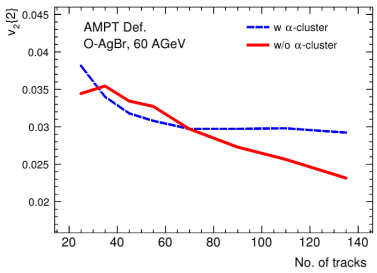

FIG. 3: Elliptic flow coefficient, $v_2\{2\}$ obtained from default AMPT model calculations with and without implementing cluster configuration for ^{16}O.

Having constrained the free parameters in the AMPT model to reproduce η-distribution for O-Ag(Br) collision at 60 AGeV, we now proceed to calculate the second order anisotropic flow coefficient, v_2 or the elliptic flow. The elliptic flow coefficient $v_2\{2\}$, has been calculated using 2-particle cumulant method. Figure 3 shows the comparison between $v_2\{2\}$ as a function of charged particle multiplicity from the AMPT model calculation with and without incorporating cluster configuration in the initial state. One can see a clear difference between the two, particularly towards the high multiplicity region, where the magnitude of $v_2\{2\}$ for cluster configuration is larger than the unclustered case. This feature seen in the model calculation can be readily tested when data become available. Further study of higher harmonics and flow fluctuations, particularly in central ^{16}O on heavy-ions (like Au, Pb, etc) collisions, could be useful in deciphering the cluster structure in ^{16}O nucleus.

References

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