Emission Pattern of High-Energy Pions: A New Probe for the Early Phase of Heavy-Ion Collisions

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The emission pattern of charged pions has been measured in Au + Au collisions at 1 GeV/nucleon incident energy. In peripheral collisions and at target rapidities, high-energy pions are emitted preferentially towards the target spectator matter. In contrast, low-energy pions are emitted predominantly in the opposite direction. The corresponding azimuthal anisotropy is explained by the interaction of pions with projectile and target spectator matter. This interaction with the spectator matter causes an effective shadowing which varies with time during the reaction. Our observations show that high-energy pions stem from the early stage of the collision whereas low-energy pions freeze out later.

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Heavy-ion collisions at relativistic energies provide a unique possibility to study nuclear matter at high densities and at high temperatures in the laboratory. These reactions last only several 10^{-23} s and within this time interval the baryonic density varies between about 3 times the normal nuclear matter density ($\rho_0 = 0.17\ \mathrm{fm}^{-3}$) in the early phase and about $0.2 \times \rho_0$ at freeze-out when the particles cease to interact [1,2]. A prerequisite for the study of the properties (e.g., the nuclear equation of state) of the dense "fireball" is to obtain information on the space-time evolution of the nuclear matter distribution in the course of the collision.

Pions are considered to be a sensitive probe of the reaction dynamics. They are produced abundantly and due to the large πN cross section pions are continuously "trapped" by forming baryonic resonances (e.g., $\pi N \rightarrow \Delta$) which then can decay by pion emission. Therefore, pions, especially those with momenta between 0.2 and 0.5 GeV/c, are expected to freeze out predominantly in the late and dilute stage of the collision. High-energy pions, however, interact less strongly with the nucleons and hence have a chance to decouple already in an early phase. Therefore, a detailed study of high-energy pions may shed light on the hot and dense stage of the collision as suggested in [3]. The first evidence for different freeze-out conditions was extracted from the π^-/π^+ ratio measured in central Au + Au collisions at 1 GeV/nucleon. The π^-/π^+ ratio as a function of transverse momentum was analyzed in terms of Coulomb interaction between pions and the nuclear fireball. It was found that high-energy pions are emitted from a more compact source than low-energy pions [4].

Our experimental approach to investigate the space-time evolution of the pion source is to exploit the absorption or rescattering of pions when interacting with the spectator fragments. The shadow cast by the spectator matter leads to a depletion of pions according to the emission time of the pions and the motion of the spectator matter. Preferential emission of pions in the reaction plane was found in asymmetric collisions and has been interpreted as an effect of shadowing by a large target nucleus [5]. In symmetric collision systems, a preferential emission perpendicular to the reaction plane has been observed both for charged [6] and neutral [7] pions and has been interpreted as absorption or rescattering effects in the spectator matter. Recently, an enhanced in-plane emission of pions was observed in Au + Au collisions [8] with more (positive) pions being emitted opposite to the target spectator fragments. Since in a hydrodynamical interpretation the preferential motion of nucleons and composite particles towards the spectator fragments is described as "flow," the complementary effect observed for pions was called "antiflow." The antiflow of pions is found to be pronounced only in peripheral Au + Au collisions and vanishes for central collisions [8].

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In this Letter we present data on pion production in Au + Au collisions at a bombarding energy of 1 GeV/nucleon as a function of the pion azimuthal emission angle, the rapidity, the transverse momentum, and the collision centrality. With this detailed information one can monitor the effect of spectator shadowing on the pion emission pattern at subsequent stages of the collision. The fast moving spectator matter represents an obstacle for the pions emitted from the fireball. This introduces a time scale which allows one to follow the evolution of the pion source and to study correlations of pion energy and freeze-out time. Emphasis is put on the investigation of high-energy pions which are measured with high statistics.

The experiments were performed with the Kaon Spectrometer [9] at the heavy-ion synchrotron SIS at GSI (Darmstadt) which delivered a beam of $^{197}\text{Au}^{65+}$ impinging onto a 1.93 g/cm^3 Au target. The spectrometer covers a momentum-dependent solid angle of $\Omega = 15-35$ msr and a momentum bite of $p_{\text{max}}/p_{\text{min}} \approx 2$ for a given magnetic field setting. The measured laboratory momenta vary between 0.156 and 1.5 GeV/c with data taken in four different magnetic field settings. The particle trajectories and momenta are reconstructed using three multiwire proportional chambers. The particle velocities are determined with two time-of-flight arrays. Both measurements allow one to identify pions up to 1.5 GeV/c. The collision centrality is determined by means of the charged particle multiplicity measured in a polar angle range between 12° and 48° using a 84-fold segmented plastic-scintillator detector. For our study we select peripheral collisions (65% ± 5% of the reaction cross section) and the 14% ± 4% most central collisions. The reaction cross section (5.9 ± 0.4 b) was measured with a minimum bias trigger which required a charged particle multiplicity of more than 2 in the polar angle range given above.

The determination of the reaction plane in every collision is based on the measurement of charged projectile spectator fragments detected between $0.5° \leq \theta_{\text{lab}} \leq 5°$ using a plastic scintillator wall of 380 modules positioned 7 m downstream from the target. The orientation of the event plane is determined by the sum of transverse momenta of the charged projectile spectator particles [10,11]. The dispersion of the reaction plane amounts to ≈45° for peripheral collisions [12].

Figure 1 depicts the nuclear matter distribution for a Au + Au collision at a beam energy of 1 GeV/nucleon at 6.5, 12.5, and 18.5 fm/c after time zero (which is the time instant when both nuclei have a distance projected to the beam axis of 2 times the nuclear radius).

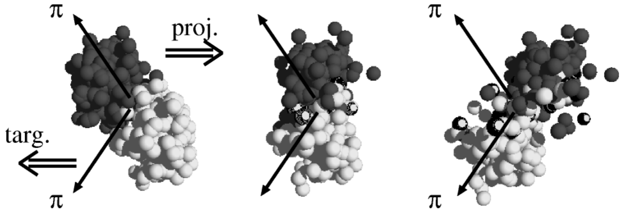

FIG. 1. Sketch of an Au + Au collision at 1 GeV/nucleon with an impact parameter of 7 fm as calculated by a transport code [13]. The snapshots are taken at 6.5 fm/c (left), 12.5 fm/c (middle), and 18.5 fm/c (right) after time zero (see text for definition of time zero). The arrows indicate the direction of the spectrometer at target rapidity.

These pictures are the result of a transport calculation based on quantum molecular dynamics for an impact parameter of $b = 7$ fm [13]. The snapshots sketch the effect of pion shadowing by spectator matter at different stages of the collision. Those pions which are emitted in the early phase of the collision and are detected around target rapidity (i.e., at backward angles as indicated by the arrows in Fig. 1) will be shadowed by the projectile spectator on one side and therefore exhibit flow to the other side. In contrast, if pions freeze out at a late stage of the collision they will be shadowed (at target rapidity) by the target spectator which results in an anti-flow-like configuration. Experimentally, we compare the number of pions emitted in the reaction plane to the side of the projectile spectator $N(\phi = 0°)$ with the number of those pions emitted into the opposite direction $N(\phi = 180°)$. The azimuthal angle $\phi = 0°$ is defined by the projectile. $N_\pi(0°)$ refers to the angular range of $-45° < \phi < 45°$, and $N_\pi(180°)$ to the angular range of $135° < \phi < 225°$.

Figure 2 shows the ratio of these numbers for π^+ and π^- mesons as a function of transverse momentum p_T in two different rapidity regions and both for near-central and peripheral collisions. In all four cases both π^+ and π^- (open and full symbols) show a similar behavior ruling out Coulomb effects as the origin of the observed effect. At midrapidity the measured ratios are close to 1 both for near-central and peripheral collisions, as expected for symmetric systems. The deviations of about 10% (for near-central collisions) reflect the systematic error of the measurement which is attributed mainly to the uncertainty in the determination of the reaction plane.

In near-central collisions (right panels in Fig. 2) the spectator fragments are small and hence shadowing effects are strongly reduced. Nevertheless, at target rapidities we observe that all pions—independent of their momentum—are emitted preferentially to the side of the target spectator (upper right panel of Fig. 2). The same asymmetry, which corresponds to pion flow, was observed by the EOS Collaboration at slightly higher incident energies [8]. Transport calculations have predicted a transition from pion antiflow to flow with decreasing impact parameter. According to these calculations, pion flow in near-central collisions is a remainder of the flow of Δ resonances which decay into protons and pions [14].

For peripheral collisions and at target rapidity (upper left panel of Fig. 2) the ratio $N_\pi(0°)/N(180°)$ decreases from about 1.2 at low p_T values to about 0.5 at high p_T. This behavior corresponds to a transition from pion number antiflow to flow with increasing transverse momentum.

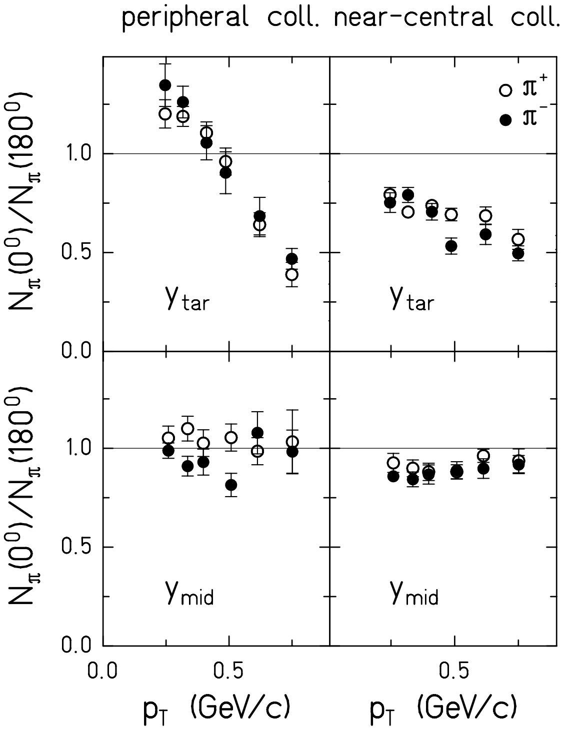

FIG. 2. Pion number ratios $N_\pi(0°)/N_\pi(180°)$ as a function of transverse momentum. $N_\pi(0°)$ and $N_\pi(180°)$ denote the number of pions emitted to the projectile and to the target side, respectively. The spectra are measured in peripheral (left panel) and near-central (right panel) Au + Au collisions at 1 GeV/nucleon and at two rapidity regions (the target rapidity region $0.01y_{\text{beam}} \le y_{\text{tar}} \le 0.10y_{\text{beam}}$ and the midrapidity region $0.44y_{\text{beam}} \le y_{\text{mid}} \le 0.56y_{\text{beam}}$). Full (open) symbols refer to π^- (π^+) emission. Only statistical errors are shown.

In earlier measurements it has been integrated over pion momentum and, hence, pion antiflow has been found since the pion yield is dominated by low-momentum pions [8]. According to transport calculations, antiflow is caused by rescattering of pions at the spectator matter in the late stage of the collision [14]. The transition from antiflow to flow as a function of transverse momentum as shown in the upper left panel of Fig. 2 is a new observation which will be discussed in more detail along with Fig. 3.

A more detailed picture of pion emission is obtained by comparing the yield of pions emitted in plane to the yield of pions emitted perpendicular to the reaction plane. The latter pions are expected to be much less affected by shadowing or rescattering by spectator matter and hence provide a nearly undisturbed view onto the pion source. In order to visualize the effect of shadowing for different pion momenta we normalize the in-plane pion spectra [$N_\pi(0°)$ and $N_\pi(180°)$] to the out-of-plane spectra $\{N_\pi(\text{perp}) = [N_\pi(90°) + N_\pi(270°)]/2\}$.

Figure 3 shows the ratios $R_0 = N_\pi(0°)/N_\pi(\text{perp})$ ("projectile side," upper panel) and $R_{180} = N_\pi(180°)/N_\pi(\text{perp})$ ("target side," lower panel) as a function of transverse momentum for peripheral collisions and target rapidities. The ratios $R_{0,180}$ in Fig. 3 do not exceed unity.

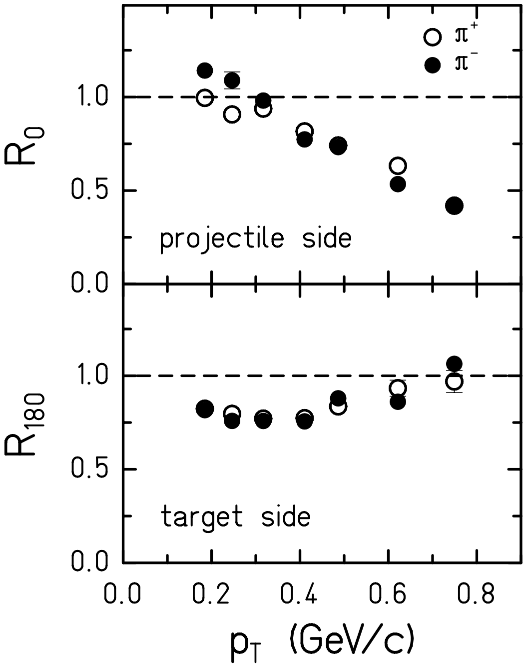

FIG. 3. Pion ratios $R_0 = N_\pi(0°)/N_\pi(\text{perp})$ (upper panel) and $R_{180} = N_\pi(180°)/N_\pi(\text{perp})$ (lower panel) as a function of the transverse momentum. $N_\pi(0°)$ and $N_\pi(180°)$ denote the number of pions emitted to the projectile and to the target side, respectively. $N_\pi(\text{perp})$ is the number of pions emitted perpendicular to the reaction plane (see text). The pions are measured in peripheral Au + Au collisions at 1 GeV/nucleon at target rapidities ($0.01y_{\text{beam}} \le y_{\text{tar}} \le 0.10y_{\text{beam}}$). Full (open) symbols refer to π^- (π^+) emission. Only statistical errors are shown.

This indicates that the azimuthal asymmetry as shown in Fig. 2 is not caused by an enhanced pion emission but rather by losses due to absorption or rescattering (which result in ratios R inferior to unity). Figure 3 allows one to extract detailed information on the emission time of pions as a function of their momentum. At pion momenta around 0.4 GeV/c, the upper left panel of Fig. 2 exhibits no asymmetry [$N_\pi(0°)/N_\pi(180°) \approx 1$], whereas Fig. 3 clearly shows that pion emission into the reaction plane is depleted ($R_{0,180} < 1$ both at the projectile and the target side). This effect is expected if pions are emitted at about 13 fm/c when they are shadowed by both the target and the projectile spectator (see Fig. 1).

Above momenta of 0.4 GeV/c, the pion loss increases with increasing momentum for pions emitted towards the projectile side (upper panel of Fig. 3), whereas the opposite trend is observed for pions emitted towards the target side (lower panel of Fig. 3). This finding shows that high-momentum pions are correlated with early emission times (which are even shorter than 13 fm/c). In contrast, low-energy pions predominantly freeze out at a later stage of the collision. This information is based on the observation that pions with momenta below 0.3 GeV/c suffer from absorption or rescattering when emitted towards the target side but remain undisturbed when emitted to the projectile side. The depletion for low-energy pions (as shown in the lower panel of Fig. 3) is less pronounced than for high-energy pions (upper panel, Fig. 3). This effect indicates that low-energy pions freeze out over an extended time span. Again, π^- and π^+ mesons behave very similarly which demonstrates that the observed effects are not caused by Coulomb interaction.

Before drawing conclusions on the time evolution of pion emission we investigate another effect. An anisotropy of the ratio $N_\pi(0°)/N_\pi(180°)$ as a function of the pion transverse momentum may be caused by the momentum dependence of the pion-nucleon cross section. The same value of transverse momentum for pions emitted towards the target and projectile remnants corresponds to different relative momenta between pions and nucleons in the remnants. We have performed calculations with a shadowing model using measured pion-nucleon scattering cross sections [15] as functions of the relative pion-nucleon momentum. The model allows one to vary the correlation between pion energy and emission time of the pion. It turns out that the momentum-dependent cross section causes the ratio $N_\pi(0°)/N_\pi(180°)$ to decrease with increasing transverse momentum, qualitatively similar to the observation. However, the calculated ratio $N_\pi(0°)/N_\pi(180°)$ remains well above unity for all transverse momenta up to 0.8 GeV/c. The observed reduction of the ratio $N_\pi(0°)/N_\pi(180°)$ to values well below 1 for large transverse momenta can be reproduced only if hard pions are emitted prior to the instant of closest approach at 13 fm/c.

Our data show that in Au + Au collisions at 1 GeV/nucleon most of the high-energy pions freeze out within 13 fm/c after time zero. Transport calculations predict a similar time scale for the emission of high-energy pions [14,16]. According to calculations, the nuclear density exceeds twice the saturation value in central Au + Au collisions at 1 GeV/nucleon within the first 15 fm/c [14]. Therefore, the investigation of high-energy pions may open a new way to study the nuclear matter equation of state at high baryonic densities.

In summary, we have studied pion production in peripheral and near-central Au + Au collisions at 1 GeV/nucleon as a function of pion transverse momentum, the azimuthal emission angle, and at different rapidities. In peripheral collisions at target rapidity, a reduced yield of high-energy pions is observed at the projectile side. This finding indicates that high-energy pions are shadowed by the incoming projectile spectator and, therefore, are emitted within the first 13 fm/c of the collision. In contrast, low-energy pions observed at backwards angles are shadowed by the target spectator, which means that they predominantly freeze out in the late phase of the collision.

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