Event anisotropy in 4.2A GeV/c C+C collisions

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Abstract

The directed and elliptic flow of protons and negative pions in 4.2A GeV/c C+C collisions is studied using the Fourier analysis of azimuthal distributions. It is found that the protons exhibit pronounced directed flow, while the flow of pions is either non existent or too weak to be detected experimentally. Also, it is found that in the entire rapidity interval the elliptic flow is very small if not zero. These results are confirmed by the Quark-Gluon-String Model (QGSM) and the relativistic transport model (ART 1.0), except that these models predict very weak antiflow of pions. The more detailed comparison with the QGSM suggests that the decay of resonances and rescattering of secondaries dominantly determine the proton and negative pion flow at this energy.

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Event anisotropy, often called flow, has been observed in heavy-ion collisions at all incident energies [1–6]. At Bevalac energies and below, the flow is usually studied in terms of the mean in-plane component of transverse momentum at a given rapidity, \( \langle p^x(y) \rangle \), [7] and additionally quantified in terms of derivative at the midrapidity \( F_y = d\langle p^x \rangle/dy \). At high energies, the Fourier expansion of the azimuthal distribution of particles is used [8–10]. 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 analysed for heavy symmetric systems at the AGS [4] and SPS [5,6] energies. It was found that this anisotropy, and particularly the elliptic flow, plays an important role for investigating properties of hadronic matter [11–14]. However, it is still not clear whether the experimentally observed event anisotropy is of a dynamic origin or is due to the shadowing of spectator matter, passing time, etc.

In this paper the directed and elliptic flow of protons and negative pions in 4.2A GeV/c C+C collisions is studied using the Fourier analysis of azimuthal distributions. The analysis is performed using 9500 C+C semicentral and central collisions obtained with the 2-m propane bubble chamber, exposed at JINR, Dubna synchrophasotron. The data for semicentral and central collisions roughly correspond to the upper 50% of the inelastic cross-section. Additionally, the same type of analysis is performed using the 400000 events generated by the QGSM [15–17] and 200000 events generated by the relativistic transport model (ART 1.0) [18]. For these events the same centrality criterion is applied as in experiment, leading to the average impact parameter \( \approx 2.6 \). In the 2-m propane bubble chamber practically all charged reaction products are detected. Negative particles, except identified electrons are considered to be \( \pi^- \). Among them remains admixture of unidentified fast electrons (\(< 5\%\)). All positive particles with momenta less than 0.5 GeV/c are classified either as protons or \( \pi^+ \) mesons according to their ionisation density and range. Positive particles above 0.5 GeV/c are taken to be protons, and because of this, the admixture of \( \pi^+ \) of approximately 18% is subtracted statistically using the \( \pi^+ \) and \( \pi^- \) momentum distributions. From the resulting number of protons, the projectile spectators (protons with momenta \( p > 3 \) GeV/c and emis-
sion angle $\theta < 4^\circ$) and target spectators (protons with momenta $p < 0.3$ GeV/c) are further subtracted. The resulting number of participant protons still contains some 4% of deuterons (with $p > 0.48$ GeV/c) which are statistically subtracted. The admixture of tritons (with $p > 0.65$ GeV/c) is not considered. The experimental data are also corrected to the loss of particles emitted at small angles relative to the optical axes of chamber. 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

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

(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), $\phi = \phi_{\text{lab}} - \Phi_{\text{plane}}$ is the particle azimuthal angle determined with respect to the reaction plane, with $\phi_{\text{lab}}$ denoting the azimuthal angle of particle in the laboratory frame and $\Phi_{\text{plane}}$ denoting the azimuthal angle of the (true) reaction plane. Since both the projectile momentum and the impact parameter vectors are available in the QGSM simulation, 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 [7]

$$Q = \sum_i p_{Ti}(y > y_{cm} + \delta) - \sum_j p_{Tj}(y < y_{cm} - \delta),$$

(2)

where $p_T$ represents the transverse momentum of the proton emitted in the forward ($y > y_{cm} + \delta$), or backward ($y < y_{cm} - \delta$), hemisphere. Here, $y_{cm}$ denotes the center of mass rapidity while the quantity $\delta (=0.2)$ removes the protons emitted around the $y_{cm}$ 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 $y_{cm} - \delta$ to $y_{cm} + \delta$). 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 [7]. 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 [7]. 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, $\Phi_{12}$, between these two estimated reaction planes is obtained. The width, $\sigma$, of the $\Phi_{12}$ distribution determines the reaction plane resolution. For C+C collisions we find $\sigma = 50^0$. The relative azimuthal angle distribution is the basis for the correction of the Fourier coefficients, $v'_n$, obtained with the estimated reaction plane. The relationship between the $v'_n$, and the Fourier coefficients $v_n$ obtained relative to the true reaction plane, is $v'_n = v_n \langle \cos(n\Delta\Phi) \rangle$, where $\langle \cos(n\Delta\Phi) \rangle$ is the correction factor determined from $\Phi_{12}$ distribution following the prescription given in [10,19]. We find $\langle \cos(\Delta\Phi) \rangle=0.56$ and $\langle \cos(2\Delta\Phi) \rangle=0.24$. The correctness of this procedure is checked using the QGSM. Using this model, the coefficients $v_1$ and $v_2$ are calculated with respect to the true reaction plane and also with respect to the estimated reaction plane. The results of the comparison will be discussed below.

Fig. 1 (top) displays the experimentally determined $v_1$ coefficient vs. $y$ (with $y$ calculated in the center-of-mass frame), for protons and negative pions together with the $v_1$ calculated with QGSM relative to the true reaction plane and relative to the estimated reaction plane. For the proper comparison with the experiment, we excluded protons satisfying cuts for the proton spectators in the experiment. In the case of protons it is seen that the values of the two QGSM results for $v_1$ are quite close. The dependence of $v_1$ on rapidity is characterised by a curve with a positive slope and with the zero-crossing at $y = 0$. The curve indicates a positive directed flow with magnitude $v_1 \approx 0.17$, at rapidities close to the beam rapidity ($0.7 < y < 1.5$). The QGSM reproduces satisfactorily the shape of $v_1(y)$ curve and the magnitude of the flow. 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, \( F = d(\langle p_x \rangle) / d(y/\gamma_b) \), with respect to rapidity normalised to beam rapidity in the lab frame (\( \gamma_b = 2.2 \)). In the present analysis we find for the slope at the midrapidity \( F = 144 \text{ MeV/c} \). After the normalisation to the mass number of the colliding system we obtain the so called scaled flow \( F_S = F / (A_1^{1/3} + A_2^{1/3}) = 31 \text{ MeV/c} \). This value is in agreement with the observed trend [2] that after reaching the maximum at beam energy around 0.7-2A GeV, the directed flow slowly decreases with increasing beam energy.

For negative pions the experimental values of \( v_1 \) indicate that the directed flow is non-existent. This result is confirmed by the model calculations of \( v_1 \) with respect to the estimated reaction plane. However, the model calculations of \( v_1 \) with respect to the true reaction plane show the existence of a very weak directed flow of pions with the sign of \( v_1 \) opposite to that of protons and with the maximum value of 0.02 around the target rapidity. This further suggests that in the collisions of light nuclei, like C+C, the very weak flow, if it exists, is not measurable because of the limited accuracy in determination of the reaction plane.

Fig. 1 (bottom) displays the experimentally determined \( v'_2 \) coefficient vs. \( y \) for protons and negative pions. This coefficient is not corrected to the reaction plane resolution since the comparison of the model calculation of \( v'_2 \), obtained as in the experiment, and the model calculation of \( v_2 \), relative to the true reaction plane, indicates that the corresponding correction procedure for \( v_2 \), as outlined above, is not applicable. The reason for this is the lightness of the colliding nuclei and the smallness of the elliptic flow. The uncorrected values of \( v'_2 \) show that in the entire rapidity interval the elliptic flow is small (\( |v'_2| \leq 0.02 \)) if not zero, and this is consistent with the predictions of QGSM. The experimental values for \( v'_2 \) also show that, for both protons and pions, the elliptic flow depends on rapidity and that around the beam and target rapidities it is positive for protons and negative for pions. The positive sign for protons indicates an enhanced emission in the reaction plane, while the negative sign for pions indicates an enhanced emission perpendicular to the reaction plane.
This behaviour points out to the shadowing by the nuclear matter as the origin of the elliptic flow.

Since the QGSM predictions are in fair agreement with the experimental results at 4.2A GeV/c, we use this model to clarify the question which of the processes are responsible for the flow effect. In this model, in collisions of light C+C nuclei, approximately 40% of protons and \( \approx 70\% \) of \( \pi^- \) originate from decay of the lowest-lying resonances (\( \Delta \)s, \( \varrho \), \( \omega \), \( \eta \) and \( \eta' \)). The rest originates from the 'non-resonant' 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 \( \approx 5\% \) of the total. Therefore, according to QGSM, we separately evaluate the flow of protons and pions originating from the following sources: (i) decay of resonances, (ii) primary non-resonant interactions (iii) and secondary non-resonant interactions.

Figure 2 (top) shows \( v_1 \) vs. rapidity for protons and negative pions originating from decay of resonances, and from primary and secondary non-resonant interactions, as well as the overall \( v_1 \) for protons and \( \pi^- \). (In these model calculations, the experimental cuts for the proton spectators were not applied, and this leads to a small difference between the two curves for overall \( v_1 \) for protons in Figs. 1 and 2). The protons originating both from the decay of resonances and from the secondary interactions show the directed flow of similar intensity. The same applies to the antiflow of pions. The protons from the primary interactions show a relatively flat \( v_1(y) \) distribution, while the pions from these interactions show a strong directed antiflow with magnitude \( \approx -0.13 \) around beam rapidity. The antiflow of pions can be also explained by the shadowing effect, but the shadowing matter is different for pions from primary and secondary interactions since these pions are produced at different collision stages. Initially (at times less than the passing time, \( t_p = 4.2 \text{ fm/c} \)) the pions are shadowed by the cold spectators. Later, after the spectator matter leaves the collision zone, the pions are shadowed by the participant nucleons. This may be the underlying mechanism that leads to the different behaviour of \( v_1 \) for pions. In heavy nuclei collisions, additionally generated by the QGSM, the protons from primary interactions, similarly to the case of
pions from primary interactions, show strong antiflow caused by the shadowing from the cold nuclear matter. In the collisions of light nuclei this shadowing is small and there is no preferential emission of the protons.

Figure 2 (bottom) shows $v_2$ vs. rapidity for protons and negative pions originating from decay of resonances, and from primary and secondary non-resonant interactions, as well as the overall $v_1$ for protons and $\pi^-$. It is seen that the particles from secondary interactions and from decay of resonances, exhibit similar behaviour. The particles from the primary interactions show a clear negative elliptic flow, and this out-of-plane emission can be attributed to the shadowing by the cold spectators.

In order to establish a less model dependent picture, the results of the experiment are also compared with the relativistic transport model, ART 1.0. These are shown in Fig. 3, where the calculations are performed both in the cascade and in the so-called 'mean field' mode. The cascade mode underestimates the magnitude of the proton flow (some 20%), and predicts a small directed antiflow of negative pions with magnitude $v_1 \approx 0.04$. In the mean field mode the model increases the magnitude of the proton flow. Also, the ART model predicts a very small proton and pion elliptic flow ($|v_2| \leq 0.01$).

In summary, the directed and elliptic flow of protons and negative pions in 4.2A GeV/c C+C 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 model. It was found that the protons exhibit strong directed flow with magnitude $v_1 \approx 0.17$ at rapidities close to the beam rapidity. The QGSM reproduces satisfactorily the shape of the $v_1(y)$ curve and the magnitude of the flow. The ART model underestimates this magnitude in the cascade mode and increases this magnitude in the mean field mode. For negative pions the flow is either non existent, or too weak to be detected experimentally due to the limited accuracy in the determination of the reaction plane. The latter was suggested by the QGSM, where calculations with respect to the estimated reaction plane predicted non existant flow, while the calculations with respect to the true reaction plane predicted a small directed antiflow with magnitude $v_1 \approx 0.02$. The predictions of the ART model are similar.
Also, it was found that in the entire rapidity interval the elliptic flow is small ($|v_2| \leq 0.02$) if not zero, and this is in agreement with the predictions of QGSM and ART 1.0. According to the QGSM, the two factors that dominantly determine the proton and negative 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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FIGURES

FIG. 1. Rapidity dependence of $v_1$ and $v_2$ for protons and $\pi^-$ for 4.2A GeV/c C+C 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.

FIG. 2. Rapidity dependence of $v_1$ and $v_2$ for protons and $\pi^-$ (solid line); for protons and $\pi^-$ originating from decay of resonances (stars), primary non-resonant interactions (full circles), and secondary non-resonant interactions (open circles), for 4.2A GeV/c C+C collisions generated with the QGSM.

FIG. 3. Experimental results for $v_1$, $v_2$ as a function of rapidity, compared with ART 1.0 model calculations.