Directed Flow of Light Nuclei in Au+Au Collisions at AGS Energies

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Directed flow of deuterons, tritons, ³He, and ⁴He is studied in Au+Au collisions at a beam momentum of 10.8 A GeV/c. Flow of all particles is analyzed as a function of transverse momentum for different centralities of the collision. The directed flow signal, \( v_1(p_t) \), is found to increase with particle mass. This mass dependence is strongest in the projectile rapidity region.

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I. INTRODUCTION

Anisotropies in the azimuthal distribution of particles, also called anisotropic (directed, elliptic, etc.) transverse flow play an important role in high energy nuclear collisions \[1,2\]. In particular, flow of composite particles such as light nuclei is of a large interest for the understanding of the nuclear collision dynamics \[3-6\]. At lower beam energies (kinetic energies from about 0.2 to 1.15 GeV per nucleon) flow of light fragments has been studied intensively both experimentally \[7-14\] and theoretically \[3,6,15\] (and references therein). A theoretically predicted increase of \(\langle p_x \rangle / A\), the mean transverse momentum per fragment nucleon projected onto the reaction plane, with particle mass was later confirmed experimentally \[7-12\]. Initially, the theoretical prediction of the effect was based on the observation that the collective motion of the higher mass fragments should be less sensitive to thermal distortions. Later, calculations \[4-6\] showed the same effect in models based on a picture where the production of light nuclei takes place by the coalescence of nucleons close to each other in momentum and configuration space. Experimental data \[11\] for particles with transverse momentum greater than 0.2 GeV/c per fragment nucleon were found to be consistent with momentum space coalescence, but a complete understanding of the effect is still lacking. Recently, a measurement of light fragment directed flow in Au+Au collisions at AGS energies has been reported by the E802 Collaboration \[16\]. Their conclusion was that, in the target (pseudo)rapidity region, the maximal (as a function of centrality) values of \(\langle p_x \rangle / A\) do not depend on the particle species implying a common directed flow velocity.

In the current paper, we go beyond our previous measurements of anisotropic flow at AGS energies \[17-19\] and present results of the analysis of directed flow of deuterons, tritons, \(^3\)He, and \(^4\)He, detected in the E877 spectrometer in Au + Au collisions at a beam momentum of 10.8\(A\) GeV/c. Directed flow of all particles is analyzed as a function of the transverse momentum for different centralities of the collision. Triton, \(^3\)He, and \(^4\)He flow patterns are analyzed in the beam rapidity region, where these particles can be easily identified. Deuteron flow is analyzed also as a function of rapidity, in the rapidity region of \(2.2 < y < 3.4\). The results of a very similar analysis of proton and charged pion flow were reported in \[19\] and many technical details relevant for the current analysis can be found there.
II. E877 APPARATUS AND FLOW ANALYSIS

The E877 apparatus is shown in Fig. 1. In the E877 setup, charged particles, emitted in the forward direction and passing through a collimator ($-134 < \theta_{\text{horizontal}} < 16 \text{ mrad}$, $-11 < \theta_{\text{vertical}} < 11 \text{ mrad}$), are analyzed by a high resolution magnetic spectrometer. The spectrometer acceptance covers mostly the forward rapidity region. The momentum of each particle is measured using two drift chambers (DC2 and DC3, position resolution about 300 $\mu$m) whose pattern recognition capability is aided by four multi-wire proportional chambers (MWPC). The average momentum resolution is $\Delta p/p \approx 3\%$ limited by multiple scattering. A time-of-flight hodoscope (TOFU) located directly behind the tracking chambers provides the time-of-flight with an average resolution of 85 ps. Energy loss in TOFU and in a Forward Scintillator array located approximately 30 m downstream of the target is used to determine the particle charge.

The particle identification is performed by combining measurements of momentum, velocity, and charge of the particle. In the present sample of light nuclei we estimate an admixture of other particle species to be no more than 15–20%. Given that particles of the admixture (mostly other light nuclei, and some protons in the deuteron sample) exhibit a similar flow signal (see below), we arrive at relative errors in the final results due to particle misidentification of less than or about 5%.

The determination of the centrality of the collision and of the reaction plane orientation are made using the transverse energy flow measured in the target calorimeter (TCal), and participant calorimeter (PCal). Both calorimeters have $2\pi$ azimuthal coverage and, combined together, provide nearly complete polar angle coverage: TCal and PCal cover the pseudorapidity regions $-0.5 < \eta < 0.8$ and $0.8 < \eta < 4.2$, respectively \[18\].

The azimuthal anisotropy of particle production is studied by means of Fourier analysis of azimuthal distributions \[20,21,17–19\]. This yields the rapidity, transverse momentum, and centrality dependence of the Fourier coefficients $v_n$ (amplitude of $n$-th harmonic) in the decomposition:

$$E \frac{d^3N}{dp} = \frac{d^3N}{p_t dp_t dy d\phi} = \frac{1}{2\pi} \frac{d^2N}{p_t dp_t dy} (1 + 2v_1 \cos(\phi) + 2v_2 \cos(2\phi) + ...), \quad (1)$$

where the azimuthal angle $\phi$ is measured with respect to the (true) reaction plane.
Similarly to the analysis presented in [18,19], the reaction plane angle is determined in four non-overlapping pseudorapidity windows. The 'reaction plane resolution', i.e. the accuracy with which the reaction plane orientation is determined, is evaluated by studying the correlation between flow angles determined in different windows. Finally, the flow signals are corrected for the finite reaction plane resolution. Details of this procedure are described in [18,19].

III. RESULTS. DIRECTED FLOW OF LIGHT NUCLEI

We present our results in Figures 2 and 3 for four centrality regions, selected in accordance with transverse energy $E_T$ measured in PCal and corresponding to the values of $\sigma_{\text{top}}(E_T)/\sigma_{\text{geo}} \approx 23–13\%, 13–9\%, 9–4\%, \text{and } <4\%$ (see Fig. 4 in [18]). The value of $\sigma_{\text{top}}(E_T)$ is obtained by an integration of $d\sigma/dE_T$ from a given value of $E_T$ to the maximal one observed, and the geometric cross section is defined as $\sigma_{\text{geo}} = \pi r_0^2(A^{1/3} + A^{1/3})^2 = 6.13$ b, for $A = 197$ and $r_0 = 1.2$ fm.

The amplitude of the first harmonic in the Fourier decomposition of the azimuthal distribution, $v_1(p_t)$, for deuterons is presented in Fig. 2. For comparison the results for protons from [19] are shown by open symbols. The deuteron directed flow signal ($v_1(p_t)$) is systematically larger than that of protons, especially at rapidities close to the projectile rapidity. The relative difference in deuteron and proton flow increases with centrality. The centrality dependence of deuteron directed flow depends on rapidity. While at rapidities $y < 2.4$ flow almost disappears at high centralities, in the beam rapidity region it decreases very little.

At rapidities close to beam rapidity, $3.0 < y < 3.2$, our acceptance permits also the determination of the mean $p_x$ of deuterons, $\langle p_x \rangle_d$. To obtain this results we use the deuteron transverse momentum spectra which were analyzed in [22]. At beam rapidities deuteron spectra were found to be approximately thermal with an effective (Boltzmann) temperature of about 80 MeV for centralities corresponding to our centrality regions 2–3, and with slightly lower effective temperatures of about 50-60 MeV for the most central collisions. Using the deuteron spectra [22] and $v_1(p_t)$ from Fig. 2 (centrality regions 1–2), one obtains values of $\langle p_x \rangle_d = v_1(p_t) \approx 270$ MeV/c, with a systematic relative error of about 20% (coming from uncertainties both in the spectra and in $v_1(p_t)$). This value of $\langle p_x \rangle_d$ is approximately
twice the value of $\langle p_x \rangle_p$ for the same centrality and rapidity regions [19]. This observation is in accordance with the results of Ref. [16]. The observed absolute values of $\langle p_x \rangle / A \approx 130$ MeV/c are similar to the values $\langle p_x \rangle / A \approx 120-135$ MeV/c [12] observed at a beam kinetic energy of about 1 GeV per nucleon and significantly larger than the values measured at still lower beam energies (cf. for instance the result of $\langle p_x \rangle / A \approx 60$ MeV/c [8] measured at a beam energy of 0.2 GeV per nucleon).

In Fig. 3, we compare the flow signals of different light nuclei in the beam rapidity region for different centralities of the collision. The flow signal increases with mass number, flow of tritons and $^3$He is the same within error-bars. There is a rather large difference between proton and deuteron flow, while for nuclei with $A \geq 2$ the mass dependence is weaker and appears to saturate. This is very similar to the mass dependence of flow at much lower beam energies of 0.2 GeV per nucleon [7], where the value of $\langle p_x / p_t \rangle$ was also analyzed in the beam rapidity region. Note the very high values of $v_1$ (of the order of 0.7-0.8) for fragments with large transverse momenta.

The error-bars shown in Figures 2 and 3 represent statistical errors only. The systematic uncertainties are dominated by three sources: i) Possible particle misidentification. It leads to relative errors in $v_1$ of approximately 5% (see above). ii) The uncertainty in the determination of the reaction plane resolution [18,19], leading to a relative error in $v_1$ of the order of 5–10%, similar for all particle species. iii) The uncertainty in correction for finite detector occupancy (see [19]). The accuracy of the correction itself we estimate to be of the order of 20–30%. The occupancy correction strongly depends on the particle transverse momentum. The correction is maximal for the lowest $p_t$ points, where it reaches the (absolute) values of 0.1–0.12 (with an uncertainty of the order of 0.03-0.05). This large uncertainty in the occupancy corrections in the spectrometer region close to the beam limits our measurements at very low $p_t$. The occupancy correction is negligible at $p_t \geq 0.6-0.8$ GeV/c.

**IV. DISCUSSION**

In a simple picture where the directed flow is solely due to a common collective motion of the matter one would expect that for light fragments $\langle p_x \rangle_A = A \langle p_x \rangle_p$. At lower beam energies this equality was found to be approximately valid at rapidities close to the projectile
rapidity [8,3]. At lower rapidities, the ratio \( \langle p_x/A \rangle / \langle p_x \rangle_p \) was found to be *increasing* with particle mass. For \( A \leq 4 \) the dependence is rather significant; \( d(\langle p_x/A \rangle)/dy \) may increase by almost a factor of 3 from protons to \(^4\text{He}\) [12,13]. In our study we analyze the transverse momentum dependence of directed flow. Note that an equality \( \langle p_x \rangle_A = A \langle p_x \rangle_p \) does not imply that \( v_1^A(p_t) = A v_1^p(p_t) \). In the *(sideward) moving thermal source* model [19,23] \( v_1(p_t) \) to first order does not depend on the mass of the particle, and, for example, \( v_1^d(p_t) = v_1^p(p_t) \). Still, in the same model \( \langle p_x \rangle_d = 2 \langle p_x \rangle_p \), which is due to the increase of \( \langle p_t \rangle \) with the mass of the particle (assuming also a linear dependence of \( v_1 \) on \( p_t \)).\(^1\) Also note that in the simple *coalescence* model where in order for nucleons to coalesce one requires that they are close to each other only in momentum space, \( v_1^A(p_t) \approx A v_1^p(p_t) \). Taking into account that \( v_1^p(p_t) \) depends almost linearly on \( p_t \) one arrives once more at the equality \( v_1^d(p_t) \approx v_1^p(p_t) \). The experimental data (Fig. 2) show that, in the rapidity region \( y < 2.6 \), \( v_1^d(p_t) \) is indeed close to \( v_1^p(p_t) \). However, at larger rapidities, we observe a significant excess of deuteron flow in comparison with that of protons. It could imply that volume effects (to form a deuteron both nucleons should be close to each other not only in momentum space but also in configuration space) and/or projectile fragmentation processes become significant in deuteron production.

In order to check if a coalescence picture including volume effects could account for our data we have used the coalescence model of Ref. [6] combined with the RQMD (version 2.3) event generator [24]. This coalescence model [6] explicitly requires the nucleons, in order to coalesce, to be close both in the momentum and in the configuration space. The closeness is defined by the cluster wave function, the parameters of which were determined by measured root mean square charge radii of the clusters (of the order of 1.5–2.0 fm). The results of our calculations of \( v_1(p_t)^{d,p} \) corresponding to the centrality region 1 are shown in Fig. 4. One can see that the model describes most of the features observed in the data (Fig. 2). The exception is, as was already observed in proton flow [19], that the data exhibit an approximately linear dependence of \( v_1 \) on \( p_t \) at all rapidities, while the model shows a rather fast saturation of \( v_1 \) in the projectile rapidity region. More relevant for the present

\(^1\) More precisely \( \langle p_x \rangle_d / \langle p_x \rangle_p \approx (T_d/T_p)(v_1^d/v_1^p) \), where \( T_d \) and \( T_p \) are deuteron and proton inverse slope constants and the ratio \( (v_1^d/v_1^p) \) stands for the average ratio of deuteron and proton \( v_1(p_t) \).
discussion though, the model does describe the fact that \( v_1^{d}(p_t) \) is very similar to \( v_1^{p}(p_t) \) at rapidities \( y < 2.6 \) and that the difference becomes large at rapidities close to beam rapidity. Looking into details of the nucleon freeze-out configuration space distribution (used for the coalescence) one can notice that, for rapidities \( y > 2.6 \), nucleons emitted in flow direction come from a significantly narrower spatial distribution (especially along the flow direction) as compared to those emitted in the opposite direction. A smaller width of the spatial distribution means a higher probability for nucleons to coalesce. As a consequence, the deuteron distributions get an extra asymmetry beyond what is due to the asymmetry in momentum space of the nucleon distributions. This may account for the effect observed both experimentally and in the model.

The difference in proton and deuteron flow as a function of rapidity could be also due to the presence of deuterons from projectile fragmentation. In a detailed comparison \cite{22} of the coalescence model \cite{6} with the E877 experimental data on deuteron production it was shown that the model fails to reproduce the deuteron \( p_t \) spectra in the projectile rapidity region, while describing the data fairly well at smaller rapidities. It suggests that the deuteron production mechanism at beam rapidity may not be (dominantly) coalescence. At present a quantitative description of the fragmentation process at the AGS energies is not available yet. However, qualitatively one could argue that deuterons from projectile fragmentation which are concentrated close to beam rapidity exhibit stronger flow as they are less distorted by thermal motion, in line with the trend observed in the data.

V. CONCLUSION

In summary, the directed flow of light nuclei has been measured in Au+Au collisions at AGS energies in the forward rapidity region. The effect has been analyzed as a function of particle transverse momentum for different centralities of the collision. The largest flow has been observed in collisions of approximately half overlapping nuclei. In such collisions and at rapidities close to the beam rapidity region, light nuclei exhibit very strong directed flow, corresponding to \( v_1 \approx 0.7-0.8 \) at particle transverse momenta of about 1 GeV/c.

The directed flow \( (v_1) \) increases with the mass of the light nucleus. Coalescence model calculations show that the increase in \( v_1 \) could be accounted for by asymmetries in the
distributions of nucleons (forming the light nucleus) both in momentum and in configuration space.

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FIGURE CAPTIONS

1. The E877 apparatus.

2. Transverse momentum dependence of the first moment \(v_1\) of the deuteron (filled circles) and proton \([19]\) (open symbols) azimuthal distributions for different particle rapidities and centralities of the collision.

3. Transverse momentum dependence of directed flow \(v_1(p_t)\) of protons, deuterons, tritons, \(^3\)He, and \(^4\)He for different centralities of the collision. All particles are from the rapidity region \(3.0 < y < 3.2\).

4. Transverse momentum dependence of \(v_1(p_t)\) of protons and deuterons in the coalescence model combined with the RQMD event generator. The centrality corresponds to the experimental region 1.
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\[ v_1(p_t) \]
FIG. 4. Transverse momentum dependence of $v_1(p_t)$ of protons and deuterons in the coalescence model combined with the RQMD event generator. The centrality corresponds to the experimental region 1.