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THE DISAPPEARANCE OF FLOW AND ITS RELEVANCE TO NUCLEAR MATTER PHYSICS

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Light charged fragments from the reaction ^{40}Ar+^{51}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 46 to 66 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 build-up 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 the predictions are sensitive to two aspects ofnuclear 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 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 shown[5] that the value of the nuclear compressibility (K) and the in-medium nucleon-nucleon cross section both affect the build-up 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 clear[10] how the in-medium cross section differs from the free nucleon-nucleon cross section.

In this Communication we report on the experimental measurement of E_{bal} for ^{40}Ar+^{51}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}Ar+^{51}V at 35 to 85 MeV/nucleon in 10 MeV/nucleon steps with Phase I of the MSU 4π Array.[11] The target was 3mg/cm^2 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$16 between 7^0 and 20^0 and Z$\leq$4 at more backward angles. Isotopic identification was obtained for Z=1 fragments between 20^0 and 160^0. The phoswiches were calibrated by matching their response to previously obtained spectra of momentum-analysed fragments. This procedure has an estimated relative uncertainty of ±10% and an absolute uncertainty of ±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 mid-rapidity-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 $Z_{mr} \geq 13$ for the 35 and 45 MeV/nucleon reactions, and $Z_{mr} \geq 14$ for the 55 to 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 **Q**, where

$$\mathbf{Q} = \sum_{j \neq i}^{N} \omega_j \mathbf{p}_j^{\perp} \quad , \quad \omega_j = \frac{p_j^z}{\mid p_j^z \mid}. \tag{1}$$

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

$$p_i^{x'} = p_i^x cos(\phi_i^{rp}) + p_i^y sin(\phi_i^{rp}) \tag{2}$$

The traditional technique,[2] involving only **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.

From the p_i^x values, we can calculate the ensemble averages $< p^x/p^{\perp} >$ 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 non-zero and opposite sign $< p^x/p^{\perp} >$ 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 $< p^x/p^{\perp} >$ 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 detecor 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 events. When no more than one particle was allowed per detector, the test events produced a slightly negative distribution of $< p^x/p^{\perp} > (y)$. 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 minimise the sensitivity to these two systematic effects, we extract the quantity $d < p^x/p^{\perp} > /dy$, called the 'flow', which has been taken to be the average slope of $< p^x/p^\perp >$ between $y = 0$ and $y = 0.8y_p$. The flow is plotted in Fig. 2 for protons, deuterons, tritons, Z=2 and Z=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 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 $d < p^x/p^\perp > /dy$, 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 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 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 $< p^x/p^\perp >$ 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 principal, 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 Z=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 function; 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.

Chi-squared (χ^2) is minimized for the triangular function when E_{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 re-optimised 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, $E_{bal} \geq 77$ MeV/nucleon and $E_{bal} \geq 76$ MeV/nucleon respectively. Similar limits of 78 MeV/nucleon 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 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 $E_{bal} \geq 76$ 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 parameterised by a 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 4a shows the extracted 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 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. 4a. 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. 4b we plot the extracted 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 1, where we list E_{bal} for different values of compressibility and in-medium nucleon-nucleon cross section. The entry in Table 1 that is labelled 'Filtered', has had a low-energy threshold of 15 MeV and an angle cut of $\theta_{lab} \leq 5^0$ applied to the nucleons before the transverse momentum is calculated. The similar E_{bal} to that from the unfiltered calculation (also in Table 1) 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 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 $^{40}Ar+^{51}V$ 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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TABLE I. Calculated E_{bal} for Ar+V collisions with different parameter sets of the BUU model.

Calculation	K (MeV)	$\frac{\sigma_{nn}}{\sigma_{nn}^{free}}$	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

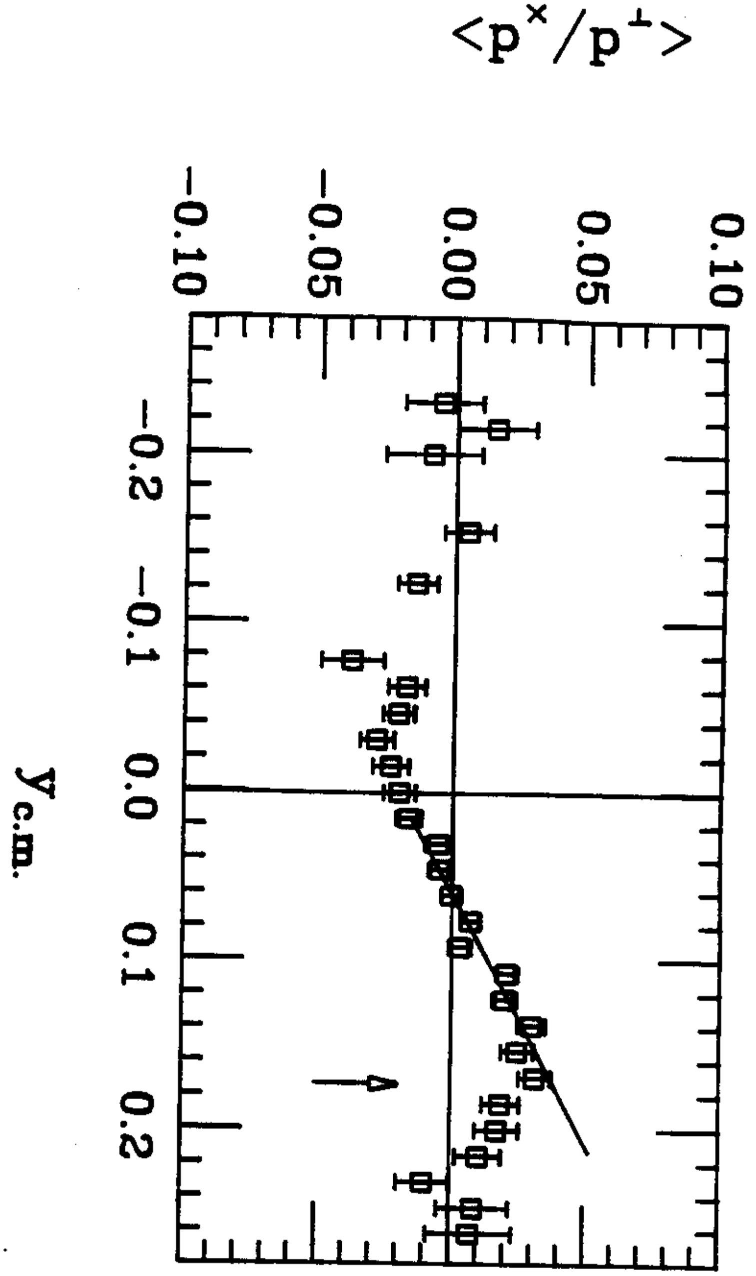

FIG. 1. The fraction of the fragment's in-plane transverse momentum for protons emitted from central Ar+V collisions at 45 MeV/nucleon. The line indicates the extracted flow for this distribution and the arrow indicates the projectile rapidity.

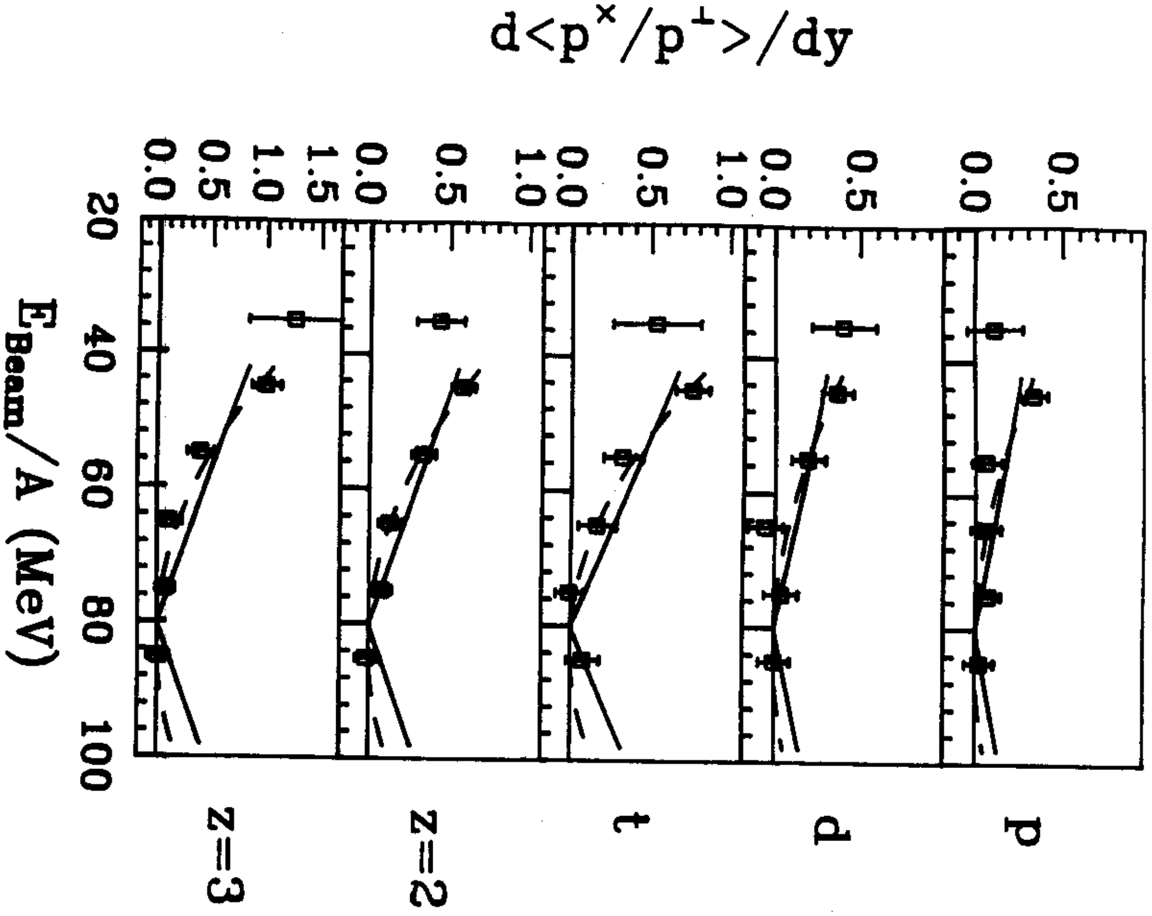

FIG. 2. The excitation functions of the measured flow for different fragments emitted in Ar+V central collisions. The lines correspond to optimal fits for a given analytic form. Note that the vertical scale changes for the different fragments.

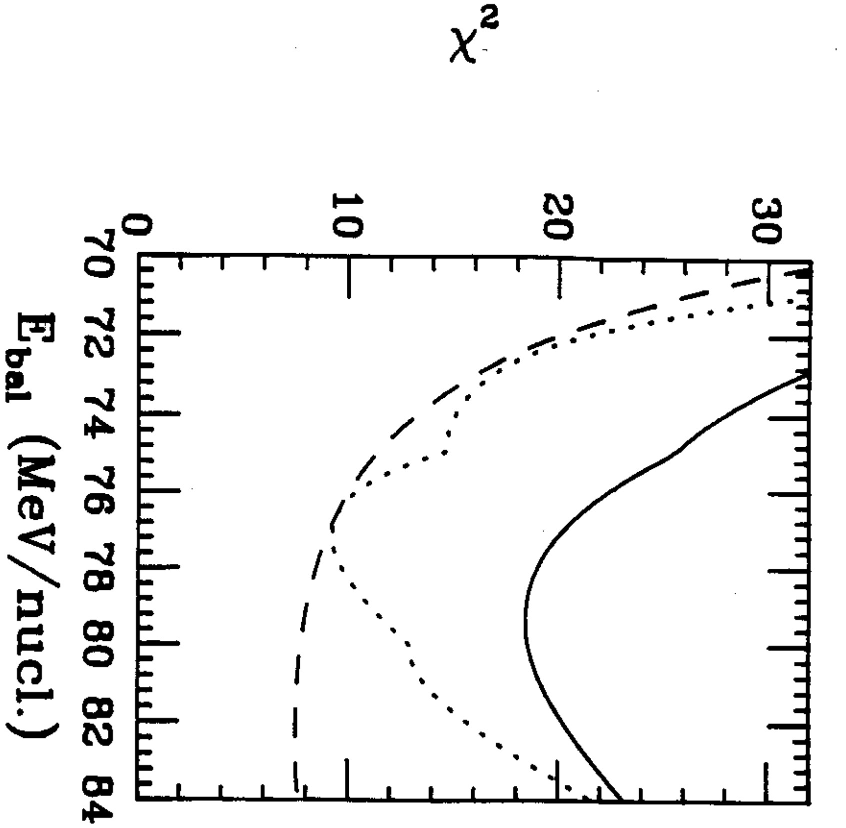

FIG. 3. Plots of the chi-squred distribution versus the E_{bal} used in the analytic fitting functions. The solid line is from the triangular function, the dashed line used the parabolic function, and the dotted line used the flat-bottomed valley function.

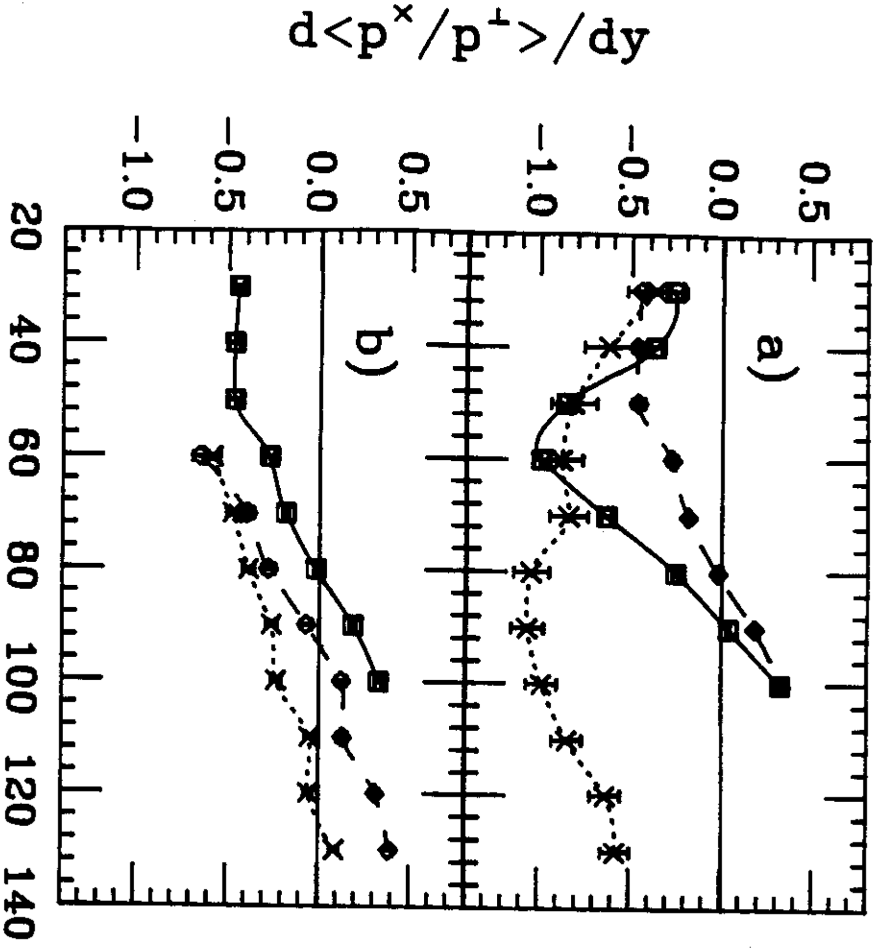

FIG. 4. The excitation functions for the calculated flow from the BUU model for Ar+V collisions. In Fig. 4a, the full line corresponds to K=200 MeV, the dashed line to K=380 MeV, while the dotted line to K=380 MeV with no nucleon-nucleon collisions. In Fig. 4b, the full line corresponds to K=200 MeV 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.

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

Calculation	K (MeV)	$\frac{\sigma_{nn}}{\sigma_{nn}^{free}}$	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

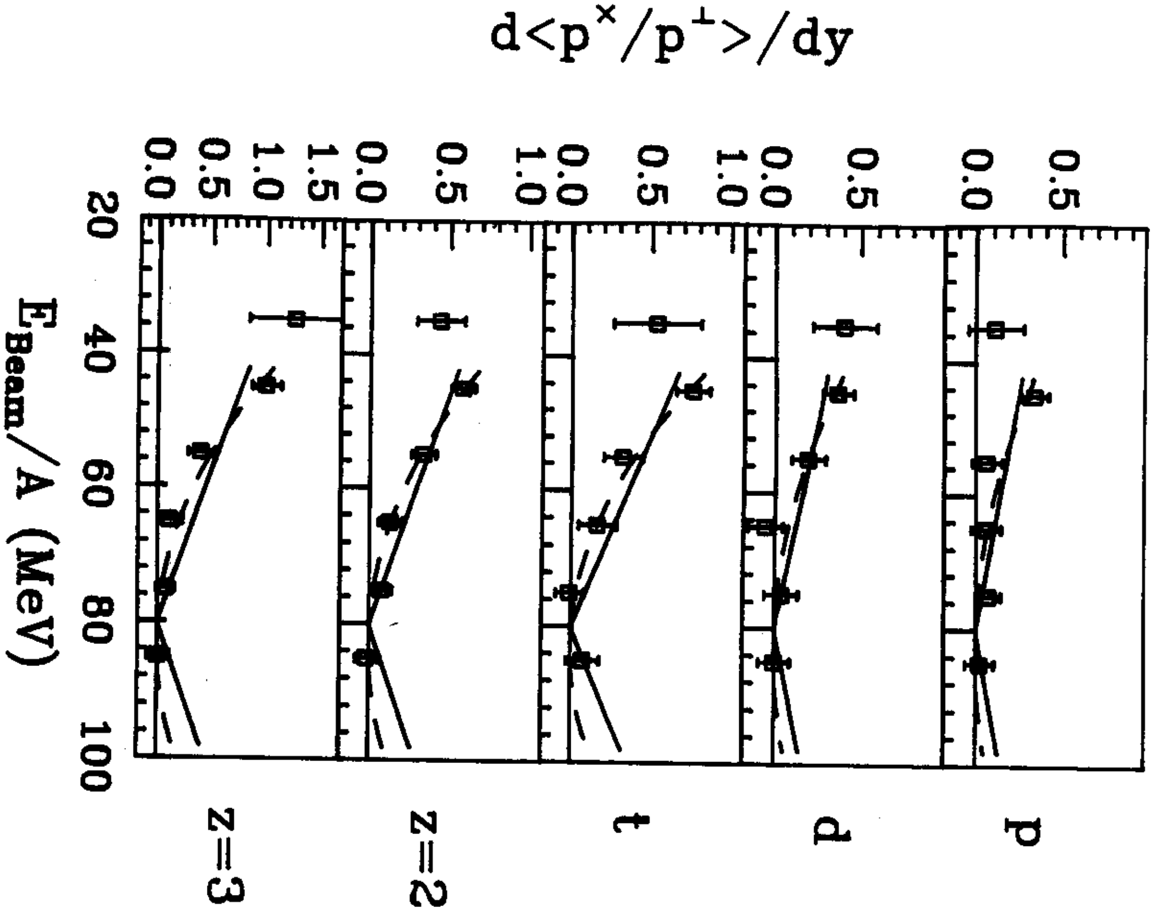

FIG. 2. The excitation functions of the measured flow for different fragments emitted in Ar+V central collisions. The lines correspond to optimal fits for a given analytic form. Note that the vertical scale changes for the different fragments.

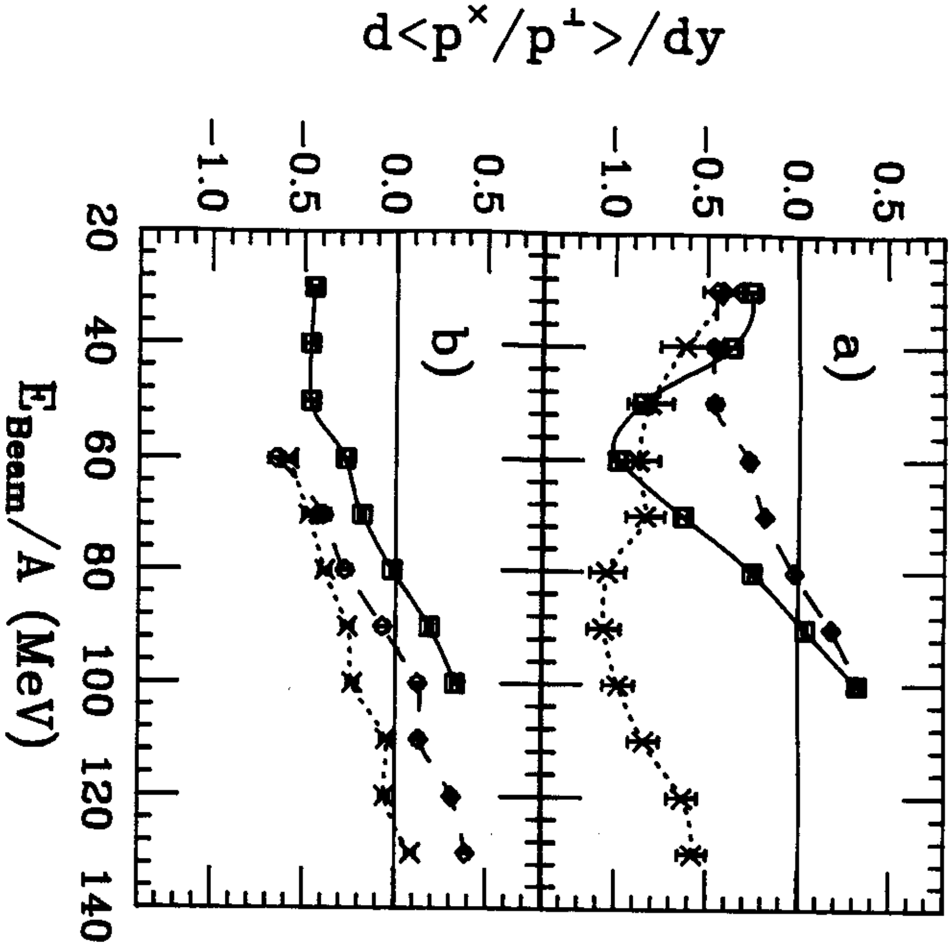

FIG. 4. The excitation functions for the calculated flow from the BUU model for Ar+V collisions. In Fig. 4a, the full line corresponds to K=200 MeV, the dashed line to K=380 MeV, while the dotted line to K=380 MeV with no nucleon-nucleon collisions. In Fig. 4b, the full line corresponds to K=200 MeV 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.