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Probing Nuclear Cluster Structure and Nucleon-Nucleon Correlations in Heavy-Ion Collisions

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This work presents a comprehensive theoretical investigation into the influence of nuclear microstructure, specifically nucleon-nucleon (NN) correlations and α-cluster structures, on initial-state fluctuations in heavy-ion collisions. By establishing a direct link between nuclear structure details and experimentally measurable observables, we provide crucial theoretical predictions for upcoming experiments at the Large Hadron Collider (LHC).
we propose a novel approach to distinguish between competing α-cluster configurations in light nuclei, using the 20Ne nucleus as a case study. We use the microscopic Brink cluster model to describe two key configurations: a bowling-pin-like α+16O structure and a bi-pyramidal 5α structure. By analyzing initial-state quantities, we identify the normalized symmetric cumulant NSC(3,2) and the Pearson coefficient ρ(ϵ32,δd⊥) as quantitative discriminators. We demonstrate that these observables exhibit a characteristic sign inversion between the two configurations. Specifically, the α+16O configuration predicts a positive NSC(3,2) and negative ρ(ϵ32,δd⊥), while the 5α configuration reverses these signs. This sign discrimination provides a robust and unambiguous method to identify α-clustering and differentiate complex nuclear structures. These analytical predictions can be directly tested in upcoming ultra-central Ne+Ne collisions at the LHC, as well as in fixed-target Pb+Ne collisions, offering complementary probes of the cluster configurations. Our work establishes a new paradigm for probing many-body quantum correlations and nuclear structure transitions through high-energy heavy-ion collisions.
Second, our research addresses two distinct but related facets of nuclear structure. First, we explore the effect of short-range NN correlations on high-energy collisions. We developed a novel Monte Carlo sampling method based on the Adaptive Grid Monte Carlo (AGMC) algorithm to efficiently generate nucleon spatial distributions that include many-body correlation effects. Our analysis reveals that higher-order initial-state fluctuation observables, particularly the third-order cumulant cE/S{3}, exhibit significant sensitivity to these correlations, with a relative deviation exceeding 10% between correlated and uncorrelated systems. This suggests that the final-state three-particle transverse momentum correlation ⟨⟨(δpT)3⟩ is a highly sensitive observable for probing NN correlations. We find that the effect of NN correlations is more pronounced in large spherical nuclei than in smaller systems, as the effects of particle position fluctuations are suppressed in larger nuclei. We also demonstrate that the NN correlation effect on the second-order eccentricity ϵ2 is significantly greater than on the third-order eccentricity ϵ3, which provides a potential solution to the v2−v3 puzzle observed in ultra-central Pb-Pb collisions. These findings not only constrain theoretical models of NN interactions but also highlight the importance of considering NN correlations when extracting properties of the quark-gluon plasma (QGP), such as the speed of sound.
In summary, this research underscores the power of heavy-ion collisions as a tool for nuclear structure research. By combining a novel Monte Carlo sampling method to incorporate NN correlations with a rigorous analytical framework for discriminating cluster structures, our work provides critical, quantitative predictions for future experimental programs, advancing our understanding of the fundamental properties of nuclear matter.

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