Azimuthal Asymmetry of Neutral Pion Emission in Au+Au Reactions at 1 GeV/Nucleon

L. B. Venema,[1] H. Braak,[1] H. Löhner,[1] A. E. Raschke,[1] R. H. Siemssen,[1] M. Šumbera,[1,*] H. W. Wilschut,[1] F.-D. Berg,[2] W. Kühn,[2] V. Metag,[2] M. Notheisen,[2] R. Novotny,[2] M. Pfeiffer,[2] J. Ritman,[2] O. Schwalb,[2] A. Gobbi,[3] K. D. Hildenbrand,[3] S. Hlaváč,[3,†] R. Holzmann,[3] R. S. Simon,[3] U. Sodan,[3] K. Teh,[3] J. P. Wessels,[3] N. Herrmann,[4] T. Wienold,[4] R. Kotte,[5] J. Mösner,[5] W. Neubert,[5] D. Wohlfarth,[5] R. Ostendorf,[6] Y. Schutz,[6] N. Brummund,[7] and R. Santo[7]

[1]*Kernfysisch Versneller Instituut, Groningen, The Netherlands*
[2]*II. Physikalisches Institut, Universität Giessen, Giessen, Germany*
[3]*Gesellschaft für Schwerionenforschung, Darmstadt, Germany*
[4]*II. Physikalisches Institut, Universität Heidelberg, Heidelberg, Germany*
[5]*Forschungszentrum Rossendorf, Dresden, Germany*
[6]*GANIL, Caen, France*
[7]*Institut für Kernphysik, Universität Münster, Münster, Germany*

(Received 29 April 1993)

The azimuthal angle distributions of neutral pions at midrapidity from Au+Au reactions at 1 GeV/nucleon incident energy have been measured. An enhanced emission of π^0's perpendicular to the reaction plane is observed. The azimuthal asymmetry is dependent on the π^0 momentum: the π^0 spectrum perpendicular to the reaction plane is harder than in the reaction plane. The strength of the observed asymmetry appears to be more pronounced for π^0 than for charged particles and neutrons.

PACS numbers: 25.75.+r

Relativistic heavy ion collisions provide the dynamical conditions to study the properties of highly excited and compressed nuclear matter. The production probability of mesons in the course of the collision and their observed momentum distribution allow us to derive the degree of thermal excitation in the collision zone [1,2]. The collective motion of nucleons from the collision zone is influenced by repulsive forces among the interacting nucleons or, in a hydrodynamic model description, by the compressional energy [3,4].

The theoretical analysis of the global event structure of heavy ion reactions was initiated by hydrodynamic models. Microscopic dynamical models [Vlasov-Uehling-Uhlenbeck, quantum molecular dynamics (QMD)] [5–7] confirmed the effect of collective sideward emission (flow) of light charged baryons which was established experimentally [8]. Recently a new component of the collective flow, the out-of-reaction-plane *"squeezeout"* of charged baryons, was discovered experimentally [9]. QMD calculations [10] reproduce these observations and show a dependence of the collective emission pattern on the equation of state of nuclear matter.

We present here the first observation of enhanced π^0 emission perpendicular to the reaction plane in the Au+Au reaction at 1 GeV/nucleon. The enhancement increases for increasing transverse momentum of the π^0 mesons. At the same time the transverse momentum spectrum of π^0 mesons emitted perpendicularly to the reaction plane is seen to be harder than the spectrum of π^0 emitted in the reaction plane.

A Au target (0.188 g/cm^2) of 0.1 mm thickness was bombarded with a Au beam extracted from the SIS accelerator of GSI with a kinetic energy of 1 GeV/nucleon. The intensity was kept near 10^6 particles per spill, with a spill duration of 4 s, and a repetition rate of 9 s. Photons from the π^0 decay (branching ratio 98.8% for two-photon decay) were detected in the two-arm photon spectrometer (TAPS) [11]. Charged particles emitted in the forward direction were detected in the forward wall of the FoPi Collaboration [12] and used for the event characterization.

In this experiment the TAPS detector system consisted of 256 BaF$_2$ detectors arranged in 4 blocks with individual charged particle veto detectors (CPV) in front of each module. The blocks were mounted in two towers which were positioned at 52° with respect to the beam direction. The angle of the blocks with respect to the horizontal plane containing the beam line was changed during the experiment in order to provide different opening angles for the π^0 decay photons and thus to cover the full momentum range of the π^0. The trigger and the time zero signals were derived from a start detector consisting of an in-beam plastic scintillation foil of 200 μm thickness. It was mounted in the beam line with a tilt angle of 45°. A ring shaped plastic scintillator with a hole of 18 mm served as veto for the beam halo and reaction products from the start detector.

The forward wall is a plastic scintillator wall covering the polar angular range from 1° to 30°. It consists of two parts, the outer plastic wall (OPW) and a zero-degree detector. Only the OPW was used in the present analysis. The OPW, covering the angular range from 7° to 30°, is made of 512 plastic bars with photomultipliers at both ends. The 512 bars are grouped into 8 sectors, each

0031-9007/93/71(6)/835(4)$06.00

© 1993 The American Physical Society

sector spanning 45° in azimuthal angle.

In the analysis the following steps were taken for particle identification. First, neutral particles were separated from charged particles by requiring the absence of a signal in the CPV modules in front of the BaF_2 modules that had fired. Second, the time-of-flight information and the BaF_2 pulse shape analysis were used to separate photons from neutrons. For the detection of charged particles a signal of the CPV was required in addition to the proper characteristic of the pulse shape in the BaF_2 scintillator. The present analysis does not separate the $\pi^\pm$ and light composite fragments from the dominating yield of protons.

The π^0 mesons are identified through the invariant mass analysis of all photon pairs detected by TAPS, using the relation $m_{\gamma\gamma} = \sqrt{2E_1E_2(1-\cos\Theta_{12})}$ where E_1 and E_2 are the photon energies and Θ_{12} is the opening angle of the photon pair. The resolution (FWHM / peak position) of the π^0 mass peak is 17%. The exact shape of the combinatorial background below the π^0 mass peak was determined by event mixing. In the mixing procedure special care was taken of the proper phase space occupation of the photons in mixed events.

The orientation of the reaction plane was determined by performing a modified transverse momentum analysis [13]. Usually [14] the transverse momenta of the particles are summed according to

$$\mathbf{Q} = \sum_{\nu=1}^{N} w_\nu \mathbf{p}_\nu^\perp(y > y_{\mathrm{c.m.}}) - w_\nu \mathbf{p}_\nu^\perp(y < y_{\mathrm{c.m.}}), \qquad (1)$$

where w_ν are weights for different kinds of particles, often taken equal to 1.0 [14,15]. In our case, each of the 8 sectors of the OPW was represented by its unit vector $\hat{\mathbf{u}}_i$ pointing to the center of a sector. The vectors $\hat{\mathbf{u}}_i$ were taken orthogonal to the beam axis. Since the coverage of the forward wall excludes the majority of particles with $y < y_{\mathrm{c.m.}}$, the *plane vector* $\mathbf{Q}$ can be approximated by

$$\mathbf{Q} \approx \sum_{\mathrm{sectors}} \hat{\mathbf{u}}_i \mathcal{M}_i. \qquad (2)$$

$\mathcal{M}_i$ is the multiplicity measured in sector i of the OPW and $\sum_{\mathrm{sectors}} \mathcal{M}_i \geq 30$ (25% of max. OPW multiplicity) was demanded in order to remove peripheral reactions. $\mathbf{Q}$ can only define the reaction plane if the flow is sufficiently pronounced. Therefore, a gate with $\|\mathbf{Q}\| \geq 5$ was applied. This removes only a fraction of 17% of all nonperipheral events, evenly distributed in multiplicity. In order to determine particle emission patterns, the reaction plane of each event was rotated so that the x axis coincided with $\mathbf{Q}$. Autocorrelations [14,16] are absent because the OPW determines the reaction plane independently of the measurement in TAPS. The angular coverages of the OPW and TAPS were mutually exclusive.

The accuracy of the reaction plane determination was estimated in two ways. First, each event was divided into two parts by randomly assigning each particle hit in the OPW to one of two subsets. From the difference between the reaction plane azimuths for these two subsets we deduce a resolution (σ) of 27° [14,17]. Second, the orientation of the reaction plane with respect to a single TAPS detector block was investigated. Since charged particles within the acceptance of TAPS are emitted at backward center of mass rapidity ($y < y_{\mathrm{c.m.}}$), we expect a 180° correlation with the preferred direction of particle emission in the acceptance of the OPW due to global momentum conservation. We found the relative azimuthal angles for the different TAPS blocks located at 180° up to an average deviation of 28°, consistent with the resolution determined earlier. The same studies were made for neutrons with similar results.

Azimuthal distributions of neutrons and charged particles relative to the reaction plane are shown in Fig. 1. The different histograms for neutrons and charged particles represent different cuts in time of flight and particle velocities range from $\beta = 0.5$ to $\beta = 0.9$ (see Table I). The angular acceptance from $50° < \Theta_{\mathrm{lab}} < 63°$ corresponds to a rapidity interval of $-0.45 < y - y_{\mathrm{c.m.}} < -0.04$. The curves which overlay the histograms in the figure are fits with

$$f(\phi) = N[1 + S_1\cos(\phi) + S_2\cos(2\phi)]. \qquad (3)$$

The $\cos(\phi)$ term is sensitive to the yield *within* the reaction plane. At backward rapidities it describes the collective sideward flow of particles in the backward hemisphere. The parameter S_1 is a measure of the strength

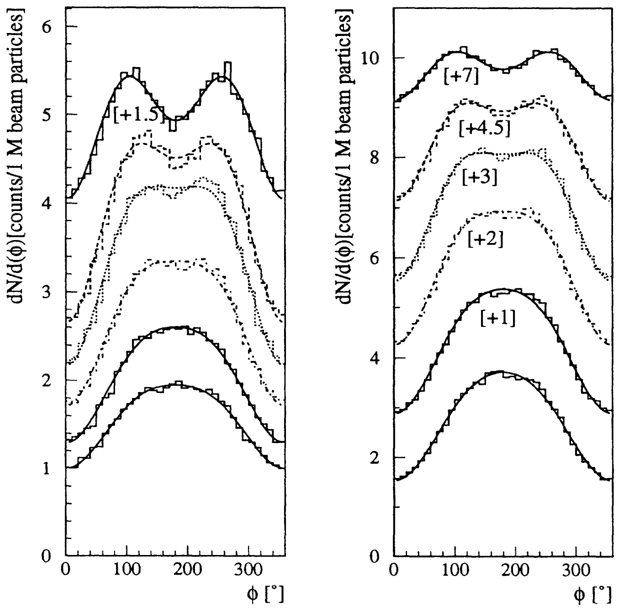

FIG. 1. Azimuthal angle (ϕ) distributions of neutrons (left) and charged particles (right) from Au+Au collisions at 1 GeV/nucleon as a function of increasing (from bottom to top) particle velocity from $\beta = 0.5$ to 0.9 (see Table I). Histograms are the experimental data and the curves represent fits according to Eq. (3). The spectra are separated in the plot by adding a constant value as given in the square brackets.

TABLE I. Strength parameters of Eq. (3) for the distribution of emission angles of charged particles and neutrons with respect to the reaction plane ($\|\mathbf{Q}\| \geq 5$). Results are presented for different particle velocity β. A systematic error of 0.03 has been estimated for S_1 and S_2.

	Charged particle			Neutrons		
β	S_1	S_2	R	S_1	S_2	R
0.49–0.53	−0.40	−0.04	1.08	−0.31	−0.05	1.10
0.53–0.58	−0.38	−0.05	1.10	−0.32	−0.05	1.10
0.58–0.63	−0.35	−0.07	1.15	−0.30	−0.07	1.14
0.63–0.69	−0.30	−0.09	1.20	−0.29	−0.09	1.19
0.69–0.78	−0.23	−0.10	1.23	−0.23	−0.10	1.23
0.78–0.88	−0.11	−0.11	1.25	−0.13	−0.13	1.30

of the flow. The parameter S_2 reflects the out-of-the-reaction-plane emission and is a measure of the strength of the so-called "squeezeout" effect. The values of these fit parameters are shown in Table I. The squeezeout ratio R is defined as

$$R = \frac{\frac{dN}{d\phi}(90^\circ) + \frac{dN}{d\phi}(270^\circ)}{\frac{dN}{d\phi}(0^\circ) + \frac{dN}{d\phi}(180^\circ)} = \frac{1 - S_2}{1 + S_2}. \tag{4}$$

Near midrapidity (the top histogram in Fig. 1) the baryons exhibit a clear effect of squeezeout and confirm earlier observations [9,15]. This squeezeout is superimposed on the backward particle flow. For slower particles, the rapidity window shifts to more backward rapidities and the squeezeout vanishes, whereas the backward flow increases in strength. The slightly stronger flow component for the charged particles, compared to the neutrons, may be attributed to the influence of composite particles [18], which are included in our charged particle selection.

Having verified the well established azimuthal asymmetry for baryons, we turn our attention to the new observable: the azimuthal distribution of neutral pions. The acceptance of TAPS covers a narrow window around midrapidity $|y_{\rm c.m.} - y| \leq 0.15$. This acceptance window is independent of the energy of the π^0. Figure 2 shows the azimuthal distribution of π^0 relative to the reaction plane for different cuts in transverse momentum. Again a parametrization according to Eq. (3) is shown with parameter values listed in Table II. From studies of the azimuthal symmetry of the forward wall response we conclude a residual systematic uncertainty in S_2 of 0.03. In the following, the azimuthally asymmetric emission of pions will be called squeezeout irrespective of its physical origin.

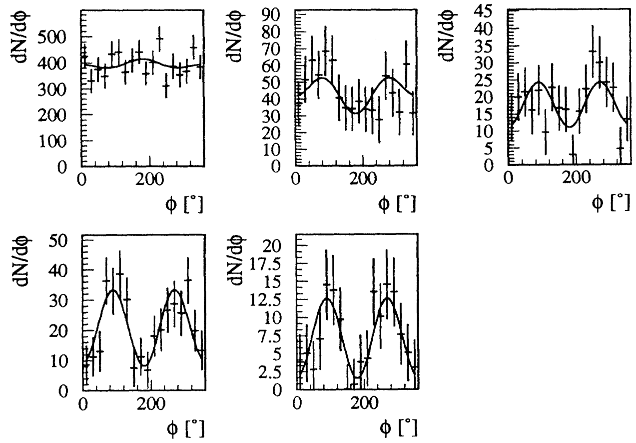

FIG. 2. Azimuthal angle (ϕ) distributions of π^0 from Au+Au collisions at 1 GeV/nucleon for increasing transverse momentum (from top left to bottom right) in equal bins of 200 MeV/c from 0 to 1000 MeV/c. The solid curves represent fits according to Eq. (3).

We observe a gradual increase in the squeezeout ratio R which has much larger values than the ratios for charged particles or neutrons. Clearly, the yield of high energy pions as compared to low energy pions is strongly reduced when emitted in the reaction plane. The magnitude of R at large p_T is remarkable. R decreases when we relax the condition $\|\mathbf{Q}\| \geq 5$ to $\|\mathbf{Q}\| \geq 0$ (see Table II). This effect is expected due to isotropic emission which is associated with small $\|\mathbf{Q}\|$. Recently the KaoS Collaboration reported [19] squeezeout for π^+ in the same reaction as studied here. They observe a dependence on transverse momentum which is not as strongly pronounced. This may indicate the importance of the rapidity window which is $y \approx y_{\rm c.m.}$ in our case versus $y \approx y_{\rm c.m.} + 0.2$ in [19].

Figure 3 shows the transverse momentum spectra of the π^0 mesons gated on two regions in azimuth: the first (I, in the reaction plane, open circles) given by

TABLE II. Strength parameters of Eq. (3) for the distribution of emission angles of π^0 with respect to the reaction plane for two gates on $\|\mathbf{Q}\|$. Results are presented for different π^0 transverse momenta near midrapidity ($|y_{\rm c.m.} - y| \leq 0.15$). The large error on R in the last p_T bin occurs due to the singularity in the definition of R at $S_2 = -1$.

p_T	$\|\mathbf{Q}\| \geq 5$			$\|\mathbf{Q}\| \geq 0$		
(MeV/c)	S_1	S_2	R	S_1	S_2	R
0–200	-0.03 ± 0.04	0.03 ± 0.03	0.9 ± 0.1	0.02 ± 0.03	0.03 ± 0.03	0.9 ± 0.1
200–400	0.12 ± 0.10	-0.18 ± 0.10	1.4 ± 0.3	0.07 ± 0.07	-0.19 ± 0.10	1.5 ± 0.3
400–600	0.04 ± 0.13	-0.38 ± 0.13	2.2 ± 0.7	0.02 ± 0.11	-0.41 ± 0.11	2.4 ± 0.6
600–800	0.03 ± 0.11	-0.64 ± 0.12	4.6 ± 1.9	0.08 ± 0.09	-0.49 ± 0.08	2.9 ± 0.6
800–1000	0.06 ± 0.20	-0.79 ± 0.24	9 ± 11	-0.12 ± 0.15	-0.54 ± 0.15	3.3 ± 1.4

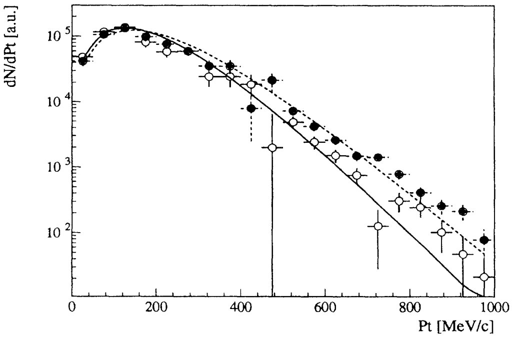

FIG. 3. Transverse momentum spectra of π^0 mesons emitted parallel to the reaction plane (I, open circles) and perpendicular to the reaction plane (II, closed circles), respectively. The curves represent a fit according to Eq. (5).

$\phi = 0° \pm 45°$ and $\phi = 180° \pm 45°$ and the other (II, out of the reaction plane, closed circles) by $\phi = 90° \pm 45°$ and $\phi = 270° \pm 45°$. The spectra were corrected for the acceptance of the detector system. The spectrum of the π^0 mesons emitted perpendicular to the reaction plane is much harder than the in-plane π^0 spectrum, as is indicated by the average transverse momentum: $\langle p_T \rangle_{\rm I} = 168 \pm 5$ MeV/c, and $\langle p_T \rangle_{\rm II} = 188 \pm 5$ MeV/c. These spectra have been compared to a thermal distribution at midrapidity

$$\frac{dN}{dp_T} \sim p_T m_T \exp\left(-\frac{m_T}{\mathcal{T}}\right), \qquad (5)$$

where $m_T = \sqrt{m_{\pi^0}^2 + p_T^2}$. Resulting $\mathcal{T}$ parameters were $\mathcal{T}_{\rm I} = 58 \pm 2$ MeV and $\mathcal{T}_{\rm II} = 70 \pm 2$ MeV, respectively. Equation (5) can only provide a rough description of the momentum distributions since in general a concave shape of the spectra is observed.

The integrated yield of π^0 emission in the reaction plane is suppressed by 10% with respect to the out-of-plane yield. This fact suggests that the main reason for the observed azimuthal asymmetry is the enhanced absorption of fast pions in the reaction plane by the spectator matter. The importance of π absorption has already been suggested by results from the Diogene group [20]. Scattering would lead effectively to a similar result: Pion scattering on spectator nucleons will preferentially occur in the reaction plane while the subsequent reemission of pions is more isotropic. Thus π^0 yield is removed from the reaction plane. The absence of azimuthal asymmetry for low energy π^0 can be explained by a higher transparency of nuclear matter for low energy π^0 as well as an enhanced emission of low energy π^0 mesons by the colder spectator matter.

Recent calculations [21] using an extension of the QMD model show an enhanced out-of-plane emission of π^0 with $R \approx 1.4$ for minimum bias data and $p_T > 400$ MeV/c. In those calculations explicit tests are made to identify the cause of the azimuthal asymmetry in pion emission. The absorption ($\pi NN \rightarrow \Delta N \rightarrow NN$) channel and scattering channel ($\pi N \rightarrow \Delta \rightarrow \pi N$) were disabled independently of each other. The authors conclude that the absorption of pions is mainly responsible for the observed anisotropy.

We conclude that a squeezeout effect for neutral pions has been observed in Au + Au collisions at 1 GeV/nucleon. A determination of the reaction plane was achieved with a resolution of 27°. The strength of the π^0 squeezeout is an arresting feature of the data which show the most pronounced azimuthal asymmetry at large π^0 momentum. Therefore, the π^0 momentum spectrum observed perpendicular to the reaction plane appears to be harder than the spectrum in the reaction plane. The azimuthal angle distributions of charged particles and neutrons exhibit both squeezeout near midrapidity and collective particle flow near the target rapidity.

We thank the accelerator crew at GSI for providing excellent beam conditions and H. Folger and the GSI target laboratory staff for target preparations. Stimulating discussions with S.A. Bass, A. Kugler, and Gy. Wolf are gratefully acknowledged. This work was supported in part by GSI, by the German BMFT, the French IN2P3 and the Dutch FOM.

---

[*] On leave of absence from Nuclear Physics Institute of Czech Academy of Sciences, Řež u Prahy, Czech Rep.

[†] Permanent address: Institute of Physics of Slovak Academy of Sciences, Bratislava, Slovak Rep.

[1] R. Hagedorn and J. Rafelski, Phys. Lett. **97B**, 136 (1980).
[2] R. Stock, Phys. Rep. **135**, 259 (1986).
[3] W. Scheid, H. Müller, and W. Greiner, Phys. Rev. Lett. **32**, 741 (1974).
[4] M. Sano *et al.*, Phys. Lett. **156B**, 27 (1985).
[5] C. Hartnack *et al.*, Nucl. Phys. **A495**, 303 (1989).
[6] G. Peilert *et al.*, Phys. Rev. C **39**, 1402 (1989).
[7] W. Cassing and U. Mosel, Prog. Part. Nucl. Phys. **25**, 235 (1990).
[8] H.Å. Gustafsson *et al.*, Phys. Rev. Lett. **52**, 1590 (1984).
[9] H.H. Gutbrod *et al.*, Phys. Lett. B **216**, 267 (1989).
[10] Ch. Hartnack *et al.*, Nucl. Phys. **A538**, 53c (1992).
[11] R. Novotny *et al.*, IEEE Trans. Nucl. Sci. **38**, 379 (1991).
[12] A. Gobbi *et al.*, Nucl. Instrum. Methods Phys. Res., Sect. A **324**, 156 (1993).
[13] A. Kugler *et al.*, in *Proceedings of the XXI International Workshop on Gross Properties of Nuclei and Nuclear Excitations, Hirschegg, Austria, 1993*, edited by H. Feldmeier (GSI, Darmstadt, 1993), p. 23 (ISSN 0720-8715).
[14] P. Danielewicz and G. Odyniec, Phys. Lett. **157B**, 146 (1985).
[15] H.H. Gutbrod *et al.*, Phys. Rev. C **42**, 640 (1990).
[16] K.G.R. Doss *et al.*, Phys. Rev. Lett. **57**, 302 (1986).
[17] W.K. Wilson *et al.*, Phys. Rev. C **45**, 738 (1992).
[18] H.H. Gutbrod, A.M. Poskanzer, and H.G. Ritter, Rep. Prog. Phys. **52**, 1267 (1989).
[19] KaoS Collaboration, P. Senger *et al.*, Prog. Part. Nucl. Phys. **30**, 115 (1993); D. Brill *et al.*, Phys. Rev. Lett. **71**, 336 (1993).
[20] J. Gosset *et al.*, Phys. Rev. Lett. **62**, 1251 (1989).
[21] S.A. Bass, C. Hartnack, H. Stöcker, and W. Greiner, UFTP Report No. 328/1993 (to be published).