MICHIGAN STATE UNIVERSITY

CYCLOTRON LABORATORY

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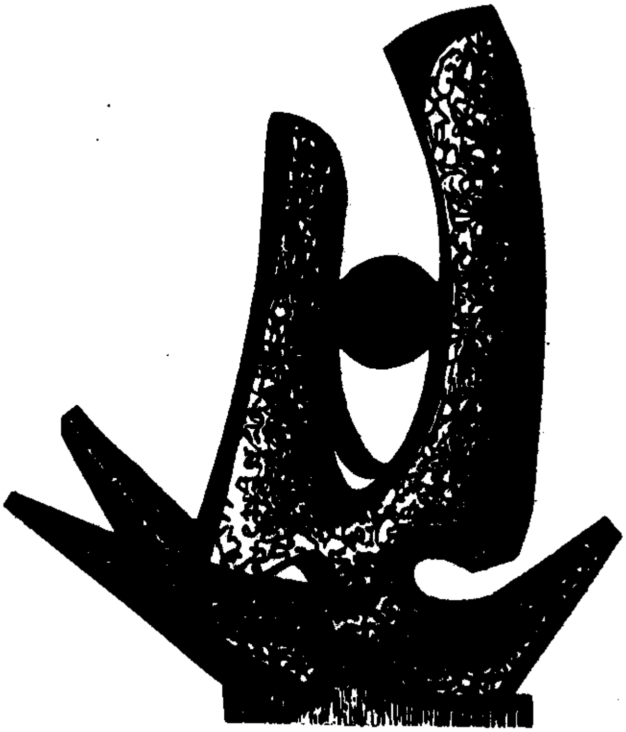
W.K. WILSON, W. BENENSON, D.A. CEBRA, J.CLAYTON,
S. HOWDEN, J. KARN, T. LI, A. VANDER MOLEN,
G.D. WESTFALL, J.S. WINFIELD, B. YOUNG,
A. NADASEN, and C.A. OGILVIE



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W.K. Wilson, W. Benenson, D.A. Cebrs, J. Clayton,

S. Howden, J. Karn, T. Li, A. Vander Molen,

G.D. Westfall, J.S. Winfield,

and B. Young
*National Superconducting Cyclotron Laboratory and*
*Department of Physics and Astronomy*
Michigan *State* University, *East Lansing, MI 48824-1321, USA*

A. Nadasen
*Department of Physics*
University of Michigan *at Dearborn, Dearborn, MI 48128, USA*

C.A. Ogilvie
*Gesselschaft fur Schwerionenforschung*
*D-t 600 Darmstadt*
*Fed. Rep. Germany*

Azimuthal distributions of fragments with respect to the reaction plane are studied in the Ar+V system as a function of beam energy. Light charged particles are found to exhibit an enhanced emission in the reaction plane which increases with the mass of the detected particle. As the beam energy is increased, the asymmetry decreases. Possible mechanisms behind the asymmetry, such as rotational collective motion and directed transverse momentum, are discussed.

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Heavy ion reactions at incident energies ranging from the Fermi energy to around E/A=100 MeV are important in the study of nuclear matter because it is believed that the mean field interaction changes from attractive to repulsive in this region. In order to draw conclusions about nuclear matter in this energy regime, it is important to understand the dynamics of the reactions. Azimuthal distributions have proved useful in the study of reaction dynamics because of their sensitivity to collective motion.[1,2,3] For example, the azimuthal distributions of fragments produced in 400 MeV/nucleon Au+Au reactions revealed anisotropy due to collective effects such as side-splash, bounce-off, and squeeze-out.[4] Collective motion has also been found in the E/A=25 to 120 MeV range.[1,2,5,6,7] Our goal here is to examine azimuthal anisotropy in the Ar+V system as a function of beam energy from E/A=35 to 85 MeV in order to provide a better understanding of reaction mechanisms in the collisions of nearly symmetric systems at these energies.

Prior studies of azimuthal asymmetry at beam energies below E/A=100 MeV have focused on two-particle correlations;[1,2,8] we will directly examine the azimuthal distributions relative to the measured reaction plane. At the lower beam energies studied, we find collective motion in the reaction plane manifested as an enhanced particle yield at azimuthal angles near the reaction plane. As the beam energy is increased, the azimuthal distributions tend towards isotropy, potentially yielding information about the changes in reaction dynamics over this transitional energy region.

The $^{40}$Ar beams from E/A=35 to 85 MeV were produced by the K-500 and K-1200 cyclotrons at the NSCL in 10 MeV steps. To obtain a nearly symmetric system, $^{51}$V was chosen as the target. Charged fragments were detected by the 170 phoswich telescopes of the MSU $4\pi$ Array.[9,10] A forward array of 45 phoswich telescopes was

Auto-correlation is avoided by omitting the particle of interest from the event when calculating the reaction plane. Thus, the complete procedure for creating an azimuthal distribution function consists of three steps. First, the particle of interest is selected from the event. Next, the reaction plane is determined using the remaining particles. Finally, the azimuthal angle ($\phi$) that the particle of interest makes with the projectile side of the reaction plane is calculated. This entire procedure, including the reaction plane calculation, is repeated for each particle of interest in the event. The resulting azimuthal distribution of the found reaction planes in the laboratory system is roughly flat to within the angular dimensions of the detectors.

Before analysis can proceed using the technique outlined above, we must establish that the azimuthal distribution can be characterized by preferential emission in the reaction plane. At higher beam energies, for instance, the existence of out of plane squeeze-out[4] could cause the found reaction plane to be 90° away from the true reaction plane. To rule out this possibility, the reaction plane found using the new technique was compared on an event by event basis with the reaction plane calculated with the method of Danielewicz and Odyniec. The differences between the two planes formed a narrowly peaked distribution centered on 0°. The new technique gives a somewhat stronger in-plane enhancement than the method of Danielewicz and Odyniec for our data, indicating a more accurate calculation of the reaction plane; however, both techniques give similar overall results. As a test, we performed simulations with various combinations of in-plane enhancement, directed transverse momentum, and multiplicity. These were filtered with a software model of our detector acceptances[10] and analyzed using the new method. As an additional check, we took random particles from different data events to create test events with no correlation, and used the new technique to search for any spurious azimuthal asymmetry. Although these studies verified that the major features of our results are not due to the technique or to detector biases, two effects emerged which should be discussed.

First, recoil effects due to momentum conservation tend to create a small bias towards finding the reaction plane 180° away from the particle of interest. We attempt to correct for this effect along the lines of Ref. 5 by rescaling the momentum of the remaining particles in the event. This is the minimum correction, however, since it assumes that all the remaining particles share the recoil. In practice this may not be the case and the effect can be stronger, leading to an enhanced probability for detection at $\phi = 180^{\circ}$.

Secondly, due to the finite solid angle of the detectors, there is a reduced efficiency for finding particles at small angles with respect to the reaction plane. Our simulations using the $4\pi$ filter code[10] lead us to expect small dips in the $\phi$ distribution around 0° and 180°, which are observed in the data.

In Fig. 1 we show the magnitude of the in-plane enhancement found in the E/A=35 MeV data for Z=1 fragments, gated on the region in which the enhancement is strongest, $y$ less than $y_{cm}$. The $\phi$ distribution peaks on the projectile and target sides of the reaction plane, 0° and 180° respectively. To quantify this enhancement, we introduce two new parameters: $F_{ip}$ and $F_{ps}$. The first parameter is the fraction of particles emitted "in plane" (within 45° of the reaction plane) and the second is the fraction of particles emitted on the "projectile side" (within 90° of the projectile side of the reaction plane). These quantities are determined by the gates shown in Fig. 1 and are calculated from the ratios of counts found in the gates to the total numbers of counts. Azimuthally isotropic emission would correspond to both fractions equaling

0.5. For reference, the data in Fig. 1 have $F_{ip} = 0.553 \pm 0.002$ and $F_{ps} = 0.480 \pm 0.002$.

The azimuthal distributions may now be studied as a function of the rapidity in the lab frame, allowing us to distinguish between some of the possible mechanisms that could be causing the asymmetry. For example, directed transverse momentum would lead to enhanced emission on the target side at low rapidity and on the projectile side at high rapidity. This emission pattern would cause $F_{ps}$ to rise as a function of rapidity, going through 0.5 at $y = y_{cm}$. On the other hand, rotation of a mid-rapidity source around an axis perpendicular to the reaction plane would result in a $F_{ps} = 0.5$ for all rapidities, while $F_{ip}$ would show enhanced particle emission in the reaction plane around $y = y_{cm}$.

The azimuthal fractions for Z=1 and 2 fragments produced in E/A=35 MeV reactions are shown in Fig. 2. We find that $F_{ps}$ is less than 0.5 at low rapidities and greater than 0.5 at high rapidities, indicating the presence of directed transverse momentum. This pattern is to be expected, since directed collective motion has been observed before in this system.[5,6] Note that the effect is stronger for He than for H, also in agreement with the previous results.

The largest $F_{ip}$ values occur at rapidities near and below $y_{cm}$, where the azimuthal distribution is characterized by a simultaneous enhancement on both the projectile and target sides, similar to that expected for rotational collective motion (see Fig. 1). This is distinct from the directed transverse momentum enhancement, which only contributes to the target side in this rapidity region. As the rapidity increases, the azimuthal asymmetry decreases to a constant value. For H this value is slightly below 0.5 due to the detector inefficiencies near 0° and 180° discussed previously. For He at high rapidities, the in-plane enhancement is almost all on the projectile side, indicating that the $F_{ip}$ asymmetry is dominated by directed transverse momentum in this region. $F_{ip}$ is not symmetric about $y_{cm}$ because the detector acceptances are not symmetric about $y_{cm}$. If we impose artificial energy thresholds which are symmetric about the center of mass, the in-plane enhancement extends through the mid-rapidity region, but the magnitude of the enhancement for $y \leq y_{cm}$ is unchanged. One explanation is that low energy particles from the projectile-like source are more isotropic, washing out the asymmetry in the middle to high rapidity range, while their counterparts from the target-like source fall below the detector's energy thresholds. Simulations which contain isotropic spectator sources and a mid-rapidity source which preferentially emits particles in the reaction plane show a similar pattern when filtered through our detector acceptances. The in-plane enhancement at each rapidity is stronger for He than for H.

To compare data at different beam energies, we place two rapidity gates on $F_{ip}(y)$. As shown in Fig. 2, the first gate is placed at low rapidity where the asymmetry is strongest ($\frac{1}{4}y_{proj} \leq y \leq \frac{1}{3}y_{proj}$). The second is placed at high rapidity where the azimuthal asymmetry is dominated by the directed transverse momentum component of the collective motion ($\frac{3}{4}y_{proj} \leq y \leq y_{proj}$). Figure 3 shows that both components of the azimuthal asymmetry decrease as the beam energy is increased. At high rapidities, $F_{ip}$ is consistent with isotropic emission for E/A near 75 to 85 MeV. Our technique does not cause this trend by losing its sensitivity to the reaction plane for the higher energy data. Simulations show that, given equal amounts of in-plane enhancement, the most critical factor in determining the reaction plane is the multiplicity, which in fact slightly increases with $E_{beam}$.

The data for the lowest beam energy agree qualitatively with measurements by by shortening the lifetime of the system.

## ACKNOWLEDGMENTS

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