

## Disappearance of Flow in Heavy-Ion Collisions

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We report the first observation of the disappearance of flow in heavy-ion collisions. This is accomplished by measuring the excitation function of the average in-plane transverse momentum for the symmetric system  $^{139}\text{La} + ^{139}\text{La}$ , using beam energies of 130, 70, and 50 MeV/nucleon. The observation is indicative of a change from dominantly repulsive to attractive scattering. We also present the results of calculations performed with the Boltzmann-Uehling-Uhlenbeck equation which support the concept of vanishing flow for this system in the energy region between 30 and 50 MeV/nucleon.

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Reaction dynamics in intermediate-energy heavy-ion collisions ( $E_{\text{lab}} = 20\text{--}1000$  MeV/nucleon) are sensitive to the attractive component of the nuclear mean field as well as to a repulsive component characteristic of individual nucleon-nucleon interactions and compressed nuclear matter. At incident energies around 35 MeV/nucleon, calculations<sup>1-3</sup> with the Boltzmann-Uehling-Uhlenbeck (BUU) model as well as measurements of polarization<sup>4</sup> demonstrate that light fragments are emitted preferentially to negative scattering angles indicative of the dominance of the attractive part of the nuclear mean field. At energies around 800 MeV/nucleon, BUU calculations predict a positive scattering angle<sup>1-3</sup> and strong energy-momentum flow is observed experimentally.<sup>5</sup> Flow has been defined as either the slope of the average in-plane transverse momentum at midrapidity, or the mean value of the in-plane transverse momentum near the projectile rapidity. In this Letter we report the observation of the disappearance of flow for the  $^{139}\text{La} + ^{139}\text{La}$  system at an incident energy of around 50 MeV/nucleon, which corresponds to the energy at which the reaction mechanism changes from repulsive to attractive scattering. Calculations with the BUU model including a momentum-dependent potential<sup>6</sup> reproduce the energy at which the flow becomes zero.

The standard definition<sup>7,8</sup> of the in-plane transverse-momentum observable is

$$p_i^x = \frac{\mathbf{p}_i^+ \cdot \mathbf{Q}^i}{|\mathbf{Q}^i|}, \quad (1)$$

in which  $p_i^x$  is the transverse momentum in the reaction plane,  $\mathbf{p}_i^+$  is the momentum component of fragment  $i$  perpendicular to the beam direction, and  $\mathbf{Q}^i$  is a vector

which characterizes the reaction plane.  $\mathbf{Q}^i$  is defined as

$$\mathbf{Q}^i = \sum_{j \neq i}^M \omega_j \mathbf{p}_j^+ . \quad (2)$$

Here,  $\omega_j$  is a weighting factor chosen to be  $+A_j$  for fragments in the forward hemisphere of the center-of-mass system and  $-A_j$  for those fragments in the backward hemisphere, where  $A_j$  is the mass number of the  $j$ th fragment. This weighting reflects the observed<sup>9</sup> larger values of transverse momentum per nucleon for heavier fragments when compared to lighter fragments. Fragment  $i$  is removed from the summation in Eq. (2) in order to eliminate self-correlation effects. The average in-plane transverse momentum per nucleon ( $\langle p^x/A \rangle$ ) as function of center-of-mass rapidity can be calculated using Eqs. (1) and (2). Because of the definition of the observable in Eq. (1) and the weighting factor in Eq. (2),  $\langle p^x/A \rangle$  in the forward hemisphere is always greater than or equal to zero. Therefore, as the beam velocity falls, the predicted change from dominantly repulsive to dominantly attractive scattering would appear at that beam velocity where one measures a value of zero for  $\langle p^x/A \rangle$  near the projectile rapidity. Such an effect is described as the disappearance of flow.

The experimental work was performed at the Lawrence Berkeley Laboratory Streamer Chamber Facility.<sup>10</sup> Using the Bevalac, central collisions of  $^{139}\text{La} + ^{139}\text{La}$  at 130, 70, and 50 MeV/nucleon were recorded in digitized photographs using the Michigan State University charge-coupled device (CCD) camera system.<sup>11</sup> The images were processed using digital-image-enhancement techniques and completely automated track finding, prematching, three-dimensional track

reconstruction, and particle-identification techniques.<sup>12</sup> These techniques were checked by a comparison to visually matched tracks and were found to have an efficiency of 80%–90% in properly identifying, matching, and reconstructing fragment tracks for events in which the charged-fragment multiplicity was between 20 and 50. The efficiency was almost 100% for those events with lower multiplicities. Mean multiplicities of the reconstructed fragment tracks were 18, 22, and 25 for the beam energies of 50, 70, and 130 MeV/nucleon, respectively. Average light intensity values recorded along the fragment tracks and the deduced rigidities were used to identify the fragment masses. The reaction plane, characterized in Eq. (2), was found on an event-by-event basis using the fragments of mass one through four. Helium-3 and tritons were separated by assuming that only the most rigid mass-three fragments were tritons. This corresponded to assigning tritons to those mass-three fragments with rigidities  $\rho \geq 750$  MeV/c. The data sets consisted of 367 events at 130 MeV/nucleon, 946 events at 70 MeV/nucleon, and 177 events at 50 MeV/nucleon collected using a central-collision trigger. Transverse momentum as defined above is suited to handle such relatively small data sets because Eqs. (1) and (2) are summed initially over individual particles and then averaged over all events.

Spectra of  $\langle p^x/A \rangle$  as a function of center-of-mass rapidity were deduced using the transverse-momentum contributions from protons through helium-4 fragments, and the results are presented in Fig. 1. These curves are asymmetric about midrapidity due to low energy detector thresholds and inefficiencies in the automated analysis software. The software inefficiencies are most evident for very heavily ionizing fragments that result in the production of very short tracks in the CCD image. Generally, such short tracks could not be easily recognized by the automated analysis software because of the high density of tracks in the region close to the target. This was true regardless of the short tracks' direction of

emission from the collision. A correction to the data points in Fig. 1 was made as detailed by Danielewicz *et al.*<sup>7</sup> to account for a drop in detection efficiency for all charged fragments emitted at azimuthal angles towards and away from the CCD cameras. These corrections represented a 10%–15% reduction in the magnitudes of the  $\langle p^x/A \rangle$  values for each rapidity bin. A single quantity to extract from these distributions is the plateau  $[\langle p^x/A \rangle]_m$  or the flow, defined in this work as the weighted mean of all  $\langle p^x/A \rangle$  values for the data bins in the region of the projectile rapidity.

The following values of the flow were extracted: At  $E_{\text{lab}} = 130$  MeV/nucleon,  $[\langle p^x/A \rangle]_m = 8.0 \pm 3.8$  MeV/c; at 70 MeV/nucleon,  $[\langle p^x/A \rangle]_m = 2.4^{+1.7}_{-2.2}$  MeV/c; and at 50 MeV/nucleon,  $[\langle p^x/A \rangle]_m = 0.7 \pm 3.1$  MeV/c. Quoted errors for these flow values include the effect of systematic uncertainties due to fragment misidentification as well as statistical error. The observed decrease in  $[\langle p^x/A \rangle]_m$  as the beam energy is lowered is qualitatively consistent with the original prediction by Molitoris, Hahn, and Stöcker<sup>1</sup> of the behavior of the transverse-momentum excitation function at intermediate energies. It should be noted that these  $[\langle p^x/A \rangle]_m$  values were obtained using the experimentally determined reaction plane for each event. In principle,<sup>8</sup> a renormalization for the actual reaction plane may be deduced by dividing each event into a pair of subevents. The reaction planes would then be determined separately for each subevent, with their angular difference representing a measure of the deviation between the found and actual reaction planes.<sup>8</sup> We find that when the transverse-momentum signal is small, as in the present data, this procedure does not yield a clearly defined deviation angle from the actual reaction plane. Consequently, we present only the unrenormalized values of the in-plane transverse momentum per nucleon.

Only one other transverse-momentum-analysis data point exists in the literature for the  $^{139}\text{La} + ^{139}\text{La}$  system. That point was obtained at a beam energy of 800 MeV/

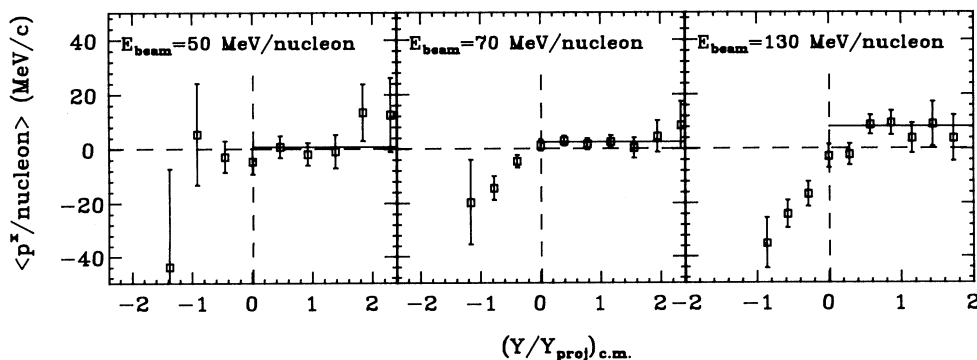


FIG. 1. The average in-plane transverse momentum as a function of center-of-mass rapidity for the beam energies of 50, 70, and 130 MeV/nucleon. The error bars are statistical. The solid lines indicate the average in-plane transverse momentum near the projectile rapidity.

nucleon, where the average transverse momentum per nucleon was found to be larger ( $72 \pm 6$  MeV/c) than that obtained at the present energies.

We have performed theoretical calculations to determine if our experimental findings are supported by nuclear transport theory. To do this we used a version of the program solving the BUU equation described in the paper by Gale *et al.*<sup>6</sup> This program includes a momentum-dependent potential that closely models realistic nuclear matter interactions and which yields a nuclear equation of state with an incompressibility of  $K = 215$  MeV. It was successfully used<sup>6</sup> in reproducing the 800-MeV/nucleon streamer-chamber data of Ref. 7. Since a central trigger was used for obtaining the experimental data, we performed the calculations at a fixed impact parameter of  $b = 2$  fm. This corresponds to an average impact parameter for the innermost 5%–6% of the total geometric cross section.

Our findings are summarized in Fig. 2. Here we display the theoretical calculations (open circles) for the average value of  $p^x$  weighted by  $\Omega = +1$  or  $-1$  corresponding to fragments emitted into the forward or backward hemisphere, respectively. This weighting for the calculations is appropriate since the BUU is a theory for the one-body density and does not include composite fragments. The calculated flow disappears and changes sign between the beam energies of 30 and 50 MeV/nucleon in the  $^{139}\text{La} + ^{139}\text{La}$  system. The statistical errors in the predictions at each energy are on the order of 1 MeV/c.

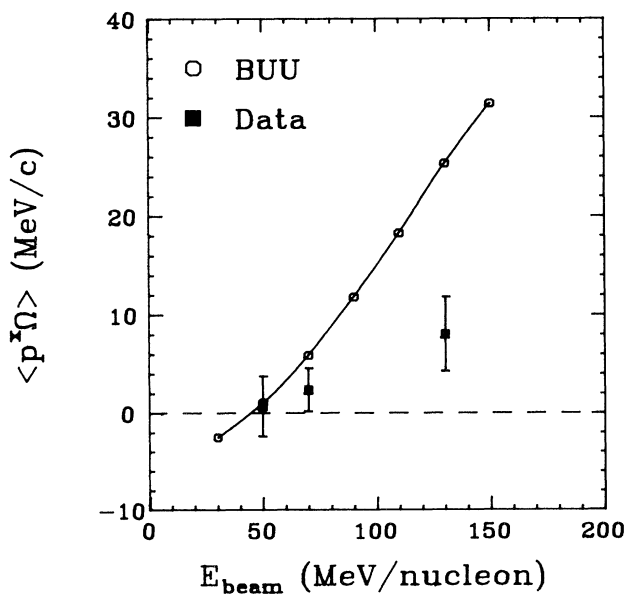


FIG. 2. Comparison of the theoretical calculations for the excitation function of the average in-plane transverse momentum (open circles) with the experimental data for the  $^{139}\text{La} + ^{139}\text{La}$  system. The solid line is drawn to guide the eye.

For comparison, the filled squares correspond to the average value of  $[\langle p^x/A \rangle]_m$  extracted from the data. It can be seen that data and calculations indicate the disappearance of flow at roughly the same beam energy. The fact that the data are about a factor of 2–3 below the calculations can be partly ascribed to the fact that the data are not corrected for the dispersion of the found reaction plane about the true reaction plane. To obtain a better comparison between data and experiment, one has to subject the results of the calculations to the same acceptance filters as the experimental data. However, since the theory is only able to describe the time evolution of the one-body density distribution, the formation of complex fragments is not included in it. It is for this reason that we cannot subject the theoretical results to the experimental acceptance filters (which depend on the fragment mass) without further model assumptions. We know that filtering the theoretical results will only result in a less steep curve in Fig. 2, but will not change the intersection point of it with the zero axis. We have also made another set of exploratory calculations for the same system, but using a momentum-independent equation of state with a compressibility of 240 MeV. Here we find that the point of vanishing flow is reached at a beam energy of 65 MeV/nucleon, thus establishing the sensitivity of the point of vanishing flow to the parameters of the equation of state.

In summary, we have obtained a portion of the excitation function of the average in-plane transverse momentum for the  $^{139}\text{La} + ^{139}\text{La}$  system. The measured flow is found to decrease to a value consistent with zero near a beam energy of 50 MeV/nucleon. Results of nuclear-transport-theory calculations performed with the Boltzmann-Uehling-Uhlenbeck equation indicate that the flow for this system should reach zero in the beam energy range between 30 and 50 MeV/nucleon. These findings can be interpreted as the signature of a change from repulsive to attractive scattering.

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