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IS THERE FLOW AT THE AGS?

Johannes P. Wessels and Yingchao Zhang
Department of Physics
SUNY at Stony Brook
Stony Brook, NY 11794-3800, USA

The E877 Collaboration:

J. Barrette⁴, R. Bellwied⁸, S. Bennett⁸, P. Braun-Munzinger⁶, W. E. Cleland⁵, M. Clemen⁵, J. Cole³, T. M. Cormier⁸, G. David¹, J. Dee⁶, O. Dietzsch⁷, M. Drigert³, S. Gilbert⁴, J. R. Hall⁸, T. K. Hemmick⁶, N. Herrmann², B. Hong⁶, Y. Kwon⁶, R. Lacasse⁴, A. Lukaszew⁸, Q. Li⁸, T. W. Ludlam¹, S. McCorkle¹, S. K. Mark⁴, R. Matheus⁸, E. O'Brien¹, S. Panitkin⁶, T. Piazza⁶, C. Pruneau⁸, M. N. Rao⁶, M. Rosati⁴, N. C. daSilva⁸, S. Sedykh⁶, U. Sonnadara⁵, J. Stachel⁶, H. Takai¹, E. M. Takagui⁷, S. Voloshin⁵, G. Wang⁴, J. P. Wessels⁶, C. L. Woody¹, N. Xu⁷, Y. Zhang⁶, Z. Zhang⁵, C. Zou⁶

¹ Brookhaven National Laboratory, Upton, NY 11973

² Gesellschaft für Schwerionenforschung, Darmstadt, Germany

³ Idaho National Engineering Laboratory, Idaho Falls, ID 83402

⁴ McGill University, Montreal, Canada

⁵ University of Pittsburgh, Pittsburgh, PA 15260

⁶ SUNY, Stony Brook, NY 11794

⁷ University of São Paulo, Brazil

⁸ Wayne State University, Detroit, MI 48202

ABSTRACT

We have employed the nearly 4π -calorimetric coverage of the E877 apparatus in order to determine flow in different regions of pseudo-rapidity from the measured transverse energy in Au+Au collisions at 11.4 A-GeV/c. Signatures for the side-splash in the reaction plane at forward and backward rapidities have been established. Indications of a non-zero eccentricity of particles in the reaction plane at mid-rapidity are also found. These observations complement analyses deriving collective longitudinal motion from dN/dy -spectra of protons, kaons, and pions as well as collective transverse motion of the same particles from m_T -spectra at midrapidity.

1. Introduction

The study of flow in nuclear collisions has been carried out at a variety of energies over the past fifteen years. It has been motivated by hydrodynamical calculations of heavy-ion collisions [1] in the quest for the compressibility modulus determining the nuclear equation-of-state. Investigations of the monopole resonance explore the shape of the equation-of-state in a very narrow region around the ground state density of nuclear matter. Experiments in search for flow phenomena in the Fermi energy

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regime [2,3] probe the balance between the attractive nuclear force and the repulsive Coulomb force comprising the mean field. The first systematic investigations of flow have been carried out at the BEVALAC [4] at several hundred A-MeV, an energy region which is still of great interest. The main focus of these experiments was on the measurement of momentum distributions of charged particles perpendicular to the beam-axis, either in the reaction plane (*side-splash*) or perpendicular to the reaction plane (*squeeze-out*). In order to describe the measured rapidity distributions in ultra-relativistic heavy-ion collisions at the AGS and at CERN [5] collective motion along the longitudinal direction has also been incorporated into the studies of flow.

While most of the above mentioned studies were done using the momenta of identified particles, we will present, for the first time, measurements of flow phenomena at 11.4 A-GeV/c using the calorimeters of the E877 apparatus at the AGS.

2. Experimental Setup

The E877-apparatus, shown below, is an upgrade to the previous E814-apparatus, which is now adapted to the high multiplicity environment of Au+Au collisions which have only recently become available at the AGS.

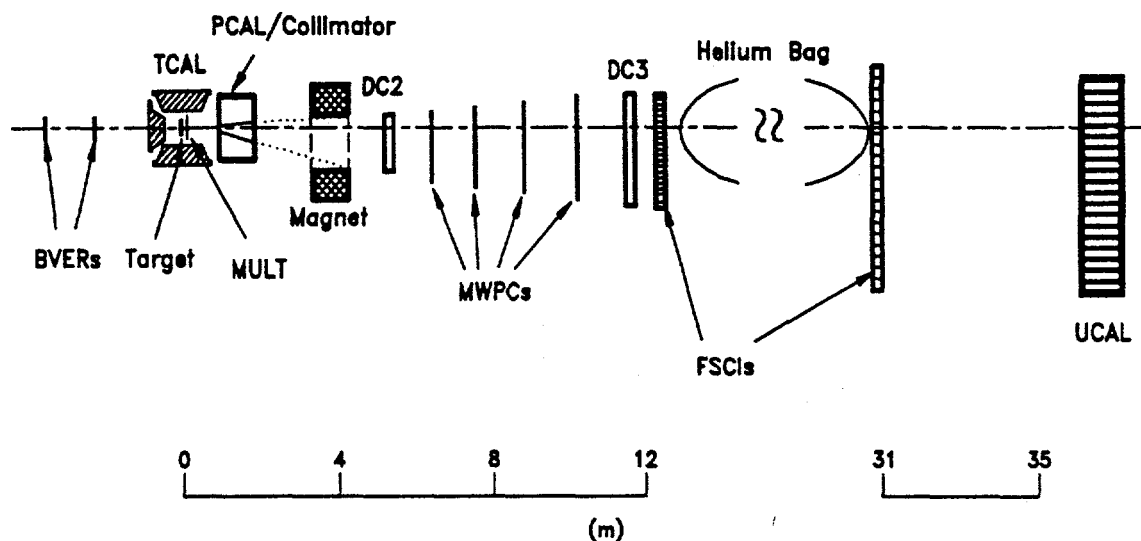


Figure 1. Layout of the E877-apparatus at the AGS

It consists of a beam telescope with the ability to determine the beam trajectory for each incoming particle (BVERs), three calorimeters (target calorimeter(TCAL), participant calorimeter(PCAL), and a forward uranium calorimeter(UCAL)). The TCAL covers $-0.5 \leq \eta \leq 0.8$, PCAL covers $0.83 \leq \eta \leq 4.5$ in pseudo-rapidity, while the UCAL is used as a measure of the forward energy. It is not used in the flow analysis since it is mostly hit by non-interacting nucleons from the projectile. The TCAL is made of 992 NaI-crystals each 5.3 radiation length deep. The PCAL is a lead-iron-scintillator sampling calorimeter subdivided into four depth sections, eight radial sections, and sixteen azimuthal sections. The spectrometer arm of the

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setup consists of a bending magnet, a set of two drift/pad-chambers(DC2, DC3), four multi-wire proportional-counters(MWPCs), and two time-of-flight walls(FSCI) allowing for particle identification in the forward rapidity region for low and medium values of the transverse momentum p_t .

3. Measuring Flow with Calorimeters

3.1. General Considerations

As mentioned above, most analyses searching for flow effects use the transverse momentum of identified charged particles in order to reconstruct what has become known as the transverse momentum tensor [6]. However, the calorimeters of the E877-apparatus measure the transverse energy (E_t) of all emitted particles. For pions this corresponds to their total transverse energy. For baryons it is their transverse kinetic energy. About 60% of the total measured E_t in the PCAL is due to pions. The effect this has on the reconstruction of something similar to the transverse momentum tensor has been discussed by Gavron [8] for Si+Pb collisions. There it is shown that especially for low multiplicity events it is important to correct for finite particle multiplicities, but it is also pointed out that the sensitivity to study flow phenomena is preserved using calorimetric information.

3.2. Construction of Azimuthal Transverse Energy Distributions

Studying the azimuthal transverse energy distributions will shed some light on the question: How much of the produced transverse energy is directed, i.e. non-isotropic? For this we consider the following:

From the energy (E_i) deposited in each calorimeter cell(i) we define $\epsilon_i^t = E_i \sin(\vartheta_i)$, the sum of which corresponds to the total transverse energy $E_t = \sum_i \epsilon_i^t$ for this event. The ϵ_i^t can be expanded into multipole components perpendicular to the beam direction (x_n, y_n)

$$x_n = \frac{\sum_i \epsilon_i^t \cos(n\phi_i)}{\sum_i \epsilon_i^t}; \quad y_n = \frac{\sum_i \epsilon_i^t \sin(n\phi_i)}{\sum_i \epsilon_i^t},$$

with integers n . The magnitude (v_n) and direction (Φ_n) of the moments of the azimuthal E_t -distribution for each event are given by:

$$v_n = \sqrt{x_n^2 + y_n^2}; \quad \Phi_n = \frac{1}{n} \tan^{-1}\left(\frac{y_n}{x_n}\right).$$

For $n = 1$ we define v_1 , the amount of "directed" transverse energy, as *directivity* (D) (compares to Q in [7]). The distribution of $d^2N/dD_x dD_y$ is symmetric about zero, when averaged over many events. For $n = 2$ in the above equations v_2 probes the *eccentricity* (denoted by α instead of D), i.e. how circular the distributions is. It is similar to $\alpha = (f_1 - f_2)/(f_1 + f_2)$ where the f_i are the eigenvalues of the two-dimensional sphericity tensor[9].

Below are discussed measurements of these quantities determined for the forward hemisphere covered by the PCAL ($1.85 \leq \eta \leq 4.5$) for different bins of the transverse energy observed in the whole calorimeter (PCAL) referenced as E_t in all following plots. This is about 90% of the total E_t (from PCAL and TCAL). In Au+Au collisions at these energies the total E_t anti-correlates tightly with the impact parameter.

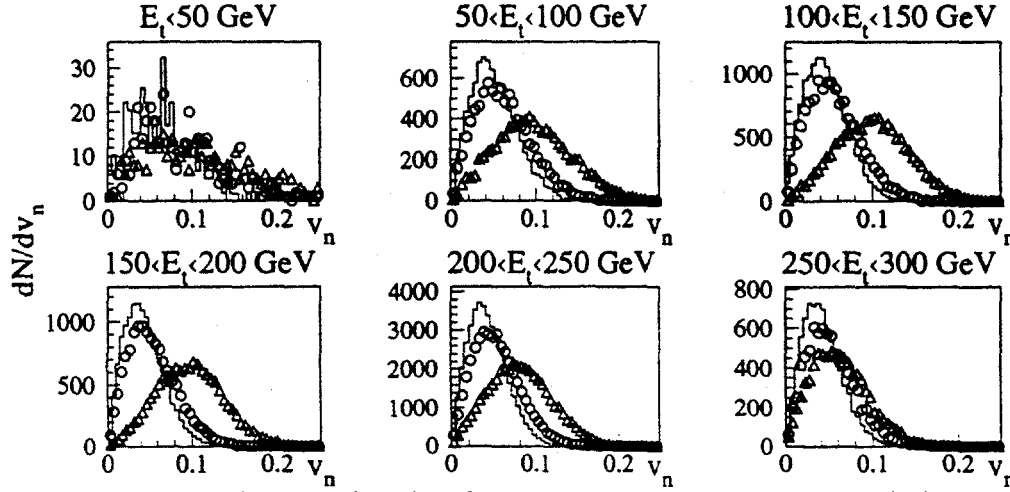


Figure 2. Distribution of multipole moments. Directivity D , $n=1(\Delta)$, and eccentricity α , $n=2(\circ)$, measured by the PCAL in forward direction ($1.85 \leq \eta \leq 4.5$) for different bins of total E_t . The histogram shows the azimuthally symmetrized dN/dD -distribution (cf. text).

Let us first look at the directivity distribution dN/dD . In order to see how much of the produced transverse energy is directed, we plot for each bin also an azimuthally symmetrized distribution (histogram), using the measured ε_i^2 and randomizing ϕ_i taking into account the segmentation of the calorimeter. This indicates what would be observed if the production of E_t was isotropically symmetric. One can see a clear evolution from peripheral (low E_t) to central (high E_t) collisions. For the most peripheral as well as for the most central collisions the distributions are closer to isotropic distributions, while at mid-impact parameters the directivity distributions are non-isotropic. The largest difference between the symmetrized and the observed distribution is for $150 < E_t < 200$ GeV. From the comparison of dN/dD - and the $dN/d\alpha$ -distributions it can be noted that the overall shape of the event is close to circular in the forward direction, in fact, the $dN/d\alpha$ - and the symmetrized dN/dD -distribution are strikingly similar.

3.3. Assessing the Shape of the Azimuthal Distributions

A difference of the data from the symmetrized dN/dD -distribution in itself does not necessarily mean that we are observing flow, because finite multiplicity effects have not yet been addressed. Suppose directivity was due to a random process governed by fluctuations in finite particle multiplicity. Then the shape of the distribution, containing N_0 events properly normalized, would be Gaussian:

$$\frac{1}{D} \frac{dN}{dD} = \frac{N_0}{\sigma^2} \exp^{-\frac{D^2}{2\sigma^2}}, \text{ for which } \langle \frac{dN}{dD} \rangle = \sqrt{\frac{\pi}{2}} \sigma, \text{ and } \text{rms}(\frac{dN}{dD}) = \sqrt{\frac{4-\pi}{2}} \sigma.$$

In this case the $\frac{\text{rms}}{\text{mean}}$ of the directivity distribution would be constant ($\simeq 0.52$). (Similar for the $dN/d\alpha$ -distribution.) Below are graphs showing the mean values of the dN/dD - and $dN/d\alpha$ -distribution and the ratio of their rms/mean as a function of E_t .

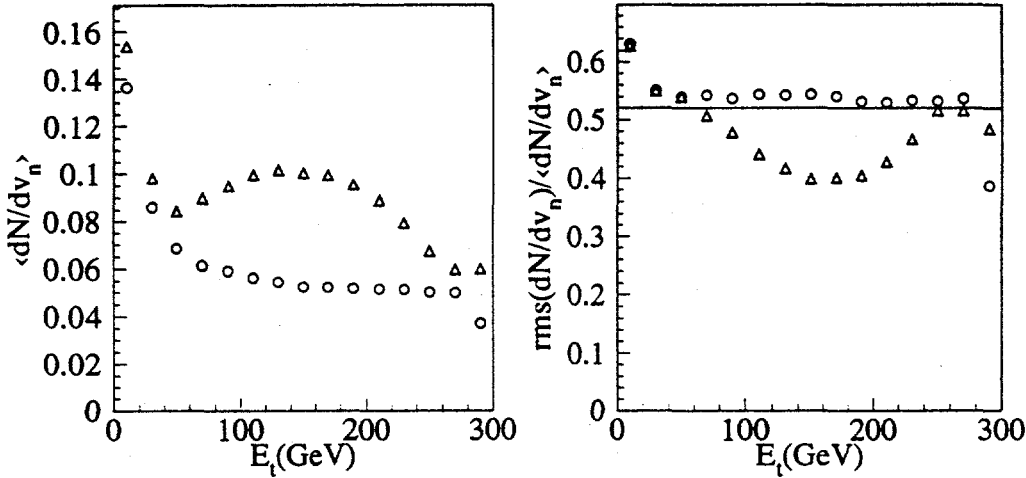


Figure 3. Mean values(left) and $\frac{\text{rms}}{\text{mean}}$ (right) of the directivity(Δ)- and eccentricity(\circ)-distribution as a function of E_t in the forward hemisphere.

The fact that $\frac{\text{rms}}{\text{mean}}$ is close to 0.52 for the $dN/d\alpha$ -distribution at all impact parameters tells us that the distribution in this pseudo-rapidity interval is mostly random governed by finite particle numbers and possibly nothing else. The same is true for the dN/dD -distribution in peripheral and the most central collisions. Note that in both cases no flow is expected. However, at mid-impact parameters where the directivity signal shows its maximum this distribution is much narrower than can be explained based on statistical arguments. The narrowing of the distribution can be attributed to the presence of directed sideways flow in this impact parameter range.

3.4. Generalized Description of Azimuthal Distributions

In a more generalized treatment of azimuthal distributions [10] it can be shown, that x_n , y_n , and v_n can indeed be constructed from any observable, whose azimuthal distribution can be measured. The distribution of all n poles of the $dN/(v_n dv_n)$ over many events is described by:

$$\begin{aligned} \frac{dN}{v_n dv_n} &= \frac{N_0}{\sigma^2} \exp\left(-\frac{\tilde{v}_n^2 + v_n^2}{2\sigma^2}\right) \int_0^{2\pi} d(n\Phi_n) \exp\left(\frac{\tilde{v}_n v_n \cos(n\Phi_n)}{\sigma^2}\right) \\ &= \frac{N_0}{\sigma^2} \exp\left(-\frac{\tilde{v}_n^2 + v_n^2}{2\sigma^2}\right) I_0\left(\frac{\tilde{v}_n v_n}{\sigma^2}\right); \quad I_0 : \text{modified Bessel - function} \end{aligned}$$

Here \tilde{v}_n is the centroid or the n th-pole anisotropy. \tilde{v}_1 corresponds to the value for the directivity (D), \tilde{v}_2 corresponds to the value for the eccentricity (α) of the event. The width σ is assumed to be the same for all distributions evaluated in the same E_t -interval.

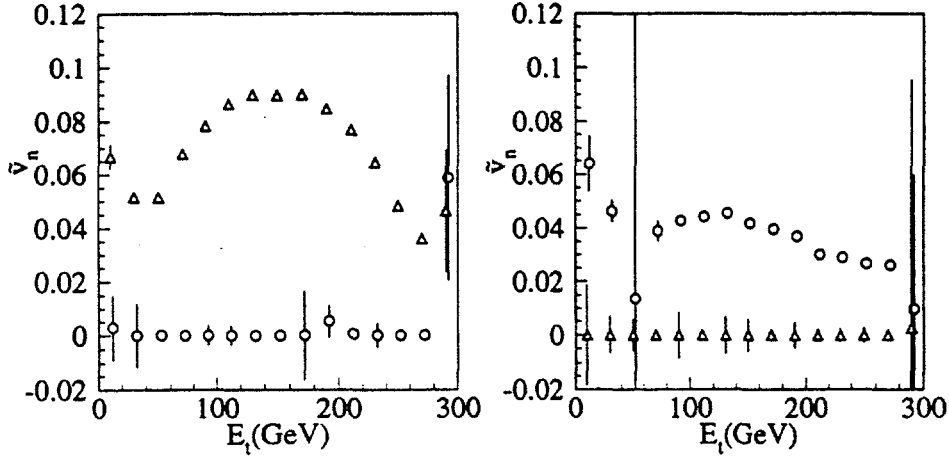


Figure 4. Results for fits to the azimuthal E_t -distributions as a function of total E_t . Shown are results for the fit-parameters \tilde{v}_n to the directivity-distribution ($n=1$) plotted as triangles, and to the eccentricity-distribution ($n=2$) plotted as circles for the forward hemisphere(left) ($1.85 \leq \eta \leq 4.5$) and at mid-rapidity(right) ($1.0 \leq \eta \leq 1.85$).

Above are the results of fits to the data using the above Bessel-function for two different regions in rapidity. Again we see a pronounced peak in the directivity at mid-impact parameters in forward direction, while the eccentricity shows no dependence on E_t in this range of rapidity. Conversely, the directivity signal remains at zero for the measurement at mid-rapidity, while \tilde{v}_2 shows a slight signal.

3.5. Reaction Plane Analysis

In the directivity analysis the vector pointing into the direction of Φ and the beam-axis span the reaction plane. Φ can be measured in forward direction by PCAL and in backward direction by TCAL. An analysis of these angles is shown in the following figure. Plotting the two angles versus each other shows the expected forward-backward anti-correlation. The angle between Φ in the forward and in the backward direction can be fitted by a constant (for the background) plus a Gaussian with its maximum at 180° and its variance corresponding to the precision of the reaction plane determination. The integral under the Gaussian divided by the constant term for different values of E_t shows the forward-backward azimuthal correlation. The variance of the Gaussian corresponds to roughly twice the resolution of the reaction plane measurement achieved in each detector, assuming equal resolution in TCAL and PCAL. From the plot we extract that over most of the impact parameter range we are able to extract the width with a precision of $\pm 35^\circ$. This will provide an excellent tool in

order to study the emission of certain particles species (π^+ , π^- , p) as analyzed in the spectrometer with respect to the reaction plane.

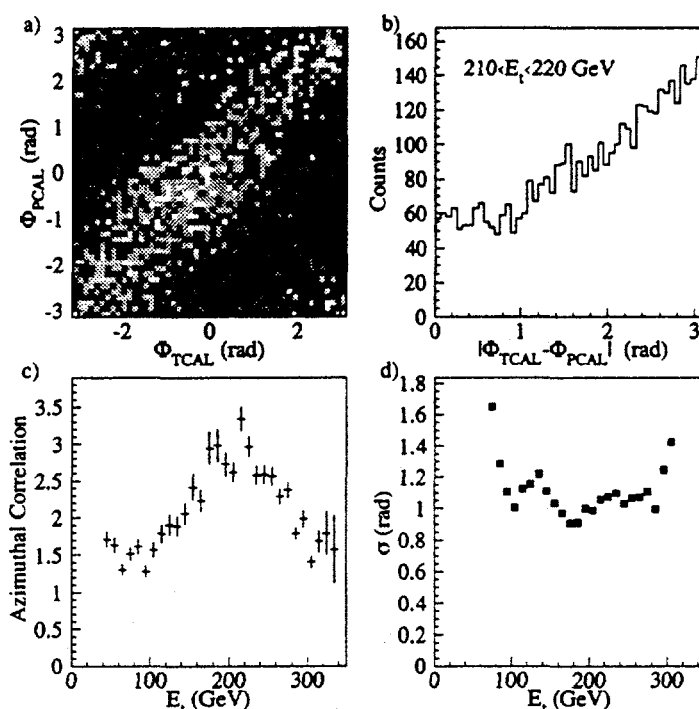


Figure 5. a) Correlation of Φ_{TCAL} vs. Φ_{PCAL} , b) relative angle between Φ_{TCAL} and Φ_{PCAL} at $210 < E_t < 220$ GeV, c) azimuthal correlation of Φ_{TCAL} and Φ_{PCAL} (cf. text), d) width of the combined reaction plane reconstruction.

Since TCAL has fairly large leakage fluctuations for energetic particles, the reaction plane determination from PCAL alone is actually better than the number quoted.

4. Conclusions and Outlook

As a result of the above discussion, we have uniquely identified the *side-splash* signal at mid-impact parameters in symmetric Au+Au collisions. Furthermore, from the analysis at mid-rapidity there seem to be first indications of a non-zero eccentricity signal. In conjunction with the results of an analysis of the rapidity distributions for protons, kaons, and pions in central Au+Au collisions in the framework of a rapidly expanding thermal source, which at the same time is also able to reproduce the measured transverse-mass spectra [5], the above results seem to call for a rephrasing of the title, namely, why shouldn't there be any flow at the AGS? It is certainly in this energy domain that, with heavy projectiles such as Au-nuclei, very high densities can be achieved. In return this would lead to a build-up of pressure gradients, that could act as the driving force for the discussed collective flow phenomena. It will now be important to examine the origin of these phenomena, in order to determine

whether indeed the initial pressure is the driving force behind the collective behaviour or, whether in fact the effects are predominantly governed by absorption. In the same light, it will be interesting to address predictions for the flow of, e.g. pions of different charge [11], or, more speculative, anti-protons[12] by combining the spectrometer and the calorimeter data.

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