The Energy Dependence of Flow in Ni Induced Collisions from 400*A* to 1970*A* MeV

J. Chance,[1] S. Albergo,[2] F. Bieser,[4] F. P. Brady,[1] Z. Caccia,[2] D. Cebra,[1,4] A. D. Chacon,[6,*] Y. Choi,[5,†] S. Costa,[2] J. B. Elliott,[5] M. Gilkes,[5] J. A. Hauger,[5] A. S. Hirsch,[5] E. L. Hjort,[5] A. Insolia,[2] M. Justice,[3] D. Keane,[3] J. C. Kintner,[1,‡] M. A. Lisa,[4,§] H. S. Matis,[4] M. McMahan,[4] C. McParland,[4] D. L. Olson,[4] M. D. Partlan,[1,‖] N. T. Porile,[5] R. Potenza,[2] G. Rai,[4] J. Rasmussen,[4] H. G. Ritter,[4] J. Romanski,[2,¶] J. L. Romero,[1] G. V. Russo,[2] R. Scharenberg,[5] A. Scott,[3,**] Y. Shao,[3,‡‡] B. Srivastava,[5] T. J. M. Symons,[4] M. Tincknell,[5] C. Tuvé,[2] S. Wang,[3] P. Warren,[5] H. H. Wieman,[4] T. Wienold,[4] and K. Wolf[6]

[1]*University of California, Davis, California 95616*

[2]*Universitá di Catania & INFN-Sezione di Catania, Catania, Italy 95129*

[3]*Kent State University, Kent, Ohio 44242*

[4]*Nuclear Science Division, Lawrence Berkeley National Laboratory, Berkeley, California 94720*

[5]*Purdue University, West Lafayette, Indiana 47907-1396*

[6]*Texas A&M University, College Station, Texas 77843*

(The EOS Collaboration)

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We study the energy dependence of collective (hydrodynamic-like) nuclear matter flow in (400–1970)*A* MeV Ni + Au and (1000–1970)*A* MeV Ni + Cu reactions. The flow increases with energy, appears to reach a maximum, and then to decrease at higher energies. A way of comparing the energy dependence of flow values for different projectile-target mass combinations is introduced, which demonstrates a more-or-less common scaling behavior among flow values from different systems. [S0031-9007(97)02592-1]

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The study of nuclear matter over a wide range of temperatures and densities and the determination of the equation of state (EOS) of nuclear matter continues to be of considerable interest [1]. Lacking the possibility of comprehensive studies of nuclear matter in bulk (as in neutron stars), one resorts to the study of transient, finite systems provided by nucleus-nucleus collisions (over a wide range of energy). It is now clear that the extraction of EOS information from nuclear collisions requires a comprehensive set of measurements of collision observables, which can be compared to realistic microscopic calculations involving the nuclear matter variables.

At GeV per nucleon energies, where the collision velocity exceeds that of nuclear sound, the collisions produce densities several times higher than ground state densities and exhibit compression-induced flow of nuclear matter [1]. However, it was not until the analysis of events from the 4π Plastic Ball/Wall [2] and Streamer Chamber [3] detector systems at the Bevalac that the matter flow characteristics could be studied and quantified for a range of systems and energies. More recently, at the Bevalac at LBNL, the EOS Collaboration carried out a comprehensive set of measurements over a wide range of energies, and projectile-target combinations [4]. Similar studies are underway at GSI in Darmstadt and, with lighter projectiles, by the DIOGENE Collaboration at Saclay [5]. EOS Collaboration data has been used to study flow for the Au + Au system at lab energies ranging from 250*A* to 1150*A* MeV [6]. Particle flow for protons, deuterons, and alpha particles has been determined, using the transverse momentum method [7]. The flow is found to increase with particle mass A, and with energy up to projectile energies of 1150*A* MeV where it tends to level out (saturate) at values close to the Plastic Ball data [8].

Here we present analyses of recent EOS Ni + Au data with energies between 400*A* and 1970*A* MeV and EOS Ni + Cu data at energies of 1000*A*, 1500*A*, and 1970*A* MeV. This study with the Ni beam allows the use of higher energy per nucleon projectiles, and so extends the energy of our flow measurements beyond the 1150*A* MeV limit of the EOS Au + Au data [6]. We also present a comparison of the flow values with predictions of two models, and introduce a scaled flow which allows the comparison of flow data from a variety of projectile-target mass systems. In total, the data provide the strongest evidence yet that, with increasing energy, flow reaches a maximum near 1000*A* MeV, and then declines.

The EOS Collaboration detector systems have been described in Refs. [4] and [6]. The data presented here were obtained using the EOS Time Projection Chamber (TPC) [9], situated in the magnetic field of the HISS Magnet. The TPC provides fairly unambiguous particle identification, as well as a measurement of momentum, for particles of charge up to $Z = 6$. Particle ID is ambiguous for rigidities above 2.4 GeV/c. Thus, some misidentification will occur and its effect is represented in the uncertainties. The target is just upstream from the TPC, and this results in a large and nearly seamless acceptance. Simulations have been performed to study the geometrical acceptance of the detector and to provide acceptance corrections.

In the present experiment, the thickness of the Au target was 730 mg/cm^2 corresponding to about 1% interaction probability. The trigger was provided by a scintillator just downstream from the target. The MUSIC (multiple sampling ionization chamber) detector, downstream from the TPC, provided an on-line check on the threshold charge of the heaviest fragment allowed by the trigger. For this analysis, data for a wide range of impact parameters were taken. We used charged particle multiplicity as a measure of the collision centrality, and have adopted the Plastic Ball [8] convention by dividing the events into five multiplicity bins with bin MUL1 corresponding to the most peripheral and bin MUL5 having the most central events. For the Ni + Au 400*A*, 600*A*, 1000*A*, and 1970*A* MeV the numbers of events analyzed were 44 000, 28 000, 28 000, and 26 000, respectively. The Ni + Cu 1000*A*, 1500*A*, and 1970*A* MeV analyses were done on recently analyzed data sets of, respectively, 29 000, 18 000, and 47 000 events. For each event, the reaction plane was determined using the transverse momenta of the particles, as proposed by Danielewicz and Odyniec [7]. The plane is determined by the vector $\vec{Q} = \sum_i w_i \vec{p}_i^{\,t}$ and the incident beam direction. Here $\vec{p}_i^{\,t}$ is the transverse momentum of particle i, and w_i is a weighting factor defined to maximize the contribution of high rapidity particles to the $\vec{Q}$ vector determination. Normally, for symmetric collisions of equal A, w_i is taken to increase linearly with rapidity up to $w_i = \pm 1$ at $|y'_{\mathrm{cm}}| = \delta$ and to be constant at ± 1 for $|y'_{\mathrm{cm}}| \geq \delta$. Using the subevent method of Ref. [7] we found the optimal reaction plane determination to be made with $\delta \simeq 0.7$. We also found that varying δ by 0.1 results in only a 1% change in the flow values. To characterize the flow, it has been customary to project each particle's $\vec{p}_t$ onto the reaction plane. We define the x direction to be in the reaction plane and the y direction to be perpendicular to the plane. Plotting the $\langle p_x/A \rangle$ (henceforth referred to as $\tilde{p}_x$) vs rapidity for all events at a given energy then yields the typical sidewards flow, S-shaped curves. Finally, before we extract flow values, we need to correct $\tilde{p}_x$ for the fact that we project onto an imperfectly known reaction plane. For this we use the subevent method of Ref. [7]. These corrections increase the $\tilde{p}_x$ values by amounts ranging from 10% (for the more central Ni + Au events) to 20% (for the more peripheral Ni + Cu events).

In Fig. 1 we show, in solid squares, the experimentally determined S-shaped plots of $\tilde{p}_x$ vs y' for the four Ni + Au systems and for multiplicity bin MUL4. Here, for the moment, we include only protons, for which we have unambiguous particle identification. Also shown in Fig. 1 (open circles and triangles) are the results from two different Boltzmann-Uehling-Uhlenbeck (BUU) transport model calculations with an equivalent impact parameter selection. For the 400 and 600 beam energy systems (top panels) we display the results from a BUU model [10] by Bauer *et al.*, while for the 1000 and 1970 systems (bottom panels) we here compare to a RBUU model [11] from Giessen. For each of the models, and all four energies, we performed calculations with a soft ($K = 200$) and a hard ($K = 380$) (versions NL1 and NL2 of Ref. [11]) equation of state. Both models are relativistically covariant, but for description purposes we will refer to the Bauer code as BUU and to the Giessen code as R(elativistical)BUU. For clarity purposes we do not display the lower energy RBUU and the higher energy BUU comparisons. For all the comparisons, we conclude that the models are able to reproduce the gross features of the S curves quite well. The differences in the beam rapidity region could be due to projectile spectator (such as bounceoff) effects, which are not properly treated in these models.

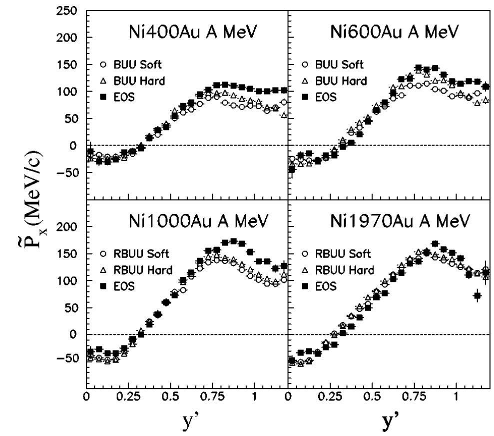

FIG. 1. S curves for the four Ni + Au energies, using protons only in multiplicity bin MUL4. The solid squares are EOS data, and the open circles and triangles are BUU model calculations, with, respectively, a soft and a hard EOS. The two top panels use the Bauer BUU code, while the bottom panels used the RBUU Giessen code. Calculations were done on all four systems with both models, but for clarity purposes we do not show all the comparisons. $\tilde{P}_x$ is the average of the x component of the momentum (see text). y' is the rapidity in the lab frame scaled by the rapidity of the beam.

Following the Plastic Ball analysis we define the flow, F, as the slope $(d\tilde{p}_x/dy')_{\tilde{p}_x=0}$ near the zero crossing (generally around $y' = 0.35$). The slope is calculated from a linear fit to the data in the region of $y' = 0.3$ to $y' = 0.6$. Similar F values are obtained using a cubic fit. The imperfect asymmetry of the S curve with respect to the $\tilde{p}_x = 0$ axis is due to both the lower acceptance in the lower rapidities, as well as reflecting transverse momentum conservation in the asymmetric collision. The larger number of (mainly target) particles (both spectator and participant) at low rapidity is balanced at higher rapidity by fewer particles having larger average p_t values. From the geometrical acceptance studies we found that acceptance corrections on the flow values are on the order of 5% for the lower energy Ni + Au 400*A* and 600*A* MeV systems. Acceptance corrections above 600*A* MeV are negligible since the detector has full acceptance for the region where the fitting is performed.

In Fig. 2 the extracted values of the slope, F (for protons in MUL4), at $y'(p_x = 0)$ are plotted vs projectile kinetic energy per nucleon and compared to the model F values. The top two panels show the asymmetric Ni + Au results (solid squares), and the bottom panel shows the flow values for the nearly symmetric Ni + Cu systems. These models do not include composite particle formation so the comparison is with the experimental proton F values. With the inclusion of bound protons (from d, t, etc.) the trend of the F values, as a function of energy, is similar.

For both the asymmetric and symmetric systems the experimental F values decline for the higher beam energies. This decline in the 1A to 2A GeV region is also observed in all the model calculations.

Given the uncertainties, though, it is difficult to draw strong conclusions regarding which versions characterize the data better. The BUU predictions, which do not include the effects of momentum dependent interactions (MDI's), show F decreasing at higher energies with the hard EOS version fitting the Ni + Au data better at lower energies and the soft matching the high energy point better.

The RBUU does include MDI's, which are known to be important [12] in flow measurements. The RBUU-Soft + MDI values show better agreement with the Ni + Cu data, while in the Ni + Au, a hard EOS is marginally closer to the data.

The energy dependence in Fig. 2 is consistent with the EOS Au + Au proton flow data of Partlan *et al.* [6] and the Plastic Ball data [8] which show the flow beginning to saturate above 800A MeV. The model predictions for Au + Au also show saturation and a gradual decline at higher energies. Predicting the energy dependence of flow is an important test of any model. For example, in one hydrodynamic model [13] the decline of flow at energies between 2 and 10 GeV was shown to be much more rapid for the case of a quark-gluon plasma as compared to a hadron gas scenario.

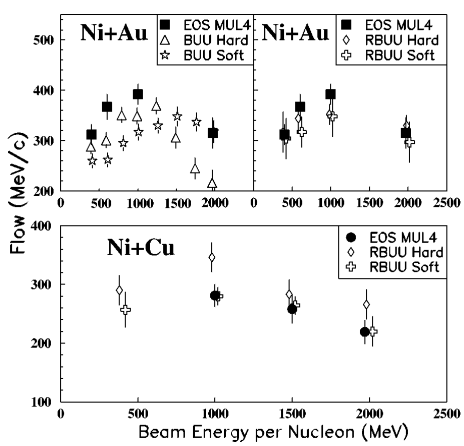

FIG. 2. Proton flow as a function of beam energy per nucleon in multiplicity bin MUL4. The top two panels are for Ni + Au EOS data. The solid symbols are the flow values from the data points in Fig. 1 while the open symbols are for soft and hard equation of state BUU (left panel) and RBUU (right panel) Ni + Au calculations. The bottom panel consists of flow values determined from Ni + Cu EOS data and a RBUU comparison.

We have studied other flow observables: the maximum value of $\tilde{p}_x$ and the sum $\sum \tilde{p}_x$, summed over all values for $y' > y'(\tilde{p}_x = 0)$. All of these observables give a flow energy dependence consistent with that for F. We have also analyzed the data using the reaction plane independent flow signal quantity [14] proposed by the FOPI group. The FOPI signal shows an energy dependence (rise and fall) similar to that of F in Fig. 2. In addition, we have examined the flow angle [8] dependence on multiplicity for the four energies. The flow angles increase, followed by a significant decrease in the range of 0.4A to 2A GeV.

It can be argued that flow should be determined from the laboratory rapidity, y, rather than from reduced rapidity, $y' = y/y_{\rm beam}$. Then flow becomes $F_y = d\tilde{p}_x/dy = F/y_p$ where y_p is the projectile beam rapidity in the lab frame. Plotting F_y vs energy we find that the rise of flow is reduced while the decline becomes more significant.

The saturation of flow is explicable or at least qualitatively reasonable. As energy increases, the nucleon-nucleon cross sections become more forward peaked. The mean nucleon transverse momentum at first rises rapidly with energy and then is almost constant above $p_z \simeq 2$ GeV$/c$. In addition, particle production is increasing rapidly, absorbing energy otherwise available for transverse momentum production. We have verified with the BUU model that direct pion production can significantly decrease the 2 GeV flow signal.

It is of great interest to compare the flow values for a wide range of data. To allow for different projectile-target (A_1, A_2) mass combinations, we divide the flow value by $(A_1^{1/3} + A_2^{1/3})$ and call $F_S = F/(A_1^{1/3} + A_2^{1/3})$ the scaled flow. Recent calculations [15] for symmetric systems show that the transverse pressure and flow scales with $A^{1/3}$. In a hydrodynamic picture, with collision velocities well above that of sound, one can argue that the pressure buildup should scale with collision (compression) length or time. This suggested the $(A_1^{1/3} + A_2^{1/3})$ scaling approximation used here. Figure 3 shows a plot of F_S vs energy per nucleon of the projectile. We include here data from the EOS experiment (solid points), along with values derived from other experiments [8,16–18] for a variety of energies and mass combinations. As closely as possible the data selected correspond to Plastic Ball multiplicity bins MUL3 and MUL4 or to an equivalent range of impact parameters. For the EOS and Plastic Ball data all the isotopes of $Z = 1$ and 2 are included, except for the 200A MeV Au + Au point [18] where the data is for $Z = 1$ and multiplicity bin MUL3. The Streamer Chamber data [16,17] normally include all protons, whether free or bound in clusters. Generally the flow values using all

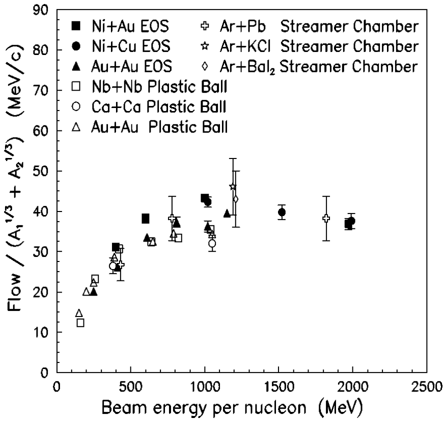

FIG. 3. Scaled flow values vs beam energy per nucleon for different projectile-target systems for Plastic Ball multiplicity bins 3 + 4. In the EOS and Plastic Ball data all isotopes of $Z = 1, 2$ are included. For the Streamer Chamber all free and bound protons are included. To improve the distinction between data points at the same beam energy, some of the beam energy values have been staggered around by as much as 20 MeV.

isotopes of $Z = 1$ and 2 are 10%–20% larger than those for protons. In Fig. 3 the scaled flow values, F_S, follow, within the uncertainties, a common trend with an initial steep rise and then an indication of a gradual decline. The Plastic Ball data are quoted with fairly small statistical uncertainties, $\simeq$4%–7%, about twice the size of the data points in Fig. 3. For the Ar + Pb [16] and Ar + KCl [17] Streamer Chamber data, we estimated the flow and statistical uncertainties from the $\tilde{p}_x$ vs y data plots, for the appropriate multiplicity ranges. Our estimated uncertainties for these flow values are in the range of 15%–23%. The 1800A MeV Ar + KCl Streamer Chamber data, as analyzed from Ref. [7], produce very large flow and scaled flow values ($F_s \simeq 92$ MeV/c) which are off the plot scale and not included in Fig. 3.

In summary, we have determined the nucleon flow for Ni + Au and Ni + Cu collisions in an energy range of 400A to 1970A MeV. For these systems flow, F, as measured by the change with normalized rapidity of the average transverse momentum, rises with energy, saturates, and then appears to decline. In general both models (BUU and RBUU) predict a similar energy dependence, with a decline of F at higher energies. Comparison of our flow results with flow data from other mass systems is made by introducing a scaled flow, $F_S = F/(A_1^{1/3} + A_2^{1/3})$ which exhibits a nearly universal flow energy dependence.

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*Present address: Loral Space Systems, Palo Alto, CA 94303.
†Present address: Sung Kwun Kwan University, Suwon, Republic of Korea 440-746.
‡Present address: Physics Department, St. Mary's College, Moraga, CA 94575.
§Present address: Physics Department, The Ohio State University, Columbus, OH 43210.
‖Present address: Nuclear Science Division, LBNL, Berkeley, CA 94720.
¶Present address: The Svedberg Laboratory, University of Uppsala, Uppsala, S751-21 Sweden.
**Present address: Physics Department, College of Wooster, Wooster, OH 44691.
‡‡Present address: Crump Institute for Biological Imaging, UCLA, Los Angeles, CA 91776.

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