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Observation of a Minimum in Collective Flow for *AT* + *V* Collisions

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We have added a new measurement at 100 MeV/nucleon to our previous excitation function for collective flow of light fragments from $^{40}Ar + ^{51}V$ collisions. In the earlier work, flow decreased as the beam energy was raised from 46 to 86 MeV/nucleon. This provided hints to the disappearance of flow, but the lack of measurements at higher beam energies precluded the observation of the reappearance of flow. At a beam energy of 100 MeV/nucleon the flow has reappeared and this allows an experimental determination of the region where attractive scattering balances with repulsive scattering in these collisions. Assuming a parabolic line-shape for the measured flow excitation function, the balance energy is found to be 81 ± 6 MeV/nucleon for deuterons and 84 ± 7 MeV/nucleon for $Z = 2$ fragments.

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It is believed that the observation of collective flow produced by collisions between heavy-ions may provide a means to characterize the nuclear equation-of-state (EOS).[1] Collective flow occurs when the measured average in-plane transverse momentum is in opposite directions for nuclear fragments emitted in the forward and backward center-of-mass hemispheres. Earlier work[2,3] has shown that variations in flow as a function of beam energy reflect the competition between attractive and repulsive scatterings in the intermediate beam energy regime. The beam energy at which the strengths of these scatterings are approximately balanced (E_{bal}) can be predicted by calculations with the Boltzmann-Uehling-Uhlenbeck (BUU) model[4] which incorporate the EOS via the nuclear compressibility. This would permit a direct comparison to be made between the empirically determined balance energy and that predicted by different models of the EOS.

In our previous work[2], it was observed that the collective flow diminished towards zero for the $^{40}Ar +^{51} V$ system as the beam energy was increased from 45 to 85 MeV/nucleon. This allowed the determination of a lower limit of $E_{bal} > 76$ MeV/nucleon for the energy at which the repulsive and attractive scatterings are balanced for the $^{40}Ar +^{51} V$ system. We have extended that study to a higher beam energy in an attempt to define more accurately the balancing energy. In this work we report on the measurement of the average in-plane transverse momentum for the reaction $^{40}Ar +^{51} V$ at a beam energy of 100 MeV/nucleon.

The experiment was performed using a beam of $^{40}Ar^{16+}$ ions from the K1200 cyclotron of the National Superconducting Cyclotron Laboratory incident on a 3 mg/cm^2 vanadium target. Charged, light fragments were detected with the phase I configuration of the Michigan State University 4π array.[5] This configuration consists of 215 phoswich detectors; 45 in a forward array spanning laboratory polar angles of 7^o-20^o, and 170 in the main ball between 20^o-160^o. Together, the solid angle subtended by the detectors is 85% of 4π. Isotopic resolution for hydrogen was achieved in the main ball phoswich detectors and Z resolution was obtained for all detectors

Peripheral collisions were suppressed on the basis of the measured mid-rapidity charge[6] (Z_{mr}). The Z_{mr} gates used in this work are the same as those in our earlier work.[2] Also, as discussed in ref. 7 the components of the detected fragment momentum vectors perpendicular to the beam direction were rescaled to correct for momentum conservation effects. Reaction planes were then determined for each central collision using a method developed by Wilson et al.[8] based upon the original Q-vector technique of Danielewicz and Odyniec.[9] The data were analyzed by first determining the average value of the fraction of a fragment's in-plane (p^x) to total ($p^\perp$) transverse momentum yielding $< p^x/p^\perp >$ as a function of y, the fragment's center of mass rapidity. We define the reduced flow to be $d < p^x/p^\perp > /dy$ in the region

$0 < y_{cm} < 0.8 y_{proj}$ where y_{cm} is the rapidity of the fragment in the center-of-mass, and y_{proj} is the center-of-mass projectile rapidity.

The flow at E=100 MeV/nucleon was extracted for p, d, t, $Z = 2$ and $Z = 3$ fragments and is presented in Figs. 1-5 along with the lower beam energy measurements of the flow excitation functions from our previous work.[2] For the deuterons and $Z = 2$ fragments the flow reappears at the highest beam energy. This phenomenon is expected because the empirical definition of the in-plane transverse momentum cannot distinguish between attractive and repulsive reaction mechanisms.[10] At lower beam energies, e.g. 35 MeV/nucleon, the non-zero flow is attributed to mainly attractive scatterings.[11] As the beam energy is raised from 45 to 85 MeV/nucleon, attractive scattering of fragments may become balanced by the buildup of pressure in the target and projectile overlap region and the increasing importance of individual N-N scatterings.[3] The result is the gradual disappearance of flow. At beam energies near 100 MeV/nucleon, the repulsive scattering dominates and directed, collective motion away from the interaction region occurs, resulting in the reappearance of flow. The flow excitation functions for p, t and $Z = 3$ do not show a clear non-zero flow at 100 MeV/nucleon. However, the estimated uncertainties in the data points do not rule out the reappearance of flow at this beam energy. The small magnitude of flow observed at 100 MeV/nucleon indicates that repulsive scattering does not strongly dominate the reaction mechanism.

The observation of the reappearance of flow in deuterons and $Z = 2$ fragments permits the extraction of an estimated E_{bal} energy for the $^{40}Ar + ^{51}V$ system. Assuming a parabolic form of the fitting function, a least-squares fit to the data yields the dashed curves in Fig. 2 and Fig. 4. E_{bal} is taken as the ordinate of the minimum point of the fitted parabola. The offsets of these minima from the flow zero-lines can be attributed to the finite detector sizes and to the slight influence of impact-parameter averaging over the Z_{mr} gates. It is found that for deuterons $E_{bal} = (81 \pm 6)$ MeV/nucleon and for $Z = 2$ $E_{bal} = (84 \pm 7)$ MeV/nucleon. The errors arise from statistical limitations of the fractional in-plane transverse momentum data, changes in the boundries of the rapidity region over which flow is defined, and from variations in the assumed analytical form of the fitting function. These results are consistent with the notion that the flow observed for different fragment types may exhibit similar E_{bal} values.[2] This is an important consideration if one wishes to compare empirical E_{bal} values with theoretical predictions based upon models which do not include a clustering mechanism.

We have measured the reduced flow as a function of rapidity for light fragments from collsions of $^{40}Ar + ^{51}V$ at a beam energy of 100 MeV/nucleon. Previously we have reported that collective flow seems to disappear at an incident energy above

76 MeV/nucleon[2] from measurements of collective flow using 35 to 85 MeV/nucleon $^{40}Ar +^{51} V$ data. In that work the flow was observed to decrease towards zero as the beam energy was increased from 45 to 85 MeV/nucleon. The energy at which collective flow is consistent with zero indicates the region where attractive scattering, dominant at low incident energies, is becoming balanced by the repulsive scattering observed at high energies. The point at which the the two types of scattering mechanisms are balanced (E_{bal}) may be understood as the energy at which there is a change in sign of the scattering angle. At 100 MeV/nucleon there is clear evidence for the reemergence of collective flow for deuterons and $Z = 2$ fragments in the $^{40}Ar +^{51} V$ system. The observation of a clear signal for flow enables us to determine E_{bal} for this system rather than set a lower limit as was possible with our previous data.

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FIGURE CAPTIONS

1) Reduced flow excitation function for protons from the $^{40}Ar +^{51} V$ reaction. The error bars are from two sources; (a)statistical accuracy of determining the slope of a line through the forward hemisphere fractional in-plane transverse momentum data, and (b)variations in the rapidity region used in fitting the straight line.

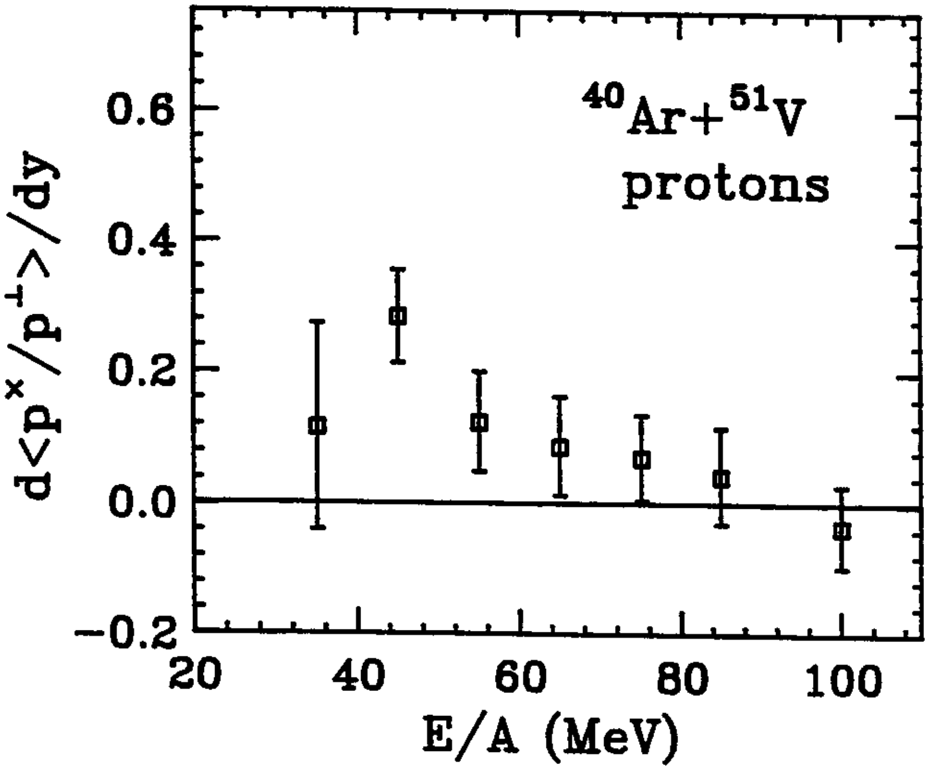
2) Reduced flow excitation function for deuterons from the $^{40}Ar +^{51} V$ reaction. The dashed line represents the results of a least squares fit of a parabola through the data points. E_{bal} is taken to be the ordinate at the minimum point on the fitted parabola.

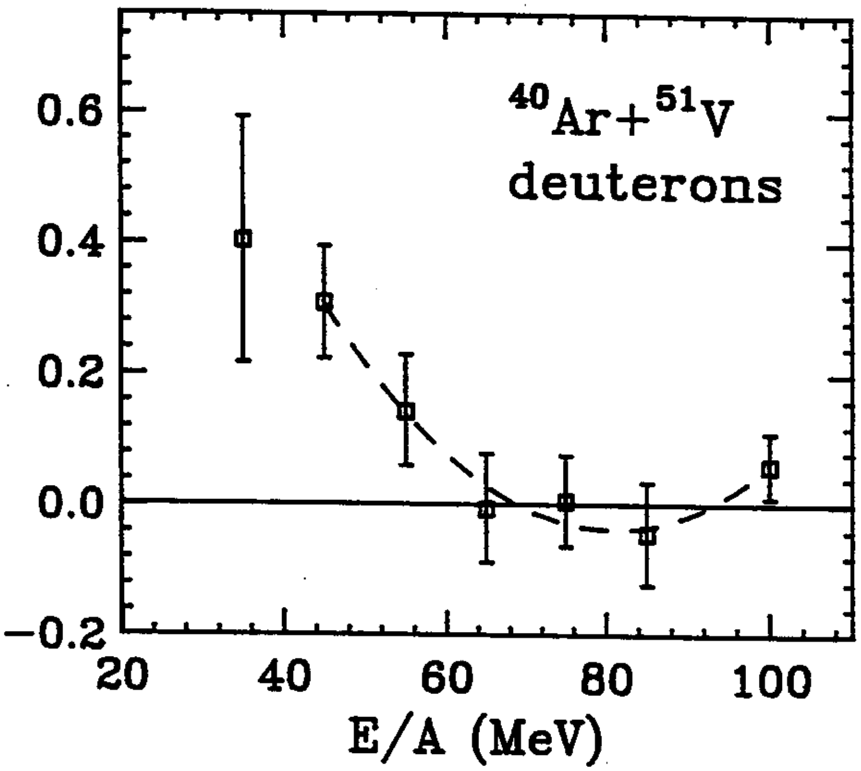
3) Same as in Fig. 1 except for tritons.

4) Same as in Fig. 2 except for $Z = 2$ fragments.

5) Same as in Fig. 1 except for $Z = 3$ fragments.

Fig 1




^{40}Ar+^{51}V
deuterons
d<p^x/p$^\perp$>/dy
0.6
0.4
0.2
0.0
−0.2
20
40
60
80
100
E/A (MeV)

[illegible]

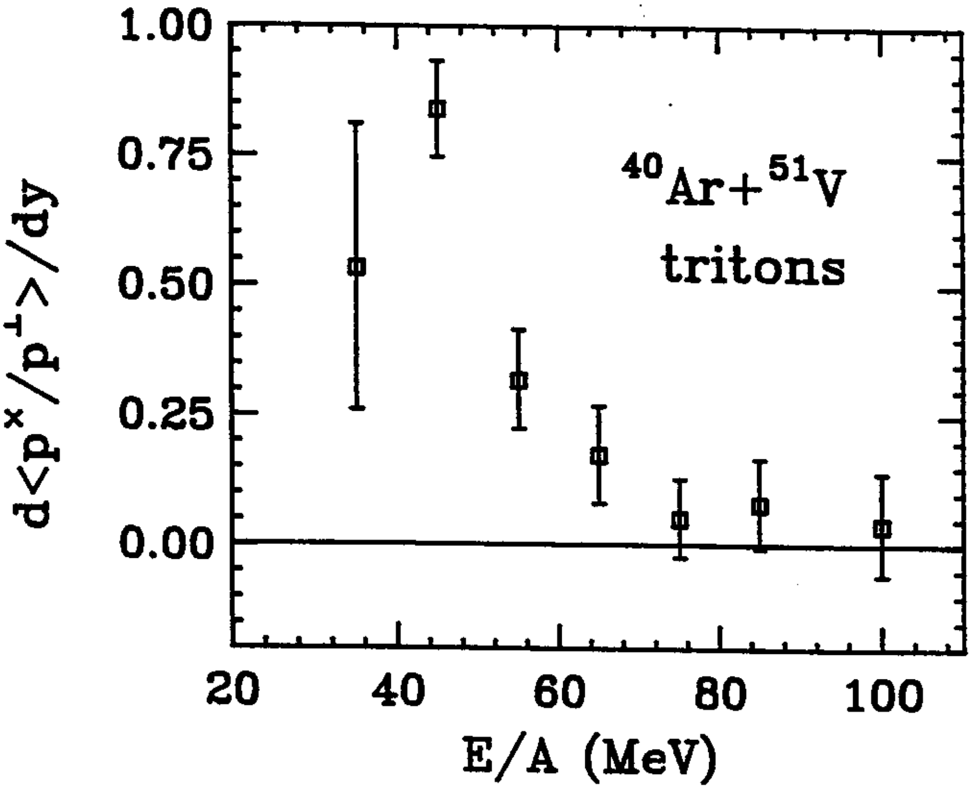

1.00
0.75
0.50
0.25
0.00
$d\langle p^x/p^\perp\rangle/dy$
^{40}Ar+^{51}V
tritons
20
40
60
80
100
E/A (MeV)

Fig 7

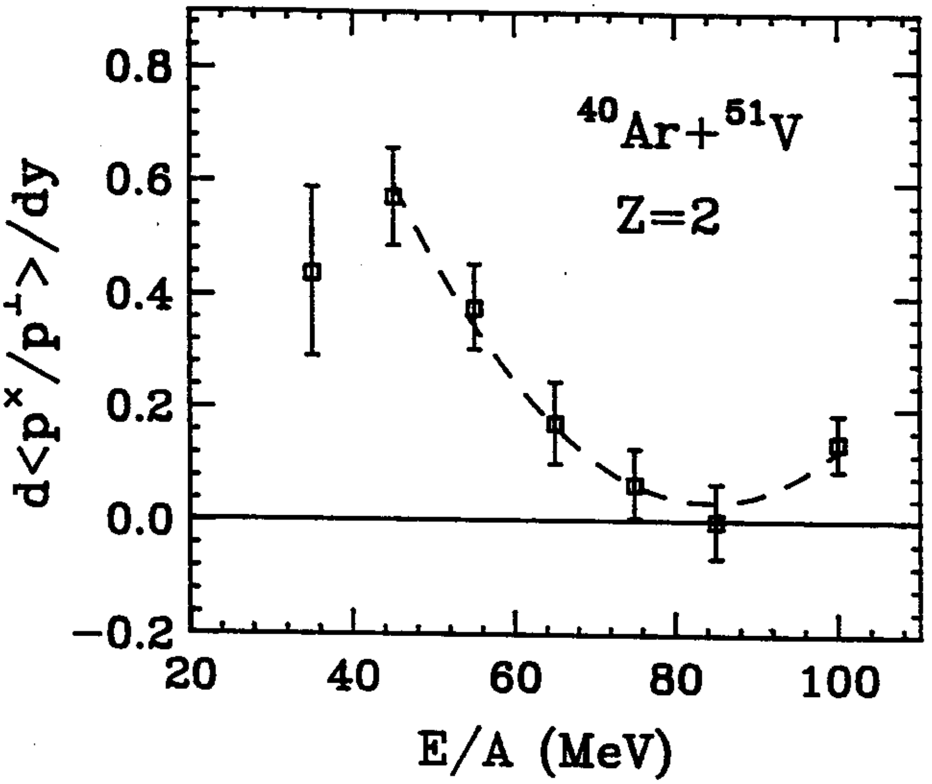


Fig 5