FLOW EFFECTS IN Bi + Pb COLLISIONS AT 1 GeV/u*

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We report particle-exclusive measurements of triple-differential cross sections for positive pions, nucleons and light nuclear fragments in multiplicity-selected collisions of 1 GeV/u ^{209}Bi+^{208}Pb. The dependence upon the azimuthal angle with respect to the reaction plane is studied as a function of the particle rapidity and transverse momentum. Flow and squeeze-out are clearly established. For the baryonic component both effects increase with increasing mass of the particle. The meson flow is anticorrelated to the baryon flow.

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1. Introduction

The collective behaviour of hot and dense nuclear matter has been predicted [1] to manifest itself in the emission pattern of nuclear fragments. Both the directed sideward flow and the squeeze-out perpendicular to the reaction plane have been observed [2] and transport models like BUU [3, 4] and QMD [5, 6] have shown that the occurrence of these flow effects and their magnitude is connected to the nuclear matter compressibility and consequently to the parameters of the nuclear equation of state.

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Pions also show flow effects [7, 8]. As the pions are mainly produced through the Δ resonance, they might follow the flow and squeeze-out of the baryons. Recent IQMD calculations [6], however, indicate that pion rescattering can lead to an anticorrelation of the pionic and baryonic flow. Our systematic particle-exclusive data provide clear experimental evidence for this anticorrelation.

2. Experiment

The experiment was performed at the Heavy-Ion Synchrotron SIS at GSI Darmstadt. A ^{209}Bi beam (1 GeV/u) with an intensity of 3×10^6 particles per spill (duration 4s) was incident on an isotopically enriched target of ^{208}Pb (420 mg/cm^2) tilted at 45° relative to the beam. Particles were detected in a block of seven hexagonal BaF_2 scintillator modules (250 mm long, 59 mm diameter), equipped in front with a common 10 mm thick plastic charged-particle veto detector (CPV). The detector distance from the target was 4.3 m. In this report we present results obtained for two detector positions, i.e. at the polar and azimuthal angles $\theta = 40°$, $\phi = 2°$ and $\theta = 23.5°$, $\phi = 4°$, respectively.

The kinetic energy, the mass and the charge of the particles observed in the plastic-scintillator BaF_2 telescope were derived from the time-of-flight (TOF), from the ΔE signal measured in the CPV and from the E signal measured in the BaF_2. The stopped positive pions with energies between 15 MeV and the punch-through energy of 170 MeV were identified by their subsequent decay chain $\pi^+ \to \mu^+ \to e^+$. Events were recorded together with the charged-particle multiplicity registered in the outer part of the forward wall (OFW) of the FOPI collaboration [9]. The modularized OFW covers polar angles from 7° to 30° and is divided into eight equal segments in azimuth. The OFW multiplicity provides information on the centrality of the collision and on the orientation of the reaction plane.

The reconstruction of the reaction plane is based on the enhanced directed emission of charged fragments in the reaction plane [2]. It uses the number of hits in each segment of the OFW to determine a vector $\vec{Q}$ defined as

$$\vec{Q} = \sum_{i=1}^{8} M_i \vec{n}_i \,. \tag{1}$$

The sum runs over all eight OFW segments, $\vec{n}_i$ is a unit vector perpendicular to the beam direction pointing to the center of the i-th segment and M_i is the charged particle multiplicity registered by the i-th segment. In the approximation of Eq. 1 the reaction plane is defined by the beam direction and the vector $\vec{Q}$. The accuracy in the determination of the reaction plane is influenced by the total charged-particle multiplicity in the OFW given by $M = \sum M_i$ and by the strength of the flow signal $\mid \vec{Q} \mid$. Two conditions are applied in order to assure the selection of events with a well-defined reaction plane. First, M must be > 60. This multiplicity cut approximately corresponds to the upper half of the multiplicity distribution and excludes peripheral events. Compared to this multiplicity cut, the supplemental condition $\mid \vec{Q} \mid > 5$ represents a small additional bias, because it excludes only 8% of the already multiplicity-selected events. The accuracy of the reaction plane determination is 28° fwhm.

3. Results

In the following we present the measured values of the triple-differential cross-sections $d^3N/dp_{t,u}dY_{\rm rel}d\varphi$, concentrating on the distribution of their azimuth with respect to the reaction plane, $\varphi = \phi - \phi_R$. Here $p_{t,u}$ is the particle transverse momentum per mass unit and $Y_{\rm rel} = (y - y_{\rm cm})/y_{\rm cm}$ is its relative rapidity with $y_{\rm cm}$ and y being the rapidity of the nucleon-nucleon center of mass system and of the detected particle in the laboratory frame, respectively. Both $Y_{\rm rel}$ and $p_{t,u}$ were determined from the particle's TOF.

Azimuthal distributions of baryons and light fragments relative to the reaction plane for three regions in relative rapidity are shown in Fig. 1. In Fig. 2 we compare the azimuthal distributions of protons and pions. Following the general systematics [10] of such spectra, we fitted these distributions by a second-order Fourier series

$$N(\varphi) = \frac{N_0}{2\pi}(1 + A\cos\varphi + B\cos 2\varphi)\ , \qquad (2)$$

keeping N_0, A and B as free parameters. The resulting fits are indicated in Figs 1 and 2 by smooth curves.

The interpretation of the coefficients A and B is as follows. For the mean cosine of the azimuthal angle with respect to the reaction plane, *i.e.* for the fraction of the particle transverse momentum which lies in the reaction plane, one obtains

$$\langle\cos\varphi\rangle = \left\langle \frac{p_{x,u}}{p_{t,u}} \right\rangle = \frac{A}{2}\,. \qquad (3)$$

For $R_{\rm out/in}$, *i.e.* for the ratio of the number of particles emitted out of the reaction plane to the number of particles emitted in the reaction plane, one obtains

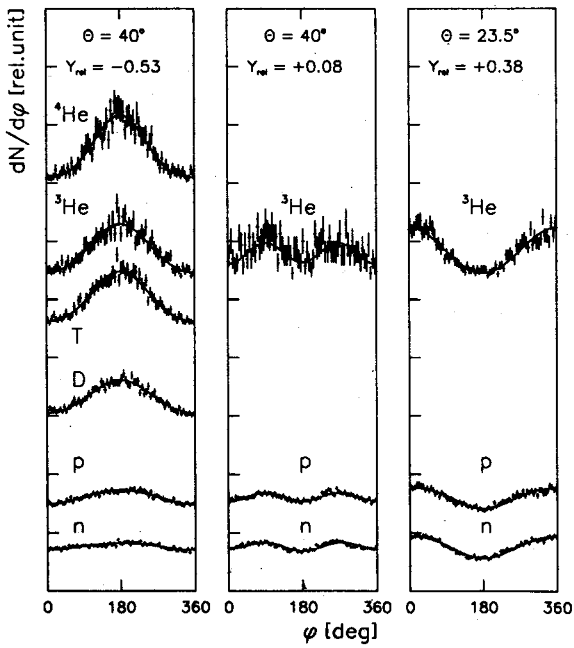

Fig. 1. Normalized azimuthal distributions of neutrons, protons, deuterons, tritons, ^{3}He and ^{4}He relative to the reaction plane for three ranges of rapidity, $-0.60 < Y_{rel} < -0.45$, $0 < Y_{rel} < 0.15$ and $0.30 < Y_{rel} < 0.45$. In the upper two rapidity ranges ^{3}He and ^{4}He could not be distinguished experimentally. The distributions, separated by suitable offsets along the ordinate, are plotted on a common linear scale. The experimental binsize is 5 deg per channel. The collision system is 1 GeV/u ^{209}Bi + ^{208}Pb.

$$R_{out/in} = \frac{N(90^\circ) + N(270^\circ)}{N(0^\circ) + N(180^\circ)} = \frac{1 - B}{1 + B}. \tag{4}$$

Hence, A is sensitive to the collective sideward flow only and B measures the particle emission perpendicular to the reaction plane. The values of the parameter A for nucleons and light nuclear fragments are given in Fig. 3 as a function of their rapidity for the two detector positions.

4. Discussion

Following the argumentation of [2, 11] the single-humped structures visible in the emission patterns of the baryons and the light nuclear fragments for TL- rapidities ($Y_{rel} < -0.15$) indicate the dominance of sideward flow. This flow is opposite to the direction of the charged particles detected in the

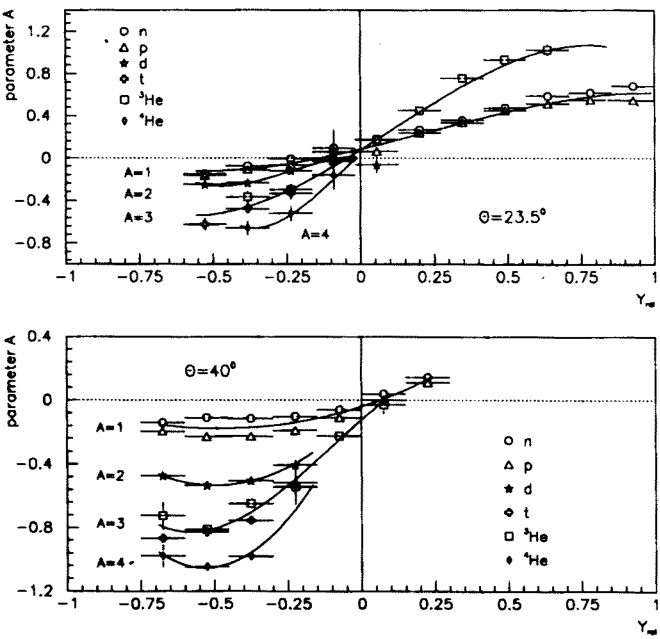

Fig. 2. Comparison of azimuthal distributions of π^+ (a,b,c) and protons (d,e,f) relative to the reaction plane for three ranges of rapidity, $-0.45 < Y_{\rm rel} < -0.15$ (a,d), $-0.15 < Y_{\rm rel} < 0.15$ (b,e) and $0.15 < Y_{\rm rel} < 0.45$ (c,f), obtained at the detector position $\theta = 40°$. The collision system is 1 GeV/u ^{209}Bi + ^{208}Pb.

OFW. The double-humped structures near CM-rapidities ($0 < Y_{\rm rel} < 0.15$) on the other hand indicate the dominance of squeeze-out effects, *i.e.* enhanced emission of high $p_{t,u}$ particles perpendicular to the reaction plane. At PL-rapidities ($Y_{\rm rel} > 0.15$) the emission pattern of baryons and light fragments is again dominated by sideward flow. The observed patterns now indicate emission in the direction of the charged particles observed in the OFW. The emission pattern of the pions at PL-rapidities, however, is anticorrelated to the baryonic flow.

4.1. Nucleons and light nuclear fragments

The sideward flow of nucleons and light nuclear fragments is usually considered as a direct manifestation of the expansion of the collision zone, *i.e.* of the velocity distribution of the expanding nuclear matter at the moment of freeze-out. One expects that the heavier fragments should show stronger flow effects than the lighter nucleons, in general agreement with our experimental findings, see Fig. 1.

The observed mass dependence of the baryonic flow can be associated with one of the following explanations:

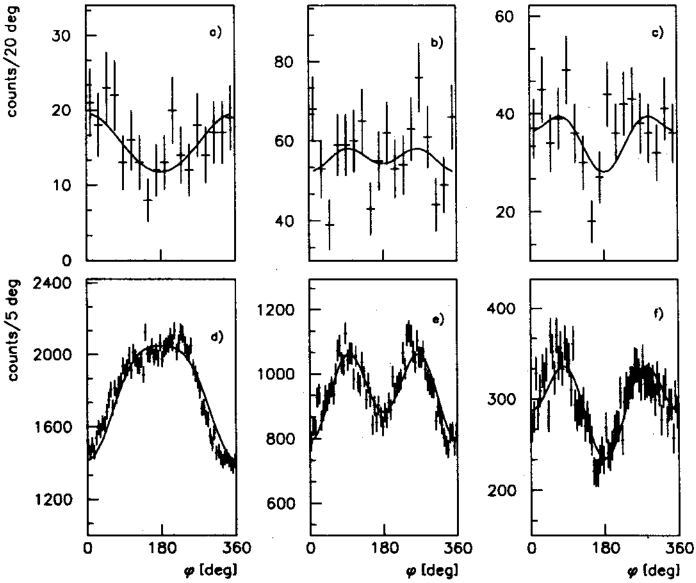

Fig. 3. Flow parameter A for nucleons and light nuclear fragments as a function of $Y_{\rm rel}$ obtained at the detector positions $\theta = 23.5^{\circ}$ and $\theta = 40^{\circ}$. For rapidity $Y_{\rm rel} > 0$ ^{3}He and ^{4}He could not be distinguished experimentally. The collision system is 1 GeV/u ^{209}Bi + ^{208}Pb.

- Let us assume that the fragments are created in local thermal equilibrium during the late stages of the collision. Particles with different masses then share the same thermal energy and have the same collective energy per nucleon. This results in more pronounced flow effects with increasing mass.
- The assumption of the fragments being created by the coalescence of n individual nucleons at freeze-out provides another possible explanation of the experimental data. In this picture the probability to find a particular fragment at emission angle φ is given as the n-th power of the corresponding value for single nucleons. Again the flow effects increase with increasing mass.

4.2. Pions

The double-humped structure of the pion emission pattern observed by us at CM-rapidities is similar to that reported recently for neutral pions by the TAPS group [7] and for positive pions by the KAOS group [8], in both cases for the system Au+Au at 1 GeV/u beam energy. The values of $R_{\rm out/in}$ determined from our data are in agreement with those of [7, 8] for high values of $p_{t,u}$ at CM-rapidities. If the pions emitted at CM-rapidities follow the flow of baryonic matter, they will be preferentially emitted perpendicular to the reaction plane. However, the same pattern results, if the pion emission would be isotropic, but the pions would be absorbed in the participant nuclear matter located mainly in the reaction plane. Hence, the KAOS and TAPS data as well as our data for CM-rapidities do not allow an unambiguous determination of the origin of the observed pion flow.

This is not the case for the pions emitted at TL-rapidities. This rapidity range was not covered in [7, 8]. From our present data it is clear, that pions with TL-rapidities are preferentially emitted in the reaction plane, but opposite to the proton flow, see Fig. 2. Obviously pion emission does not follow the baryonic flow. Such an effect was predicted in [6] for TL-rapidities and interpreted as a consequence of the strong absorption of pions by the spectator nuclear matter.

5. Conclusion

We have unambiguously observed a mass dependence in the flow and squeeze-out for nucleons and light nuclear fragments over the full rapidity range as well as a qualitative difference in the emission pattern of charged pions as compared to that of protons at target-like rapidity. The latter effect can be associated with the dominance of rescattering which the pions experience in the spectator matter of the collision system.

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