Out-of-Plane Pion Emission in Relativistic Heavy-Ion Collisions: Spectroscopy of Δ Resonance Matter

S. A. Bass,[1,2] C. Hartnack,[2,3] H. Stöcker,[1] and W. Greiner[1]
[1]*Institut für Theoretische Physik, Frankfurt am Main, Germany*
[2]*Gesellschaft für Schwerionenforschung Darmstadt, Postfach 11 05 52, 6100 Darmstadt, Germany*
[3]*Laboratoire de Physique Nucléaire, Nantes, France*
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Azimuthal correlations of pions are studied with the quantum molecular dynamics model. Pions are preferentially emitted perpendicular to the reaction plane. Our analysis shows that this anisotropy is dominated by pion absorption on the spectator matter in the reaction plane. Pions emitted perpendicular to the reaction plane undergo less rescattering than those emitted in the reaction plane and might therefore be more sensitive to the early hot and dense reaction phase.

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The successful and timely completion of new experimental facilities at Darmstadt (GSI) and Berkeley (LBL) allows for the first time the experimental investigation of correlations of secondary particles—pions and other mesons—with the outgoing baryon resonance matter. This is important to probe the properties of hot and dense baryon-rich matter in heavy-ion collisions [1-8]. It has been thought that the pion multiplicity reflects the thermal energy per nucleon in addition to the compressional energy of high nuclear density [9,10]. However, the large cross section for pion-nucleon interactions in the intermediate and later phases of heavy-ion collisions has severely hampered the usefulness of pion spectra in the investigation of nuclear properties and reaction dynamics. The new experimental 4π setups at two of the major heavy-ion research facilities, GSI (FOPI, KaoS, TAPS) and LBL (TPC), enable the investigation of the emission pattern and correlations of primary and secondary particles in a far more detailed manner than ever before.

The hydrodynamical model predicts a *bounceoff* of nuclear matter in the reaction plane [11,12] which has experimentally indeed been discovered [13,14]. We have demonstrated recently that strong anticorrelations of pions vs baryons must be expected in the reaction plane, using a Vlasov-Uehling-Uhlenbeck (VUU) model [15]. At higher energies indications for this anticorrelation have now been observed [16,17].

In this Letter we study the azimuthal correlation of pions emitted in collisions of Au+Au at a beam energy of 1 GeV/nucleon. For our investigation we use an extension of the quantum molecular dynamics (QMD) model [18-21] which explicitly incorporates isospin and pion production via the delta resonance (IQMD) [22-24]. In the QMD model the nucleons are represented by Gaussian shaped density distributions. They are initialized in a sphere of radius $R=1.14A^{1/3}$ fm, according to the liquid drop model. Each nucleon is supposed to occupy a volume of h^3, so that the phase space is uniformly filled. The initial momenta are randomly chosen between 0 and the local Thomas-Fermi momentum. The A_P and A_T nucleons interact via two- and three-body Skyrme forces, a Yukawa potential, momentum-dependent interactions, a symmetry potential (to achieve a correct distribution of protons and neutrons in the nucleus), and explicit Coulomb forces between the Z_P and Z_T protons. They are propagated according to Hamilton's equations of motion. Hard N-N collisions are included by employing the collision term of the well known VUU/BUU (Boltzmann-Uehling-Uhlenbeck) equation [5,25-28]. The collisions are done stochastically, in a similar way as in the cascade models [29,30]. In addition, the Pauli blocking (for the final state) is taken into account by regarding the phase space densities in the final states of a two-body collision.

Pions are treated in the IQMD model via the delta resonance. The following inelastic reactions are explicitly taken into account: (a) $NN\rightarrow\Delta N$ (hard Δ production), (b) $\Delta\rightarrow N\pi$ (Δ decay), (c) $\Delta N\rightarrow NN$ (Δ absorption), and (d) $N\pi\rightarrow\Delta$ (soft Δ production). Experimental cross sections are used for processes (a) and (d) [31]; for the delta absorption, process (c), we use a modified detailed balance formula [32] which takes the finite width of the delta resonance into account. A mass-dependent Δ decay width has been taken from [33]. In between these inelastic reactions pions are propagated on curved trajectories with Coulomb forces acting upon them. The different isospin channels are taken into account using the respective Clebsch-Gordan coefficients:

$$\Delta^{++}\rightarrow 1(p+\pi^+),\quad \Delta^{+}\rightarrow \tfrac{2}{3}(p+\pi^0)+\tfrac{1}{3}(n+\pi^+),$$
$$\Delta^{0}\rightarrow \tfrac{2}{3}(n+\pi^0)+\tfrac{1}{3}(p+\pi^-),\quad \Delta^{-}\rightarrow 1(n+\pi^-).$$

After a pion is produced (be it free or *bound* in a delta), its fate is governed by two distinct processes: (1) absorption, $\pi NN\rightarrow\Delta N\rightarrow NN$ and (2) scattering, $\pi N\rightarrow\Delta\rightarrow\pi N$.

Now let us investigate particle emission perpendicular to the reaction plane. The hydrodynamical model predicted a squeezeout of high energetic nucleons perpendic-

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ular to the reaction plane [5,34,35]. This effect, which has also been predicted by QMD calculations [22] and has been confirmed by experiment [36], is due to the high compression of nuclear matter in the central hot and dense reaction zone (it is a genuinely collective effect, increasing linearly with A).

Do pions show a similar behavior? The azimuthal (φ) distribution of the pions is plotted to investigate this question. φ is the angle between the transverse momentum vector $\mathbf{p}_t$ and the x axis (which lies in the reaction plane and is perpendicular to the beam axis). Thus $\varphi=0°$ denotes the projectile hemisphere and $\varphi=180°$ corresponds to the target hemisphere.

Figure 1 shows the respective distributions for neutral pions in the transverse momentum bins $p_t \leq 50$ MeV and $p_t \geq 400$ MeV at a minimum bias impact parameter distribution. The distributions have been normalized in order to fit into the same figure. The analysis was performed at 0° to 180° and then symmetrized for 180° to 360°. The plotted distributions have been extracted by fitting the calculated points (shown for the high p_t bin) according to the function $a[1+b\cos(\phi)+c\cos(2\phi)]$. The azimuthal angular distribution for π^0 with low p_t shows maxima at $\varphi=0°$ and $\varphi=180°$ corresponding to a preferential emission in the reaction plane. The high p_t π^0, however, show a maximum at $\varphi=90°$. This maximum is associated with preferential particle emission perpendicular to the reaction plane. The inset shows data from the TAPS Collaboration [37] for the region $400 \leq p_t \leq 600$ MeV and midrapidity. We observe a good qualitative agreement between the theoretical prediction and the experiment. It should be noted, however, that both theory and experiment need much better statistics to allow a conclusive comparison.

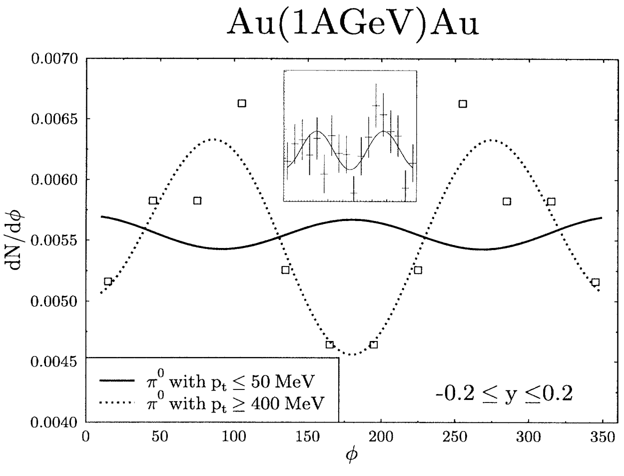

FIG. 1. Normalized azimuthal angular distribution $dN/d\varphi$ for π^0 with low and high transverse momentum p_t at midrapidity in the reaction Au(1A GeV)Au and minimum bias impact parameter distribution. The points were fitted according to the function $a\,[1+b\cos(\phi)+c\cos(2\phi)]$. The maximum at $\varphi=90°$ corresponds to a preferential emission of high p_t pions perpendicular to the reaction plane. This is due to pion absorption by large pieces of baryonic spectator matter located predominantly in the reaction plane. Perpendicular to the plane there is no such spectator matter and pions with high p_t can leave the reaction zone without further interaction. Low p_t pions have rescattered more often, which is only possible in the reaction plane. The inset shows data from the TAPS Collaboration for the region $400 \leq p_t \leq 600$ MeV and midrapidity.

The magnitude of the observed anisotropy and its dependence on impact parameter and transverse momentum is best studied by using the following ratio:

$$R_{\text{out/in}} = \left. \frac{dN/d\varphi(\varphi=90°)+dN/d\varphi(\varphi=270°)}{dN/d\varphi(\varphi=0°)+dN/d\varphi(\varphi=180°)} \right|_{y=y_{\text{c.m.}}} .$$

For $R_{\text{out/in}}$ values greater than 1, pions are emitted preferentially perpendicular to the reaction plane. Figure 2 shows the transverse momentum dependence of $R_{\text{out/in}}$ for Au+Au collisions with an impact parameter of $b=6$ fm: In contrast to pions with low transverse momentum, which are emitted preferentially in the reaction plane, high p_t pions are preferentially emitted perpendicular to the reaction plane. This effect is stronger for π^+ than for π^-. The difference is due to the different $\pi N \rightarrow \Delta$ production cross section for π^+ and π^- and due to Coulomb forces pushing the π^+ away from the spectator matter which is located mostly in the reaction plane. The π^- on the other hand are being attracted by those spectator protons. These effects decrease the number of π^- leaving the reaction zone in a direction perpendicular to the reaction plane. Recent measurements from the KaoS Collaboration [38] confirm the systematic of the p_t dependence.

We have investigated the cause of the observed prefer-

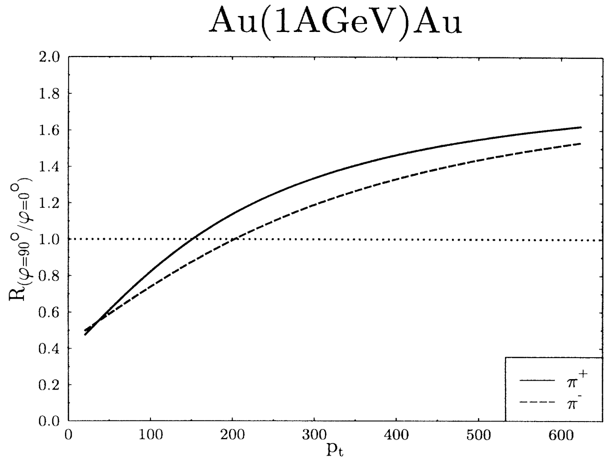

FIG. 2. Squeezeout ratio $R_{\text{out/in}}$ versus transverse momentum p_t for π^+ and π^-. Pions with $p_t \geq 300$ MeV are preferentially emitted perpendicular to the reaction plane. Pions with $p_t \leq 100$ MeV are rather emitted in the reaction plane because they have undergone frequent rescattering, which can only happen in the reaction plane.

ential emission perpendicular to the reaction plane: Pion absorption as well as scattering can be eliminated by deactivating the reaction $\pi N \rightarrow \Delta$; then no squeezeout is observed.

In order to decide whether the anisotropy is caused by absorption or by scattering the reaction $\Delta N \rightarrow NN$ can be deactivated. Thus pion absorption is suppressed but scattering is allowed: No anisotropy is observed. Therefore we conclude that the anisotropy is dominated by the pion absorption process [39].

The impact parameter dependence of the azimuthal anisotropy is shown in Fig. 3 for π^+ and π^-. No preferential emission is observed for central collisions; the anisotropy increases with the impact parameter. This behavior stresses the importance of spectator matter for the observed effect. We conclude that the preferential emission of high p_t pions perpendicular to the reaction plane stems from pion absorption by large pieces of baryonic spectator matter located predominantly in the reaction plane. Perpendicular to the plane there is no such spectator matter and pions with high p_t can leave the reaction zone without further interaction. In the reaction plane pions are likely to scatter several times. This causes a loss of transverse momentum. Therefore we observe an excess of low p_t pions in the reaction plane.

Figure 4 shows the distribution of the number of delta generations n_Δ a pion goes through before its freezeout. Here n_Δ is shown for π^+ emitted both in the reaction plane as well as perpendicular to it. $n_\Delta - 1$ is therefore the number of times a pion scatters before freezeout. We observe that 90% of the produced pions scatter at least once before leaving the reaction zone. A large number of pions scatter even more often, 2% up to 10 times. The observed preferential emission perpendicular to the reaction plane is due to an excess of high p_t pions which on the average have undergone fewer collisions (≤ 2) than the pions in plane. Those pions which make this effect do rescatter rarely; they are emitted early but carry information on the high density phase of the reaction. They stem from the decay of the most massive delta resonances which are mostly produced early on in the reaction. Therefore high p_t pions emitted perpendicular to the event plane should be the most sensitive pionic probes for the investigation of the hot and early reaction zone.

The calculations presented in this Letter were performed on a Fujitsu VP supercomputer which is comparable to a Cray Y-MP and required 100 CPU hours. It will be interesting to study the dependence of the observed azimuthal anisotropy on the projectile energy and mass. We will do this in a forthcoming publication as soon as the necessary CPU time is available.

It is important to note that the preferential emission of pions perpendicular to the reaction plane addresses different physical concepts from the respective nucleonic *squeezeout*. In nucleonic matter not only the scattering cross section but also collective effects (described by the nuclear equation of state) govern the magnitude of the squeezeout. The pionic effect, however, is dominated by the $N\Delta \rightarrow NN$ cross section.

We have investigated the azimuthal angular distribution of pions in heavy-ion collisions. A preferential emission of high energy pions at midrapidity perpendicular to the reaction plane is observed. We find this effect dom-

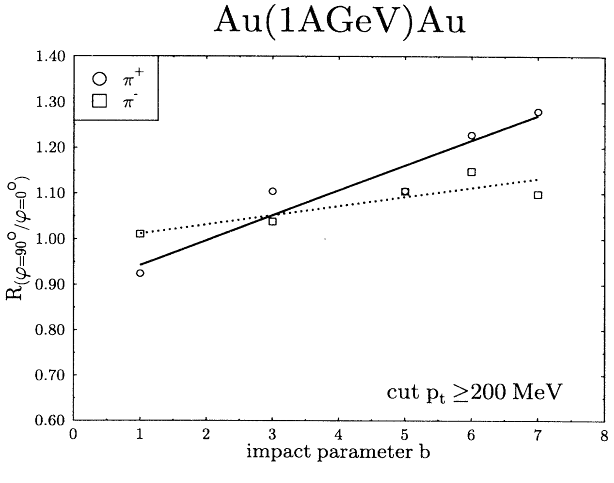

FIG. 3. Squeezeout ratio $R_{\text{out/in}}$ versus impact parameter for π^+ and π^- with a transverse momentum cut $p_t \geq 200$ MeV. The anisotropy is more pronounced at large impact parameters. This is due to the anisotropy caused by pion absorption by large pieces of baryonic spectator matter which do not exist for small impact parameters. The difference between π^+ and π^- is caused by the different $\pi N \rightarrow \Delta$ production cross section for π^+ and π^- and by Coulomb forces.

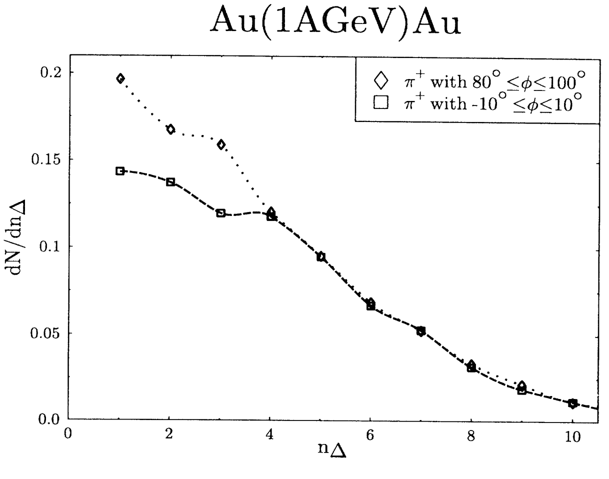

FIG. 4. Distribution of the number of delta generations n_Δ a pion goes through before its freezeout for π^+ emitted in the reaction plane and perpendicular to it. 90% of the produced pions scatter at least once before leaving the reaction zone. The observed preferential emission perpendicular to the reaction plane is due to an excess of pions which on the average have undergone fewer collisions (≤ 2) than the pions in plane.

inated by the delta absorption channel. High energy pions emitted perpendicular to the reaction plane undergo less scattering than those in plane and are an interesting new probe for the hot and early reaction zone.

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[1] S. Nagamiya, M. C. Lemaire, E. Moeller, S. Schnetzer, G. Shapiro, H. Steiner, and I. Tanihata, Phys. Rev. C **24**, 971 (1981).

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

[3] L. P. Csernai and J. I. Kapusta, Phys. Rep. **131**, 225 (1986).

[4] R. Stock, Phys. Rep. **135**, 261 (1986).

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

[6] R. B. Clare and D. Strottman, Phys. Rep. **141**, 179 (1986).

[7] B Schürmann, W. Zwermann, and R. Malfliet, Phys. Rep. **147**, 3 (1986).

[8] W. Cassing, V. Metag, U. Mosel, and K. Niita, Phys. Rep. **188**, 365 (1990).

[9] H. Stöcker, W. Greiner, and W. Scheid, Z. Phys. A **286**, 121 (1978).

[10] P. Danielewicz, Nucl. Phys. **A314**, 465 (1979).

[11] H. Stöcker, J. A. Maruhn, and W. Greiner, Z. Phys. A **293**, 173 (1979).

[12] H. Stöcker, J. A. Maruhn, and W. Greiner, Phys. Rev. Lett. **44**, 725 (1980).

[13] L. P. Csernai, W. Greiner, H. Stöcker, I. Tanihata, S. Nagamiya, and J. Knoll, Phys. Rev. C **25**, 2482 (1982).

[14] H. H. Gutbrod, A. M. Poskanzer, and H. G. Ritter, Rep. Prog. Phys. **52**, 1267 (1989).

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

[16] The E-802 Collaboration, T. Abbott *et al.*, Phys. Rev. Lett. **70**, 1393 (1993).

[17] H. R. Schmidt and the WA80 Collaboration, GSI Report No. 92-10, 1992 (unpublished).

[18] J. Aichelin and H. Stöcker, Phys. Lett. B **176**, 14 (1986).

[19] J. Aichelin, A. Rosenhauer, G. Peilert, H. Stöcker, and W. Greiner, Phys. Rev. Lett. **58**, 1926 (1987).

[20] G. Peilert, H. Stöcker, A. Rosenhauer, A. Bohnet, J. Aichelin, and W. Greiner, Phys. Rev. C **39**, 1402 (1989).

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

[22] Ch. Hartnack, H. Stöcker, and W. Greiner, in *Proceedings of the International Workshop on Gross Properties of Nuclei and Nuclear Excitations XVI, Hirschegg, Kleinwalsertal, Austria, 1988,* edited by H. Feldmeier (Gesellschaft für Schwerionenforschung, Darmstadt, 1988).

[23] C. Hartnack, L. Zhuxia, L. Neise, G. Peilert, A. Rosenhauer, H. Sorge, J. Aichelin, H. Stöcker, and W. Greiner, Nucl. Phys. **A495**, 303 (1989).

[24] Ch. Hartnack, Ph.D. thesis [GSI Report No. 93-5, 1993 (unpublished)].

[25] H. Kruse, B. V. Jacak, and H. Stöcker, Phys. Rev. Lett. **54**, 289 (1985).

[26] J. Aichelin and G. Bertsch, Phys. Rev. C **31**, 1730 (1985).

[27] G. Wolf, G. Batko, W. Cassing, U. Mosel, K. Niita, and M. Schäfer, Nucl. Phys. **A517**, 615 (1990).

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

[29] Y. Yariv and Z. Frankel, Phys. Rev. C **20**, 2227 (1979).

[30] J. Cugnon, Phys. Rev. C **22**, 1885 (1980).

[31] B. J. VerWest and R. A. Arndt, Phys. Rev. C **25**, 1979 (1982).

[32] P. Danielewicz and G. F. Bertsch, Nucl. Phys. **A533**, 712 (1991).

[33] J. Randrup, Nucl. Phys. **A314**, 429 (1979).

[34] H. Stöcker, L. P. Csernai, G. Buchwald, G. Graebner, H. Kruse, R. Y. Cusson, J. A. Maruhn, and W. Greiner, Phys. Rev. C **25**, 1873 (1982).

[35] G. Buchwald, G. Gräbner, J. Theis, H. Stöcker, K. Frankel, M. Gyulassy, J. Maruhn, and W. Greiner, Phys. Rev. C **28**, 2349 (1983).

[36] 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).

[37] TAPS Collaboration, L. Venema *et al.*, Phys. Rev. Lett. **71**, 835 (1993).

[38] KaoS Collaboration, D. Brill *et al.*, Phys. Rev. Lett. **71**, 336 (1993).

[39] S. A. Bass, C. Hartnack, R. Mattiello, H. Stöcker, and W. Greiner, in Proceedings of the XXXI International Winter Meeting on Nuclear Physics in Bormio, Italy, 1993 (to be published).