Measurement of elliptic flow of light nuclei at $\sqrt{s_{NN}} = 200, 62.4, 39, 27, 19.6, 11.5,$ and $7.7$ GeV at the BNL Relativistic Heavy Ion Collider


(STAR Collaboration)

1AGH University of Science and Technology, FACS, Cracow 30-059, Poland
2Argonne National Laboratory, Argonne, Illinois 60439, USA
3Brookhaven National Laboratory, Upton, New York 11973, USA
4University of California, Berkeley, California 94720, USA
5University of California, Davis, California 95616, USA
6University of California, Los Angeles, California 90095, USA
7Central China Normal University, Wuhan, Hubei 430079, China
8University of Chicago, Chicago, Illinois 60607, USA
9Crenighton University, Omaha, Nebraska 68178, USA
10Czech Technical University in Prague, FNSPE, Prague, 115 19, Czech Republic
11Nuclear Physics Institute AS CR, 250 68 Prague, Czech Republic
12Frankfurt Institute for Advanced Studies FIAS, Frankfurt 60438, Germany
13Institute of Physics, Bhubaneswar 751005, India
14Indian Institute of Technology, Mumbai 400076, India
15Indiana University, Bloomington, Indiana 47408, USA

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We present measurements of second-order azimuthal anisotropy \(v_2\) at midrapidity \(|y|<1.0\) for light nuclei \(d, t, ^3\text{He}\) (for \(\sqrt{s_{NN}} = 200, 62.4, 39, 27, 19.6, 11.5,\) and \(7.7\) GeV) and antinuclei \(\bar{d}, \bar{t}, \bar{^3}\text{He}\) (\(\sqrt{s_{NN}} = 200\) GeV) in the STAR (Solenoidal Tracker at RHIC) experiment. The \(v_2\) for these light nuclei produced in heavy-ion collisions is compared with those for \(p\) and \(\bar{p}\). We observe mass ordering in nuclei \(v_2(p_T)\) at low transverse momenta (\(p_T < 2.0\) GeV/c). We also find a centrality dependence of \(v_2\) for \(t\) and \(^3\text{He}\). The magnitude of \(v_2\) for \(t\) and \(^3\text{He}\) agree within statistical errors. Light-nuclei \(v_2\) are compared with predictions from a blast-wave model. Atomic mass number (\(A\)) scaling of light-nuclei \(v_2(p_T)\) seems to hold for \(p_T/A < 1.5\) GeV/c. Results on light-nuclei \(v_2\) from a transport-plus-coalescence model are consistent with the experimental measurements.

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I. INTRODUCTION

One of the main goals of high-energy heavy-ion collision experiments is to study phase structures in the QCD phase diagram [1,2]. With this purpose, the Relativistic Heavy Ion Collider (RHIC) has finished the first phase of the Beam Energy Scan (BES) program [3–9]. It was found that the identified hadron \(v_2\) shows approximate number-of-constituent-quark (NCQ) scaling at high \(p_T\) at the higher beam energies. This scaling behavior is an expected signature of partonic collectivity via quark coalescence in the strongly interacting medium of quarks and gluons formed in heavy-ion collisions [10–16]. Such a scaling behavior also suggests partonic...
momentum space distributions of both the constituents and the freeze-out properties at a later stage of the evolution. Unlike understanding the light-nuclei production mechanism and of azimuthal anisotropy of light nuclei offers a tool to study light-nuclei production via coalescence. Measurements best at the low-density limit, low relative production of density \[18,19,22\]. Since the coalescence mechanism works at the low-density limit, low relative production of nucleons in heavy-ion collisions offers an ideal situation to study light-nuclei production via coalescence. Measurements of azimuthal anisotropy of light nuclei offers a tool to understand the light-nuclei production mechanism and freeze-out properties at a later stage of the evolution. Unlike the case of quark coalescence, in a nucleon coalescence, the momentum space distributions of both the constituents and the products are measurable in heavy-ion collision experiments.

Prior measurements of elliptic flow \((v_2)\) of light nuclei have been carried out at the top RHIC energy \((\sqrt{s_{NN}} = 200 \text{ GeV})\) by the PHENIX \[23\] and the STAR \[24,25\] experiments. The PHENIX Collaboration has measured the \(v_2\) of deuterons \((d)\) and antideuterons \((\bar{d})\) at intermediate transverse momenta \((1.1 < p_T < 4.5 \text{ GeV}/c)\). How the \(v_2\) of these light nuclei scale with those of \((\text{anti})\) protons also has been reported \[23\].

The STAR collaboration has measured the \(v_2\) of \(d, \bar{d}, ^3\text{He}\), and \(^3\text{He}\) in Au + Au collisions at \(\sqrt{s_{NN}} = 200 \text{ GeV}\) in the years 2004 \[24\] and 2007 \[25\].

In this work we expand upon previous studies with a detailed investigation on the energy and centrality dependence of \(v_2\) of light nuclei with more event statistics. During the BES program, the STAR experiment has taken data over a wide range of collision energies from \(\sqrt{s_{NN}} = 7.7 \text{ GeV}\) to 200 GeV. In this paper we present the measurement of \(v_2\) at midrapidity \(|y| < 1.0\) for light nuclei \(d, t, ^3\text{He}\) \((\sqrt{s_{NN}} = 200, 62.4, 39, 27, 19.6, 11.5, \text{and} 7.7 \text{ GeV})\), and antinuclei \(\bar{d}\) \((\sqrt{s_{NN}} = 200, 62.4, 39, 27, \text{and} 19.6 \text{ GeV})\) and \(^3\text{He}\) \((\sqrt{s_{NN}} = 200 \text{ GeV})\).

The paper is organized as follows: Section II briefly describes the experimental setup, the detectors, and the particle (and light nuclei) identification (PID) techniques. The centrality definition, event selection, event plane reconstruction, and the event plane resolution correction are also discussed, along with the extraction procedure of light-nuclei \(v_2\). Presented in Sec. III are the \(v_2\) results for minimum-bias collisions, the centrality dependence, and a physical interpretation of the results. A comparison between light-nuclei \(v_2\) measured in this experiment and those calculated from blast-wave and transport-plus-coalescence models is also shown. Section IV summarizes the physics observations and discusses the main conclusions from the results.

II. EXPERIMENTAL SETUP

STAR is a multipurpose experiment at the RHIC facility at Brookhaven National Laboratory. It consists of a longitudinally oriented (beam direction) solenoidal magnet and a collection of detectors for triggering, PID, and event categorization \[27\]. The main detectors used for this analysis are the time projection chamber (TPC) \[29\] and the time of flight (TOF) detector \[29\]. The following subsections briefly describe their operations and PID techniques.

A. Time projection chamber measurements

The TPC is the primary tracking device in the STAR experiment which uses ionization in a large gas volume to detect trajectories of charged particles. Curvature in the solenoidal field enables determination of the charge sign and rigidity (momentum/charge). The TPC has full azimuthal coverage and a uniform pseudorapidity range of \(|\eta| < 1.0\) \[28\]. The TPC can record up to 45 hit positions and specific ionization energy loss \((dE/dx)\) samples along tracks. Truncated means of the \(dE/dx\) samples are used for PID by comparing to theoretical expectations, using improved Bethe–Bloch functions \[26\], at the measured rigidities to characterize the probability for being any particular species. PID consequently allows deduction of the particles’ charges and momenta. A representative plot of measured track \(dE/dx\) versus rigidity is shown in Fig. 1(a) for minimum-bias (defined later) Au + Au collisions at \(\sqrt{s_{NN}} = 19.6 \text{ GeV}\). The theoretical curves are shown as solid lines.

Primary collision vertices are found through fits involving candidate global tracks, and a typical central collision at the top RHIC energy (with perhaps \(
\approx 1000\) reconstructed tracks) may achieve a vertex position resolution of \(~350 \mu m\). These global tracks are then refitted by using their vertex as a constraint to create a collection of primary tracks.

B. Time of flight measurements

The TOF detector \[29\] in STAR uses multigap resistive plate chambers (MRPCs) and was fully installed in the year 2010. It covers \(2\pi\) in azimuth within the pseudorapidity interval \(|\eta| < 0.94\). The TOF detector and the vertex position detector (VPD) \[30\] measure the time interval \(t\) over which a particle travels from the primary collision vertex to a read-out cell of the TOF detector. This time-interval information is combined with the total path length \(S\) measured by the TPC to provide the inverse velocity, \(1/\beta\), via \(1/\beta = ct/S\), where \(c\) is the speed of light. The track mass-squared is then given by \(m^2 = p^2(1/\beta^2 - 1)\). For collision energies below \(\sqrt{s_{NN}} = 39 \text{ GeV}\) the VPD efficiency is too low to use in every event. Instead, for these data sets a start time for each collision is inferred by working backwards from the TOF-measured stop times of a very limited selection of particles which are very clearly identified in the TPC. The total time interval resolution obtained of 90–110 ps results in PID capabilities that are complementary to those from the TPC \(dE/dx\) at low momenta and also extend to momenta of several GeV. A representative plot of \(m^2\) as a function of the particle momentum is shown in Fig. 1(b) for minimum-bias Au + Au collisions at \(\sqrt{s_{NN}} = 19.6 \text{ GeV}\). As the mass of a particle is a constant quantity, we expect horizontal bands for individual (anti) nuclei as shown by the dotted lines in Fig. 1(b). The large background at low \(p_T (<1.0 \text{ GeV}/c)\) is the result of mismatched tracks in TOF. However, this does not affect the measurement of light nuclei because the TOF detector has been used to identify light nuclei in the high \(p_T (>1.0 \text{ GeV}/c)\) region. The matched tracks in TOF corresponds to 70% to
75% of the total tracks measured by the TPC. This matching efficiency is higher at lower beam energies due to low detector occupancy. We selected individual nuclei by using the $m^2$ which lie within $3\sigma$ from the constant mean (dotted line).

### C. Trigger and event selection

The minimum-bias events for all of the collision energies are based on a coincidence of the signals from the zero-degree calorimeters (ZDCs) [31], VPD, and/or beam-beam counters (BBCs) [32]. Due to larger beam emittance at lower collision energies, (Au + Au)-triggered events are contaminated with Au + beam-pipe events. The radius of the beam pipe going through the center of the TPC is 3.95 cm. Therefore, such Au + beam-pipe events are removed by requiring the primary vertex position to be within a transverse radius of less than 2 cm in the $XY$ plane [4]. The $z$ position of the primary vertices (vertex $z$) is limited to the values listed in Table I [4] to ensure good-quality events.

Furthermore, an extensive quality assurance of the events was performed based on the mean transverse momenta, the mean vertex position, the mean interaction rate, and the mean multiplicity in the detector. Run periods were removed if one of those quantities was more than $3\sigma$ away from the global mean value. The total number of minimum-bias events used in this analysis after these quality assurance cuts for each collision energy are shown in Table I.

### D. Centrality definition

The centrality of each event is defined based on the uncorrected charged particle multiplicity ($dN_{\text{events}}/dN_{\text{charge}}^{\text{raw}}$) distribution, where $N_{\text{events}}$ is the number of events and $N_{\text{charge}}^{\text{raw}}$ is the number of charged particles measured within $|\eta| < 0.5$ [4]. Thus, for example, 0%–5% central events correspond to the events in the top 5% of the multiplicity distribution. The charged particle multiplicity distributions for all energies can be described by a two-component model [33]. The two-component model is a Glauber Monte Carlo simulation in which the multiplicity per unit pseudorapidity ($dN_{\text{charge}}/d\eta$) depends on the two components; namely, number of participant nucleons ($N_{\text{pan}}$) and number of binary collisions ($N_{\text{coll}}$):

$$\frac{dN_{\text{charge}}}{d\eta} = n_{p p} \left[ (1 - x) \frac{N_{\text{pan}}}{2} + x N_{\text{coll}} \right].$$

The fitting parameter $n_{p p}$ is the $dN_{\text{charge}}/d\eta$ in minimum-bias p + p collisions and $x$ is the fraction of charged particles produced from the hard component. The centrality class is defined by calculating the fraction of the total cross section obtained from the simulated multiplicity. Due to trigger inefficiencies, many of the most-peripheral events were not recorded. This results in a significant difference between the measured distribution of charged particle multiplicities and the Glauber Monte Carlo (MC) simulation for peripheral collisions. When determining $v_2$ in a bin of multiplicity width...
enough to see variation in the trigger inefficiency across the bin (e.g., for a minimum-bias measurement), it is necessary to compensate for this variation by weighting particle yields in each event by the inverse of the trigger efficiency at that event’s multiplicity [4]. The correction is about 5% for the peripheral (70%–80%) events, and becomes negligible for central events. However, the corrections are severe for 80%–100% central events. Therefore, 80%–100% central events are not included in the current analysis, and minimum bias is defined for all data presented here as 0%–80%. In addition to the trigger inefficiency, two additional corrections are also applied to account for the vertex-θ-dependent inefficiencies. These corrections account for the acceptance and detector inefficiencies and the time-dependent changes in dNevents/dNcharge.

E. Event plane and resolution correction

The azimuthal distribution of produced particles with respect to reaction plane angle (Ψr) can be expressed in terms of a Fourier series,

\[
\frac{dN}{d(\phi - \Psi_r)} \propto 1 + 2v_1 \cos(\phi - \Psi_r) + 2v_2 \cos[2(\phi - \Psi_r)] + \cdots, \tag{2}
\]

where \( \phi \) is the azimuthal angle of the produced particle, \( \Psi_r \) is defined as the angle between the x axis in the laboratory frame and the axis of the impact parameter. Because we cannot directly measure \( \Psi_r \), we must use a proxy. The second-order azimuthal anisotropy or elliptic flow (\( v_2 \)) is measured with respect to the second-order event plane angle (\( \Psi_2 \)) instead. \( \Psi_2 \) is calculated by using the azimuthal distribution of all reconstructed primary tracks (\( N \)) [34]:

\[
\Psi_2 = \frac{1}{2} \tan^{-1} \left( \frac{Q_{2,2}}{Q_{2,0}} \right). \tag{3}
\]

\( Q_{2,1} \) and \( Q_{2,2} \) are defined as

\[
Q_{2,1} \cos(2\Psi_2) = Q_{2,1} = \sum_{i=1}^{N} w_i \cos(2\phi_i), \tag{4a}
\]

\[
Q_{2,2} \sin(2\Psi_2) = Q_{2,2} = \sum_{i=1}^{N} w_i \sin(2\phi_i), \tag{4b}
\]

where \( w_i \) are the weights which optimize the event plane resolution [34]. In this analysis, the weights scale with track \( p_T \), then saturate above 2.0 GeV/c. To reduce biases due to short-range correlation, we utilize the subevent plane method [34]. In this analysis, the two subevents were defined in \( \eta \) windows of \( \eta^- (-1.0 < \eta < -0.05) \) and \( \eta^+ (0.05 < \eta < 1.0) \). Event plane angles are calculated within each \( \eta \) window, \( \Psi_{2\eta^-} \) and \( \Psi_{2\eta^+} \), respectively, and \( v_2 \) is calculated in each subevent by using the opposite subevent’s event plane angle. The \( \eta \) gap (\( \Delta \eta = 0.1 \)) between the subevents reduces the short-range nonflow contributions and avoids the self-correlation. However, long-range correlations may persist [35].

Due to the acceptance inefficiency of the detectors, the reconstructed event plane distributions are not uniform. Therefore, we apply event-by-event recenter [36] and shift [37] corrections. Finite multiplicities also restrict the degree to which the found event plane angles coincide with the true reaction plane angle. Hence, a resolution correction is applied to the observed elliptic flow (\( v_2^{\text{obs}} \)): \( v_2 = v_2^{\text{obs}}/R_2 \). We determine the resolution correction factor (\( R_2 \)) in the \( \eta \) subevent plane method as follows [34]:

\[
R_2 = \sqrt{\langle \cos[2(\Psi_{2\eta^+} - \Psi_{2\eta^-})] \rangle}. \tag{5}
\]

The resolution as a function of centrality for \( \eta \) subevent planes is shown in Fig. 2 for Au + Au collisions. \( R_2 \) grows with increasing multiplicity (which is small for peripheral collisions) and with increasing \( v_2 \) (which is small for the

![FIG. 2. Resolution correction factor \( R_2 \) of subevent planes as a function of centrality for Au + Au collisions at \( \sqrt{s_{NN}} = 200, 62.4, 39, 27, 19.6, 11.5 \), and 7.7 GeV.](image-url)
most central collisions), so its value peaks in mid-central (20%–30%) collisions where neither is small.

F. Extraction of yield and $v_2$ of nuclei

To identify light nuclei, we define a variable $Z$ such that

$$Z = \ln\left(\frac{(dE/dx)_{\text{expt}}}{(dE/dx)_{\text{theory}}}\right),$$

where $(dE/dx)_{\text{expt}}$ is the energy loss of the light nuclei measured by the TPC detector in the experiment and $(dE/dx)_{\text{theory}}$ is the theoretical energy loss as obtained from the modified Bethe–Bloch formula [26]. After cutting on $m^2$ from the TOF [see Fig. 1(b)] to reduce backgrounds under the signals, the yields are extracted from the $Z$ distributions in various $p_T$ and $(\phi - \Psi_2)$ bins for each species of interest with a two-Gaussian function (one for the signal, the other for the background). Figure 3(a) shows sample $Z$ distributions for $\bar{d}$, $t$, and $^3$He, respectively, within $0 < (\phi - \Psi_2) < \pi/10$ for $1.3 < p_T < 1.9$ GeV/c, $2.1 < p_T < 3.4$ GeV/c, and $1.9 < p_T < 2.5$ GeV/c for minimum-bias Au + Au data at $\sqrt{s_{NN}} = 39$ GeV. The azimuthal angle variation of this yield is then fit with a second order Fourier function to get the elliptic flow coefficient ($v_2^{\text{obs}}$). Figure 3(b) shows the $(\phi - \Psi_2)$ distributions for $\bar{d}$, $t$, and $^3$He for the same $p_T$ ranges as shown for $Z$ distributions in Fig. 3(a). Because the $(\phi - \Psi_2)$ distribution is expected to be symmetric about 0 and $\pi/2$, the data points have been folded onto $0-\pi/2$ to reduce the statistical errors.

The fitted second-order Fourier functions are shown in Fig. 3(b). Event plane resolution correction factors are determined in each centrality bin. For $v_2$ integrated over multiple centrality bins, species-yield-weighted means of the individual centrality bins’ resolutions are used: $v_2 = v_2^{\text{obs}}(\frac{1}{R_c})$ [38].

G. Calculation of systematic uncertainty and removal of beam-pipe contaminations

We reduced light-nuclei contaminants from interactions with the beam pipe by cutting tightly on the projected distance of closest approach (DCA) to the primary vertex. Remaining contaminants from such interactions are removed statistically by fitting the DCA distribution of nuclei with that of antinuclei (which are expected to have no such background) in each $(\phi - \Psi_2)$ bin. Systematic uncertainties are determined by varying cuts used in particle identification and background rejection, and by varying fitting methods and ranges when measuring yields. The absolute magnitude of uncertainties range over 2%–5% for intermediate $p_T$ (1.0 < $p_T$ < 3.0 GeV/c) and over 5%–8% for low and high $p_T$.

III. RESULTS AND DISCUSSION

A. General properties of $v_2(p_T)$

Figure 4 shows the energy dependence of the $v_2$ of the light (anti) nuclei $d$, $\bar{d}$, $t$, $^3$He, and $^3\overline{\text{He}}$ as a function of $p_T$ for minimum-bias Au + Au collisions. Insufficient statistics preclude measuring differential antinuclei $v_2$ at several collision energies. The $v_2(p_T)$ of all light-nuclei species and antinuclei species ($\bar{d}$ at $\sqrt{s_{NN}} = 19.6 - 200$ GeV and $^3\overline{\text{He}}$ at $\sqrt{s_{NN}} = 200$ GeV) show a monotonically increasing trend.
with increasing $p_T$ (Fig. 4). Mass ordering of $v_2(p_T)$ for $p_T < 2.0$ GeV/$c$ is clear in both Figs. 4 and 5, where the $v_2(p_T)$ of $\pi^+$, $K^0_s$, and $p$ from Refs. [4,9] are also included (heavier species have a lower $v_2$ in this $p_T$ range). Such ordering occurs naturally in a hydrodynamic plus coalescence model of heavy-ion collisions [39]. The negative $v_2$ observed for some (anti)-nuclei could be the result of interplay between transverse flow, modulation of transverse flow with respect to $\Psi_r$, and the geometry of the source.

Figure 6 presents the difference of $v_2(p_T)$ between $d$ and $\bar{d}$ ($\Delta v_2$), along with the difference between $p$ and $\bar{p}$ for comparison [4,9]. Statistical uncertainties are too large to draw conclusions about any collision-energy dependence, but the $\Delta v_2$ data are qualitatively consistent with the (anti) protons and the results of fitting a constant at each energy (solid lines in Fig. 6) are consistently positive: 0.0012 ± 0.0014, 0.009 ± 0.005, 0.0044 ± 0.0046, 0.017 ± 0.009, 0.024 ± 0.019 for $\sqrt{s_{NN}} = 200, 62.4, 39, 27, 19.6, 11.5$, and 7.7 GeV, respectively.

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FIG. 6. The difference in $v_2$ of $d$ and $\bar{d}$ as a function of $p_T$ for minimum-bias Au + Au collisions at $\sqrt{s_{NN}} = 200, 62.4, 39, 27,$ and 19.6 GeV, along with differences between $p$ and $\bar{p}$ [4]. Solid lines correspond to constants fit to the data (see text for details).

Figure 7 shows $v_2(p_T)$ of $d$ and $\bar{d}$ in 0%–30% and 30%–80% central events for where they could be measured in Au + Au collisions at $\sqrt{s_{NN}} = 2.7$ GeV. For 200 GeV $v_2$ are measured in three centralities: 0%–10%, 10%–40%, and 40%–80%. The observed centrality dependencies are qualitatively similar to those seen in identified hadrons [4,6], with $d$ and $\bar{d}$ showing similar behavior for all centralities measured.

B. Blast-wave model

The nuclear fireball model was first introduced by Westfall et al. to explain midrapidity proton-inclusive spectra [40]. Later, Siemens and Rasmussen [41] generalized a non-relativistic formula by Bondorf, Garpm, and Zimanyi [42] to explain nucleons and pions as they are produced in a blast wave of an exploding fireball. The blast-wave model has evolved since then, with more parameters to describe both $p_T$ spectra and anisotropic flow of produced particles [39,43,44]. The blast-wave parametrization modeled by the STAR Collaboration [44] has been recently used to fit the $v_2$ of identified particles [45]. This version of blast wave has four parameters; namely, kinetic freeze-out temperature ($T$), transverse expansion rapidity ($\rho_0$), amplitude of its azimuthal variation ($\rho_a$), and the variation in the azimuthal density of the source elements ($\xi_2$) [45]. The fit parameters obtained from blast-wave fits to the $v_2$ of identified particles are listed in Table I of Ref. [45]. We used the same blast-wave model and

FIG. 7. Centrality dependence of midrapidity $v_2(p_T)$ of $d$ (open markers) for Au + Au collisions at $\sqrt{s_{NN}} = 7.7–200$ GeV and $\bar{d}$ (solid markers) for $\sqrt{s_{NN}} = 27–200$ GeV. For $\sqrt{s_{NN}} = 200$ GeV, circles correspond to 0%–10%, triangles to 10%–40%, and squares to 40%–80% central events. For other collision energies, circles correspond to 0%–30% and squares to 30%–80% central events.
The blast-wave model and parameter values have been used from Ref. [45]. (Some data points in the lower panels are off scale.)

The low relative production of light nuclei and the scaling behavior of their elliptic flow seems to be favored by the coalescence formalism over the other methods, such as thermal production which can reproduce the measured particle ratios in data [47,48]. Because protons and neutrons have the same \(v_2\) expected from NCQ scaling, then we can readily see that the \(v_2\) of \(t\) and \(^3\text{He}\) will be the same as they have the same atomic mass number (\(A = 3\)). We find that, within statistical errors, our measurement of \(v_2(p_T)\) for \(t\) and \(^3\text{He}\) confirms this assumption. Although simple \(A\) scaling seems to hold for the collision energies presented, the actual mechanism might be a more dynamic process including production and coalescence of nucleons in the local rest frame of the fluid cell. This scenario might give rise to deviations from simple \(A\) scaling.

It is arguable that light nuclei could have also formed via coalescence of quarks because the scaling behavior holds when \(v_2\) and \(p_T\) are scaled by the number of constituent quarks (e.g., six for \(d\), \(\bar{d}\) and nine for \(t\), \(^3\text{He}\)) instead of mass number. Although this process seems physically acceptable, the survival of light nuclei, with their low binding energies (∼few MeV), is highly unlikely under the high temperatures requisite for dissociating nucleons into quarks and gluons.

To further verify the applicability of nucleon coalescence into light nuclei in heavy-ion collisions, we have run the string-melting version of the A Multi Phase Transport (AMPT, version v1.25t7d) [49] model of the collisions in conjunction with a dynamic coalescence model. The AMPT model has been used to reproduce charged particle multiplicity, transverse momentum spectra at RHIC and the Large Hadron Collider (LHC), as well as \(v_2\) of identified particles at RHIC [49].
FIG. 9. Atomic mass number (A) scaling of the midrapidity $v_2$ of $p$, $\bar{p}$, $d$, $t$, $^3$He, and $^3$He from minimum-bias Au + Au collisions at $\sqrt{s_{NN}} = 200, 62.4, 39, 27, 19.6, 11.5, \text{and} 7.7$ GeV. Gray solid (black dotted) lines correspond to third order polynomial fits to the $p$ ($\bar{p}$) $v_2$ data. The ratios of $[v_2/A]/[v_2]_{fit}$ for $d$, $t$, and $^3$He are shown in the lower panels at each corresponding collision energy. (Some data points in the lower panels are off scale.)

The dynamic coalescence model has been used extensively at both intermediate [50] and high energies [51]. In this model, the probability for producing a cluster is determined by the overlap of the cluster’s Wigner phase-space density with the nucleon phase-space distribution at freeze-out procured from AMPT. For light nuclei, the Wigner phase-space densities are obtained from their internal wave functions, which are taken to be those of a spherical harmonic oscillator [19,52]. For the coalescence model we have used radii of 1.96, 1.61, and 1.74 fm for $d$, $t$, and $^3$He, respectively [53]. These parameters are kept fixed for the collision-energy range presented. The model’s results for $v_2$ of $d$, $t$, and $^3$He are shown as solid bands in Fig. 10. The data and model agree within errors over nearly all energies and $p_T$ measured, supporting the theory that

FIG. 10. Midrapidity $v_2$ of $d$, $t$, and $^3$He are compared with the results of AMPT + coalescence calculations (solid bands).
light nuclei are produced via nucleon coalescence in heavy-ion collisions. Recently, the ALICE collaboration has measured production of $d$ and $\bar{d}$ in Pb+Pb collisions at $\sqrt{s_{NN}} = 2.76$ TeV [54]. In that study, light-nuclei spectra were found to exhibit a significant hardening with increasing centrality. The stiffening of light-nuclei spectra at ALICE could be the result of increased hard scattering, modified fragmentation, or increased radial flow. However, the analysis lacks conclusive evidence regarding the production mechanism of light nuclei in heavy-ion collisions. In the collision-energy range presented in this paper, it seems that nucleonic coalescence might be the leading mechanism of light-nuclei formation in heavy-ion collisions.

IV. SUMMARY

Measurements of the second-order azimuthal anisotropy, $v_2(p_T)$ at midrapidity ($|y| < 1.0$) have been presented for light nuclei $d$, $t$, $^3$He (for $\sqrt{s_{NN}} = 200, 62.4, 39, 27, 19.6, 11.5,$ and $7.7$ GeV), and antinuclei $\bar{d}$ ($\sqrt{s_{NN}} = 19.6$––$200$ GeV) and $^3$He ($\sqrt{s_{NN}} = 200$ GeV). Similar to hadrons over the measured $p_T$ range, light-(anti)nuclei $v_2(p_T)$ show a monotonic rise with increasing $p_T$, mass ordering at low $p_T$, and a reduction for more central collisions. It is observed that $v_2$ of nuclei and antinuclei are of similar magnitude for $\sqrt{s_{NN}} = 39$ GeV and above. The difference $\Delta v_2$ between $d$ and $\bar{d}$ is found to be always positive within the statistical uncertainty. $\Delta v_2$ of light nuclei seems to qualitatively follow the difference between $p$ and $\bar{p}$ as a function of collision energy. The blast-wave model parametrization, used for reproduction of the identified particle $v_2$ in the similar beam energies, is found to underestimate the light-nuclei $v_2$ in the low-$p_T$ (<1.0 GeV) region but approximately reproduces the measurements at intermediate $p_T$. Within the statistical uncertainty $^3$He and $t$ nuclei have almost similar magnitude of $v_2$ for all collision energies. The fact that all the light-nuclei $v_2$ generally follow an atomic mass number scaling indicates that the coalescence of nucleons might be the underlying mechanism of light-nuclei formation in high-energy heavy-ion collisions. This observation is further corroborated by carrying out a model-based study of nuclei $v_2$ using a transport-plus-coalescence model, which reproduces well the light-nuclei $v_2$ measured in the data except for the extremely low collision energies.

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