Anisotropic flow of identified particles in Au+Au collisions at AGS energy

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Anisotropic flow of protons, $\pi^\pm$, $K^\pm$, deuterons, tritons, $^3$He, and $^4$He is analyzed as a function of transverse momentum for different centralities of the collision.

1. E877 experimental setup and flow analysis

The E877 experimental setup is discussed in detail elsewhere \cite{1-4}. In the current analysis, for the reaction plane determination and the evaluation of the reaction plane resolution, we exploit the almost $4\pi$ calorimeter coverage of the apparatus (the Target Calorimeter (TCal) covers the pseudorapidity range $-0.5 < \eta < 0.8$, the Participant Calorimeter (PCal) $0.8 < \eta < 4.2$). Charged particles, emitted in the forward direction ($-134 < \theta_{\text{horizontal}} < 16$ mrad, $-11 < \theta_{\text{vertical}} < 11$ mrad), are analyzed by a high resolution magnetic spectrometer. The average momentum resolution is $\Delta p/p \approx 3\%$ limited by multiple scattering. A time-of-flight hodoscope located behind the tracking chambers (10 m from the target) provides time-of-flight information with a typical resolution of 85 ps. For the identification of charge=2 particles we also use the Forward Scintillator array located approximately 33 m downstream of the target.

The centrality of the collisions is determined by the transverse energy deposited in the PCal (see Table 1).

| Centrality | PCal $E_t$ (GeV) | $\sigma_{\text{top}}/\sigma_{\text{geo}}$ | $b$ (fm) |
|------------|-----------------|---------------------------------|--------|
| 1          | 150 – 200       | 0.23 – 0.13                     | 5 – 7  |
| 2          | 200 – 230       | 0.13 – 0.09                     | 4 – 5  |
| 3          | 130 – 270       | 0.09 – 0.04                     | 3 – 4  |
| 4          | $> 270$         | $< 0.04$                        | $< 3$  |

Table 1. Centrality regions. The impact parameter range was estimated in accordance with $\sigma_{\text{top}}/\sigma_{\text{geo}} \approx (b/2R)^2$.

To describe the anisotropy in particle production we use a Fourier expansion of the azimuthal distributions \cite{5,6} (see also \cite{2,3}), where the anisotropic flow signal is represented by $v_n$, the amplitudes of different harmonics. In this analysis we discuss mostly directed flow, $v_1(p_t)$, with emphasis on the dependence on the particle transverse momentum. All results shown below are corrected for the reaction plane resolution in accordance with the procedure described in \cite{4,5,6}.

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2. Results

Protons. The directed flow signal, \( v_1(p_t) \), of protons almost linearly depends on \( p_t \) (see Figures 1 and 4; for a complete set of proton and pion data and also results on \( v_2 \) see [3]). This behavior naturally follows from the assumption that directed flow is a consequence of the sideward motion of the thermal source with velocity \( \beta_x \) [3]). Small deviations from a linear dependence at low \( p_t \) can be explained in this case by taking into account the transverse radial expansion of the source [7]. Note that in such a picture the shape of \( v_1(p_t) \) depends on the magnitude of radial expansion velocity \( \beta_r \), providing the possibility to study radial expansion by means of an anisotropic flow analysis. Using this model we fit our proton data under the assumption that the source temperature is fixed, \( T = 110 \) MeV. The results of the fit are shown in Fig. 1 and the fit parameters (directed and radial velocities, \( \beta_x \) and \( \beta_r \), in this case) are presented in Fig. 2.

Figure 1. Directed flow of protons (open symbols) and deuterons (solid symbols) for collisions in centrality region 2. A (solid line) fit to the proton data was performed taking into account the radial expansion of the source.

Figure 2. Directed and radial velocities of the proton source from the fit to \( v_1(p_t) \).

Charged pions. Directed flow of \( \pi^+ \) and \( \pi^- \) (see Figures 6 and 7 in [3]) is very similar for \( p_t > 100 \) MeV/c (being negative at \( 100 < p_t < 300–500 \) MeV/c with values \( v_1 \approx -0.05 \) – –0.1, and becoming positive at higher \( p_t \) values), and is different at \( p_t < 100 \) MeV/c (at
$p_t < 40$ MeV/c negative pions exhibit positive flow!). Such behavior at least qualitatively can be explained by four factors: 1) shadowing by the comoving nucleons, 2) transverse motion of the source (the same as for protons), 3) Coulomb interactions with comoving protons, and 4) $\Delta$ (and, to some extent, $\Lambda$) decays. Note that the Coulomb effect in this case is different from the one widely discussed in the literature, namely, from the distortion of the spectra due to the central potential. In our case the comoving protons (mostly spectators) are shifted with respect to the pions in the transverse plane; then Coulomb interaction would result in directed flow of negative pions in the direction of proton flow, and of positive pions in the opposite direction. A very rough estimate of the signal in the case of a static Coulomb field result in $v_1(p_t \to 0) \approx \langle r \rangle / a$, where $\langle r \rangle$ is the relative source shift and $a$ is the (pion) Bohr radius. Note that the signal in this case is proportional to the particle mass (inversely proportional to Bohr radius); then “Coulomb flow” of kaons should be even larger than that of pions.

Note also the rather non-trivial dependence on $p_t$ of the flow signal $v_1$ of pions from decays of $\Delta$ resonances. Simple considerations show that the “kinematics” of such kind of flow under assumption that $\Delta$ flow follows the proton flow (moving thermal source) is exactly the same as in the picture of “a transversely moving and radially expanding thermal source” [7]. It means that pions from $\Delta$ decays would exhibit negative flow at low $p_t$ and follow protons at high transverse momentum.

**Kaons.** The magnetic field polarity used for the analyzed data set provided good acceptance only for positively charged kaons. The observed flow signal (Fig. 3) is very small (compatible with zero) for $p_t > 200$ MeV/c. In the low $p_t$ region strong (negative) flow is observed. It could be due to Coulomb interaction with comoving protons (see above). The currently undergoing analysis of the (different field polarity data) $K^-\overline{K}$ flow will clarify the role of Coulomb interaction in kaon flow.

![Figure 3. $K^+$ directed flow in the rapidity region $2.4 < y < 2.8$](image)

**Deuterons.** Deuterons exhibit strong directed flow (see Figures 1 and 4). Note that in the moving thermal source model $v_1(p_t)$ in first order does not depend on the mass of the particle; then $v_1^{deuteron}(p_t) = v_1^{proton}(p_t)$. Also, in a simple coalescence model (without volume effects) $v_1^{deuteron}(p_t) \approx 2v_1^{proton}(p_t/2) \approx v_1^{proton}(p_t)$. The observed significant excess of deuteron flow in comparison with that of protons implies that volume effects (and/or projectile fragmentation) are significant in deuteron production.

**Tritons, $^3\text{He}$, and $^4\text{He}$.** The results on anisotropic flow of light nuclei in the beam rapidity region are presented in Fig. 4. Contamination between different species in this
data sample is less than 15%. Directed flow monotonically increases with particle mass and reaches values up to about 0.8 for high $p_t$ particles.

![Figure 4. Directed flow of light nuclei in the rapidity region $3.0 < y < 3.2$.](image)

3. **Summary**

The transverse momentum dependence of directed flow has been studied in Au+Au collisions at the BNL AGS for different types of particles: protons, charged pions, $K^+$, and light nuclei. Even a brief look at these data reveals rich and interesting physics. At present, the quality of the experimental data in this field is more advanced than theory and good/detailed models are needed for the interpretation of the data.

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