Fragment Flow in Au+Au Collisions

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(Received 27 October 1994; revised manuscript received 13 July 1995)

Exclusive measurements have been made of Au+Au reactions with beam energies ranging from $0.25A$ to $1.15A$ GeV. We present measurements of directed collective flow averaged over all light fragments with masses up to alphas, as well as separate measurements for protons, deuterons, tritons, ^{3}He, ^{4}He, and Li. The results show a strong increase of the directed flow with fragment mass at all energies measured. Experimental results are compared with a quantum molecular dynamics model. We find that neither the "soft" nor the "hard" equation of state can describe the data over the entire range of beam energies.

PACS numbers: 25.75.+r, 25.70.Pq

Collective phenomena in particle emission have been established in high energy nucleus-nucleus collisions [1]. Their existence has been connected to the response of quasibulk hot and dense nuclear matter created during the collision process. The preferential emission of particles, or directed flow, is considered an important signature of nuclear compression and, indirectly, the nuclear matter equation of state. Prior experiments indicated an energy dependence of flow based on measurements that averaged over particle species. Larger flow for heavier mass fragments was observed from the partial identification of the charge $Z = 1$ and $Z = 2$ species at energies up to $0.4A$ GeV [2–7]. This observation suggests that heavier fragments may carry more direct information on the bulk properties of nuclear matter. Thus a complete study of fragment formation and directed flow would provide valuable data on the equation of state. Previous experiments, however, had limited detector capabilities; and the data, considered all together, could not constrain the dynamical parameters used in theoretical models. In this paper we present new measurements on the energy dependence of fragment flow for Au+Au collisions using beam energies of $0.25A$, $0.4A$, $0.6A$, $0.8A$, $1.0A$, and $1.15A$ GeV. This substantial body of data is made available by a detector which measures the majority of the observable signal and thus avoids the earlier experimental problems.

The experiment was conducted with a state-of-the-art time projection chamber (TPC) at Lawrence Berkeley National Laboratory's Bevalac heavy ion accelerator facility. The details of the design of the TPC can be found in Ref. [8]. The Au target was located near the entrance of the active TPC volume to allow a large solid angle acceptance in the center-of-mass system. This setup provided nearly complete acceptance in the forward hemisphere and, depending on the beam energy, a decreasing coverage in the backward hemisphere. The detector measured the rigidity and specific energy loss associated with each track. The resolution was sufficient to identify $\pi^{\pm}$, protons, deuterons, tritons, ^{3}He, ^{4}He, ^{6}Li, ^{7}Li, and charge states of fragments up to $Z = 8$ in events containing up to 140 or more charged tracks.

Approximately 12 000 events have been analyzed at each beam energy. The global transverse momentum analysis of Danielewicz and Odyniec [9] was used to estimate the reaction plane of each event. This type of analysis systematically underestimates the transverse momentum in the reaction plane, and therefore in all the data shown the subevent method of Ref. [9] was used to correct the in-plane transverse momenta on average. The magnitude of these corrections ranged from 10% at $0.25A$ GeV to 6% at $1.15A$ GeV.

The collective flow of matter from the participant region is characterized by the slope at midrapidity of the

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$\langle P_x/A \rangle$ vs y_n curve [10]. Here, $y_n = y/y_b$ is the fragment rapidity normalized by the beam rapidity y_b. This normalized rapidity has been used extensively in the literature [10,11] and is useful for making comparisons of the participant distributions at different beam energies. P_x is the projection of the transverse momentum onto the reaction plane. The slope characterizes the transverse velocity imparted to the participants during the collision. In principle, the maximum value of $\langle P_x(y_n)/A \rangle$ should provide complementary information away from midrapidity, but in practice it is influenced by bounceoff spectator fragments and is a less useful quantity for comparisons.

Collective flow is studied as a function of impact parameter by dividing the data into multiplicity bins in a manner similar to the Plastic Ball analysis [1]. The entire multiplicity distribution is divided into five bins, with $M1$ containing the lowest multiplicity events and $M5$ the highest. This method has the advantage that the multiplicity bins become wider as the beam energy increases, providing bins that correspond to similar ranges of impact parameters at each energy.

Figure 1 shows $\langle P_x/A \rangle$ vs y_n for the six different beam energies where all fragments up to ^{4}He are included. In the Plastic Ball convention, our data belong to multiplicity bins $M3$ and $M4$ where the observed flow is a maximum. The curves display the typical "S" shaped behavior; however, they are not completely antisymmetric about $y_n = 0$, because the TPC has reduced acceptance in the backward hemisphere. We have fit the data with a function of the form $f(y_n) = a_0 + Fy_n$ over the region $-0.18 < y_n < 0.29$ for all the energies. The coefficient F (slope parameter) is extracted and plotted in Fig. 2 as a function of beam energy.

Our data are shown in Fig. 2 along with the Plastic Ball data [4]. The error bars are statistical only. The two data sets agree very well; the minor discrepancies at the highest energies can be explained by the fact that the Plastic Ball data are not corrected for detector acceptance effects, which were significant for their high energy data. Both our data and the Plastic Ball data exhibit a "logarithmiclike" behavior with an indication that a plateau might be attained at the higher Bevalac energies. This is significant since the value of F was expected to plateau and subsequently decrease with increasing beam energy [12]. A simple logarithmic curve has been fit to the EOS data points and is shown as a solid line. The energy at which F vanishes is called the "balance energy" and is extracted from the fit to have a value of 47 ± 5 MeV per nucleon. From low energy studies, the balance energy for a Au+Au system was extrapolated to be <60 MeV per nucleon [13].

The individual proton and deuteron flow excitation functions are depicted in Fig. 3. Figure 4 shows the excitation functions for the triton, ^{3}He, ^{4}He, and Li fragments. As before, the solid curves represent logarithmic fits to the data. Two observations are readily made from the data. First, the heavier fragments demonstrate greater values of F at all beam energies. Second, the energy dependence of F is more pronounced for the heavier fragments. The differences in magnitude and energy dependence of F for the separate fragment species are features that are averaged out in the data shown in Fig. 2. This mass dependence is the subject of particular interest as its origin is not entirely understood. It may be due in part to thermal dispersion, which is more significant for the lightest fragments; in this case, the heavier fragments provide a more sensitive measure of the collective motion [3]. However, it has been shown that the increase in sideward flow per nucleon with fragment mass is generally described by momentum-space coalescence for particles with transverse momentum above $0.2A$ GeV/c [14].

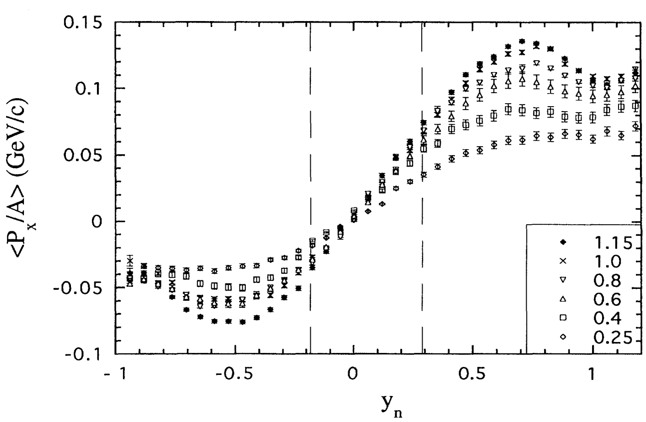

FIG. 1. $\langle P_x/A \rangle$ vs y_n for each beam energy. The data are from events in multiplicity bins $M3$ and $M4$ in the Plastic Ball convention. The fragments included are p, d, t, ^{3}He, and ^{4}He. The dashed lines indicate the region in which the fits were made.

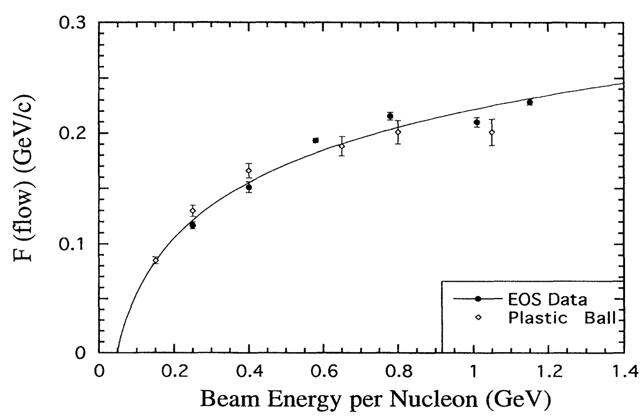

FIG. 2. Energy dependence of flow from EOS data and Plastic Ball data of Ref. [4]. The error bars are statistical only. The solid curve is a logarithmic fit to the EOS data.

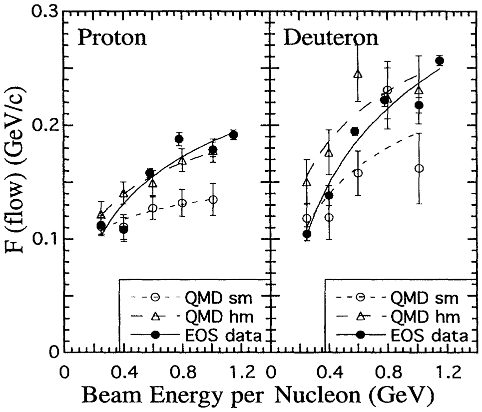

FIG. 3. Collective flow for protons and deuterons from our data and QMD model calculations using a hard equation of state with momentum dependent interactions (hm) and a soft equation of state with momentum dependent interactions (sm). Error bars are statistical only. The QMD calculations have been filtered to include the systematic bias of the EOS TPC detector, but ignoring all influence of particle misidentification for reasons given above.

The effects of acceptance and efficiency of the EOS TPC detector on the observable flow have been studied, using Monte Carlo event generators and GEANT based simulations of the detector response. These simulations include effects of geometrical acceptance, track merging, track reconstruction efficiency, and particle identification. The results of these studies indicate that the acceptance and efficiency depend on the fragment type, relative fragment yields, event multiplicity, and beam energy. Thus the systematic error is dependent on the input model data, and no single number serves to adequately characterize the systematic error. It is important to point out that different model data will, in general, experience different detector biases. In addition to the detector bias on flow, selecting a different fit region or function could produce slight variations in the values of F. Therefore, comparisons of F from different experiments or theoretical calculations should be made with well-defined conditions.

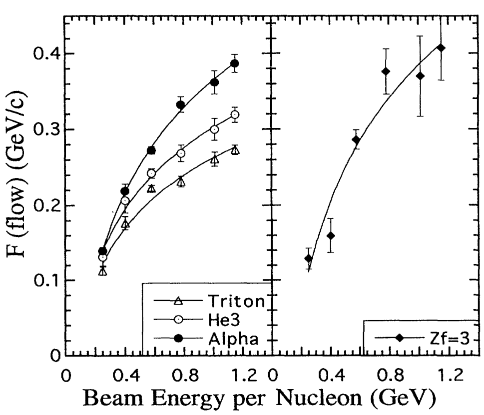

FIG. 4. Collective flow for triton, ^{3}He, ^{4}He, and Li. Error bars are statistical only. The solid curves are logarithmic fits to the data.

The parameters of the nuclear equation of state are deduced via comparisons of theoretical calculations with experimental data. To that end, we have performed calculations using the quantum molecular dynamics (QMD) [15,16] model. This model provides a microscopic treatment of the space-time evolution of a collision by using local two- and three-body Skyrme, Coulomb, and Yukawa interactions. Neither global nor local equilibrium is assumed, and the nuclear equation of state is simulated by different parametrizations for the nuclear interactions. The strength of the nuclear compression is quoted normally in terms of the incompressibility constant K. A "soft" equation of state is represented by a value of $K = 200$ MeV, while a "hard" equation of state is represented by a value of $K = 380$ MeV. In these QMD calculations, momentum dependent interactions (MDI) are included, which provide an additional repulsion between nucleons, resulting in a stiffer equation of state than would otherwise be implied by a particular value of K. We have performed QMD calculations [16] at beam energies of $0.25A$, $0.4A$, $0.6A$, $0.8A$, and $1.0A$ GeV for both hard and soft equations of state. For the nucleon-nucleon cross sections we use unmodified, experimental cross sections.

The results of our calculations are shown in Fig. 3 as open circles for the soft EOS with MDI (sm) and open triangles for the hard EOS with MDI (hm) for protons and deuterons only. The error bars are statistical only. The flow derived from the QMD calculations has been filtered to include the systematic bias of the EOS TPC detector. However, the QMD model fails to reproduce the observed relative mass yields, thus the effects of particle misidentification are misleading and have not been included in the model filter. Although the particle yields are not correct in QMD, the single particle spectra of the QMD calculations have been found to be in reasonable agreement with the data as reported in Refs. [17,18]. The QMD calculations qualitatively reproduce the trend of increasing flow with increasing beam energy, and the protons are consistent with a hard EOS. However, the energy dependence of flow for the deuterons is inconsistent with both the hard and soft EOS. At low energies, calculations with a soft EOS seem to reproduce the data for the deuterons, whereas at higher energies a hard EOS appears to be favored. The mass dependence of flow in QMD resembles the data only to the extent that the deuteron results are always greater than the proton values. There were insufficient alpha particles in the calculations to provide an accurate comparison. In light of the observed mass dependence of flow, the relative yield of different fragments is very important when comparing experimental quantities averaged over fragment species to predictions; for example, it would be difficult to interpret the QMD model calculations of the observable shown in Fig. 2 since the relative yields are not correctly reproduced by QMD.

Fragment flow has recently drawn theoretical attention because of its greater sensitivity to collective behavior. This sensitivity may help resolve the competing explanations of nuclear matter flow. Unlike earlier cascade model calculations [19], Kahana *et al.* [20] have asserted that collective flow is well described by using the hadronic cascade model, ARC, without the need for an explicit mean field to simulate the nuclear equation of state. However, using the relativistic Boltzmann-Uehling-Uhlenbeck approach, Blättel *et al.* [21] found that, while stochastic N-N collisions can provide a sizable transverse flow, the most important quantity for the mean-field contribution is the height of the potential in the participant zone which, in turn, is determined predominantly by the momentum dependence of the interaction. Moreover, Jaenicke *et al.* [22] show that microscopically derived potentials exhibit a strong momentum dependence in contradistinction to the usual forms of mean-field parametrizations. Consequently, they argue that very little compression is achieved at Bevalac energies, and thus flow may not be sensitive to the equation of state.

Most theoretical studies with transport or wave packet models use mean-field potentials appropriate for cold nuclear matter. Recently, Puri *et al.* [23] have suggested that the interactions between nucleons in a hot nuclear medium can be significantly different from cold nuclear matter. They have studied heavy ion reactions within the conventional QMD formalism but substitute temperature dependent potentials derived from the solution of the Bethe-Goldstone equations for nuclear matter at finite temperatures. Several interesting observations are made, but, of particular note here, is that nuclear matter becomes softer (smaller compressibility K) due to elevated local temperatures. Consequently, calculations show less directed flow as compared to the cold potential. This effect is of the same order as the difference between the usual soft and hard EOS. Although a detailed comparison cannot be made with our data, we can draw an inference based upon the following information. The conventional soft EOS, including momentum dependence, is almost identical to the temperature dependent mean-field potential in the limit of zero temperature as indicated by Table I and Fig. 3(b) of Ref. [23]. Thus, with temperature dependence included, one could expect less flow compared with the QMD predictions using a soft-cold EOS at all beam energies above $0.25A$ GeV and for all fragments. Unfortunately, this would further compound the discrepancy between our data and theory. In general, the disparity in the models with regard to momentum dependent interactions, stochastic N-N collisions, and temperature effects must be settled before drawing any inferences about the nuclear matter equation of state.

In summary, we have presented the first comprehensive measurement of directed flow for protons, deuterons, tritons, ^{3}He, ^{4}He, and Li from Au+Au collisions using beam energies in the range $0.25A$ to $1.15A$ GeV. An increase of the directed flow with fragment mass is observed at all energies. Also, the differences in fragment flow become progressively larger with rising beam energy. These flow measurements provide rigorous constraints on competing microscopic theories. In particular, our QMD calculations reflect the trends, but neither a soft nor a hard equation of state is able to reproduce the measurements over the entire energy range.

This work was supported in part by the Director, Office of Energy Research, Office of High Energy and Nuclear Physics, Division of Nuclear Physics of the U.S. Department of Energy under Contracts Nos. DE-AC03-76SF00098, DE-FG02-89ER40531, DE-FG02-88ER40408, DE-FG02-88ER40412, DE-FG05-88ER40437, and by the National Science Foundation under Grant No. PHY-9123301.

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