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Author

Ritter, H.G.

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A.M. Poskanzer, A. Warwick and H. Wieman

Gesellschaft für Schwerionenforschung,
Darmstadt,
West Germany

and

Nuclear Science Division
Lawrence Berkeley Laboratory
University of California
Berkeley, California 94720

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FLOW OF NUCLEAR MATTER*

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B. Kolb, H. Löhner, B. Ludewigt, A.M. Poskanzer, A. Warwick and H. Wieman,
Gesellschaft für Schwerionenforschung, Darmstadt, West Germany and Nuclear
Science Division, Lawrence Berkeley Laboratory, University of California,
Berkeley, California 94720

The systems Nb + Nb and Au + Au have been measured at different energies at the Bevalac with the Plastic Ball spectrometer. Distributions of the flow angles as a function of charged particle multiplicity are presented. Also shown is a transverse momentum analysis for 400 MeV per nucleon Nb + Nb.

The study of the nuclear matter equation of state is a prime objective of high energy heavy ion physics. The pion yield has been proposed as a tool to measure the amount of compressional energy in the reaction[1] and to derive a model dependent equation of state. It should be possible to achieve the same goal by measuring all the relevant thermodynamical quantities like temperature, entropy and density simultaneously. Since we do not know how to measure the density at the point of maximal compression directly, we have to retreat to more indirect observables and in fact, a recent measurement of the entropy production suggests the need for the inclusion of compression[2]. Collective flow of nuclear matter upon reexpansion has been proposed since a long time as the most important signature for the compression effects predicted by an equation of state[3]. Recently, collective flow has been observed in Nb + Nb collisions at 400 MeV per nucleon measured with the Plastic Ball[4]. Two collective effects, the side-splash of the participants and the bounce-off of the spectator nucleons have been established. Collective flow has been observed as well in collisions of asymmetric target projectile-combinations measured with the Streamer chamber[5].

In this paper we are presenting data on collective flow for collisions of 150, 250, 400, 650 and 800 MeV per nucleon Au + Au and 400 and 650 MeV per nucleon Nb + Nb, again measured with the Plastic Ball spectrometer[6] at the Bevalac. The events are analyzed with the kinetic energy flow method[7] and the distributions of flow angles are discussed.

Since the charged particle multiplicity is related to the impact parameter, we classify the events according to the participant proton multiplicity (N_p),

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defined and used in ref. 2 and 8. The average multiplicity depends on the target-projectile mass and on the bombarding energy. In order to make meaningful comparisons the multiplicity bins chosen should correspond always to approximately the same range in normalized impact parameter. The best approach to reach that goal is to divide the multiplicity distribution into bins of constant fractions of the maximum multiplicity. The multiplicity distribution has roughly the same form for all systems and energies: a monotonic decrease with increasing multiplicity with a rather pronounced plateau before the final sharp decrease at the highest multiplicities. Therefore the maximum multiplicity (N_p^{max}) can be defined at the point where the curve drops to one half the plateau height. Table 1 contains this value of N_p^{max} and also the mean value of the multiplicity distributions for all systems reported here. The data accumulated with a minimum bias trigger are then divided into 5 bins, 4 equal width bins between 0 and maximum multiplicity and one bin with multiplicities larger than N_p^{max}.

For each event the flow analysis yields the angle of the major axis of the best fit ellipsoid relative to the beam axis (flow angle θ) and the aspect ratios. Both kinds of values are influenced and distorted by fluctuations. Even for multiplicities as high as 100 charged particles the distortion of the aspect ratios is still larger than 30 percent[9], whereas the amount of directed energy flow in the data has been estimated to be of the order of 10% of the energy available in the center of mass system[4]. Therefore it can not be expected that the aspect ratios contain useful information. In fact, within the stated limitations the aspect ratios for the highest multiplicity events are compatible with isotropic emission. Consequently we obtain essentially one parameter, the flow angle, as a result of the energy flow analysis. However, the jacobian free distribution[9] $dN/d(\cos\theta)$ of the measured angles is easily calculated and allows us to distinguish between isotropic and directed emission.

The distribution of the flow angles for Ca + Ca, Nb + Nb and Au + Au, at 400 MeV per nucleon is shown in fig. 1. The trend towards larger flow angles as the target-projectile mass increases has been reported before[4] and clearly continues in going from Nb to the heaviest system measured thus far, Au + Au. An increase with mass has been predicted qualitatively by Vlasov-Uehling-Uhlenbeck calculations[10], however that predicted increase is more pronounced than the one observed here. For a quantitative comparison a careful analysis including all experimental biases has to be performed.

Also important is the energy dependence of the flow angles. This is shown in fig. 2 for 5 different Au + Au energies from 150 Mev per nucleon up to 800 MeV per nucleon. The general trend observed is that the flow angle decreases

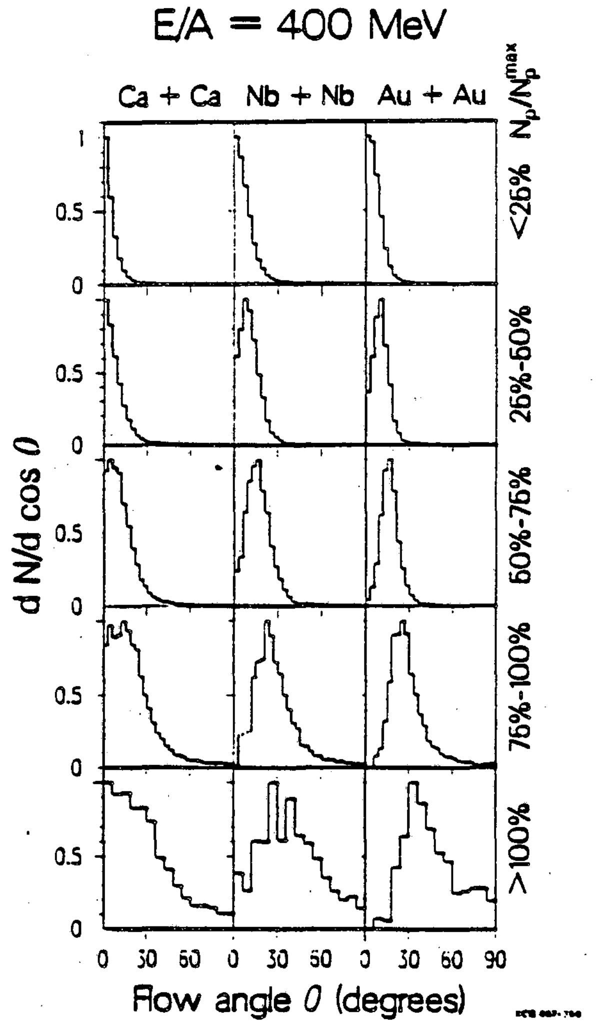

FIGURE 1
Jacobian free distributions of the flow angles (dN/dcos θ) for the systems Ca + Ca, Nb + Nb and Au + Au all at 400 MeV per nucleon.

with increasing energy above 250 MeV per nucleon. At the lowest energy the reaction mechanism responsible for the flow effect might lose importance in favor of other mechanisms known from low energy heavy ion reactions, such as e.g. deep inelastic scattering. In addition the division into bins of constant fractions of the maximum multiplicity might not be appropriate at 150 MeV per nucleon since the maximum multiplicity of 64 participant protons indicates that total disintegration into hydrogen and helium isotopes is not yet reached even for the most violent collisions.

The fact that the flow angles become smaller with increasing energy does not indicate that the flow effect gets smaller; it means however that the mean transverse momentum does not increase quite as fast as the longitudinal momentum. On the contrary, since the decrease in angle is only small, it is possible that the mean perpendicular momentum transfer increases with energy. If one is allowed to relate the collective perpendicular momentum transfer to

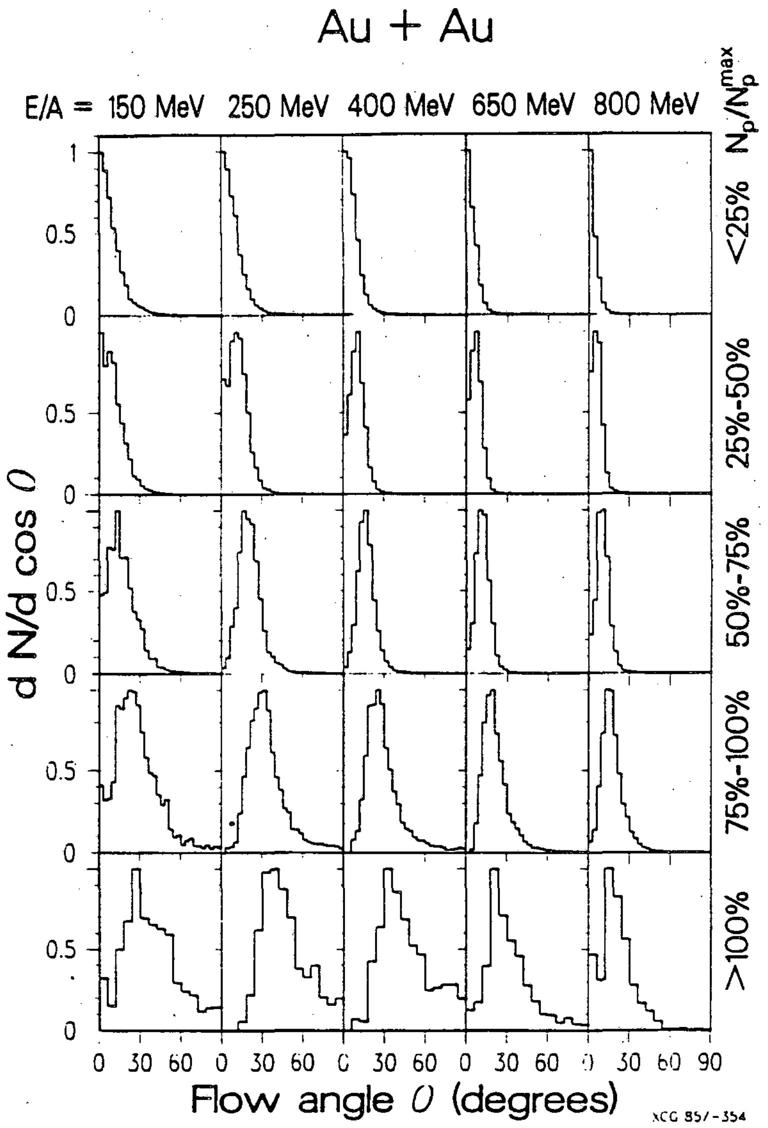

FIGURE 2
Jacobian free distributions of the flow angles for the system Au + Au at 5 different energies.

the pressure built up, then that would indicate that the pressure increases with energy.

As mentioned before, reducing all the information available for each event to one observable, the flow angle, is a rather "inclusive" representation of the data. Since all the experimental biases and inefficiencies are folded into this observable it is extremely difficult to compare the experimental results with theoretical predictions. The reaction plane can also be determined from the collective transverse momentum transfer between the forward and backward hemispheres in the center of mass[11,12] and recently Danielewicz and Odyniec have proposed a more "exclusive" way to analyze and to present the data[12] where the mean transverse momentum per nucleon $<p_x/A>$ in this reaction plane is plotted as a function of the center of mass rapidity. By removing auto-correlations this method is sensitive to the real dynamic correlations and has lead to indications for collective flow effects in cases where the energy flow analysis was not sensitive enough[12,13]. Of course the reaction plane determined by the transverse momentum analysis should be identical to the one determined by the flow analysis. This is proven in fig. 3 which shows the difference in azimuthal angle φ between the reaction planes as determined by the two different methods.

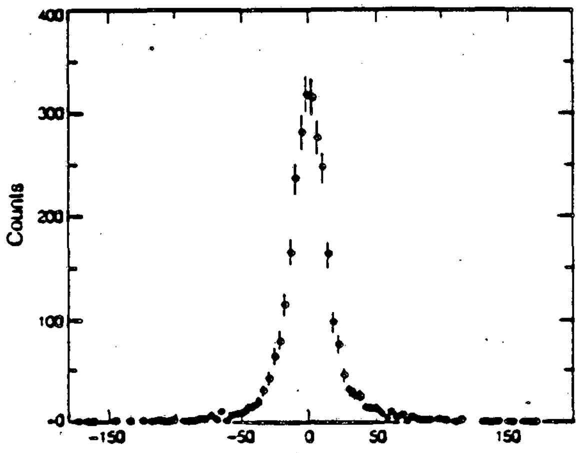

FIGURE 3
Difference in azimuthal angle φ between the reaction plane determined with the flow analysis and with the transverse momentum method for 650 MeV per nucleon Au + Au data.

Figure 4 shows the mean transverse momentum per nucleon projected into the flow plane for the reaction Nb + Nb at 400 MeV per nucleon and for the multiplicity bin that contains between 75 and 100% of N_p^{max}. In this graph the auto-correlations have been removed, according to the prescription given in ref. 12, by calculating the reaction plane for each individual particle from the transverse momentum sum of all the other particles. In determining the reaction plane particles were not excluded near mid rapidity as in ref. 12. The curve shows the s-shape typical for the collective transverse momentum transfer between the forward and backward hemispheres. The maximum momentum transfer of about 100 MeV/c per nucleon is an important quantity that can be compared to theoretical predictions. However, the influence of experimental biases on that quantity needs further study. At the target and projectile rapidities the curve bends towards the axis because of contamination from spectator matter. The slope of the curve near the origin can be related to both the flow angle and the aspect ratios of the flow ellipsoid[14]. The strong

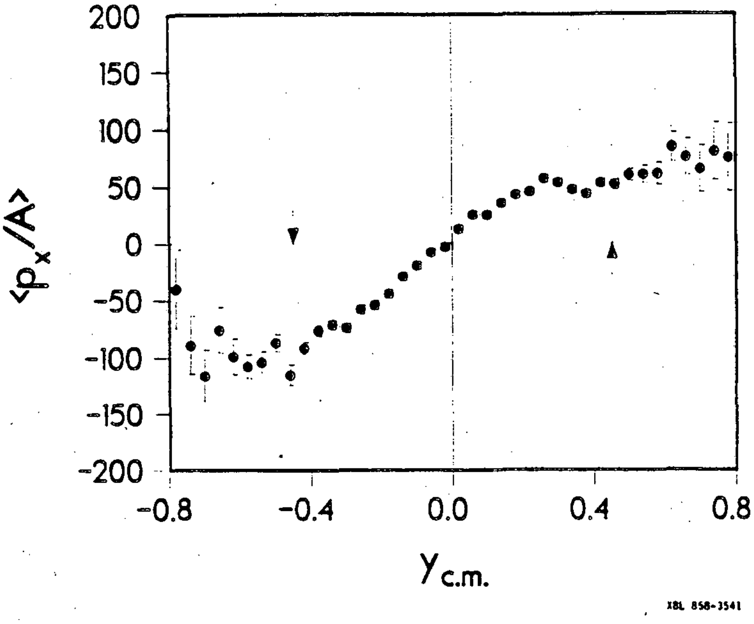

FIGURE 4
Mean transverse momentum per nucleon in the reaction plane as a function of the c.m. rapidity for 400 MeV per nucleon Nb + Nb data. Presented here is the fourth multiplicity bin. Auto-correlations are removed.

dynamical correlations present in the data are not only supported by the magnitude of the momentum transfer but also by the fact that removing the auto-correlations did not influence the curve in fig. 4. Therefore the real correlations must be much stronger than possible distortions and fluctuations.

The fact that collective flow is observed in the data indicates that a pressure build up has developed during the collision. However, the question whether that pressure is due only to kinetic effects from the heating of matter and to fermi motion or whether that pressure is due to potential energy effects can not be answered by the experiment alone. A very careful quantitative comparison of the experimental results with model predictions has to be performed where all the effects of experimental efficiency and acceptance have to be taken into account. Qualitatively the effect had been predicted first by hydrodynamical models[3] and Buchwald et al. have calculated the flow effect for Nb + Nb[15]. The equation of state used in those hydrodynamical models was sensitive to the magnitude of the flow angle[16]. The effect has been predicted as well by a model using classical equations of motion[17] and has been confirmed in two recent publications[18]. In this model the compression is simulated by the nucleon-nucleon potentials. There are other models based on the Boltzmann equation[19,20] and especially ref. 20 performs a detailed study of both effects observed, the side-splash and the bounce-off.

Besides those models that all use compressional energy in some form there are recent cascade calculations where flow effects have been observed using a purely thermal equation of state. Malfliet[21] uses the Enskog equation that has a Van der Waals like equation of state and thus contains non-ideal gas terms. Cugnon et al.[22] and Kitazoe et al.[23] observe sidewards emission within the standard cascade model. Those results clearly underline the necessity for a better comparison. Figure 5 shows the distribution of the mean transverse momentum per nucleon projected into the reaction plane (auto-correlations removed) as a function of the c.m. rapidity for Nb + Nb collisions at 400 MeV per nucleon calculated with Cugnon's cascade code[24]. The events have been filtered with the experimental acceptance and the multiplicity bin has been chosen to correspond to the conditions used for the experimental data presented in fig. 4. It is obvious that the effect observed in the data is much stronger than the one predicted by the cascade calculation. Recent comparisons between different cascade codes and between cascade codes and the data are in agreement with that result[25] but a more quantitative and systematic comparison will be needed.

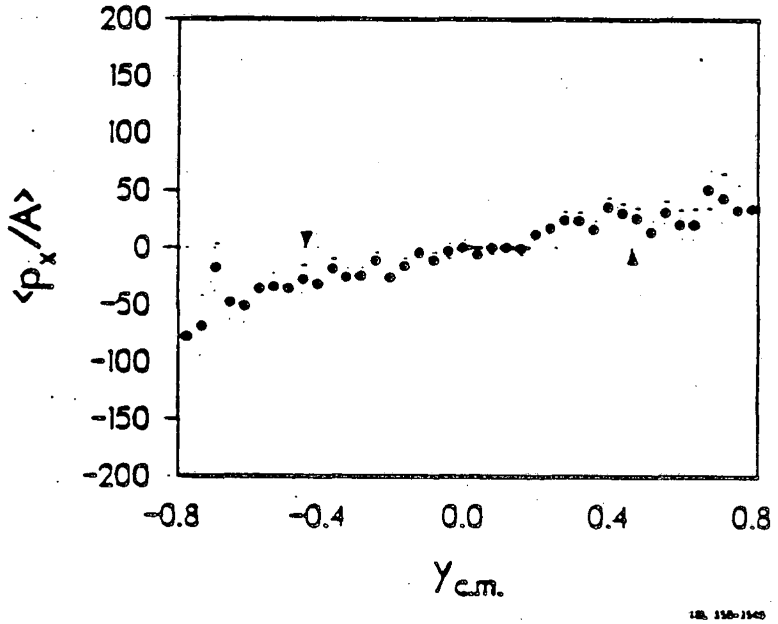

FIGURE 5
Mean transverse momentum per nucleon in the reaction plane as a function of the c.m. rapidity for 400 MeV per nucleon Nb + Nb events calculated with the Cugnon cascade code. Auto-correlations are removed.

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Table 1: Maximal participant proton multiplicities and mean multiplicities for the different target-projectile combinations

E/A (MeV)	150	250	400	650	800
Au	64 28	92 38	112 47	128 59	134 62
Nb			64 26	72 31	
Ca			30 14		

LAWRENCE BERKELEY LABORATORY
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BERKELEY, CALIFORNIA 94720