Anisotropic flow in 4.2*A* GeV/*c* C+Ta collisions

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Anisotropic flow of protons and negative pions in 4.2*A* GeV/*c* C+Ta collisions is studied using the Fourier analysis of azimuthal distributions. The protons exhibit pronounced directed flow. Directed flow of pions is positive in the entire rapidity interval and indicates that the pions are preferentially emitted in the reaction plane from the target to the projectile. The elliptic flow of protons and negative pions is close to zero. Comparison with the quark-gluon-string model and relativistic transport model show that they both yield a flow signature similar to the experimental data.

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The anisotropic transverse flow of particles has been actively studied in nuclear collisions over a wide range of energies. At lower energies [1–5], the flow is usually studied in terms of the mean in-plane component of transverse momentum at a given rapidity, $\langle p^x(y)\rangle$ [1], and additionally quantified in terms of derivative at midrapidity $F_y = d\langle p^x\rangle/dy$. At high energies, the Fourier expansion of the azimuthal distribution of particles constructed with respect to the reaction plane is used [6–8]. In this expansion the first harmonic v_1 quantifies the directed flow while the second harmonic v_2 quantifies the elliptic flow. Using the Fourier expansion, the anisotropic transverse flow was analyzed for heavy symmetric systems at the AGS [6,9,10], SPS [11,12], and RHIC [13] energies. It was found that the flow observables are important tools for investigating properties of high density region created during the initial collisions. In particular, the elliptic flow measurements may provide an important constraint on the equation of state (EOS) of high density nuclear matter [14,15].

In this paper, the anisotropic transverse flow of protons and negative pions in 4.2*A* GeV/*c* C+Ta collisions is studied using the Fourier analysis of azimuthal distributions. The analysis is performed using 1000 C+Ta semicentral and central collisions obtained with the 2-m propane bubble chamber, exposed at JINR, Dubna synchrophasotron. The semicentral and central collisions are selected by rejecting ≈50% events with the smallest multiplicity of participant protons. Additionally, the same type of analysis is performed using 100 000 events generated by the quark-gluon-string model (QGSM) [16], and the same number of events generated by the relativistic transport model (ART 1.0) [17]. For these events the same centrality criterion is applied as in experiment, leading to the average impact parameter $\langle b\rangle \approx 4.54$ (4.05) fm according to QGSM (ART 1.0).

In order to study the inelastic interactions with tantalum nucleus, (^{181}Ta), three tantalum foils (1 mm thick and 93 mm apart) were placed inside the chamber working in the 1.5-T magnetic field. The characteristics of the chamber allow precise determination of the multiplicity and momentum of all charged particles, as well as identification of all negative and positive particles with momenta less than 0.5 GeV/*c*. All recorded negative particles, except the identified electrons, are taken to be π^-. Among them remains admixture of unidentified fast electrons (<5%) and negative strange particles (<1%). All positive particles with momenta less than 0.5 GeV/*c* are classified either as protons or π^+ mesons according to their ionization density and range. Positive particles above 0.5 GeV/*c* are taken to be protons, and because of this, the admixture of π^+ of ≈7% is subtracted statistically using the number of π^- mesons with $p > 0.5$ GeV/*c* as follows: $n_p = n_+ - n_{\pi^+}(p \leqslant 0.5\ \mathrm{GeV}/c) - 0.82\times n_{\pi^-}(p > 0.5\ \mathrm{GeV}/c)$, where n_+ denotes the number of single positively charged particles, and 0.82 takes into account the proton deficit in tantalum nuclei and consequently also π^+ deficit. From the ratio for each momentum interval we determine the weight of protons which we further use when calculating distributions of other kinematical variables. From the resulting number of protons, the projectile spectators (protons with momenta $p > 3$ GeV/*c* and emission angle $\theta < 4°$) and target spectators (protons with momenta $p < 0.3$ GeV/*c*) are further subtracted. The resulting number of participant protons still contains some 17% of deuterons (with $p > 0.48$ GeV/*c*) and 11% of tritons (with $p > 0.65$ GeV/*c*). The experimental data are also corrected to the loss of particles emitted at small angles relative to the optical axes of chamber and to the loss of particles absorbed by the tantalum plates. The aim of this correction is to obtain isotropic distribution in azimuthal angle and smooth distribution in emission angle (both measured with respect to the direction of the incoming projectile).

The azimuthal distribution of particles may be represented with the first three terms of the corresponding Fourier expansion

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

where the two coefficients, v_1 and v_2, quantify the directed and elliptic flow via $v_1 = \langle\cos(\phi)\rangle$ and $v_2 = \langle\cos(2\phi)\rangle$. In Eq. (1), $\phi = \phi_{lab} - \Phi_{plane}$ is the particle azimuthal angle determined with respect to the reaction plane, with ϕ_{lab} denoting

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the azimuthal angle of particle in the laboratory frame and Φ_{plane} denoting the azimuthal angle of the (true) reaction plane. Since both the projectile momentum and the impact parameter vectors are available in the QGSM/ART simulations, they are used to determine the corresponding reaction plane. In the experiment the reaction plane is determined, for each event, using the projectile momentum vector and the vector **Q** determined from [1]

$$\mathbf{Q}=\sum_i \mathbf{p}_{Ti}(y>y_{\text{c.m.}}+\delta)-\sum_j \mathbf{p}_{Tj}(y<y_{\text{c.m.}}-\delta), \qquad (2)$$

where $\mathbf{p}_T$ represents the transverse momentum of the proton emitted in the forward ($y>y_{\text{c.m.}}+\delta$), or backward ($y<y_{\text{c.m.}}-\delta$), hemisphere. Here, $y_{\text{c.m.}}$ denotes the center-of-mass (c.m.) rapidity of participant protons while the quantity δ ($=0.2$) removes the protons emitted around the $y_{\text{c.m.}}$, which are not contributing to the determination of the reaction plane. The reaction plane angle for a proton is determined using this expression only if this proton is not included in the above sum (i.e., if its rapidity lies in the interval from $y_{\text{c.m.}}-\delta$ to $y_{\text{c.m.}}+\delta$). Otherwise, in order to avoid autocorrelation (which is an effect of the finite multiplicity), the **Q** vector is constructed by the analogous expression in which the contribution of this proton is simply omitted [1]. We found that the reaction plane angle distribution is essentially flat, thus confirming the absence of significant distortions which could influence the magnitude of the extracted flow parameters. The accuracy with which the reaction plane angle is determined, i.e., the reaction plane resolution, is evaluated by the subevent method [1,8]. In this method, each event is divided randomly into two subevents, and then the corresponding two reaction planes are determined. Subsequently, the absolute value of the relative azimuthal angle Φ_{12} between these two estimated reaction planes is obtained. The relative azimuthal angle distribution is the basis for the correction of the Fourier coefficient v_1' obtained with the estimated reaction plane. The relationship between the v_1', and the Fourier coefficient v_1 obtained relative to the true reaction plane, is $v_1'=v_1\langle\cos(\Delta\Phi)\rangle$, where $\langle\cos(\Delta\Phi)\rangle^{-1}$ is the correction factor determined from Φ_{12} distribution following the prescription given in [8,18]. We find $\langle\cos(\Delta\Phi)\rangle=0.59$. The correctness of this procedure is checked using the QGSM. Using this model, the coefficient v_1 vs rapidity, for protons and negative pions, is calculated with respect to the true reaction plane and also with respect to the estimated reaction plane. The result of comparison is presented in Fig. 1.

The QGS calculations show that the v_1 values obtained with respect to the estimated reaction plane, after applying correction procedure, are somewhat underestimated around projectile rapidity for protons and negative pions. The QGS calculations also show that the correction procedure for v_2' as outlined above is not applicable because of the smallness of the elliptic flow. Therefore, in the following analysis, this coefficient is not corrected to the reaction plane resolution.

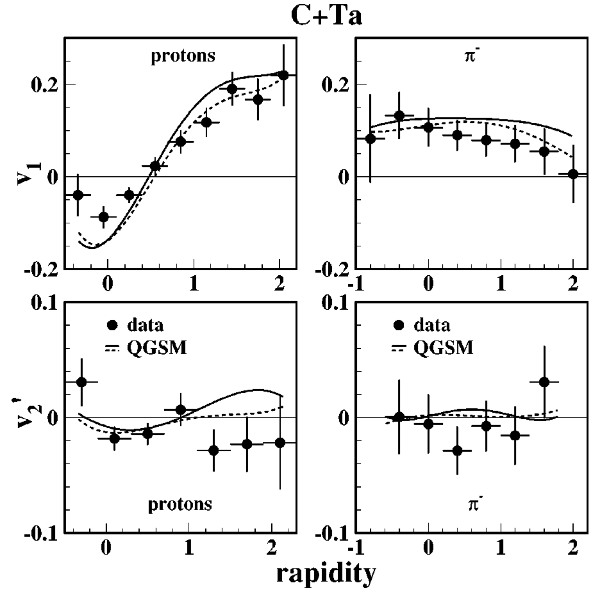

FIG. 1. Rapidity dependence of v_1 and v_2' for protons and π^- for 4.2A GeV/c C+Ta collisions: Top, filled circles represent the experimental results for v_1 while the solid (dashed) line represents the QGSM calculation for v_1 with respect to the true (estimated) reaction plane; bottom, filled circles represent uncorrected experimental v_2' values (see text), while the solid (dashed) line represents the QGSM calculation for v_2 (v_2') with respect to the true (estimated) reaction plane.

Figure 1 (top) displays the experimentally determined v_1 coefficient vs y (with y calculated in the lab frame), for protons and negative pions. In the case of protons the dependence of v_1 on rapidity is characterized by a curve with a positive slope and with the zero crossing at $y\approx0.5$, that corresponds to average rapidity of protons. The curve indicates a positive directed flow with magnitude $v_1\approx0.2$, at rapidities close to the projectile rapidity ($y_p=2.2$, at p $=4.2A$ GeV/c). The QGSM reproduces satisfactorily the shape of $v_1(y)$ curve and within error bars reproduces the magnitude of the flow. The experimental results are also compared with the relativistic transport model ART 1.0. These are shown in Fig. 2, where the calculations are performed both for *stiff* and *soft* EOS. ART model yields a directed flow which follows trend similar to the experimental data, but underestimates the flow intensity in the projectile and target rapidity region.

Using the extracted values of v_1 and their relation to the mean transverse momentum projected onto the reaction plane, $v_1=\langle p_x\rangle/\langle p_T\rangle$, we can evaluate $\langle p_x\rangle$ as a function of rapidity and determine the slope, $F=d\langle p_x\rangle/d(y/y_b)$, with respect to rapidity normalized to projectile rapidity in the lab frame. In the present analysis we find for the slope at midrapidity $F=215\pm32$ MeV/c. Comparison with the other results obtained at the same energy, for various C-nucleus combinations shows increasing of the slope with the target mass: $F=144$ MeV/c for CC [19], 134 MeV/c for CNe [20], and 198 MeV/c for CCu [20]. After the normalization to the mass number of the colliding system we obtain the

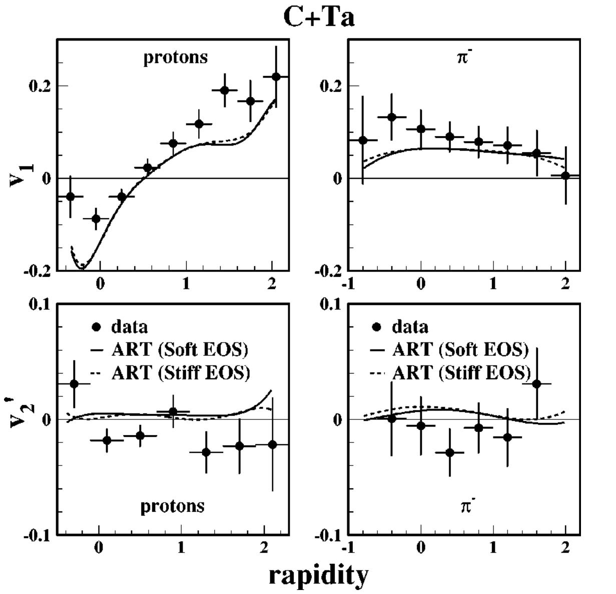

FIG. 2. Experimental results for v_1, v_2' as a function of rapidity, compared with ART 1.0 model calculations.

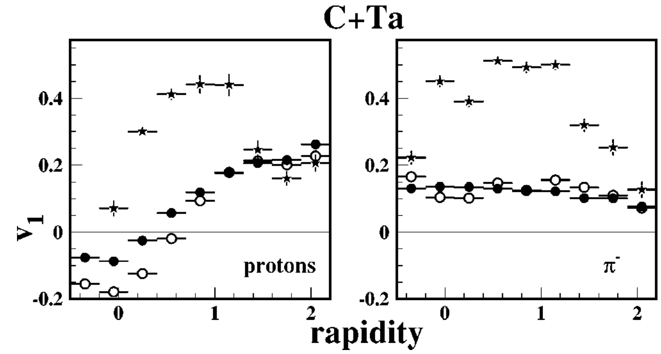

FIG. 3. Rapidity dependence of v_1 for protons and π^- originating from: primary nonresonant interactions (*stars*), decay of resonances (*full circles*), and secondary nonresonant interactions (*open circles*), for 4.2*A* GeV/*c* C+Ta collisions generated with the QGSM.

so-called scaled flow $F_S = F/(A_1^{1/3}+A_2^{1/3}) = 27\pm 4$ MeV/c, that allows a comparison of the energy dependence of flow values for different projectile and target mass combinations. This value is in agreement with the observed trend [3] that after reaching the maximum at a beam energy around 0.7–2 *A* GeV, the directed flow slowly decreases with increasing beam energy.

For negative pions the experimental values of v_1 are positive in the entire rapidity interval. The v_1 is largest in the target rapidity region ($v_1^{max}\approx 0.10$) and monotonically decreases with increasing rapidity towards the projectile rapidity. Such v_1 dependence on y reflects the fact that the pions are preferentially emitted in the reaction plane from the target to the projectile. This behavior is attributed to a shadowing effect of the heavy target. Both QGSM and ART model cannot strictly account for the $v_1(y)$ dependence for negative pions.

Figure 1 (bottom) displays the experimentally determined v_2' coefficient versus y for protons and negative pions. The uncorrected values of v_2' show that in the entire rapidity interval the elliptic flow is small $|v_2'|\leqslant 0.02$ if not zero, and this is consistent with QGSM (Fig. 1) and ART (Fig. 2) predictions. The values of v_2' additionally confirm the result [14] that at beam energy of ≈ 4 GeV the elliptic flow exhibits a transition from negative (out-of-plane) to positive (in-plane) elliptic flow.

Since the QGSM predictions are in fair agreement with the various experimental results at 4.2*A* GeV/*c*, we use this model to clarify the question which of the processes are responsible for the flow effect. In this model, for C+Ta collisions $\approx$43% of protons and $\approx$83% of π^- originate from decay of the lowest-lying resonances (Δ's, ϱ,ω,η, and η'). The rest originates from the nonresonant primary and secondary interactions of the type: $NN\rightarrow NN\pi$, $\Delta N\rightarrow\Delta N$, $\pi N\rightarrow\pi N$, $\pi NN\rightarrow NN$. The protons and pions from primary interaction escape the collision zone without further rescattering and comprise $\approx$1% of the total. According to QGSM, we separately evaluate the flow of protons and pions originating from the following sources: (i) decay of resonances; (ii) primary nonresonant interactions; and (iii) secondary nonresonant interactions.

Figure 3 shows v_1 vs rapidity for protons and negative pions originating from the decay of resonances, and from primary and secondary nonresonant interactions. The protons originating both from the decay of resonances and from the secondary nonresonant interactions show a directed flow of similar intensity. The same applies to the flow of pions. For both protons and pions from the primary interactions the directed flow has a maximum around $y\approx 0.6$, and decreases towards the projectile and target rapidities. These protons and pions are produced at the early stage of the collision, and both are shadowed by the cold spectators. Later, after the spectator matter leaves the collision zone, rescattering of protons near the beam (target) rapidity region is small, while the pions are still affected with the shadowing effect of the participant nucleons through both pion rescattering and reabsorptions. This could be the underlying mechanism that leads to the different intensity and dependence on rapidity for the directed flow of pions and protons.

In summary, the directed and elliptic flow of protons and negative pions in 4.2*A* GeV/*c* C+Ta collisions was examined using the Fourier analysis of azimuthal distributions of experimental events and also by using the events generated by the QGSM and ART 1.0. The protons exhibit strong directed flow with magnitude $v_1\approx 0.2$ at rapidities close to the projectile rapidity. The directed flow of pions is positive in the entire rapidity and slightly peaked at target rapidity, where $v_1\approx 0.1$. This behavior indicates that the pions are preferentially emitted in the reaction plane from the target to the projectile. For both sets of particles in the entire rapidity interval the elliptic flow is close to zero ($|v_2'|\leqslant 0.02$), this being consistent with the result that at beam energy of ≈ 4 GeV the elliptic flow shows a transition from negative to positive. A comparison with the quark-gluon-string model (QGSM) and relativistic transport model (ART 1.0) shows that they both yields the flow signature similar to the experimental data. Additionally, the QGSM shows that two factors that dominantly determine the proton and pion flow at this energy, are the decay of resonances and the rescattering of secondaries. The shadowing by the cold spectator matter affects only the flow of the particles produced at the early stage of the collision.

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