Light Nuclei Collectivity from $\sqrt{s_{\text{NN}}}=3$ GeV Au+Au Collisions at RHIC

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In high-energy heavy-ion collisions, partonic collectivity is evidenced by the constituent quark number scaling of elliptic flow anisotropy for identified hadrons. A breaking of this scaling and dominance of baryonic interactions is found for identified hadron collective flow measurements in \( \sqrt{s_{NN}} = 3 \) GeV Au+Au collisions.
In this paper, we report measurements of the first- and second-order azimuthal anisotropic parameters, $v_1$ and $v_2$, of light nuclei ($d$, $t$, $^3$He, $^4$He) produced in $\sqrt{s_{NN}} = 3$ GeV Au+Au collisions at the STAR experiment. An atomic mass number scaling is found in the measured $v_1$ slopes of light nuclei at mid-rapidity. For the measured $v_2$ magnitude, a strong rapidity dependence is observed. Unlike $v_2$ at higher collision energies, the $v_2$ values at mid-rapidity for all light nuclei are negative and no scaling is observed with the atomic mass number. Calculations by the Jet AA Microscopic Transport Model (JAM), with baryonic mean-field plus nucleon coalescence, are in good agreement with our observations, implying baryonic interactions dominate the collective dynamics in 3 GeV Au+Au collisions at RHIC.

I. INTRODUCTION

Collective motion of particle emission in high-energy heavy-ion collisions, often referred to as collective flow, is a general phenomenon observed over a wide range of collision energies. The flow anisotropy parameters, $v_n$ (where $n$ represents the $n$-th harmonic order), are used to describe the azimuthal anisotropies in particle momentum distributions with respect to the reaction plane \[1\]. The first- and second-order azimuthal anisotropies, $v_1$ and $v_2$, are important probes of nuclear matter. In high energy collisions at the top RHIC and LHC energies, they provide information on the collective hydrodynamic expansion and transport properties of the produced Quark Gluon Plasma (QGP), while at lower collision energies of the order of a few GeV, they are sensitive to the compressibility of the nuclear matter and nuclear equation of state \[2\,3\]. The collision-energy dependence of $v_1$ and $v_2$ for different particle species has been observed experimentally \[4\,5\], and provides valuable information on the dynamical evolution of the strongly interacting matter.

At high LHC energies, significant $v_2$ and $v_3$ values are reported for $d$ \[6\,7\]. In parallel and at lower energies, compared to protons, enhanced values of $v_1$ and $v_2$ for light nuclei ($d$, $t$, and $^3$He) were observed in prior heavy-ion collision experiments \[8\,14\]. These measurements suggest that the $v_1$ of heavier nuclei have more pronounced energy dependences and may carry more direct information on the collective motion of nuclear matter. Recently, the HADES experiment reported the measurements of anisotropic flow of $p$, $d$ and $t$ from $\sqrt{s_{NN}} = 2.4$ GeV Au+Au collisions \[15\]. The STAR collaboration observed the atomic mass number ($A$) scaling of light nucleus $v_2$ for the reduced transverse momentum ($p_T$) range of $p_T/A < 1.5$ GeV/c at $\sqrt{s_{NN}} = 7.7 - 200$ GeV \[14\]. Similar to the number of constituent quark (NCQ) scaling of hadron collective flow \[16\], under the assumptions of small $v_n$ and light nucleus formation by nucleon coalescence in momentum space, light nucleus collective flow is expected to follow an approximate $A$ scaling

$$v_n^d(p_T, y)/A \approx v_n^{T}(p_T/A, y). \quad (1)$$

The STAR observation \[14\] favors nucleon coalescence, while the true production mechanism of light nuclei in heavy-ion collisions is still an open question. At lower energies, however, the $v_1$ is not negligibly small as reported in this paper.

Keeping up to $v_1^2$, Eq. (1) for $n = 2$ becomes

$$v_2^A(p_T, y)/A \approx v_2^{T}(p_T/A, y) + \frac{A - 1}{2} \left(v_1^{T}(p_T/A, y)\right)^2. \quad (2)$$

The coalescence model assumes that light nuclei are formed via the combination of nucleons when these nucleons are near each other both in coordinate and momentum space near the time of kinetic freeze-out \[17\,20\]. Due to the longer passing time of the colliding ions in the few GeV regime, the interference between the expanding central fireball and the spectator remnants becomes more significant than at higher energies. Since flow is strongly affected by the spectators, one expects to gain insight into the collision dynamics and the nucleon coalescence behavior from the measurements of light nuclei $v_1$ and $v_2$ in the few GeV energy regime. In this paper, we report the measurements of $v_1$ and $v_2$ as functions of particle rapidity ($y$) and transverse momentum ($p_T$) for $d$, $t$, $^3$He, and $^4$He in fixed-target $\sqrt{s_{NN}} = 3$ GeV Au+Au collisions at the STAR experiment.

II. EXPERIMENT AND DATA ANALYSIS

The data used here were recorded in the fixed-target program by the STAR experiment \[21\]. The lab energy of the beam is 3.85 GeV per nucleon, equivalent to the center-of-mass energy of $\sqrt{s_{NN}} = 3$ GeV. A detailed description of the STAR detector can be found in \[21\]. The main tracking and particle identification (PID) detectors are the Time Projection Chamber (TPC) \[22\] and the Time-of-Flight (TOF) barrel \[23\] located inside a 0.5 T solenoidal magnetic field. For the fixed target configuration, the Au target is installed inside the vacuum pipe 200 cm to the west of the TPC center. The TPC covers the full azimuth and a pseudorapidity range $0.1 < \eta < 2$, and the TOF covers the range $0.1 < \eta < 1.5$ in the laboratory frame. In this paper, the beam direction is defined as positive, and the particle rapidity is given in the collision center-of-mass frame.

For each event, the reconstructed primary vertex is required to be within 2 cm of the target position along the beam axis. The transverse $x, y$ position of the vertex is required to be within 2 cm of the target located at $0, 2$ cm. The event centrality is estimated from the charged-particle multiplicity measured in the TPC within $-2 < \eta < 0$ with the help of a Glauber Monte Carlo model \[24\].

Charged-track trajectories are reconstructed from the measured space point information in the TPC. In order to select the primary tracks, a requirement of less than 3 cm is applied on their distance of closest approach (DCA) from the event.

* Deceased
vertex. To avoid effects from track splitting, each track should have at least 15 TPC space points, and have more than 52% of the total possible TPC points used in the track fitting. The TPC reconstruction efficiency is around 80% for all light nuclei species.

The charged particle identification is accomplished by the specific energy loss \( dE/dx \) measured in the TPC. Figure 1 shows the average \( dE/dx \) distribution of charged particles as a function of rigidity (momentum/charge). The curves denote the Bichsel expectation for each particle species. At low momenta, the \( dE/dx \) bands corresponding to different particle species are clearly separated and the particle type can be determined via the variable \( z \),

\[
z = \ln \left( \frac{\langle dE/dx \rangle}{\langle dE/dx \rangle_B} \right),
\]

where the \( \langle dE/dx \rangle_B \) is the corresponding Bichsel expectation. The expected value of \( z \) for a given particle type is zero. At higher momenta, these bands start to overlap. A combination of \( z \) and \( m^2/q^2 \) of the particle is used to identify the high momentum light nuclei with a PID purity higher than 96%. A particle’s \( m^2 \), where \( m \) is mass of the particle, is determined by measuring the particle speed using the TOF system. Figure 1 shows the \( m^2/q^2 \) distribution as a function of particle rigidity.

FIG. 1. (a) The \( dE/dx \) of charged tracks versus rigidity in Au+Au collisions at \( \sqrt{s_{NN}} = 3 \) GeV. The curves are Bichsel expectations for the corresponding particle species labeled. (b) Particle \( m^2/q^2 \) versus rigidity. The bands correspond to \( n^+ \), \( K^+ \), \( p \), \( ^3\text{He} \), \( d \), and \( t \) as labeled. \( ^3\text{He} \) and \( ^{6}\text{Li} \) have the same \( m^2/q^2 \) as \( d \) and \( ^{6}\text{He} \) has the same \( m^2/q^2 \) as \( t \).

The proton \( v_1 \) and \( v_2 \) are measured over the range of 0.4 < \( p_T \) < 2.0 GeV/c. In this measurement, the lower cutoffs of light nucleus \( p_T \) are restricted to the same value in terms of \( p_T/A > 0.4 \) GeV/c. The \( p_T \) upper limits are determined based on the \( p_T \) versus \( y \) acceptances shown in Fig. 2 within -0.5 < \( y \) < 0 after studied light nucleus species is identified. The values for \( v_1 \) and \( v_2 \) are extracted in the chosen \( p_T \) ranges: 0.8 < \( p_T \) < 3.5 GeV/c for \( d \), 1.2 < \( p_T \) < 4.0 GeV/c for \( t \) and \( ^3\text{He} \), and 1.6 < \( p_T \) < 4.0 GeV/c for \( ^4\text{He} \). As a result of the limited \( \eta \) coverage of the TOF detector, within -0.1 < \( y \) < 0, the \( t \) and \( ^4\text{He} \) do not have coverage for \( p_T \) < 2.1 GeV/c and \( p_T \) < 2.8 GeV/c, respectively.

The coefficients \( v_1 \) and \( v_2 \) are determined via a particle’s azimuthal angle in momentum space relative to the azimuth of the reaction plane spanned by the beam direction and the impact parameter vector. While the reaction plane orientation can not be accessed directly in measurements, it is common to use the event plane angle to be a proxy of the true reaction plane. In this analysis the first-order event plane \( \Psi_1 \) is adopted for both the \( v_1 \) and \( v_2 \) calculations. The \( \Psi_1 \) value is reconstructed by using information from the event plane detector (EPD). A vector

\[
\vec{Q} = (Q_x, Q_y) = \left( \sum_i w_i \cos(\phi_i), \sum_i w_i \sin(\phi_i) \right)
\]

is calculated event-by-event. The \( \phi_i \) is the azimuthal angle of the \( i^{th} \) module of the EPD, and its weight \( w_i \) is proportional to the energy deposition. The non-uniformities in the EPD are corrected by subtracting the \( \langle Q_x \rangle, \langle Q_y \rangle \) from \( \vec{Q} \) in each event, where the angle brackets indicate averaging over all events. Then the \( \Psi_1 \) is given by \( \Psi_1 = \tan^{-1}(Q_y/Q_x) \). A shifting method is utilized to make the distribution of the reconstructed \( \Psi_1 \) uniform.

The values \( v_1 \) and \( v_2 \) are computed via \( v_n = \langle \cos[n(\phi - \Psi_1)] \rangle/R_n \). The \( pT^- \) and \( y \)-dependent reconstruction efficiency of particle tracks is corrected using a Monte Carlo calculation of simulated particles embedded into real collision events. The event plane resolution \( R_n \) is determined via a three sub-event plane correlation method, where the sub-event planes are reconstructed separately in different \( \eta \) ranges of the EPD and TOF. At \( \sqrt{s_{NN}} = 3 \) GeV, the resolutions peak in the centrality range 30-40% with value of 0.75 and 0.41 for \( v_1 \) and \( v_2 \), respectively.

The systematic uncertainties of the measured flow harmonics come from the method of selecting charged tracks, from particle identification, and from the event plane resolution. They are estimated point-by-point on \( v_1 \) and \( v_2 \) as a function of \( y \) and \( p_T \) for each light nucleus species. The systematic uncertainties arising from the track selection are determined by varying the selection requirements. The
values amount to about 2% after the statistical fluctuation effects are removed [26]. The systematic uncertainties related to the particle misidentification are determined by varying the cuts on $z$ and $m^2$, and are found to be 2% to 8% depending on the light nucleus species and their $p_T$. A common systematic uncertainty arises from the event plane resolution, and is determined by using combinations of different $\eta$ sub-events; it is estimated to be less than 2% and 3% for $v_1$ and $v_2$, respectively, within the centrality bin 10-40%. Additional systematic uncertainty on the $dv_1/dy$ slope parameter comes from the chosen fit range, and is estimated by taking the difference between the fit values from default range $-0.5 < y < 0$ and from $-0.4 < y < 0$. The typical magnitude of this systematic uncertainty is found to be 3% for all light nucleus species. In the following figures, the total systematic uncertainty of each data point is represented by the open boxes.

III. RESULTS AND DISCUSSIONS

The $p_T$ dependencies of the light nucleus $v_1$ in different rapidity intervals are shown in Fig. 4. Figure 3 shows that the values of $v_1$ are negative for all light nuclei, including protons, approximately follow a scaling for $-0.3 < y < 0$ especially near mid-rapidity. The $v_1$ scaling behavior suggests the light nuclei are formed via nucleon coalescence in Au+Au collisions at $\sqrt{s_{NN}} = 3$ GeV. The scaling worsens for $p_T/A > 1$ GeV/c in the range $-0.4 < y < -0.3$, where the $v_1$ values are large and the simple coalescence of Eq. (1) may not apply. Increasing contamination of target-rapidity ($y = -1.045$) fragments may also play a role.

The upper panels of Fig. 4 show the dependencies of $v_2$ in different rapidity intervals. At mid-rapidity, $-0.1 < y < 0$, the $v_2$ values are negative for all measured light nucleus species. Moving away from mid-rapidity, the $v_2$ magnitudes decrease gradually, and become positive for $t$, $^3$He, and $^4$He at larger $p_T$, while the $v_2$ of protons and $d$ remain negative within $-0.4 < y < 0.4$. Moreover, the proton $v_2$ has a stronger non-monotonic $p_T$ dependence compared to other light nuclei. The lower panels of Fig. 4 show $v_2$ as a function of $p_T/A$ and they do not follow the same trend. Taking into account the effect of $v_1$ by Eq. (4), the naive momentum coalescence expectation of $v_2$ for $d$ is shown in the dashed curves. While the $v_1$ effect may explain the trend with increasing rapidity, the $v_2$ data significantly deviate from the curve (shown only for $d$, but similar behavior is also found for $t$, $^3$He, and $^4$He). This indicates that no $A$ scaling is observed in these data for light nucleus $v_2$ at $\sqrt{s_{NN}} = 3$ GeV. The $A$ scaling has been observed for $p_T/A < 1.5$ GeV/c in higher energy Au+Au collisions at $\sqrt{s_{NN}} = 7.7 - 200$ GeV [14]. There, as a supporting evidence for the formation of the QGP, the $v_2$ of hadrons follow an approximate NCQ scaling [27,28,29].

Figure 5 shows light nucleus $v_1$ and $v_2$ as a function of rapidity integrated in the chosen $p_T$ ranges. There is a clear mass ordering both for $v_1$ and $v_2$, namely, the heavier the mass of a nucleus, the stronger the rapidity dependence in $v_1$ and $v_2$. At mid-rapidity, $-0.1 < y < 0$, the value of $v_2$ is negative and nearly identical for $p$, $d$, and $^3$He. The negative $v_2$ at mid-rapidity may be caused by shadowing of the spectators as their passage time is comparable with the expansion time of the compressed system at $\sqrt{s_{NN}} = 3$ GeV [11,12]. During the expansion of the participant zone, the particle emission directed toward the reaction plane is blocked by the spectators that are still passing the participant zone. Moving away from mid-rapidity, the proton $v_2$ remains negative and those of other light nuclei gradually become positive. A similar strong rapidity dependence of light nucleus $v_2$ has also been reported by the HADES experiment [15]. Nuclear fragmentation may play a role in the production of those light nuclei, the effect of which is beyond the scope of the present investigation.

To further understand light nucleus formation and the scaling behavior of $v_1$ and $v_2$, we employ a transport model, Jet AA Microscopic Transportation Model (JAM) [30], to simulate the proton and neutron production from the initial collision stage to the final hadron transport in $\sqrt{s_{NN}} = 3$ GeV Au+Au collisions. Both the cascade mode and the mean-field mode of JAM calculations are performed. In the cascade mode, particles are propagated as in vacuum (free streaming) between collisions with other particles. In the mean-field mode [31], a momentum-dependent potential with the incompressibility parameter $\kappa = 380$ MeV is acting on the nucleon evolution. The resulting proton $v_1$ and $v_2$ from the mean-field mode are consistent with the experimental observations (see solid-lines in Fig. 5). However, the simulation results from JAM cascade mode underestimate the magnitudes of proton $v_1$ and give positive values for proton $v_2$ at mid-rapidity. Moreover, the proton $v_2$ has a stronger non-monotonic $p_T$ dependence compared to other light nuclei. The lower panels of Fig. 4 show $v_2$ as a function of $p_T/A$ and they do not follow the same trend. Taking into account the effect of $v_1$ by Eq. (4), the naive momentum coalescence expectation of $v_2$ for $d$ is shown in the dashed curves. While the $v_1$ effect may explain the trend with increasing rapidity, the $v_2$ data significantly deviate from the curve (shown only for $d$, but similar behavior is also found for $t$, $^3$He, and $^4$He). This indicates that no $A$ scaling is observed in these data for light nucleus $v_2$ at $\sqrt{s_{NN}} = 3$ GeV. The $A$ scaling has been observed for $p_T/A < 1.5$ GeV/c in higher energy Au+Au collisions at $\sqrt{s_{NN}} = 7.7 - 200$ GeV [14]. There, as a supporting evidence for the formation of the QGP, the $v_2$ of hadrons follow an approximate NCQ scaling [27,28,29].

Figure 5 shows light nucleus $v_1$ and $v_2$ as a function of rapidity integrated in the chosen $p_T$ ranges. There is a clear mass ordering both for $v_1$ and $v_2$, namely, the heavier the mass of a nucleus, the stronger the rapidity dependence in $v_1$ and $v_2$. At mid-rapidity, $-0.1 < y < 0$, the value of $v_2$ is negative and nearly identical for $p$, $d$, and $^3$He. The negative $v_2$ at mid-rapidity may be caused by shadowing of the spectators as their passage time is comparable with the expansion time of the compressed system at $\sqrt{s_{NN}} = 3$ GeV [11,12]. During the expansion of the participant zone, the particle emission directed toward the reaction plane is blocked by the spectators that are still passing the participant zone. Moving away from mid-rapidity, the proton $v_2$ remains negative and those of other light nuclei gradually become positive. A similar strong rapidity dependence of light nucleus $v_2$ has also been reported by the HADES experiment [15]. Nuclear fragmentation may play a role in the production of those light nuclei, the effect of which is beyond the scope of the present investigation.

To further understand light nucleus formation and the scaling behavior of $v_1$ and $v_2$, we employ a transport model, Jet AA Microscopic Transportation Model (JAM) [30], to simulate the proton and neutron production from the initial collision stage to the final hadron transport in $\sqrt{s_{NN}} = 3$ GeV Au+Au collisions. Both the cascade mode and the mean-field mode of JAM calculations are performed. In the cascade mode, particles are propagated as in vacuum (free streaming) between collisions with other particles. In the mean-field mode [31], a momentum-dependent potential with the incompressibility parameter $\kappa = 380$ MeV is acting on the nucleon evolution. The resulting proton $v_1$ and $v_2$ from the mean-field mode are consistent with the experimental observations (see solid-lines in Fig. 5). However, the simulation results from JAM cascade mode underestimate the magnitudes of proton $v_1$ and give positive values for proton $v_2$ at mid-rapidity. Moreover, the proton $v_2$ has a stronger non-monotonic $p_T$ dependence compared to other light nuclei. The lower panels of Fig. 4 show $v_2$ as a function of $p_T/A$ and they do not follow the same trend. Taking into account the effect of $v_1$ by Eq. (4), the naive momentum coalescence expectation of $v_2$ for $d$ is shown in the dashed curves. While the $v_1$ effect may explain the trend with increasing rapidity, the $v_2$ data significantly deviate from the curve (shown only for $d$, but similar behavior is also found for $t$, $^3$He, and $^4$He). This indicates that no $A$ scaling is observed in these data for light nucleus $v_2$ at $\sqrt{s_{NN}} = 3$ GeV. The $A$ scaling has been observed for $p_T/A < 1.5$ GeV/c in higher energy Au+Au collisions at $\sqrt{s_{NN}} = 7.7 - 200$ GeV [14]. There, as a supporting evidence for the formation of the QGP, the $v_2$ of hadrons follow an approximate NCQ scaling [27,28,29].

Figure 5 shows light nucleus $v_1$ and $v_2$ as a function of rapidity integrated in the chosen $p_T$ ranges. There is a clear mass ordering both for $v_1$ and $v_2$, namely, the heavier the mass of a nucleus, the stronger the rapidity dependence in $v_1$ and $v_2$. At mid-rapidity, $-0.1 < y < 0$, the value of $v_2$ is negative and nearly identical for $p$, $d$, and $^3$He. The negative $v_2$ at mid-rapidity may be caused by shadowing of the spectators as their passage time is comparable with the expansion time of the compressed system at $\sqrt{s_{NN}} = 3$ GeV [11,12]. During the expansion of the participant zone, the particle emission directed toward the reaction plane is blocked by the spectators that are still passing the participant zone. Moving away from mid-rapidity, the proton $v_2$ remains negative and those of other light nuclei gradually become positive. A similar strong rapidity dependence of light nucleus $v_2$ has also been reported by the HADES experiment [15]. Nuclear fragmentation may play a role in the production of those light nuclei, the effect of which is beyond the scope of the present investigation.
FIG. 3. (a) The $p_T$ and rapidity dependencies of $v_1$ for $p$, $d$, $t$, $^3$He, and $^4$He in 10-40% mid-central Au+Au collisions at $\sqrt{s_{NN}} = 3$ GeV. (b) The same results as (a) but both $v_1$ and $p_T$ are scaled by $A$. For $t$ and $^4$He, there are no data points at $p_T/A < 0.7$ GeV/c in $-0.1 < y < 0$ due to limited acceptance. The data points in each rapidity are scaled for clarity. Statistical and systematic uncertainties are represented by vertical lines and open boxes, respectively. The dashed lines represent the fit to a third-order polynomial function of the data points to guide the eye.

A first order polynomial function is employed to fit $v_1$ in Fig. 5 within rapidity range $-0.5 < y < 0$. The extracted slope parameters, $dv_1/dy$, scaled by $A$, for light nuclei are shown in Fig. 6 as functions of the collision energy, together with existing data from higher energies. The values of $(dv_2/dy)/A$ at 3 GeV for all measured light nuclei are positive and grouped together with that of the protons. The results of the JAM model in mean-field mode plus coalescence calculations for $p$, $d$, $t$, $^3$He and $^4$He in 3 GeV Au+Au collisions are also shown with corresponding

FIG. 4. Upper panels: The $p_T$ and $y$ dependencies of $v_2$ for $p$, $d$, $t$, $^3$He, and $^4$He in 10-40% mid-central Au+Au collisions at $\sqrt{s_{NN}} = 3$ GeV. Lower panels: The same results as in upper panels but both $v_2$ and $p_T$ are scaled by $A$. The dashed lines are the $v_2$ expectation for $d$ by Eq. (2). Statistical and systematic uncertainties are represented by vertical lines and open boxes, respectively.
At higher collision energies, the $v_1$ of $d$ has been measured from $\sqrt{s_{NN}} = 7.7 - 39$ GeV $Au+Au$ collisions by the STAR experiment [13]. At $\sqrt{s_{NN}} = 7.7$ GeV, the $v_1$ slope of $d$ follows $A$ scaling within the statistical and systematic uncertainties. For energy $\sqrt{s_{NN}} > 7.7$ GeV, the value of proton $dv_1/dy$ is negative and the corresponding $v_1$ slopes of $d$ are positive with larger uncertainties. The different scaling behavior of light nuclei $dv_1/dy$ at $\sqrt{s_{NN}} = 7.7$ GeV and $\sqrt{s_{NN}} > 11.5$ GeV may indicate a different production mechanism. At higher energies where a QGP is formed, the dominant interactions are partonic in nature. At 3 GeV, baryonic interactions are likely dominant and light nuclei may primarily be formed via coalescence of nucleons. Fragmentation contribution may also play a role which requires further investigation.

FIG. 5. Rapidity dependencies of light nucleus $v_1$ (a) and $v_2$ (b) in 10-40% mid-central Au+Au collisions at $\sqrt{s_{NN}} = 3$ GeV. For $t$ and $^4He$, the points in $-0.1 < y < 0$ are absent due to limited acceptance. The dash-dotted line and solid line represent the results for protons from the cascade and mean-field modes of JAM, respectively. The bands are the results for light nuclei from JAM mean-field plus coalescence calculations. Systematic uncertainties are represented by open boxes.

bars. The same experimental cuts have been applied in the calculations and the resulting slope parameters are consistent with the data including the relative order. The agreement between experimental data and model calculations implies that at 3 GeV these light nuclei are formed via the coalescence processes and baryonic interactions dictate their dynamics.

FIG. 6. Light nucleus scaled $v_1$ slopes $\left(\frac{d(v_1/A)}{dy}\right)_{y=0}$ as a function of collision energy in 10-40% mid-central Au+Au collisions. Statistical and systematic uncertainties are represented by vertical lines and open boxes, respectively. The data points above 7 GeV are taken from [13]. The proton result at $\sqrt{s_{NN}} = 4.5$ GeV is for 10-25% Au+Au collisions [34]. For clarity, the data points are shifted horizontally. Results of the JAM model in the mean-field mode plus coalescence calculations are shown as color bars.

IV. SUMMARY

In summary, we present the directed flow $v_1$ and elliptic flow $v_2$ of $d$, $t$, $^3He$, and $^4He$ for 10-40% centrality in Au+Au collisions at $\sqrt{s_{NN}} = 3$ GeV. The light nucleus $v_1$, as function of both transverse momentum and particle rapidity, follow an approximate atomic mass number $A$ scaling at rapidity $-0.5 < y < 0$, consistent with the nucleon coalescence model calculations. On the other hand, the light nucleus $v_2$ do not follow the simple $A$ scaling, even after taking into account the contribution from the comparable magnitude of $v_T^2$. At mid-rapidity $-0.1 < y < 0$, the value of $v_2$ is negative for all light nuclei, implying a shadowing effect due to the longer passage time of the spectators. Away from the mid-rapidity, the values of light nucleus $v_2$ become positive and the corresponding proton $v_2$ remains negative. The JAM model, with the baryon mean-field (incompressibility parameter $\kappa = 380$ MeV and a momentum dependent potential), and a nucleon coalescence qualitatively reproduce both the $v_1$ and $v_2$ as functions of rapidity for all reported light nuclei. On the other hand, the results from the JAM cascade mode plus coalescence fail to describe the data. Our results suggest that the light nuclei are likely formed via the coalescence of nucleons at $\sqrt{s_{NN}} = 3$ GeV Au+Au collisions, where baryonic interactions dominate the collision dynamics.

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