FLOW PHENOMENA AT AGS ENERGIES

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Abstract

In this talk some of the latest data on directed sideward, elliptic, radial, and longitudinal flow at AGS energies will be reviewed. A method to identify the reaction plane event by event and the measurement of its resolution will be discussed. The distributions of global observables (transverse energy $E_T$ and charged particle multiplicity $N_c$), as well as those of identified particles will be shown. Finally, the data will be put in context with measurements at other beam energies. These systematics will then be discussed in terms of possible signatures of the QCD phase transition.

1 Introduction

In order to describe the evolution of ultrarelativistic heavy ion collisions theorists mainly employ two types of models. On the one hand, there are cascade-type calculations such as RQMD[1], ARC[2] or, ART[3]. Except for the case when mean field effects are explicitly included into the calculations, these codes do not contain any ‘collectivity’. On the other hand, there are hydrodynamical models[4, 5, 6, 7, 8] that do not yet attempt to describe the hadronization phase of the collision, but provide an insight into the collective expansion of a nuclear fluid with a given equation of state. Both types of codes have been successfully applied to describe selected sets of experimental data. While it is agreed, that the hadronic freezeout obstructs the ‘view’ into the early stage of the collision some of the models predict a distinct minimum in the sideward flow[3] as a function of bombarding energy, if a phase transition to the quark gluon plasma (QGP) is assumed. Another interesting prediction is that as the bombarding energy is raised, there will be a point (‘softest point’) at which the pressure over energy density will reach a minimum at the phase transition and the system will develop a maximum in the collective radial flow[8, 9].

Here, I would like to review some of the recent experimental advances made at the AGS in terms of the observation of collective flow. Measurements of the E877 collaboration, in particular of the reaction plane, will be presented.
in some detail and results from other collaborations (E802, E866, E891) will be used where appropriate.

2 Event by Event Reconstruction of the Reaction Plane

The first evidence for the presence of collective motion at AGS energies (about $10\cdot\text{AGeV/c}$) was found in the systematic study of the transverse energy carried per charged particle as a function of the mass of the collision system \[10\]. As the system size increases the transverse energy per charged particle increases drastically. Shortly after this, evidence for sideward flow was found through a Fourier analysis of the azimuthal transverse energy distribution \[11\]. It was shown, how the sideward flow reaches a maximum for semicentral events and vanishes for peripheral and the most central collisions. In this analysis the reaction plane was not reconstructed on an event by event basis. Having established the sideward flow effect, it is now possible to reconstruct the reaction plane for each event except for the most central events, in which the reaction plane is not defined and in peripheral events in which not enough energy is deposited in the calorimeters used in the analysis. The calorimeters (TCal, PCal - for a description of the detectors and the methods outlined below see \[12\]) are both highly segmented in polar and azimuthal angle. Each calorimeter cell $j$ measures a fraction $E^j_T$ of the total transverse energy $E_T$ at an azimuthal angle $\phi_j$. The azimuthal angle $\Psi^{(i)}_n$ of the $n$-th moment of the transverse energy distribution in a pseudorapidity interval $\eta_i$ is given by

$$\tan\Psi^{(i)}_n = \frac{\sum_j (\pm) E^j_T \sin n\phi_j}{\sum_j (\pm) E^j_T \cos n\phi_j} \quad (1)$$

where the sign is taken negative (positive) for $\eta$ backward (forward) of midrapidity. Assuming that the only correlation between different rapidity intervals is due to the initial direction of the impact parameter vector $\vec{b}$ the angle $\Psi^{(j)}_1$ reflects the orientation of the reaction plane $\Psi_R$ with some resolution. This resolution can be measured by a pairwise correlation of the angles $\Psi_1$ from at least three independent $\eta$ intervals

$$\langle \cos (\Psi^{(i)}_1 - \Psi^{(j)}_1) \rangle = \langle \cos (\Psi^{(i)}_1 - \Psi_R) \rangle \langle \cos (\Psi^{(j)}_1 - \Psi_R) \rangle. \quad (2)$$

The azimuthal distribution of any observable $X$ (eg. $E_T, N_c$) with respect to the reaction plane can be studied by a Fourier decomposition of the form

$$q'_n = \frac{\langle \sum_k X^k \cos n(\phi_k - \Psi^{(i)}_1) \rangle}{\langle \sum_k X^k \rangle}. \quad (3)$$
This will be the subject of the following two sections. In order to get to the resolution corrected values \( v_n \), the measured Fourier coefficients \( v'_n \) need to be unfolded

\[
v_n = \frac{v'_n}{|\langle \cos n(\Psi_1^{(i)} - \Psi_R) \rangle|}.
\] (4)

The correction factors for the first moment \( v_1 \) associated with the sideward flow and the second moment \( v_2 \) associated with the elliptic flow are shown in Fig. 1.

![Fig. 1. The inverse correction factor for the first moment \( v_1 \) (a) and the second moment \( v_2 \) (b) due to the finite resolution in the reaction plane angle \( \Psi_R \) for four different bins in pseudorapidity as a function of centrality (from E877[12]).](image)

3 Correlation of Global Observables with the Reaction Plane

Right downstream of the target E877 has a silicon pad multiplicity detector[10]. This device consists of two discs each segmented in polar and azimuthal angle into 512 pads. For the data shown in Fig. 2 the target calorimeter TCal \((-0.5 < \eta < 0.8)\) has been used to determine the reaction plane angle \( \Psi_1 \). For some intermediate centrality bin, where the sideward flow is maximal [11], the charged particle multiplicity is shown as measured with respect to the reaction plane. In panel (b) three slices through the double differential distributions
plotted in (a) are shown. The distributions are peaked in the forward (backward) rapidity slice $\eta = 2.4(1.1)$ back to back with respect to each other. Note, that the reaction plane was determined in an independent way in a different pseudorapidity window. In the bin at central rapidity $\eta = 1.7$ and to some extent also in the forward window one can clearly see a nonzero quadrupole component in the multiplicity distribution. This corresponds to an elliptic shape of the azimuthal distribution with the major axis in the reaction plane.

Fig. 2. (a) Double-differential charged particle distribution for an intermediate centrality bin. Three pseudorapidity slices through the distribution are shown in (b) along with fits of a Fourier series up to second order (from E877[12]).
The azimuthal distribution of transverse energy with respect to the reaction plane has been studied by Fourier decomposition as outlined in the previous section. Due to the near $4\pi$ calorimetric coverage of the experiment the full $\eta$ range could be analyzed. The reaction plane was always determined in a different $\eta$ region than the one analyzed to avoid autocorrelations. The distributions are shown in Fig. 3 in windows of increasing centrality ($E_T$) from top left to bottom right. The solid symbols are the values obtained for the dipole component $v_1$. One can clearly see how it increases from peripheral to semicentral collisions and then decreases again for the most central collisions. The curves are not symmetric about midrapidity since protons and pions contribute differently for different pseudorapidities. In the following section this and the fact that the response to the charged particle multiplicity and transverse energy measurement will be exploited to disentangle the contributions of nucleons and pions to the measured sideward flow.
As was already noted in the distribution of charged particles the quadrupole component $v_2$ is nonzero. For intermediate centralities this is the case at all pseudorapidities. Recently, it has been proposed that both, magnitude and orientation, of this moment may be sensitive to the pressure developed early in the collision\cite{13}. There, the magnitude of the observed elliptic flow can only be reproduced if mean fields are included into the calculation (cf. Fig. 6).

4 Sideward Flow of Identified Particles

The observed anisotropies in the transverse energy $v_1^{(E_T)}$ and charged particle $v_1^{(N_c)}$ distributions are a superposition of the contributions due to nucleons $v_1^n$ and pions $v_1^\pi$. They can be obtained by solving

$$v_1^{(N_c)} = \frac{dN_c^\pi / d\eta \cdot v_1^{(N_c,\pi)} + dN_c^n / d\eta \cdot v_1^{(N_c,n)}}{dN_c^\pi / d\eta + dN_c^n / d\eta},$$  \hspace{1cm} (5)
\[ v^{(E_T)}_1 = \frac{dE^\pi_T/d\eta \cdot v_1^{(E_T,\pi)} + dE^n_T/d\eta \cdot v_1^{(E_T,n)}}{dE^\pi_T/d\eta + dE^n_T/d\eta} \]  

for \( v^n_1 \) and \( v^\pi_1 \) with some minimal assumptions (for details see [12]). Multiplying these coefficients with the measured \( \langle p_t \rangle \) of protons and pions [13, 16] one obtains the average transverse momentum \( \langle p_x \rangle \) in the reaction plane versus rapidity. The solid stars and open crosses depicted in Fig. 4 are the results of this deconvolution. They are shown along with the analysis of the now available [17] triple differential cross sections of identified protons, \( \pi^+ \), and \( \pi^- \) (circles, squares, and triangles). The histograms show the results of two cascade calculations. ARC with an energy dependent mixture of repulsive and attractive scattering for the individual baryon collisions (cf. [18]) reproduces the data rather well. RQMD in its cascade mode underpredicts the observed flow of protons. With the inclusion of a repulsive mean field RQMD also gives reasonable agreement with the data.

Experimentally, it is interesting to note that the two pion species show almost exactly the same magnitude of \( \langle p_x \rangle \). If there were a sizable residual Coulomb interaction with the strongly flowing protons this would not be expected.

5 Transverse Radial and Longitudinal Flow of Identified Particles

In an analysis of measured particle ratios, both at the AGS and the SPS from Si- and S-induced reactions respectively, it was found that the hadrochemical composition of the final state can be described with the emission from an equilibrated system [19]. The temperatures deduced were \( T = 120-140 \) MeV and \( 160-170 \) MeV respectively (cf. Fig. 6). Furthermore, it was noted that the transverse mass spectra at midrapidity of different mass particles could only be described, if on top of the thermal energy the particles were subject to collective transverse radial flow. For the quoted temperatures and a flow profile linear in radius, the average radial expansion velocities \( \langle \beta_t \rangle \) were \( 0.36 \pm 0.03 \) and \( 0.27 \pm 0.03 \) respectively at AGS and SPS. For the heaviest collision system Au+Au at the AGS an analysis of data presented at Quark Matter ’96 show that there \( \langle \beta_t \rangle = 0.45 \pm 0.03 \).

Similarly, the shape of the rapidity distribution of identified particles, as shown in Fig. 5, can only be reconciled with emission from a thermal source, if that source is longitudinally expanding. The dashed lines represent emission from a stationary thermal source, while the solid lines correspond to emission
from a thermal source expanding with an average longitudinal velocity \(\langle \beta_l \rangle = 0.5\). This is the same average velocity as the one extracted from the relatively small collision system Si+Al at the AGS. All but the \(K^-\) spectra are well described with such an assumption.

### 6 Systematics of Flow

A few interesting things can be learned from a systematic study of the various types of flow for different collision systems and bombarding energies. The freezeout temperature rises continuously as the bombarding energy is increased. Both, at AGS and SPS energies they are in accordance with the temperatures expected at the phase transition between a hot hadron gas and
the QGP \cite{19}. This would provide circumstantial evidence for the fact, that the system may have made the transition to the QGP before freezeout.

At energies between SIS and SPS a maximum in the transverse radial flow is reached. A maximum is expected, where the lifetime of the system is largest such that a high degree of collectivity in the subsequent expansion can be achieved - one of the predictions of hydrodynamics with a phase transition\cite{8}.

The longitudinal flow velocities increase faster than logarithmically between AGS and SPS energies. This is expected, if stopping seizes to be complete.
The sideward flow $F$ (top right) in this representation is defined as

$$F = \frac{(d\langle p_x/A\rangle/dy')/(A_1^{1/3} + A_2^{1/3})}{A_1^{1/3} + A_2^{1/3}}$$

where $y' = y/\text{beam}$ and $A_{1,2}$ are the masses of projectile and target in order to be able to compare to asymmetric systems (see [22]). The E877 data was added to the systematics. The data seem to level off between SIS and AGS energies. One-fluid hydrodynamic calculations predict a vanishing of this quantity between the two energies. Data are not yet conclusive here.

Elliptic flow has first been discovered by the Plastic Ball at the Bevalac [23] and was coined ‘squeezeout’ because there the major axis was perpendicular to the reaction plane, reminiscent of the shadowing due to the projectile and target nucleons. In raising the beam energy the sign of $v_2$ changes and is now more sensitive to the high initial pressure in the collision [13]. Whether this trend continues at the SPS as shown in the figure is not completely clear yet, since the data from NA49 [24] does not allow for the reconstruction of the reaction plane and therefore the sign of $v_2$ has not been verified. Also, the magnitude depends on the assumption that pions contribute mostly to the measured signal and that for them transverse momentum and transverse energy are similar.

7 Outlook

With the advent of very detailed datasets, it should finally be possible to determine some of the fundamental thermal and hydrodynamical properties of highly excited nuclear matter and to discern some of the models that try to describe it. At SPS energies first direct hints of the elusive QGP have been reported through the measurement of dielectrons [25] and dimuons [26]. On the hadronic side this is corroborated by the findings of the freezeout temperature at the phase transition line. These signals should be largest, when the largest system with highest energy and baryon density is formed. In order to determine this point, the EOS collaboration is now exploring the bombarding energy region between SIS and AGS energies and the CERN experiments will prepare for a run at the lowest attainable energy at the SPS to get data in the region above AGS energies.

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