Directed flow and particle production in Au+Au collisions from experiment E877 at the AGS

Jean Barrette

Foster Radiation Laboratory, McGill Univ., Montreal, Canada H3A 2B2

For the E877 Collaboration:

J. Barrette⁴, R. Bellwied⁸, S. Bennett⁸, R. Bersch⁷, P. Braun-Munzinger⁷, W.C. Chang⁷, W.E. Cleland⁵, M. Clemen⁵, J.D. Cole³, T.M. Cormier⁸, Y. Dai⁴, G. David¹, J. Dee⁷, O. Dietzsch⁶, M.W. Drigert³, J.R. Hall⁸, T.K. Hemmick⁷, N. Herrmann², B. Hong⁷, S. Johnson⁷, Y. Kwon⁷, R. Lacasse⁴, Q. Li⁸, T.W. Ludlam¹, A. Lukaszew⁸, S.K. Mark⁴, S. McCorkle¹, R. Matheus⁸, D. Miśkowiec⁷, J.T. Murgatroyd⁸, E. O'Brien¹, S. Panitkin⁷, T. Piazza⁷, M. Pollack⁷, C. Pruneau⁸, M.N. Rao⁷, M. Rosati⁴, N.C. da Silva⁶, S. Sedykh⁶, U. Sonnadara⁵, J. Stachel⁷, N. Starinsky⁴, E.M. Takagui⁷, S. Voloshin⁵, T. Vongpaseuth⁷, G. Wang⁴, J.P. Wessels⁷, C.L. Woody¹, N. Xu⁷, Y. Zhang⁷, C. Zou⁷

¹BNL - ²GSU - ³Idaho Nat. Eng. Lab. - ⁴McGill Univ. - ⁵Univ. of Pittsburgh - ⁶Univ. de São Paulo - ⁷SUNY, Stony Brook - ⁸Wayne State Univ.

1. INTRODUCTION

In this article we summarize recent results on the study of Au+Au collisions at 10.8A GeV/c obtained at the AGS by the E877 Collaboration. New results on the directed sideward flow are presented. In particular, the dependence of proton and pion production on the direction of the reaction plane will be discussed. It is shown that the sideward flow is mainly due to nucleons and that pions show little flow effects. Two-pion correlation functions are studied to derive the density at freeze-out. Further, we inspect the correlations as a function of the pion direction relative to the reaction plane. A dependence of the deduced source sizes on the pair direction and momentum is observed. The measured source sizes are compared to results obtained in lighter systems. Measured m_t spectra of pions and kaons are also presented. The pion spectra show an enhancement at low m_t similar to that observed in Si+Pb and which was attributed to Δ resonance excitation. However, in contrast to Si+Pb now a clear difference between the π^+ and π^- spectra is seen. The K^+ spectra, which showed a very steep component over a small p_t range in the previously studied Si+Pb reaction [1] exhibit for Au+Au an unexpected structure at very low p_t .

The E877 experimental setup is an upgrade of the E814 setup which has been previously described (see e.g. [2, 3]). Its main components are two calorimeters providing

MASTER

DISTRIBUTION OF THIS DOCUMENT IS UNLIMITED α

nearly 4π coverage, a charged particle multiplicity detector, and a forward magnetic spectrometer. The spectrometer covers, in one fixed setting, an angular range in the magnet bend plane of $-134 < \theta_x < 16$ mr and $-11 < \theta_y < 11$ mr in the perpendicular plane. This spectrometer allows the measurement of p_t spectra down to $p_t=0$. The spectrometer upgrade includes the addition of four multiwire proportional chambers to provide redundancy in the tracking and of a highly segmented (166 slats) time-of-flight hodoscope, installed 12 m downstream from the target, to handle the higher multiplicity associated with the Au projectiles. The detectors of this hodoscope have an average time resolution of 85 psec resulting in an improved mass resolution. The data presented in the following are for central Au+Au collisions. The centrality is determined by the transverse energy measured in one of the calorimeters.

2. TRANSVERSE ENERGY PER CHARGED PARTICLE

In Ref. [4] it was shown that the transverse energy production in central Au+Au collisions is about 35% larger than expected from simple scaling of the available center-of-mass energy when going from the light symmetric system Si+Al to Au+Au. This is consistent with higher energy densities being reached in heavier systems. In the 1993 run the electronics of the 1024 pixel Si multiplicity detector was modified and ADCs were added to measure the energy loss in each pad of the detector. This allowed us to correct for the large occupancy in the detector. The results on the charged multiplicity distributions in Au+Au collisions are the subject of a separate contribution to this conference [5] and of a preprint [6]. Combining these two sets of data, we can determine the average value of the transverse energy per charged particle in the pseudorapidity range where the calorimeters and the multiplicity detector overlap. The results are shown in Fig. 1 where they are compared to similar data for p+Pb [7, 8] and Si+Pb [2, 9] at 14.6A GeV/c obtained with the same setup. For Au+Au the transverse energy and multiplicity data have been measured at slightly different energies (11.4A GeV/c for $dE_t/d\eta$ vs. 10.8A GeV/c for $dN_c/d\eta$). We estimate that this can lead to a 4% systematic error in the deduced value of E_t per charged particle. The p+Pb results are for minimum bias events, while the Si+Pb results correspond to the 7% most central collisions.

In each system, we note a relatively weak pseudorapidity dependence. However, a very sizable increase in the transverse energy per charged particle is observed in the Au+Au system. The measured values are well reproduced by RQMD [5, 8]. In the model, the dependence on the mass of the projectile comes from the change in the amount of transverse energy deposited per nucleon, and to a lesser extent from contributions of produced particles. The observed trend is also consistent with a larger transverse collective energy in heavy systems as suggested by the results reported below.

3. EVENT ANISOTROPY AND DIRECTED FLOW

The study of collective flow at energies between 100 MeV/nucleon and a few GeV/nucleon has been a very important source of information on the role of the mean field in the dynamics of heavy-ion collisions and on the properties of the nuclear equation of state, particularly in the determination of the compressibility of normal nuclear matter. At

Figure 1: Comparison of the transverse energy per charged particle for p+Pb, Si+Pb, and Au+Au reactions.

AGS and CERN there is evidence of collective flow in the transverse and longitudinal expansion of the hot matter [10]. However, at these energies, the signatures for directed sideward flow resulting in an azimuthal event anisotropy were expected to be very weak. The observation of sideward flow at these energies is very important since it could provide unique information on the thermal pressure gradient present in the collisions and possibly on the equation of state of hot baryonic matter.

Recently the E877 Collaboration reported [11] the first evidence for directed flow in Au+Au collisions at AGS energies. The evidence comes from a pronounced azimuthal anisotropy of E_T in different pseudorapidity intervals combined with a strong forward-backward anticorrelation between the direction of the observed transverse energy in the E877 calorimeters. An analysis of the data using a Fourier expansion method [12] has been used to determine that, in the forward pseudorapidity range $1.85 < \eta < 4.7$, up to 9% of the transverse energy is in the form of sideward flow. This is about a factor of two larger than predicted by RQMD. This is further discussed in a separate contribution to this conference [13].

Flow is expected to be strongly dependent on the particle species. For example, recent calculations using the RQMD event generator predict that, in Au+Au collisions, the directed transverse momentum of all produced particles ($\pi, K, \bar{p}$) will be opposite to the nucleon flow [14]. The authors of Ref. [14] use the term “antiflow” to characterize this behavior. This predicted dependence on the particle species is related to the relative absorption of the particles in nuclear matter and thus could be sensitive to in-medium cross sections.

We have studied the correlations between the identified particles detected in the forward spectrometer and the direction of the flow as determined by the transverse energy measured in the calorimeters. Spectra for protons emitted in the reaction plane at $y=2.95$ are shown in Fig. 2. The spectra are for protons detected on the same and opposite side of

Figure 2: Comparison of the transverse momentum spectra of protons emitted in the reaction plane to the same (•) and opposite (o) side of the forward directed flow.

the forward directed flow. Particles within $\pm 22.5^\circ$ of the reaction plane were included to increase statistics. These data are for the 13% most central collisions and include impact parameters where large forward-backward anisotropy and thus a flow signal is observed [11]. In agreement with RQMD predictions, a very clear excess of protons emitted on the same side as the directed flow is observed.

Fig 3 shows the ratio of the two spectra as a function of p_t . For protons, the value of these ratios is greater than one indicating that for all p_t values the protons are emitted preferentially in the direction of the flow. Furthermore, the ratio increases almost linearly with p_t and reaches about 2 at $p_t=1$ GeV/c. For pions from the same event sample (right part of Fig. 3) we observe no anisotropy. The observed anisotropy at $y=2.95$ for protons corresponds to an average measured p_x (i.e. the projection of p_t onto the reaction plane) of about 60 MeV/c. This indicates that a significant fraction of the proton transverse momentum is in the form of sideward collective flow.

Figure 3: Ratios of the yield of protons (left panel) and pions (right panel) emitted to the same side and to the opposite side of the directed flow as a function of p_t .

The same analysis was done selecting events with very high directivity D where $D=(E_x^2+E_y^2)^{1/2}/E_t$. This corresponds to events with particularly strong directed flow for which also the reaction plane is better defined. The results are presented in Fig. 4 for events where $D > 0.12$ (about 30% of the events of Fig. 3). The results for protons

are similar to those shown in Fig. 2. However, a clear anisotropy is now observed for π^+ which on average show ratios smaller than one. This is better shown by the full line in Fig. 4 which is a linear fit to the data resulting in a slope of -0.71 c/GeV as compared to a value of 1.02 c/GeV for protons. Thus, pions are preferentially emitted away from the direction of the flow, in qualitative agreement with the predictions of RQMD. The anisotropy is, however, smaller than for protons and the pions do not seem to show as strong an “antiflow” as predicted by the model.

Figure 4: Same as Fig. 3 but for events with large directivity. The solid lines are linear fits to the data.

It is interesting to note that fitting with a Boltzmann distribution to the p_t spectra shown in Fig. 2 yields Boltzmann temperatures that differ by more than 10% [13]. These results show that in heavy systems we should exert caution as to the interpretation of the slope of the particle spectra obtained in inclusive measurements where the reaction plane is not defined.

4. TWO-PION CORRELATION FUNCTIONS

The study of two-particle correlations offers unique information on the space-time evolution of the colliding system. In particular, it has been used to determine the source size at freeze-out. We have obtained preliminary data on two-pion correlations in central Au+Au collisions. More details on these data are given in a contribution to this conference [15]. In Fig. 5 the experimental $\pi^-\pi^-$ and $\pi^+\pi^+$ correlations as a function of Q_{inv} are shown. Here, Q_{inv} is defined as the momentum difference in the pair center-of-mass system. These data correspond to the 10% most central part of the reaction cross section. The measured correlation functions are corrected for tracking efficiency and Coulomb interaction. They are fitted assuming a Gaussian density distribution. The one-dimensional fit is of the form $C(Q_{inv}) = 1 + \lambda \exp(-Q_{inv}^2 R^2)$. Caution should be exerted in interpreting the resulting radius parameter R as the actual radius of the source. It is known that the deduced radius parameters will depend strongly on the functional form assumed for the source, on the acceptance of the detector, and finally on the position-momentum correlation of the particles emitted from the source. Nevertheless, the present data are compared to similar results obtained in the same experimental conditions for the system Si+Pb at 14.6 A GeV/c [16, 17] (see Table 1). The measured radii for Au+Au are roughly 1.3 times

Figure 5: Experimental two-pion correlation functions as a function of Q_{inv} . The lines are one-dimensional fits to the data assuming a Gaussian source.

larger than those obtained for Si+Pb. If we assume that this increase is isotropic then this corresponds to an increase in volume by a factor 2.2. This factor is comparable to the 2.3-fold increase observed in the charged particle multiplicity per unit rapidity between the two systems for collisions of the same centrality [2, 5, 6] and would indicate that freeze-out happens at similar particle densities in both systems.

Table 1: Comparison of the source parameters for Au+Au and Si+Pb obtained from a Gaussian fit to the one dimensional $\pi^- \pi^-$ and $\pi^+ \pi^+$ correlation functions. The results for Si+Pb are from Ref. [16].

	R (fm) Au+Au	R (fm) Si+Pb	Ratio
$\pi^- \pi^-$	5.3 ± 0.3	4.4 ± 0.6	1.2 ± 0.2
$\pi^+ \pi^+$	5.1 ± 0.3	3.4 ± 1.2	1.5 ± 0.5

Interesting results are obtained by looking at the correlations as a function of the direction of the pair relative to the reaction plane and thereby the direction of the sideways flow. In Fig. 6, the pion correlations as a function of q_z and q_x are shown. Here, q_z is the longitudinal component of the relative momentum and q_x is the relative transverse momentum in the plane of the spectrometer. For the q_z and q_x correlations the four columns correspond to pairs which are emitted in the reaction plane to the same side ($\pm 45^\circ$) as the directed flow, pairs in the reaction plane but opposite to the flow direction, and pairs emitted normal to the reaction plane (up or down), respectively. To increase

Figure 6: Two-pion correlation functions for pairs emitted in various directions with respect to the reaction plane. See text for definitions of the orientations. The lines are the results of two dimensional fits assuming Gaussian source distributions.

the statistics, the data for the two types of pions have been added in this two-dimensional analysis.

The results of a two-dimensional fit to the measured distributions are given in Table 2. We observe a decrease in the transverse radius R_x for events where pairs are detected on the same side as the directed flow as compared to events where the pairs are emitted opposite to the flow. A weak dependence of R_z , the longitudinal radius, on the direction of the pairs relative to the reaction plane is also seen. This effect is possibly related to the fact that pions are emitted from the surface of the expanding fireball, creating a momentum-position correlation for the pions at freeze-out and leading to a dependence

Table 2: Radius parameters extracted from two dimensional Gaussian fits to the pion correlation function for pairs detected in the reaction plane to the same and opposite side of the direction of the flow, and for pairs emitted out of the reaction plane.

	$R_z(\text{fm})$	$R_x(\text{fm})$
In-opposite	2.3 ± 0.2	5.8 ± 0.4
In-same	2.8 ± 0.3	4.8 ± 0.4
Out	2.8 ± 0.3	5.0 ± 0.3

Figure 7: Reconstructed mass spectra of tracked positively charged particles for different p_t slices at rapidity $y=2.2-2.3$ (evaluated for kaons).

of the correlation function on the anisotropy of the event and the direction of observation relative to the event axis. Clearly such a dependence will be very useful in better understanding the relation between the source expansion and particle absorption or in general the space-time evolution of the system as it cools down towards freeze-out.

5. PARTICLE SPECTRA

The large multiplicity associated with Au beams challenges the performance of small angle spectrometers such as in the E877 setup. Typical mass spectra for reconstructed tracks of positively charged particles are shown in Fig. 7. The pion and proton peaks are very clean with little background. At all p_t , the kaon peaks are well separated due to the good resolution of the time-of-flight hodoscope. The kaon yield has been determined by fitting the region of the mass spectra corresponding to kaons with a Gaussian peak superimposed on an exponential background (as indicated in Fig. 7).

The experimental kaon m_t spectra corresponding to the top 10% of the reaction cross section are shown in Fig. 8. Only statistical errors are shown. At high m_t , the K^+ spectra present a typical exponential behavior as shown by the dashed lines which are exponential fits to the data. However, below $m_t - m_K = 0.020 \text{ GeV}/c^2$ a strong enhancement is observed similar to preliminary data on kaon production in Si+Pb collisions reported at QM93 [1]. This steep component at low m_t is also seen in the preliminary K^- spectra (right panel in Fig. 8). Furthermore, the measured K^+ spectra exhibit a very narrow minimum at $m_t - m_K = 0$. Within the present limited statistics for K^- we do not see such a minimum at $m_t - m_K = 0$. The systematic errors for the kaon data are estimated to be about 25%. We

Figure 8: Left: Experimental K^+ spectra. The dashed lines are exponential fits to the data above $m_t - m_K = 0.02$ GeV/c². Right: Experimental K^- spectra. In each panel, the bottom spectrum is absolutely normalized. Spectra at lower rapidities have been multiplied by increasing powers of 10.

have studied various instrumental effects which could produce the observed surprising structure, including non-uniformities in the tracking efficiency and uncertainties in the spectrometer acceptance. The effect remains thus far unexplained but further studies are underway.

Because of the large temperature reached in heavy-ion collisions at the AGS, baryonic resonances are expected to play an important role. A strong enhancement of the pion p_t spectra at low p_t over the predictions of a simple thermal model has been observed both at CERN and at the AGS [18]. It has been shown [19, 20] that in Si+Pb collisions at 14.6A GeV/c this enhancement can be explained as being mostly due to pions resulting from the decay of the $\Delta(1232)$ resonance and that its amplitude is consistent with 36 $\pm$ 5% on the nucleons being in the Δ resonance at freeze-out. This yield is consistent with a freeze-out temperature of $T=120-140$ MeV. RQMD calculations predicts that Au+Au collisions at the present energy will give rise to “resonance matter” where the Δ density will be larger than the nucleon density and would in fact reach 2.5 times normal nuclear matter density [21].

In Fig. 9, preliminary results are presented for the π^- and π^+ spectra measured in central Au+Au collisions. For both particles these spectra show very strong enhancements below $m_t - m_\pi = 0.20$ GeV/c² very similar to that observed in the Si+Pb system. A more

Figure 9: Pion m_t spectra for central Au+Au collisions in different rapidity intervals. Starting with $y=3.6-3.7$ each successive distribution has been multiplied by increasing powers of 10.

quantitative analysis of these data in terms of the Δ abundance is in progress.

The π^- and π^+ spectra were measured with opposite magnetic fields of the E877 spectrometer magnet. This results in identical acceptance for both particles and reduces systematic uncertainties when comparing the spectra. A systematic difference between the π^- and π^+ spectra is seen at very low m_t . A clear excess of the π^- yield over the π^+ yield is observed. It may be due to a difference in the fraction of the pion yield originating from resonance decay. A more likely explanation is that the net positive charge of the fireball provides an attractive (repulsive) potential for negative (positive) particles. This might also explain the hole in the K^+ spectra near zero p_t . However, the expansion has to be slow for a strong Coulomb effect to develop.

Financial support from US DoE, the NSF, the Canadian NSERC, and CNPq Brazil is gratefully acknowledged.

References

- [1] J. Stachel for the E814 Collaboration, Nucl. Phys. **A566** (1994) 183c.
- [2] J.Barrette *et al.*, E814 Collaboration, Phys. Rev. **C46** (1992) 312.
- [3] J.Barrette *et al.*, E814 Collaboration, Phys. Rev. **C50** (1994) 3047.
- [4] J.Barrette *et al.*, E814 Collaboration, Phys. Rev. Lett. **70** (1993) 2996.
- [5] S. Voloshin, E877 Collaboration, these proceedings.
- [6] J. Barrette *et al.*, E814 Collaboration, Phys. Rev. **C**, in print, Feb. 95.
- [7] G. Wang, Ph.D. Dissertation, McGill Univ., 1994.
- [8] J. Barrette *et al.*, E814 Collaboration, submitted for publication.
- [9] Z. Zhang, Ph.D. Dissertation, Univ. of Pittsburg, 1993.
- [10] P. Braun-Munzinger, J. Stachel, J.P. Wessels, and N. Xu, Phys. Lett. **B344** (1995) 43.
- [11] J.Barrette *et al.*, E877 Collaboration, Phys. Rev. Lett. **73** (1994) 2532.
- [12] S. Voloshin and Y.Zhang, preprint, hep-ph/9407282.
- [13] Y.Zhang and J.P. Wessels, E877 Collaboration, these proceedings.
- [14] A. Jahns, C. Spieles, H. Sorge, H. Stöcker, and W. Greiner, Phys. Rev. Lett. **72** (1994) 3464.
- [15] D. Miśkowiec, E877 Collaboration, these proceedings.
- [16] N. Xu for the E814 Collaboration, Nucl. Phys. **A566** (1994) 585c.
- [17] J.Barrette *et al.*, E814 Collaboration, Phys. Lett. **B333** (1994) 33.
- [18] J. Simon-Gillo, Nucl. Phys. **A566** (1994) 175c.
- [19] T.K. Hemmick for the E814 Collaboration, Nucl. Phys. **A566** (1994) 435c.
- [20] J. Barrette *et al.*, E814 Collaboration, submitted to Phys. Lett. **B**, Preprint SUNY-RHI-94-10.
- [21] M. Hofmann, R. Mattiello, H. Sorge, H. Stöcker, and W. Greiner, submitted for publication (1994).

DISCLAIMER

This report was prepared as an account of work sponsored by an agency of the United States Government. Neither the United States Government nor any agency thereof, nor any of their employees, makes any warranty, express or implied, or assumes any legal liability or responsibility for the accuracy, completeness, or usefulness of any information, apparatus, product, or process disclosed, or represents that its use would not infringe privately owned rights. Reference herein to any specific commercial product, process, or service by trade name, trademark, manufacturer, or otherwise does not necessarily constitute or imply its endorsement, recommendation, or favoring by the United States Government or any agency thereof. The views and opinions of authors expressed herein do not necessarily state or reflect those of the United States Government or any agency thereof.