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Light nuclei elliptic flow at mid-rapidity in $\sqrt{s_{NN}} = 3.0 - 3.9$ GeV Au+Au collisions using coalescence model

Authors: Dr. Yue Xu, He, Dr. Xionghong, Zhang, Prof. Ya-Peng, He, Dr. Xionghong

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Abstract

Light nuclei collective flow is an important probe for understanding their production mechanisms in heavy-ion collisions. The STAR collaboration has reported that the atomic mass number (A) scaling of light nuclei elliptic flow v2 is broken at $\sqrt{s_{NN}} = 3.0-3.9$ GeV. The observations reveal that, while protons maintain negative v2 values at mid-rapidity at both 3.0 and 3.2 GeV, light nuclei v2 exhibit a sign change from negative at 3.0 GeV to positive at 3.2 GeV. In this study, we investigate v2 of protons and deuterons in mid-central Au+Au Collisions at $\sqrt{s_{NN}} = 3.0$, 3.2, 3.5 and 3.9 GeV using the JAM2 microscopic transport model. Deuterons are formed via nucleon coalescence, with the spatial distance ΔR and momentum difference ΔP between constituent protons and neutrons serving as the coalescence criteria. Our calculations successfully reproduce the sign change in deuteron v_2 at 3.2 GeV. We observe a strong dependence of nucleon coalescence probability on the azimuthal angle relative to the reaction plane. This effect is primarily driven by the transverse momentum dependence of the mean spatial⟨ΔR⟩and momentum⟨ΔP⟩separations between nucleon pairs, which vary with the nucleon azimuthal angle. Moreover, our analysis demonstrates that the stiffness of the nuclear equation of state plays a crucial role in determining the energy dependence of this sign change in deuteron v2 at $\sqrt{s_{NN}} = 3.2$ GeV

Full Text

Preamble

Light Nuclei Elliptic Flow at Mid-Rapidity in $\sqrt{s_{NN}} = 3.0 - 3.9$ GeV Au+Au Collisions Using a Coalescence Model

Y. Xu[1], X. H. He[2,3], and Y. P. Zhang[2,3]

^{1}School of Physics, Harbin Institute of Technology, Harbin 150001, China
^{2}Institute of Modern Physics, Chinese Academy of Sciences, Lanzhou, Gansu 730000, China
^{3}School of Nuclear Science and Technology, University of Chinese Academy of Sciences, Beijing 100049, China

Light nuclei collective flow serves as an important probe for understanding their production mechanisms in heavy-ion collisions. The STAR collaboration has reported that the atomic mass number (A) scaling of light nuclei elliptic flow v_2 is broken at $\sqrt{s_{NN}} = 3.0 - 3.9$ GeV. The observations reveal that while protons maintain negative v_2 values at mid-rapidity at both 3.0 and 3.2 GeV, light nuclei v_2 exhibits a sign change from negative at 3.0 GeV to positive at 3.2 GeV. In this study, we investigate v_2 of protons and deuterons in mid-central Au+Au collisions at $\sqrt{s_{NN}} = 3.0$, 3.2, 3.5, and 3.9 GeV using the JAM2 microscopic transport model. Deuterons are formed via nucleon coalescence, with the spatial distance ΔR and momentum difference ΔP between constituent protons and neutrons serving as the coalescence criteria. Our calculations successfully reproduce the sign change in deuteron v_2 at 3.2 GeV. We observe a strong dependence of nucleon coalescence probability on the azimuthal angle relative to the reaction plane. This effect is primarily driven by the transverse momentum dependence of the mean spatial $\langle \Delta R \rangle$ and momentum $\langle \Delta P \rangle$ separations between nucleon pairs, which vary with the nucleon azimuthal angle. Moreover, our analysis demonstrates that the stiffness of the nuclear equation of state plays a crucial role in determining the energy dependence of this sign change in deuteron v_2 at $\sqrt{s_{NN}} = 3.2$ GeV.

INTRODUCTION

The study of nuclear matter at extreme temperatures and densities offers valuable insights into the properties of strongly interacting many-body systems described by quantum chromodynamics (QCD). The macroscopic properties of nuclear matter under extreme conditions are most evident in measurable collective features, which represent the common dynamics of multiple particles produced in a single reaction. These collective features manifest as collective flow, characterized by the motion of numerous outgoing particles exhibiting either aligned directional movement or uniform velocity magnitudes [**?**]. The measurement of azimuthal anisotropies in particles produced from collisions has emerged as a crucial probe for elucidating the fundamental characteristics of the quark-gluon plasma and the architecture of hadrons [**?**, **?**]. The observation of hadron elliptic flow (v_2) shows approximate number-of-constituent-quark (NCQ) scaling at large p_T at high beam energies at RHIC and LHC. This scaling is interpreted as a signature for the emergence of the quark-gluon plasma (QGP) formed during these collisions [**?**].

In heavy-ion collisions, the production mechanism of light nuclei (such as deuteron, triton, ^{3}He, ^{4}He, etc.) remains a topic of ongoing debate [**?**]. A widely accepted theoretical model is that these nuclei are formed through the coalescence of nucleons, which can be either newly produced or transported from the colliding nuclei [?]. According to this model, light nuclei emerge at the late stage of the collision evolution when the constituent nucleons come into close proximity in both coordinate space and momentum space [?]. A key feature of this model, analogous to the NCQ scaling in the flow of hadrons, is that the collective flow of light nuclei is expected to exhibit scaling behavior with respect to their atomic mass number (A). The distinction between quark coalescence and nucleon coalescence lies in the fact that, in nucleon coalescence, both the momentum and spatial distribution of the constituent nucleons—protons—can be directly measured in heavy-ion collision experiments, along with the resulting light nuclei.

The STAR collaboration has reported that the A scaling of light nuclei v_2 holds in the low transverse momentum range ($p_T/A < 1.5$ GeV/c) at $\sqrt{s_{NN}} = 7.7-200$ GeV [?]. The results of transport-plus-coalescence models for light nuclei v_2 are also consistent with experimental measurements. However, recent measurements in Au+Au collisions by the STAR fixed-target experiments have revealed distinct scaling patterns for light nuclei anisotropic flow at $\sqrt{s_{NN}} = 3.0-3.9$ GeV [?]. The directed flow (v_1) of light nuclei clearly follows an A scaling, strongly supporting coalescence as the dominant production mechanism for these clusters. In contrast, their v_2 shows breakdown of the A scaling behavior under the same collision conditions. Moreover, the proton v_2 values are negative at mid-rapidity for collision energies of 3.2 GeV [?]. Similarly, for deuteron and ^{3}He, the v_2 values are negative at mid-rapidity at 3.0 GeV but approach zero and become positive at 3.2 GeV, respectively.

The negative v_2 at low energies is attributed to the shadowing effect of the spectators in the collision. Given that the transition energy for the sign change of v_2 differs between protons and light nuclei, it is essential to investigate whether this shadowing effect exhibits mass-dependent behavior or if the final phase-space distribution of nucleons plays a more dominant role. Such an investigation could provide critical insights into the formation time and mechanisms of light nuclei in heavy-ion collisions.

In this paper, we employ the newly developed Jet AA Microscopic transport model (JAM2) [?, ?], combined with a nucleon coalescence model, to calculate the v_2 of protons and deuterons in mid-central Au+Au collisions at $\sqrt{s_{NN}} = 3.0-3.9$ GeV. We investigate the nucleon coalescence probability as a function of azimuthal angle with respect to the reaction plane for collisions at $\sqrt{s_{NN}} = 3.0$, 3.2, 3.5, and 3.9 GeV. Additionally, we explore the dependence of proton and deuteron v_2 on the stiffness of the equation-of-state (EoS) at the studied energies, providing theoretical predictions that can be directly compared with STAR experimental data.

II. METHOD

The calculation begins with event generation for Au+Au collisions using JAM2 at the specified energies. Within the JAM2 framework, the initial positions of incoming nucleons are sampled according to the nuclear density distribution. The nuclear collision is determined by summing the contributions of binary hadron-hadron collisions based on their closest approach distances. Particle production is modeled through resonance and string excitations, followed by their subsequent decays. For this analysis, we employ the mean-field model of JAM2 with incompressibility parameters of $\kappa = 210$ MeV and 380 MeV.

The spatial positions and momenta of protons and neutrons are recorded at a fixed time of 50 fm/c for subsequent coalescence into light nuclei. During the afterburner coalescence stage, deuteron formation occurs when the phase-space distance between a proton-neutron pair falls below specified thresholds. For each proton-neutron pair, we calculate the relative spatial distance $\Delta R = |R_1 - R_2|$ and relative momentum distance $\Delta P = |P_1 - P_2|$ in the rest frame of the pair. A deuteron is formed when both $\Delta R < 4.5$ fm and $\Delta P < 0.3$ GeV/c are simultaneously satisfied. The choice of parameters ΔR and ΔP is based on the work of [**?**], where these coalescence criteria effectively describe the yield of deuterons at $\sqrt{s_{NN}} = 3.0$ GeV. Although our analysis excludes light nuclei with mass number $A > 2$ (which could otherwise reduce the available nucleon pool for deuteron production), this simplification serves our primary objective to focus on understanding the v_2 sign change between protons and deuterons and facilitates the estimation of ΔR and ΔP for all proton-neutron pairs. The potential overestimation of deuteron yields in this approximation does not affect our investigation into the v_2 sign change, because the yields of nuclei with $A > 2$ are suppressed compared to deuterons, and the sign change phenomenon in coalescence reflects the phase-space distribution of nucleons rather than the absolute yields of light nuclei.

In JAM2, the default event-plane angle is set to zero, and consequently, the particle v_2 is calculated as $v_2 = \langle \cos 2\phi \rangle$, where ϕ represents the particle' s azimuthal angle and the angle brackets denote the average over all particles in all events. In our analysis, collision centrality is determined using the impact parameter b, defined as the minimum distance between the centers of the colliding nuclei. To facilitate direct comparison with STAR experimental data, all presented results are calculated for impact parameters in the range $b = 4.3 - 8.5$ fm, corresponding to the 10-40% centrality interval.

III. RESULTS AND DISCUSSION

[Figure 1: see original paper] presents the elliptic flow v_2 for (a) protons and (b) deuterons in Au+Au collisions ($b = 4.3 - 8.55$ fm) at $\sqrt{s_{NN}} = 3.0$ GeV (solid circles), 3.2 GeV (squares), 3.5 GeV (triangles), and 3.9 GeV (crosses), calculated using JAM2 plus afterburner nucleon coalescence. The results were calculated within $0.4 < p_T < 1.0$ GeV/c and $0.8 < p_T < 2.0$ GeV/c for protons and deuterons, respectively.

Figure 1 shows the v_2 results for protons and deuterons as a function of particle rapidity in Au+Au collisions at 3.0, 3.2, 3.5, and 3.9 GeV. The results were calculated using the same transverse momentum range ($0.4 < p_T/A < 1.0$ GeV/c) as implemented in the STAR experimental analysis [**?**]. At mid-rapidity, the v_2 exhibits distinct energy-dependent behavior for protons and deuterons. Specifically, protons show negative v_2 values at $\sqrt{s_{NN}} = 3.0$ and 3.2 GeV, transitioning to positive values at $\sqrt{s_{NN}} = 3.5$ and 3.9 GeV. In contrast, deuterons show negative v_2 values only at $\sqrt{s_{NN}} = 3.0$ GeV, maintaining positive values above 3.2 GeV. These results are quantitatively consistent with the experimental measurements from the STAR collaboration [**?**].

The negative v_2 at low collision energies can be attributed to the spectator shadowing effect, where the prolonged passage time of non-interacting spectators along the impact parameter direction significantly influences the anisotropic expansion of the fireball. However, while this effect should in principle affect all particle species uniformly, both experimental data and coalescence model calculations reveal a discrepancy at $\sqrt{s_{NN}} = 3.2$ GeV: protons and deuterons have opposite v_2 signs at mid-rapidity. This contradiction arises from the dynamics of deuteron formation. In our calculation, deuterons are formed through the coalescence of nucleons at a time of 50 fm/c, a late stage in the system’ s evolution when the influence of spectators has become negligible. This delayed formation picture could explain why deuteron v_2 maintains positive values even when proton v_2 is negative at 3.2 GeV. These results suggest that light nuclei formation in heavy-ion collisions occurs at late stages, where the spectator effect no longer plays a significant role in shaping the collective flow patterns.

To gain deeper quantitative insight into how the coalescence afterburner affects deuteron v_2, we examine the azimuthal angle (ϕ) distributions of particles. The collective flow coefficients v_n are quantitatively characterized through Fourier expansion of the particle azimuthal distribution with respect to the reaction plane angle, which is represented by the $dN/d\phi$ distribution in our calculations. In our analysis, we specifically investigate the $dN/d\phi$ distributions to explore the origin of the opposite v_2 signs between protons and deuterons at mid-rapidity ($0 < y < 0.5$).

The investigation focuses on three distinct particle populations: (i) protons prior to coalescence, (ii) surviving free protons after coalescence, and (iii) deuterons formed through the coalescence process. Their respective $dN/d\phi$ distributions are shown in Fig. 2 [Figure 2: see original paper]. We analyze the azimuthal distributions by fitting them with the Fourier expansion:

$$\frac{dN}{d\phi} \propto [1 + 2v_1\cos(\phi) + 2v_2\cos(2\phi)],$$

where the v_2 values extracted from this fitting show excellent agreement with those presented in Fig. 1, which were obtained via the event plane method using

$\langle\cos(2\phi)\rangle$. This consistency check is crucial, as the STAR measurements rely on the event plane method, while the $dN/d\phi$ distributions provide insights into the evolution of v_2 throughout the coalescence process.

In the energy range explored in this study, the collision system exhibits a strong v_1 alongside nearly vanishing v_2 at mid-rapidity. Consequently, the $dN/d\phi$ distribution is dominated by the v_1 component. To extract the v_2 contribution more clearly, we have applied a folding procedure around $\pi/2$ to the results presented in Fig. 2, with the folded distributions shown in Fig. 3 [Figure 3: see original paper]. These distributions exhibit distinct energy dependencies: At $\sqrt{s_{NN}} = 3.0$ GeV, both total protons and surviving free protons after coalescence show pronounced yield enhancements near $\phi = \pi/2$, corresponding to negative v_2 values. The distributions become isotropic at $\sqrt{s_{NN}} = 3.2$ and 3.5 GeV, indicating the nearly vanishing v_2 for total protons. Meanwhile, deuterons show a slight enhancement near $\phi = 0$ at 3.2 GeV, corresponding to a positive v_2 value. At the highest investigated energy of $\sqrt{s_{NN}} = 3.9$ GeV, the ϕ yield shows consistent enhancement near $\phi = 0$ for all three particle populations. By comparing the ϕ distributions before and after coalescence, we can directly examine how the coalescence probability varies with azimuthal angle, providing unique insights into the formation dynamics of light nuclei in heavy-ion collisions.

Under the assumption that protons and neutrons have identical ϕ distributions, the coalescence model predicts that deuteron production follows the relation:

$$\frac{dN_d}{d\phi} = P(\phi)\left(\frac{dN_p}{d\phi}\right)^2,$$

where P represents the coalescence probability. We should not expect the coalescence process to be isotropic across all azimuthal directions, and the coalescence probability P may have ϕ dependence due to the anisotropic nature of the collision system. Figure 4 [Figure 4: see original paper] shows the coalescence probability P distribution as a function of ϕ calculated using the proton and deuteron ϕ distributions from Fig. 2.

The coalescence probability of nucleons shows a clear azimuthal dependence across all studied energies, with a minimum near $\phi = \pi/2$ (perpendicular to the reaction plane direction), though the dependence weakens as the collision energy increases. This indicates that nucleon coalescence is significantly more probable for particles moving parallel to the reaction plane compared to those moving perpendicularly. Consequently, nucleons contributing to negative v_2 around $\phi = \pi/2$ have a reduced probability of coalescing and forming deuterons, thereby explaining the observed sign change in deuteron v_2 relative to protons at certain energies.

Since the deuteron is formed by satisfying the conditions $\Delta R < 4.5$ fm and $\Delta P < 0.3$ GeV/c, the minimum coalescence probability near $\phi = \pi/2$ suggests that nucleons oriented perpendicular to the reaction plane are statistically less likely to satisfy the spatial or momentum constraints for deuteron formation compared to those along the reaction plane. To investigate this phenomenon quantitatively, we analyze the average spatial $\langle \Delta R \rangle$ and momentum $\langle \Delta P \rangle$ separations as functions of proton p_T in the range of $0.4 < p_T < 2$ GeV/c, as shown in Fig. 5 [Figure 5: see original paper]. Both $\langle \Delta R \rangle$ and $\langle \Delta P \rangle$ have strong p_T dependence, increasing monotonically with proton p_T above 0.5 GeV/c, where the $\langle \Delta R \rangle$ reaches its minimum. The observed systematic increase in both $\langle \Delta R \rangle$ and $\langle \Delta P \rangle$ with collision energy across the measured p_T range reflects the stronger radial flow and higher pressure gradients developed in the more energetic collisions.

Figure 6 [Figure 6: see original paper] shows the azimuthal angle dependence of mean transverse momentum ($\langle p_T \rangle$) for protons in the range $0.4 < p_T < 2.0$ GeV/c and $0 < y < 0.5$ from JAM2 model calculations. A characteristic enhancement of $\langle p_T \rangle$ around $\phi = \pi/2$ is observed at $\sqrt{s_{NN}} = 3.0 - 3.5$ GeV, demonstrating the spectator squeeze-out effect at these energies. The stronger transverse momentum boost for protons perpendicular to the reaction plane becomes more pronounced at lower energies due to the increased passage time of spectator matter, which amplifies the anisotropic pressure gradients. By $\sqrt{s_{NN}} = 3.9$ GeV, the $\langle p_T \rangle$ becomes nearly isotropic. Higher momentum protons around $\phi = \pi/2$ exhibit larger $\langle \Delta R \rangle$ and $\langle \Delta P \rangle$ separations (Fig. 5), reducing their coalescence probability (Fig. 4), which directly impacts deuteron formation. Therefore, this azimuthal-dependent $\langle p_T \rangle$ and coalescence probability explains the breaking of mass-number scaling at the studied energies and the sign change of deuteron v_2 at $\sqrt{s_{NN}} = 3.2$ GeV.

Figure 7 [Figure 7: see original paper] compares the v_2 results obtained using two different nuclear incompressibility parameters ($\kappa = 210$ MeV and 380 MeV), representing soft and stiff EoS respectively. At $\sqrt{s_{NN}} = 3.0$ GeV, both proton and deuteron v_2 values remain negative regardless of the EoS stiffness. However, for $\sqrt{s_{NN}} = 3.5$ and 3.9 GeV, all calculated v_2 values are positive. The transitional energy of $\sqrt{s_{NN}} = 3.2$ GeV shows particularly interesting behavior: while proton v_2 stays negative, deuteron v_2 shows strong sensitivity to the EoS stiffness, remaining negative for the stiff EoS but turning positive for the soft EoS. This striking difference implies that the nuclear EoS plays a crucial role in determining the sign inversion of light nuclei v_2. Furthermore, the energy dependence of the v_2 splitting between protons and deuterons is also sensitive to the EoS stiffness. As the collision energy decreases from $\sqrt{s_{NN}} = 3.9$ to 3.0 GeV, the magnitude of this v_2 splitting systematically diminishes, with this trend being particularly pronounced for the stiff EoS. At the lowest studied energy ($\sqrt{s_{NN}} = 3.0$ GeV), the proton and deuteron v_2 become identical for the stiff EoS case, while maintaining a small but finite difference for the soft EoS. The observed energy evolution of v_2 for protons and deuterons offers crucial constraints on both the nuclear equation of state and light nuclei production mechanisms. These results could serve as valuable theoretical inputs for interpreting STAR measurements.

IV. SUMMARY

Using the JAM transport model with a nucleon coalescence afterburner, we investigate the elliptic flow v_2 of protons and deuterons in mid-central ($b = 4.3-8.5$ fm) Au+Au collisions at $\sqrt{s_{NN}} = 3.0-3.9$ GeV. Deuterons are formed via coalescence of nucleon pairs satisfying $\Delta R < 4.5$ fm and $\Delta P < 0.3$ GeV/c. For protons, the spectator squeeze-out effect generates negative v_2 at $\sqrt{s_{NN}} =$ 3.2 and 3.5 GeV, accompanied by enhanced $\langle p_T \rangle$ perpendicular to the reaction plane. Notably, at $\sqrt{s_{NN}} = 3.2$ GeV, protons exhibit negative v_2 at mid-rapidity, while coalescence-produced deuterons show positive v_2, in agreement with STAR measurements.

To address the breaking of mass-number scaling in light nuclei v_2 at $\sqrt{s_{NN}} = 3.0 - 3.9$ GeV, particularly the observed sign change at 3.2 GeV, we analyze the $dN/d\phi$ distributions of protons and deuterons in the rapidity window $0 < y < 0.5$. The results indicate that nucleons near $\phi = 0$ or π (along the reaction plane) are more likely to satisfy the coalescence criteria, leading to higher coalescence probability compared to nucleons near $\phi = \pi/2$. Additionally, the parameters ΔR and ΔP show strong dependence on p_T, with larger values at higher p_T. The enhancement of $\langle p_T \rangle$ near $\phi = \pi/2$ reduces the coalescence probability, which influences deuteron formation along the azimuthal angle and disrupts mass-number scaling in the energy range of several GeV. This effect, in particular, leads to the observed sign inversion of deuteron v_2 at mid-rapidity at 3.2 GeV. These findings provide deeper insights into late-stage nucleon coalescence dynamics, particularly regarding the mass-number scaling violation of light nuclei flow in heavy-ion collisions, and help enhance our understanding of NCQ scaling behavior at lower collision energies.

Furthermore, simulations with different values of nuclear incompressibility ($\kappa =$ 210 MeV and 380 MeV) show that the stiffness of the equation of state plays a critical role in the sign inversion of deuteron v_2 at $\sqrt{s_{NN}} = 3.2$ GeV. This insight provides a valuable means to constrain the nuclear incompressibility parameter κ using experimental data from STAR.

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REFERENCES

[1] N. Herrmann, J. P. Wessels, and T. Wienold, Annual Review of Nuclear and Particle Science 49, 581 (1999).
[2] Z.-W. Lin and L. Zheng, Nuclear Science and Techniques 32, 113 (2021).
[3] Z.-B. Tang, W.-M. Zha, and Y.-F. Zhang, Nuclear Science and Techniques 31, 81 (2020).

[4] S. Voloshin, Nuclear Physics A 715, 379c (2003), Quark Matter 2002.
[5] D. Molnár and S. A. Voloshin, Phys. Rev. Lett. 91, 092301 (2003).
[6] J. Adams, M. M. Aggarwal, et al. (STAR Collaboration), Phys. Rev. Lett. 95, 122301 (2005).
[7] X. Dong, S. Esumi, P. Sorensen, N. Xu, and Z. Xu, Physics Letters B 597, 328 (2004).
[8] A. Adare, S. Afanasiev, et al. (PHENIX Collaboration), Phys. Rev. C 85, 064914 (2012).
[9] B. B. Abelev et al. (ALICE), JHEP 06, 190 (2015), arXiv:1405.4632 [nucl-ex].
[10] M. Wang, J.-Q. Tao, H. Zheng, W.-C. Zhang, L.-L. Zhu, and A. Bonasera, Nuclear Science and Techniques 33, 37 (2022).
[11] Z.-H. Wang, Y.-L. Zhang, and Z.-Q. Feng, Nuclear Science and Techniques 36, 229 (2025).
[12] Y.-L. Cheng, S. Zhang, and Y.-G. Ma, The European Physical Journal A 57, 330 (2021).
[13] L.-L. Zhu, B. Wang, M. Wang, and H. Zheng, Nuclear Science and Techniques 33, 45 (2022).
[14] H. H. Gutbrod, A. Sandoval, P. J. Johansen, A. M. Poskanzer, J. Gosset, W. G. Meyer, G. D. Westfall, and R. Stock, Phys. Rev. Lett. 37, 667 (1976).
[15] L. Liu, C. Hu, X. He, S. Shi, and G. Xie, Physics Letters B 855, 138853 (2024).
[16] L. Zhu, C. M. Ko, and X. Yin, Physical Review C 92, 064911 (2015).
[17] W. Zhao, L. Zhu, H. Zheng, C. M. Ko, and H. Song, Physical Review C 98, 054905 (2018).
[18] M. Kachelrieß, S. Ostapchenko, and J. Tjemsland, Physical Review C 108, 024903 (2023).
[19] H. Sato and K. Yazaki, Physics Letters B 98, 153 (1981).
[20] S. Sombun, K. Tomuang, A. Limphirat, P. Hillmann, C. Herold, and M. Bleicher, Phys. Rev. C 99, 014901 (2019).
[21] N. Yu, Z.-M. Zhang, H.-G. Xu, and M.-X. Song, Nuclear Science and Techniques 36, 65 (2025).
[22] L. Adamczyk, J. K. Adkins, et al. (STAR Collaboration), Phys. Rev. C 94, 034908 (2016).
[23] M. Abdallah, B. Aboona, et al. (STAR Collaboration), Physics Letters B 827, 136941 (2022).
[24] Han, C, EPJ Web Conf. 296, 05014 (2024).
[25] Han, C, in Quark Matter (Houston, Texas, USA, 2023).
[26] Y. Nara, N. Otuka, A. Ohnishi, K. Niita, and S. Chiba, Phys. Rev. C 61, 024901 (1999).
[27] Y. Nara and A. Ohnishi, Phys. Rev. C 105, 014911 (2022).
[28] Y. Xu, X. He, and N. Xu, Chinese Physics C 47, 074107 (2023).

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