Azimuthally Anisotropic Emission of Pions in Symmetric Heavy-Ion Collisions

D. Brill,[1] W. Ahner,[2] P. Baltes,[3] R. Barth,[2] C. Bormann,[1] M. Cieślak,[2] M. Dębowski,[2] E. Grosse,[2] W. Henning,[2,*] P. Koczoń,[2] B. Kohlmeyer,[4] D. Miśkowiec,[2] C. Müntz,[3] H. Oeschler,[3] H. Pöppl,[4] F. Pühlhofer,[4] S. Sartorius,[3] R. Schicker,[2] P. Senger,[2] Y. Shin,[1] J. Speer,[4] J. Stein,[1] K. Stiebing,[1] R. Stock,[1] H. Ströbele,[1] K. Völkel,[4] A. Wagner,[3] and W. Waluś[5]

[1]*Johann Wolfgang Goethe-Universität, D-6000 Frankfurt/Main, Germany*
[2]*Gesellschaft für Schwerionenforschung, D-6100 Darmstadt, Germany*
[3]*Technische Hochschule Darmstadt, D-6100 Darmstadt, Germany*
[4]*Philipps-Universität, D-3550 Marburg, Germany*
[5]*Jagiellonian University, PL-30-059 Kraków, Poland*
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Triple differential cross sections $d^3\sigma/dp^3$ for charged pions produced in symmetric heavy-ion collisions were measured with the KaoS magnetic spectrometer at the heavy-ion synchrotron facility SIS at GSI. The correlations between the momentum vectors of charged pions and the reaction plane in $^{197}\text{Au} + {}^{197}\text{Au}$ collisions at an incident energy of 1 GeV/nucleon were determined. We observe, for the first time, an azimuthally anisotropic distribution of pions, with enhanced emission perpendicular to the reaction plane. The anisotropy is most pronounced for pions of high transverse momentum in semicentral collisions.

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One of the central goals in the study of relativistic nucleus-nucleus collisions is to extract information about the dynamics of hot and compressed nuclear matter. The study of the decompression features is expected to yield information about the compressional energy built up by the two colliding nuclei. Theoretical models predict that collective observables of the expanding system represent suitable probes for a description of nuclear matter under extreme conditions [1,2]. Indeed, a number of experiments have found that part of the compressional energy reappears in the form of directed and collective flow effects of the nucleons [3-7]. A sidewards deflection of the spectator fragments ("bounce off") is found as well as directed flow of nucleons from the overlap region between the colliding nuclei (participants) in the reaction plane ("side splash"). Additionally, an azimuthally anisotropic emission perpendicular to the event plane is observed for protons, neutrons, and light nuclei ("squeeze out") [7-10].

In addition to the participant and spectator nucleons, newly created hadrons, predominantly mesons, are observed in relativistic nucleus-nucleus collisions. The study of the multiplicity, emission pattern, and momentum distribution of these mesons provides important information about hot and compressed nuclear matter [1,11,12]. Previous studies have shown that resonance excitation of nucleons becomes increasingly important around 1 GeV/nucleon bombarding energy [13,14]. The most important processes in this energy domain are Δ_{33} production and decay which are responsible for the creation, rescattering, and absorption of pions via the channels $N\pi \leftrightarrow \Delta$ and $\Delta N \leftrightarrow NN$. These processes are responsible for the short mean free path of pions in nuclear matter. The probability of an interaction in the nuclear medium depends on the geometry of the collision. Ab-

sorption and rescattering influence the experimental observables such as, for example, the pion emission pattern. For a better understanding of the above mechanisms, triple differential cross section measurements with respect to the reaction plane and as a function of impact parameter are necessary. First measurements of the emission pattern of pions in symmetric as well as in asymmetric heavy-ion collisions were done with the streamer chamber at the LBL Bevalac [15]. These studies have shown evidence of in-plane correlation in the π^- emission pattern. Similar findings for asymmetric systems were reported by the DIOGENE group [16]. These measurements indicated a preferential in-plane emission of charged pions on the projectile side. This behavior was attributed to a stronger pion absorption by the heavier target spectator remnant on the side opposite to the projectile. In contrast to these in-plane flow effects no preferred out-of-plane emission of pions comparable to the nucleon squeeze out has been observed up to now.

In this Letter we present results on measurements of the correlation between the reaction plane and the momentum vectors of pions emitted in symmetric heavy-ion collisions. We observe, for the first time, an azimuthally anisotropic distribution of pions with enhanced emission perpendicular to the reaction plane.

The experiment was performed at the heavy-ion synchrotron (SIS) facility at GSI using the KaoS magnetic spectrometer [17]. This spectrometer is a double-focusing quadrupole-dipole configuration with large solid angle (15-30 msr) and wide momentum acceptance. Particle identification is obtained by measuring momentum and velocity. The momentum is determined from the focal plane position of the particle, whereas the velocity is deduced from time of flight.

Two scintillator detector arrays external to the spec-

trometer provide information to characterize the event by global variables [17,18]. A large-angle hodoscope gives information on the particle multiplicity which is a measure of the impact parameter. This detector consists of 96 modules and accepts charged particles in the polar angular range $12° < \Theta_{lab} < 48°$. Particles detected in this angular range are predominantly participating protons and charged pions. The second external detector, the small-angle hodoscope, is located 7 m downstream of the target. This array is composed of 380 modules and covers polar angles $0.5° < \Theta_{lab} < 11°$. Most of the particles emitted to this angular range are spectator nucleons. This detector system provides information on position, charge, and time of flight. Projectile spectators are identified by the ΔE signal in the scintillator modules and by time of flight. The position information of the identified spectators is used to reconstruct the event plane.

We used ^{197}Au projectiles of 1 GeV/nucleon with a beam intensity of 10^5 particles per spill and a gold target with a thickness of 1.93 g/cm². The pions are measured over a momentum range of $270 < p_{lab} < 1140$ MeV/c and within a polar angular range of $40° < \Theta_{lab} < 48°$. This angular range corresponds to an interval in normalized rapidity of $0.55 < y/y_{proj} < 0.75$. The measurements were done with three different magnetic field settings corresponding to the different momentum ranges listed in Table I.

The impact parameter distribution for each event sample was studied using the correlation of the particle multiplicity in the large-angle hodoscope and the summed nuclear charge Z_{sum} of spectator fragments in the small-angle hodoscope [17,18]. To classify the reaction centrality we have divided the multiplicity distribution into three bins corresponding to peripheral, semicentral, and central collisions.

For the reconstruction of the event plane the transverse momentum method is used [3]. This method yields a reaction plane for each event defined by a vector Q which is the vector sum of the transverse momenta of all spectator particles observed in the small-angle hodoscope. The accuracy in this determination of the event plane is estimated by subdividing each event randomly into two subevents and by subsequently evaluating the correlation of these two subevents. The uncertainty obtained by this method as a function of normalized multiplicity is shown in Fig. 1. The reconstructed azimuthal angle of the event plane has a dispersion of 20–25 degrees for semicentral collisions. For peripheral collisions the dispersion increases due to the low multiplicity of detected particles in the small-angle hodoscope. For central collisions the dispersion increases due to the intrinsic azimuthal symmetry of
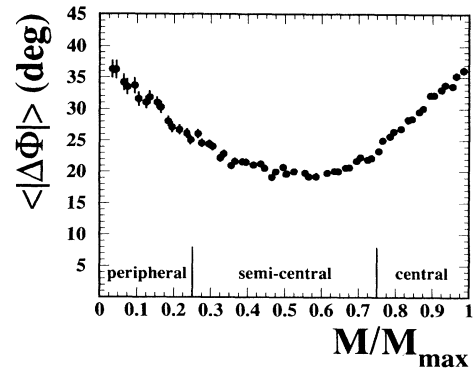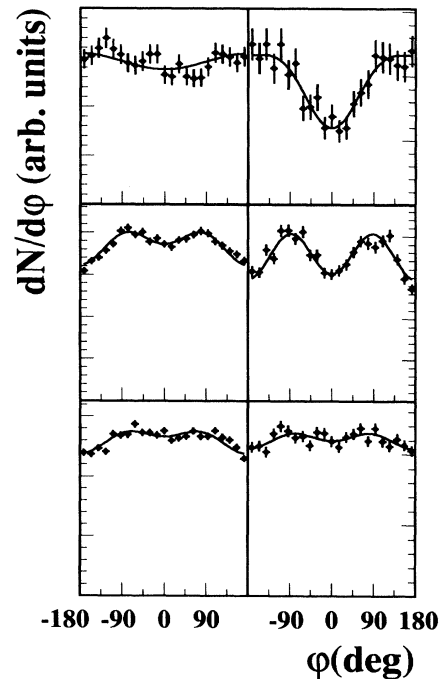

FIG. 1. Mean value of the absolute azimuthal angle difference between the measured and the true reaction plane as calculated by the transverse momentum method. The values are shown as a function of the normalized multiplicity of the large-angle hodoscope ($M_{max} = 65$).

FIG. 2. Azimuthal distributions of the vector Q for peripheral, semicentral, and central collisions (from top to bottom). The ordinate is linear starting at zero. Shown on the left are π^+ in the range $160 < p_T < 260$ MeV/c, on the right, π^+ in the range $260 < p_T < 600$ MeV/c. The solid lines are fits with $\cos(\varphi)$ and $\cos(2\varphi)$ terms. $\varphi = 0°$ represents an in-plane emission of pions parallel to the Q vector, $\varphi = \pm 180°$ an in-plane emission antiparallel to the Q vector. $\varphi = \pm 90°$ corresponds to an emission of pions perpendicular to the reaction plane.

TABLE I. The momentum ranges and the number of pions in the corresponding event sample.

Momentum range p_{lab} (MeV/c)	Number of π^+
270–470	90 000
410–730	25 000
640–1140	12 000

the reaction geometry. A possible experimental bias in the determination of the event plane is investigated by studying the proton azimuthal distributions [19]. From a comparison with earlier measurements [9] we conclude that the experimental bias is negligible.

Figure 2 shows for three different centralities the azimuthal distributions of the vector Q for events in which a π^+ is observed in the spectrometer. The angle shown is the relative azimuthal angle between the measured reaction plane and the emitted pion. The left-hand side covers the transverse momentum range $160 < p_T < 260$ MeV/c, the right-hand side $260 < p_T < 600$ MeV/c. The azimuthal distribution of the peripheral collisions shows a strong anticorrelated flow component for high momentum pions. This behavior is consistent with the result of recent Vlasov-Uehling-Uhlenbeck calculations predicting anticorrelated pion flow caused by the rescattering of pions on spectator matter [20]. The anticorrelation disappears for more central collisions due to the decreasing number of spectators.

At semicentral impact parameters the distributions show maxima at $\pm 90°$ with respect to the event plane. This pattern represents a preferred emission of pions out of the reaction plane. Such a behavior has been previously found for nucleons at midrapidity and was called "off-plane squeeze out" [8,9]. For central collisions the reaction geometry approaches azimuthal symmetry which is reflected in an almost azimuthally isotropic spectrum shown in the bottom part of Fig. 2.

The distributions shown in Fig. 2 can be parametrized by the expression $N(\varphi) \sim 1 + P_1\cos(\varphi) + P_2\cos(2\varphi)$. Fits lead to χ^2 per degree of freedom ranging from 0.6 to 1.8. The value of P_2 is used to quantify the ratio R of the number of pions emitted perpendicular to the reaction plane to the number of pions emitted in the reaction plane.

$$R = \frac{N(90°) + N(-90°)}{N(0°) + N(180°)} = \frac{1 - P_2}{1 + P_2}. \quad (1)$$

A value of R larger than unity implies preferred out-of-plane emission. The dependence of R on the pion transverse momentum is shown in Fig. 3 for semicentral collisions. The value of R is larger than 1 for all transverse momenta and shows an approximate linear dependence on transverse momentum. The solid line in Fig. 3 represents a linear fit. The numerical value found for the slope parameter is $(1.26 \pm 0.04) \times 10^{-3}$ [MeV/c]$^{-1}$ for π^+. The same analysis done for low-statistics π^- data yields a similar value of $(1.25 \pm 0.08) \times 10^{-3}$ [MeV/c]$^{-1}$. The two slope parameters agree within 1 standard deviation. It is important to note that the fitted values of P_2 are affected by the uncertainty in determining the reaction plane. The true values of P_2 can, however, be derived by multiplying the fitted P_2 values with a correction factor. In our case, this correction factor is about 1.6. For example, in the case of semicentral collisions we find that for
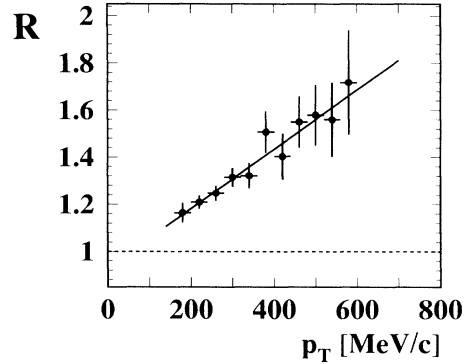

FIG. 3. The out-of-plane/in-plane ratio R for π^+ as a function of the transverse momentum for semicentral collisions. The dashed line at $R = 1$ indicates no preferred out-of-plane emission. Only statistical error bars are shown. Note that the values R are not corrected for the uncertainty in determining the reaction plane.

π^+ the corrected value of P_2 is about -0.15 at $p_T = 200$ MeV/c and about -0.4 at $p_T = 600$ MeV/c.

The anisotropy can be a consequence of the dynamical squeeze out of the nucleons due to the pressure buildup in the hot interaction zone. Since the Δ resonances are expected to flow with the nucleons similar anisotropy effects could be exhibited by their decay products, the pions. However, such a flow effect will be diluted by the decay kinematics of $\Delta \rightarrow N\pi$. On the other hand, theoretical studies show that in the case of in-plane flow of pions the effect is not mainly caused by the flow of the Δ resonances [21]. In another interpretation the anisotropy is caused by shadowing effects. Reabsorption and rescattering of pions is stronger in plane than out of plane due to the nuclear matter located in the reaction plane. Pions emitted into the reaction plane can be absorbed and reemitted isotropically with, however, a lower average kinetic energy. This causes a net decrease of pion abundance in the event plane for high momentum pions. This interpretation is consistent with our observed momentum dependence of the measured azimuthal asymmetry as shown in Fig. 3. Recent calculations using an extension of the quantum molecular dynamics model [22] predict similar asymmetries in the pion emission pattern as observed in our experiment. An alternative and more speculative interpretation of the enhanced out-of-plane yield is the correlated emission of pions [23].

In summary, we have determined the correlation between the reaction plane and the momentum vectors of charged pions emitted in relativistic heavy-ion collisions. An enhanced emission of charged pions perpendicular to the reaction plane is observed. The ratio of pions emitted out of plane to those emitted in plane increases as a function of transverse momentum. The high-energy pions emitted perpendicular to the event plane are little affected by comoving expanding matter and spectators.

Since these pions originate predominantly from the hot and dense collision zone, they might be best suited to provide further information of the equation of state of nuclear matter.

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*Present address: Argonne National Laboratory, Argonne, IL 60439.

[1] H. Stöcker and W. Greiner, Phys. Rep. 137, 277 (1986).

[2] W. Cassing, V. Metag, U. Mosel, and K. Niita, Phys. Rep. 188, 363 (1990).

[3] P. Danielewicz and G. Odyniec, Phys. Lett. 157B, 147 (1985).

[4] H. A. Gustafsson et al., Phys. Rev. Lett. 52, 1590 (1984).

[5] R. E. Renfordt et al., Phys. Rev. Lett. 53, 763 (1984).

[6] D. Beavis et al., Phys. Rev. C 33, 1113 (1986); K. G. R. Doss et al., Phys. Rev. Lett. 59, 2720 (1987); P. Danielewicz et al., Phys. Rev. C 38, 120 (1988).

[7] J. Gosset et al., Phys. Lett. B 247, 233 (1990).

[8] M. Demoulins et al., Phys. Lett. B 241, 476 (1990).

[9] H. H. Gutbrod, K. H. Kampert, B. W. Kolb, A. M. Poskanzer, H. G. Ritter, and H. R. Schmidt, Phys. Lett. B 216, 267 (1989); H. H. Gutbrod, K. H. Kampert, B. W. Kolb, A. M. Poskanzer, H. G. Ritter, R. Schicker, and H. R. Schmidt, Phys. Rev. C 42, 640 (1990).

[10] LAND and FOPI Collaborations, Y. Leifels, in Proceedings of the International Workshop on Gross Properties of Nuclei and Nuclear Excitations XX, Hirschegg, Austria, 1992, edited by H. Feldmeier (G.S.I. Report No. ISSN 0720-8715, Darmstadt, Germany, 1992), p. 15; Y. Leifels et al. (to be published).

[11] J. Harris, R. Bock, R. Brockmann, A. Sandoval, R. Stock, H. Ströbele, G. Odyniec, L. Schroeder, R. E. Renfordt, D. Schall, D. Bangert, W. Rauch, and K. L. Wolf, Phys. Lett. 153B, 377 (1985).

[12] J. Aichelin et al., Phys. Rev. Lett. 58, 1926 (1987).

[13] J. Aichelin, Phys. Rep. 202, 233 (1991).

[14] A. Lang, W. Cassing, U. Mosel, and K. Weber, Nucl. Phys. A541, 507 (1992).

[15] D. Keane, D. Beavis, S. Y. Chu, S. Y. Fung, W. Gorn, Y. M. Liu, G. VanDalen, and M. Vient, in Proceedings of the Fourth Nuclear Dynamics Workshop, Copper Mountain, Colorado, 1986, edited by V. Viola (Indiana University Report No. CONF-860270, UC-34C INC-40007-37, 1986).

[16] J. Gosset et al., Phys. Rev. Lett. 62, 1251 (1989).

[17] P. Senger et al., Nucl. Instrum. Methods Phys. Res., Sect. A 327, 393 (1993).

[18] W. Ahner et al., Z. Phys. A 341, 123 (1991).

[19] D. Brill, Ph.D. thesis, Frankfurt/Main, 1993 (to be published).

[20] S. A. Bass, C. Hartnack, R. Mattiello, H. Stöcker, and W. Greiner, Phys. Lett. B 302, 381 (1993).

[21] B. A. Li, W. Bauer, and G. F. Bertsch, Phys. Rev. C 44, 2095 (1991).

[22] S. A. Bass, C. Hartnack, H. Stöcker, and W. Greiner (to be published).

[23] S. Pratt, Phys. Lett. B 301, 159 (1993).