

Disappearance of flow and its relevance to nuclear matter physics

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Light charged fragments from the reaction $^{40}\text{Ar}+^{51}\text{V}$ at 35–85 MeV/nucleon in 10 MeV/nucleon steps have been measured with a 4π detector. The observed transverse collective momentum in central collisions decreases monotonically from 45 to 85 MeV/nucleon. The data are interpreted assuming that the attractive mean field deflects the fragments to negative scattering angles. As the beam energy is raised, the attractive scattering is opposed by the buildup of compressed nuclear matter. A lower limit of 76 MeV/nucleon is placed on the beam energy where the attractive deflection is balanced by the repulsive side-splash mechanism. The results are compared to theoretical predictions and it is demonstrated that the predictions are sensitive to two aspects of nuclear matter physics: the in-medium nucleon-nucleon cross section and the nuclear compressibility.

Recently Krofcheck *et al.*¹ reported the disappearance of transverse momentum flow in an excitation function of La+La collisions at intermediate energies. At high beam energies, the observed collective motion^{2,3} is thought to be generated by compressed nuclear matter that was formed in the early stages of the reaction. This directed collective motion, or side splash, corresponds to repulsive scattering of the fragments. Directed collective motion occurs when the transverse momentum is of the opposite direction for fragments emitted in the forward and backward center-of-mass hemispheres. At lower beam energies, directed collective motion was also predicted^{4,5} and has recently been observed at 35 MeV/nucleon for Ar+V reactions.⁶ The collective motion at these energies is explained by the attractive mean field which deflects the fragments to negative scattering angles.⁷ The balancing between these two dynamic effects, i.e., the disappearance of flow, may elucidate the role of compression in these collisions.

The advantage of this approach is that the determination of the beam energy at which the balance occurs, E_{bal} , can be directly compared to the results of microscopic transport models. The measurement of zero collective motion removes the need to correct for the dispersion of the found reaction plane with respect to the true reaction plane. There is also no need to impose experimental biases on the theoretical calculation and, in addition, the theory's lack of fragment formation should not complicate the comparison to experiment. The assumptions behind this will be discussed later, but it should be noted that all the above complications affect the magnitude of finite collective motion and hence make it difficult to compare finite collective motion to theory.

It has been shown⁵ that the value of the nuclear compressibility (K) and the in-medium nucleon-nucleon cross section both affect the buildup of compression in this beam-energy range. There is considerable discussion in the literature on the value of the compressibility. Some authors favor $K \sim 150$ MeV,⁸ while others suggest $K \sim 300$ MeV.⁹ Similarly, it is not clear¹⁰ how the in-

medium cross section differs from the free nucleon-nucleon cross section.

In this Rapid Communication we report on the experimental measurement of E_{bal} for $^{40}\text{Ar}+^{51}\text{V}$ and then investigate whether this can be used to provide information on the in-medium cross section and the nuclear compressibility.

We have measured light charged fragments from the reactions $^{40}\text{Ar}+^{51}\text{V}$ at 35 to 85 MeV/nucleon in 10 MeV/nucleon steps with Phase I of the Michigan State University 4π Array.¹¹ The target was 3 mg/cm² and the beams were provided by the K500 and K1200 cyclotrons of the National Superconducting Cyclotron Laboratory. The Phase I configuration of the 4π Array contains phoswich detectors only and for beam energies above 45 MeV/nucleon their gains were set to measure fragments with $Z \leq 16$ between 7° and 20° and $Z \leq 4$ at more backward angles. Isotopic identification was obtained for $Z = 1$ fragments between 20° and 160° . The phoswiches were calibrated by matching their response to previously obtained spectra of momentum-analyzed fragments. This procedure has an estimated relative uncertainty of $\pm 10\%$ and an absolute uncertainty of $\pm 15\%$. Full details of the gains for the 35 MeV/nucleon beam and of the energy thresholds and angular coverage common throughout this experiment are given in Ref. 6.

Central collisions were selected from the data set using the measured midrapidity charge (Z_{mr}) as an impact parameter filter,¹² where Z_{mr} is the sum of the charges of those fragments that fall within the rapidity window $0.75y_t \leq y \leq 0.75y_p$. The symbol y represents the fragment's rapidity in the center-of-mass frame and y_t and y_p refer to the rapidity of the target and projectile, respectively. The central gates are $Z_{\text{mr}} \geq 13$ for the 35 and 45 MeV/nucleon reactions, and $Z_{\text{mr}} \geq 14$ for the 55–85 MeV/nucleon reactions. It is estimated by the methods of Ref. 12 that these gates select events corresponding to a mean impact parameter of 30% of the maximum impact parameter.

A new technique for obtaining the reaction plane has recently been outlined by Wilson *et al.*¹³ This method utilizes the presence of both rotational and directed collective motion in the reaction plane. The angle ϕ_i^{RP} of the estimated reaction plane for each particle i in an event of N particles is found by minimizing the perpendicular distance between a straight line through the origin ($p^x = p^y = 0$) and the set of points $[(p_j^x, p_j^y), j \neq i, j \in N]$. In this notation $\mathbf{p}_j^\perp = (p_j^x, p_j^y)$ is the perpendicular momentum of the fragment j and p_j^z is the momentum along the beam axis. We require that $N \geq 3$. The sense of this line is determined by its proximity to the vector \mathbf{Q} , where

$$\mathbf{Q} = \sum_{j \neq i} \omega_j \mathbf{p}_j^\perp, \quad \omega_j = \frac{p_j^z}{|p_j^z|}. \quad (1)$$

The in-plane transverse momentum ($p_i^{x'}$) of fragment i is then

$$p_i^{x'} = p_i^x \cos(\phi_i^{\text{RP}}) + p_i^y \sin(\phi_i^{\text{RP}}). \quad (2)$$

The traditional technique,² involving only \mathbf{Q} , has the disadvantage in that it is only sensitive to directed collective motion in the reaction plane. As in Ref. 6, the perpendicular momenta were rescaled to correct for the effects of momentum conservation. Note that this provides the minimum feasible correction. Throughout the rest of this paper $p^{x'}$ will be abbreviated by p^x .

The reaction plane found by this new technique was compared for each event to the azimuthal angle of \mathbf{Q} . The difference between these reaction planes forms a distribution that is peaked at 0° and has a half-width at half-maximum of 15° at 35 MeV/nucleon which increases to 20° at 85 MeV/nucleon. Another measure of the accuracy of the reaction plane technique is the resulting azimuthal angular distributions of the fragments. These distributions, which have been recently investigated by Wilson *et al.*¹³ peak at 0° and 180° with respect to the reaction plane. The half-width at half-maximum of these distributions provides an upper limit to the dispersion of the found reaction plane. The upper limit for the dispersion at 35 MeV/nucleon is 60° , which increases to 75° for 85 MeV/nucleon.

From the $p_i^{x'}$ values, we can calculate the ensemble averages $\langle p^x/p^\perp \rangle$ as a function of the center-of-mass rapidity y . This is the average fraction of a fragment's perpendicular momentum that lies within the reaction plane and a typical distribution is plotted in Fig. 1 for protons emitted at 45 MeV/nucleon. The characteristic signature of directed collective motion is observed; namely nonzero and opposite sign $\langle p^x/p^\perp \rangle$ in the forward and backward center-of-mass hemispheres. The lack of symmetry is thought to be due to the residual effects of momentum conservation and an effect due to the finite solid angle of each detector. As explained in Ref. 6, the constraint of momentum conservation displaces the $\langle p^x/p^\perp \rangle$ distribution by a small and negative amount. Since the displacement is expected to be uniform, this should not alter the slope of the distribution near $y=0$. The finite solid angle of each detector reduces the efficiency of finding the reaction plane near the particle of interest (i in the above example). This effect was simulated by taking random fragments from different events to create uncorrelated test

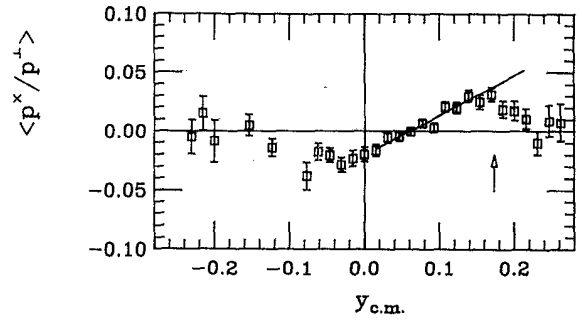


FIG. 1. The fraction of the fragment's in-plane transverse momentum for protons emitted from central Ar+V collisions at 45 MeV/nucleon. The line indicates the extracted reduced flow for this distribution and the arrow indicates the projectile rapidity.

events. When no more than one particle was allowed per detector, the test events produced a slightly negative distribution of $\langle p^x/p^\perp \rangle(y)$. Removing the above restraint, the test events produced a distribution that was consistent with zero for all values of rapidity. This effect was similar for all of the beam energies studied in this experiment.

To minimize the sensitivity to these two systematic effects, we extract the quantity $d\langle p^x/p^\perp \rangle/dy$, called the "reduced flow," which has been taken to be the average slope of $\langle p^x/p^\perp \rangle$ between $y=0$ and $y=0.8y_p$. The reduced flow is plotted in Fig. 2 for protons, deuterons, tritons, $Z=2$ and 3 fragments emitted in the reactions between 35 and 85 MeV/nucleon.

From Fig. 2 it is clear that, at a given energy, the collective motion increases with the mass of the emitted fragment. There is some evidence that the collective motion

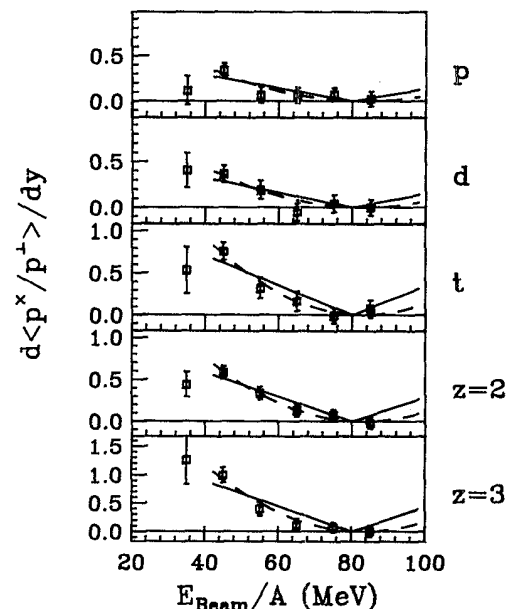


FIG. 2. The excitation functions of the measured reduced flow for different fragments emitted in Ar+V central collisions. The lines correspond to optimal fits for a given analytic form. Note that the vertical scale changes for the different fragments.

increases between the beam energies 35 and 45 MeV/nucleon. Above 45 MeV/nucleon there is a monotonic decrease of the measured collective motion. This is consistent with the dominance of attractive scattering at low energies, which at higher energies is in competition with the increasing role played by nucleon-nucleon collisions compressing the nuclear matter. The data do not exhibit evidence of a turn around in $d\langle p^x/p^+ \rangle/dy$, and hence we have not reached the energy domain where the repulsive side splash clearly dominates. However, because the observed collective motion is consistent with zero at the highest beam energies in Fig. 2, we can establish a lower limit on E_{bal} . The data indicates that E_{bal} may be the same for different fragments. This is a necessary condition before comparisons can be made with theoretical models that do not produce fragments.

The error on each datum in Fig. 2 comes from the extraction of the reduced flow and those systematic errors that are different for each beam energy. The latter have been found from different rapidity ranges for finding the slope of the $\langle p^x/p^+ \rangle$ distributions, alternative choices for the isotopic labeling of heavy fragments, and modifications to the correction for momentum conservation. The common systematic errors are small and do not contribute to the error in E_{bal} . The mean beam energy for each data point is approximately 0.1 MeV/nucleon below the nominal beam energy due to losses in the target. In principle, theoretical calculations should be averaged over this energy range, however the effect is expected to be negligible. There is a 1% relative uncertainty in each beam energy due to variations in the extraction from the cyclotrons and a 0.5% absolute energy uncertainty which is common throughout the experiment.

The reader is reminded that E_{bal} is different from the beam energy where the observed collective motion is first consistent with zero. In the extreme example of a measured excitation function resembling the shape of a flat-bottomed valley, E_{bal} would lie at approximately the middle of the flat-bottomed region. From the triton, $Z=2$ and 3 excitation functions in Fig. 2, there is still finite collective motion at 65 MeV/nucleon; therefore, E_{bal} must be above this energy. To provide a quantitative estimate of the lower limit of E_{bal} , we have fitted the data set (45–85 MeV/nucleon) in Fig. 2 with three types of analytic functions: triangular, parabolic, and a function representing one side of a flat-bottomed valley. For each functional form there is a common energy apex or origin and individual slope coefficients for each fragment type.

χ^2 is minimized for the triangular function when $E_{\text{bal}}=79$ MeV/nucleon and this fit is shown as solid lines in Fig. 2. The distribution of χ^2 for this analytic form as a function of the apex energy is shown as a solid line in Fig. 3. The slopes of the lines were reoptimized for each value of the apex energy. At the 65% and 90% confidence levels where χ^2 has increased by 1.0 and 2.71, $E_{\text{bal}} \geq 77$ MeV/nucleon and $E_{\text{bal}} \geq 76$ MeV/nucleon, respectively. Similar limits of 78 and 76 MeV/nucleon were placed using a parabolic function shown as dashed lines in Fig. 2. The distribution of χ^2 is shown in Fig. 3 as a dashed line. For the flat-bottomed valley, E_{bal} is taken to be midway between the energy at which the side of the valley begins

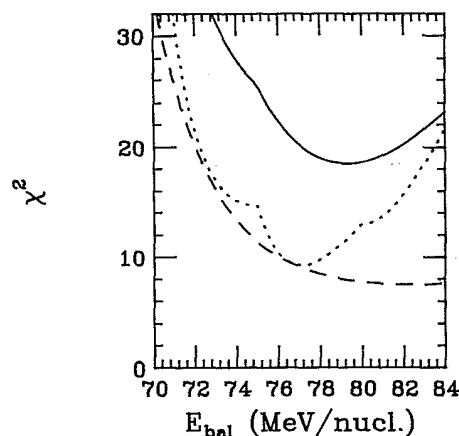


FIG. 3. Plots of the χ^2 distribution versus the E_{bal} used in the analytic fitting functions. The solid line is from the triangular function, the dashed line used the parabolic function, and the dotted line used the flat-bottomed valley function.

and 85 MeV/nucleon. The 65% and 90% confidence limits are 76 and 75 MeV/nucleon, while the χ^2 distribution for this function is shown as a dotted line in Fig. 3. Since these limits are approximately independent of the fitting function, we place an overall lower limit of $E_{\text{bal}} \geq 76$ MeV/nucleon. Apparently, the data do not extend into the region where the side-splash mechanism dominates, hence we cannot rely on the form of the analytic function to place an upper limit on E_{bal} .

One of the current theoretical models of nuclear collisions in this energy range is the Boltzmann-Uehling-Uhlenbeck (BUU) model. For a recent review the reader is referred to Bertsch and das Gupta.¹⁴ We have used this model to aid our understanding of the dynamics of the reactions, and to investigate whether the model may be used to determine either the in-medium nucleon-nucleon cross section or the nuclear compressibility from the measured values of E_{bal} . Before a detailed comparison to experiment can be made, a thorough theoretical study on the contribution of the nuclear surface needs to be conducted. Also, effects such as the Coulomb potential and the momentum dependence of the nuclear interaction need to be included. Note that the momentum dependence of the mean field is weaker for the range of momenta sampled in these reactions than for reactions at several hundred MeV/nucleon.

We have performed BUU calculations of $A=40$ on $A=51$ nuclei at an impact parameter of 2 fm for a range of bombarding energies. The nuclear mean field is parametrized by density-dependent Skyrme interaction. The in-medium nucleon-nucleon cross section (σ_{NN}) is taken to be a specified fraction of the free nucleon-nucleon cross section. For details on the values of the parameters the reader is referred to Ref. 14. Figure 4(a) shows the extracted reduced flow (taken with respect to the known reaction plane) for two different values of the nuclear compressibility (K). A lower value of K allows the system to compress more easily and hence the balance between attractive and repulsive forces occurs at a lower beam energy. The predicted collective motion between 20 and 50

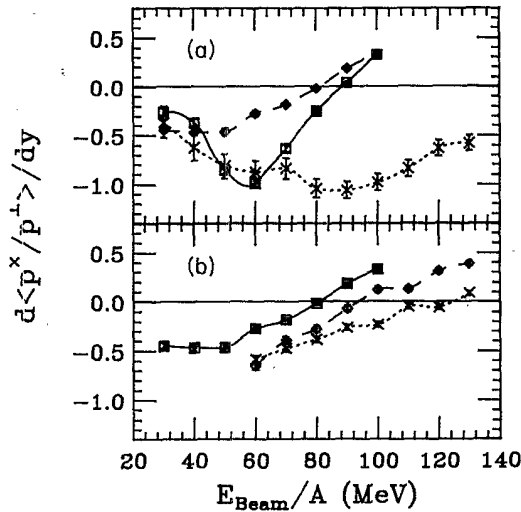


FIG. 4. The excitation functions for the calculated reduced flow from the BUU model for Ar+V collisions. (a) The dashed line corresponds to $K=200$ MeV, the solid line to $K=380$ MeV, while the dotted line corresponds to $K=380$ MeV with no nucleon-nucleon collisions. (b) The solid line corresponds to $K=200$ MeV with the in-medium cross section equal to the free cross section, the dashed line has had the cross section scaled by 0.9, while the dotted line has had the cross section scaled by 0.7.

MeV/nucleon remains either constant or increases depending on the value of the compressibility. It will be interesting to study this behavior with more complete calculations. If the collisions are turned off, the BUU model predicts the dotted curve shown in Fig. 4(a). This demonstrates that the effects of the attractive mean field are still significant at high beam energies and that, in the full calculation, it is the compression built up by the model's collision term that leads to the transition from attractive to repulsive scattering. In Fig. 4(b) we plot the extracted reduced flow for different values of $\sigma_{NN}/\sigma_{NN}^{free}$. It is clear that E_{bal} is strongly sensitive to the value of the cross section.

We have summarized the results of these and other calculations in Table I, where we list E_{bal} for different values of compressibility and in-medium nucleon-nucleon cross section. The entry in Table I that is labeled "Filtered," has had a low-energy threshold of 15 MeV and an angle cut of $\theta_{ab} \leq 5^\circ$ applied to the nucleons before the transverse momentum is calculated. The similarity of E_{bal} to that from the unfiltered calculation (also in Table I) is an indication that E_{bal} is independent of energy thresholds and angular ranges of the measurements. This makes it possible to compare directly theoretical and experimental

TABLE I. Calculated E_{bal} for Ar+V collisions with different parameter sets of the BUU model.

Calculation	K (MeV)	$\sigma_{NN}/\sigma_{NN}^{free}$	E_{bal} (MeV/nucleon)
	200	1.0	80
	380	1.0	88
	200	0.9	96
	200	0.8	108
	200	0.7	122
Filtered	380	1.0	87

values of E_{bal} without passing the theoretical results through an experimental filter.

In summary, we have determined a lower limit of $E_{bal} \geq 76$ MeV/nucleon for $^{40}\text{Ar}+^{51}\text{V}$ central collisions. There is some evidence that E_{bal} is independent of the mass of the measured fragment and that applying experimental cuts on theoretical calculations does not change the prediction of E_{bal} . Measuring zero collective motion also removes the need to take into account the dispersion of the estimated reaction plane from the true reaction plane. These three factors make it possible to compare directly the experimental measurement of E_{bal} to theoretical predictions.

Our theoretical studies indicate that E_{bal} is strongly dependent on the in-medium cross section and weakly dependent on the nuclear compressibility. Definitive constraints on these quantities must wait for both upper and lower limits on E_{bal} , for the inclusion of the Coulomb and momentum-dependent nuclear interactions in the theory, and for more theoretical work on the surface term in the nuclear interaction. To be useful the experimental determination of E_{bal} must be accurate to better than a few MeV/nucleon. The measurement of heavy fragments will improve the accuracy of E_{bal} because their collective motion grows most rapidly for beam energies near E_{bal} .

It is worth noting that Krofcheck *et al.*¹ measured $E_{bal} \leq 50$ MeV/nucleon for La+La collisions. It is possible that the measured mass dependence of E_{bal} may provide independent constraints on the values of the in-medium cross section and the nuclear compressibility.

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