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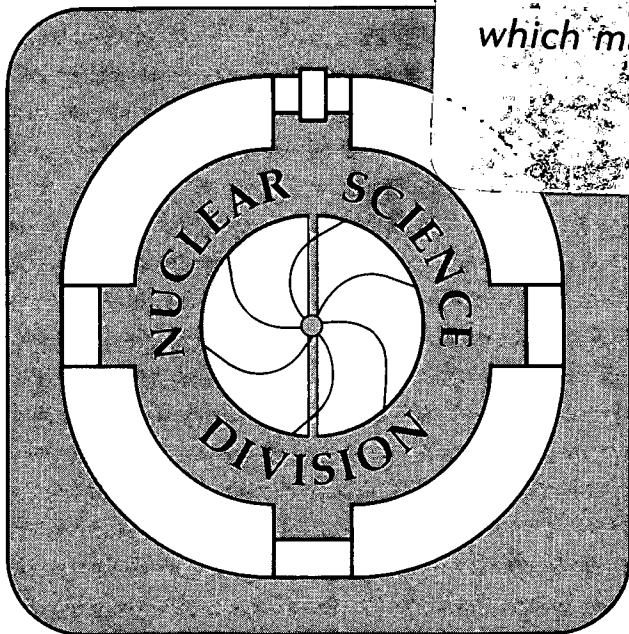
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July 1987

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## FRAGMENT FLOW IN NUCLEAR COLLISIONS

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## ABSTRACT

The flow of light nuclei ( $Z = 1, 2$ ) and intermediate mass nuclear fragments ( $3 \leq Z < 10$ ) is measured in collisions of 200 MeV/nucleon Au + Au over a large solid angle. An increase in the fragment position and momentum space alignment relative to the reaction plane is observed: the fragments exhibit stronger flow effects than light particles.

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A collective sideways flow of light particles ( $Z=1,2$ ) has recently been observed in relativistic nucleus-nucleus collisions.<sup>1,2</sup> Initially predicted by theoretical fluid dynamics,<sup>3,4,5</sup> collective flow also arises in various other models<sup>6,7,8,9</sup> incorporating compressional degrees of freedom in the form of a pressure-density relation, i.e., an equation of state. In these models the amount of transverse flow is directly related to the stiffness of the nuclear equation of state. As two incident nuclei collide, the pressure and density increase in the interaction region. At non-zero impact parameters there is an inherent asymmetry in the pressure, which results in a transverse flow of matter in the directions of lowest pressure. Several calculations,<sup>10,11,12</sup> capable of producing nuclear fragments ( $Z > 2$ ), predict that a stronger collective flow effect should be observed for nuclear fragments than light particles emitted in the reaction. Until now, experiments identifying heavier fragments have only studied single fragment inclusive distributions or two-particle coincidence measurements, providing no information on fragment flow. In this Letter we present results from the first large solid angle study<sup>13</sup> of the production of light particles ( $Z = 1,2$ ) and intermediate mass fragments ( $3 \leq Z \leq 9$ ), and provide the first conclusive evidence that the fragments exhibit stronger flow effects than light particles.

The GSI/LBL Plastic Ball/Wall detector system<sup>14</sup> was used to study light and intermediate mass fragments over a large solid angle in 200 MeV/nucleon Au + Au reactions at the Bevalac. The Plastic Ball consists of 815  $\text{CaF}_2(\Delta E)$ -Plastic Scintillator(E) telescope modules covering the angular region from  $10^\circ \leq \theta_{\text{lab}} \leq 160^\circ$  with H and He isotope identification.

Computer-controlled high voltage modules were implemented on the 160 Ball modules at  $\theta_{lab} \leq 30^\circ$ , to enable online gain-matching. With a careful reduction in gain for these forward Ball modules, their dynamic range was extended, enabling the simultaneous measurement of all produced nuclei from H to Ne. Unit separation of nuclear charges for  $1 \leq Z < 10$  was obtained with isotope separation for  $Z = 1$  and 2.<sup>13</sup> A calibration for the fragment charge identification was made by detecting low energy  $^{12}\text{C}$  beams and  $^{12}\text{C}$  fragmentation products at the Bevalac using time-of-flight techniques. In order to be identified, fragments were required to traverse the 4 mm thick  $\text{CaF}_2$   $\Delta E$  scintillator producing a low energy cut-off in the laboratory of  $E_{lab} \approx 35\text{--}40$  MeV/nucleon. Since the velocity of the c.m. system corresponds to  $E_{lab} \approx 50$  MeV/nucleon energy, the low energy cut-off is unimportant in the forward direction of the c.m. system. The measurements of intermediate mass fragments were only performed at  $\theta_{lab} \leq 30^\circ$  which corresponds mainly to the forward hemisphere in the c.m. The Plastic Wall covers angles  $\theta_{lab} < 10^\circ$  with 60 pairs of scintillation counters, providing particle identification for  $1 \leq Z \leq 6$  and velocities  $\beta \geq 0.3$  (45 MeV/nucleon) via time-of-flight and energy loss. The acceptance for light charged particles extends over  $4\pi$  allowing each event to be characterized by charged particle multiplicity. In addition, there was a zero degree gas proportional chamber<sup>15</sup> covering  $0 \pm 2$  degrees in the laboratory. This detector with its five wire planes enabled extremely high position resolution for large projectile remnants.

Multiplicity distributions of fragments with  $3 \leq Z < 10$ , observed in the forward hemisphere of the c.m.frame, are displayed in Fig. 1. Events are

divided into five total charged-particle multiplicity  $M$  bins,<sup>16</sup> corresponding to  $0 < M \leq 23$ ,  $23 < M \leq 46$ ,  $46 < M \leq 69$ ,  $69 < M \leq 92$  and  $M > 92$ . These multiplicity bins are labeled MUL1, MUL2, MUL3, MUL4, and MUL5, respectively and range from peripheral collisions with few observed charges to central collisions with very high multiplicities. As seen in Fig. 1, most peripheral collisions (MUL1) result in a low multiplicity of intermediate mass fragments. These fragments are observed to have energies close to that of the projectile, and a large projectile remnant is usually observed in the zero degree detector. Smaller remnants are observed as the charge multiplicity increases, corresponding to decreasing impact parameter.

In central collisions (MUL4 and MUL5) practically all of the projectile charge is observed in the form of light and intermediate mass fragments, with no large projectile remnant remaining. As seen in Fig. 1 there are on the average 3-4 fragments in the forward hemisphere per event for central collisions. Extrapolation of this measurement to  $4\pi$  leads to 8 or more intermediate mass fragments in central collisions, with a significant number of events producing as many as 20 fragments. These numbers are slight underestimates due to the low  $\beta$  cut-off for fragments. However, the total charge measured in the forward c.m. hemisphere for these two multiplicity bins sums to 80 to 90 percent of the projectile charge signifying that most of the fragments are observed.

Many fragments produced in central collisions are emitted at large angles and with rapidities intermediate between those of the projectile and target. A near isotropic emission pattern is observed in the c.m. of single fragment inclusive distributions for near-central collisions (MUL4) with a smooth

transition to isotropy in the most central ones(MUL5). This is expected for fragment production from the participant region of projectile-target overlap. If this system were equilibrated, the particle and fragment energy spectra in the perpendicular direction would be a measure of the temperature.

In order to study the flow of fragments, the transverse momentum analysis technique<sup>17</sup> was employed to determine the reaction plane of each event. In this method the vector difference of the transverse momentum components of particles going forward and those going backwards in the c.m. is used together with the beam axis to define the reaction plane. This difference corresponds to the collective transverse momentum transfer in the c.m. The transverse momentum  $p_{\perp}$  of each particle is then projected onto the reaction plane, where the particle of interest has been excluded from determination of the plane (i.e., autocorrelations are removed), yielding the inplane transverse momentum  $p_x$ . For each particle the fraction of the particle's transverse momentum that lies in the reaction plane is calculated. Displayed in Fig.2 is the mean value of the transverse momentum alignment  $\langle p_x/p_{\perp} \rangle$  in the MUL3 multiplicity bin for particles as a function of their rapidity for  $Z = 1,2,3$  and 6. Positive and negative values of  $\langle p_x/p_{\perp} \rangle$  correspond to emission projected into the reaction plane, but on opposite sides. Fig. 2 clearly shows that an increasingly larger part of the fragment's transverse momentum lies in the reaction plane as the fragment mass increases. The  $Z = 3,6$  fragments are more aligned in the plane than the  $Z = 1,2$  particles which are interpreted to flow collectively.<sup>1,2,6,7,8,9,17</sup> Furthermore, the absolute value of the transverse momentum per nucleon projected into the reaction plane is observed to increase weakly with fragment mass.<sup>18</sup>



Having studied the alignment of fragments in momentum space, the spatial correlation of the fragments with the reaction plane will now be examined. Presented in Fig. 3 are directivity plots showing the azimuthal correlation of emitted light particles and fragments with the reaction plane. The angle plotted is the azimuthal emission angle of each particle or fragment with respect to the reaction plane defined by the  $Z = 1, 2$  light particles with autocorrelations removed. The left-hand column labeled MUL2 contains relatively peripheral collisions, and the right, MUL4, relatively central ones. Collisions at extremely large or small impact parameters result in poorly-defined reaction planes and are not shown here. The two curves in each box correspond to rapidities of the emitted particles and fragments: near-midrapidity  $0.32 < y < 0.42$  (circles) and near-projectile rapidity  $0.52 < y < 0.62$  (crosses), where the projectile rapidity is 0.64. A strong azimuthal correlation is observed between all  $Z \geq 2$  nuclei and the azimuthal direction of maximum collective momentum transfer in the flow plane,  $\phi = 0$ . The correlation is rather flat for  $Z = 1$  and becomes increasingly stronger for heavier fragments. Projectile rapidity fragments are more correlated than midrapidity ones. The effect on projectile rapidity fragments is larger in central collisions than peripheral ones, whereas the midrapidity fragment correlations have very little dependence upon the centrality of the collision. In the limit of complete thermalization, azimuthally symmetric emission of midrapidity particles is expected. However, the presence of a correlation between fragments and the reaction plane suggests this picture is too simple; dynamic compression-decompression effects are present for the midrapidity fragments and high multiplicity (central) events.

The observed correlations are predicted to arise from collective flow of matter in the collision. This should be more important for central collisions than peripheral ones, and a stronger correlation is indeed seen on the right side of Fig. 3. The mass dependence of the correlation is also consistent with predictions of flow.<sup>10,11,12</sup> In addition to fluid dynamics, the collective flow of fragments could result from the development of dynamic instabilities during expansion,<sup>19</sup> fragment emission from a system in thermal and/or chemical equilibrium<sup>7,20,21</sup> with additional dynamic effects, and partial- or non-equilibrium processes. One might expect that the correlations from collective motion will be somewhat reduced by the random thermal motion generated in such energetic collisions. However, this is not always the case. For a system of nucleons and fragments in thermal equilibrium at a fixed freezeout temperature, the thermal energy is equally partitioned. Thus, the thermal energy per nucleon in a fragment of mass  $A$  has a  $1/A$  dependence. The flow energy, which is originally compressional energy built up in the early stages of the collision, should have a linear  $A$  dependence, i.e., the compressional energy per nucleon is independent of  $A$ . The final fragment energy will be the sum of the thermal and flow energies. Thus, the flow energy is an increasingly larger fraction of the fragment energy and the thermal energy less important as the fragment mass  $A$  increases. The observations in Figs. 2 and 3 unambiguously demonstrate that the fragments exhibit stronger flow effects, both in momentum and position space, than do the lighter particles. Note, however, that it may not be possible to distinguish production of fragments in equilibrium models from coalescence of nucleons using the flow data alone, since the  $A$  dependence in both approaches is the same.<sup>22</sup>

Results from the first large solid angle measurement of fragment formation in peripheral and central heavy ion collisions have been presented. The events are characterized through the  $4\pi$  measurement of the light charged particles, allowing the identification of multifragmentation events and analysis of the flow of the emitted nucleons and nuclear fragments. On the mean, 8-9 intermediate mass fragments ( $Z \geq 3$ ) are produced in central Au + Au collisions at 200 MeV/n, with up to 20 possible. The transverse momentum per nucleon characterizing the flow and the alignment of the fragments both in position and momentum space relative to the reaction plane is observed to increase with the mass of the fragment. The observation of a stronger flow of fragments than that previously observed for light particles supports theoretical predictions of the existence of an enhanced collective flow of heavier nuclear fragments. This enhanced flow of fragments is particularly exciting as it provides a new and more-sensitive probe of the nuclear matter equation of state for future studies.

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FIGURE CAPTIONS

1. Fragment ( $Z \geq 3$ ) multiplicity distributions for 200 MeV/n Au + Au for five total participant charge multiplicity bins increasing from MUL1 to MUL5. These multiplicities correspond to fragments emitted in the forward hemisphere of the c.m. system.
2. The mean value of the transverse momentum projected onto the reaction plane (defined in text) divided by the transverse momentum vector modulus as a function of c.m. rapidity for 200 MeV/nucleon Au + Au. Displayed are the values for  $Z = 1, 2, 3$  and  $Z \geq 6$ .
3. Directivity plots (azimuthal angular correlations) for  $Z = 1, 2, 3$  and 6 relative to the azimuthal direction of maximum collective momentum transfer in the flow plane ( $\phi = 0$ ) determined by the  $Z = 1, 2$  particles (with autocorrelations removed). The left-hand column corresponds to peripheral collisions (MUL2) and the right-hand column to relatively central ones. The data are plotted for 200 MeV/nucleon Au + Au for two rapidity intervals (o's)  $.32 < y \leq .42$  and (x's)  $.52 < y \leq .62$ .

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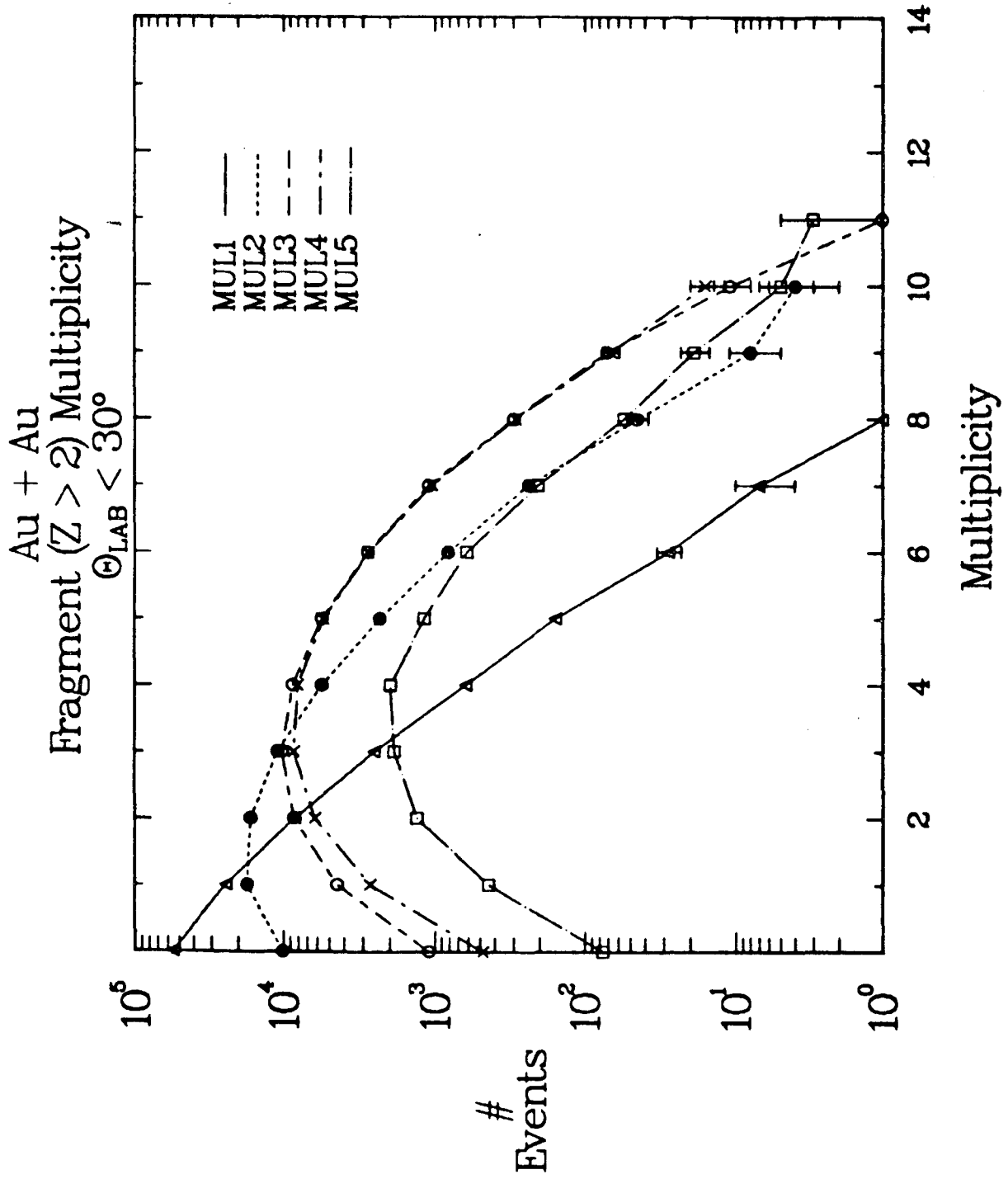
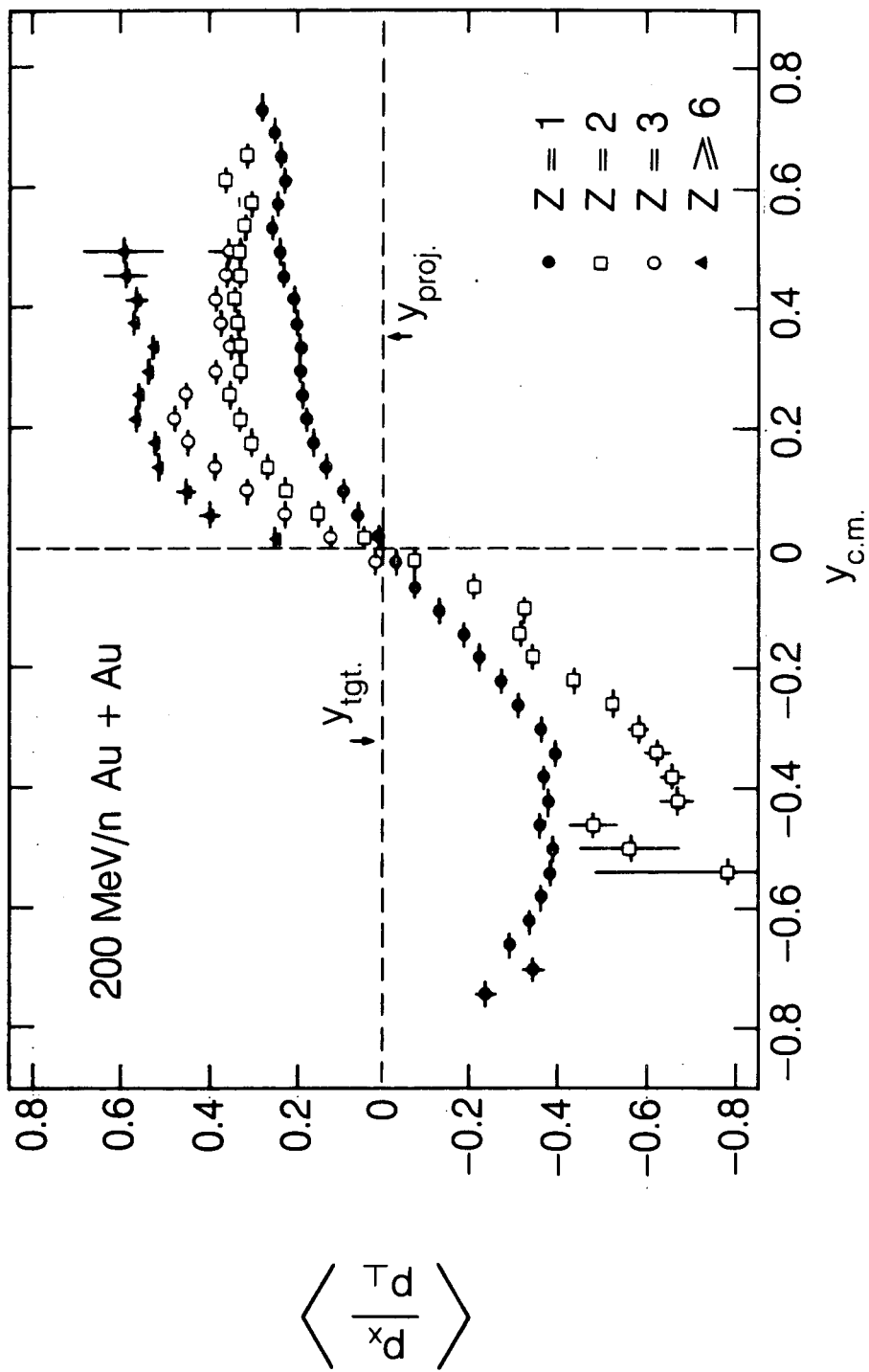


Figure 1



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Figure 2

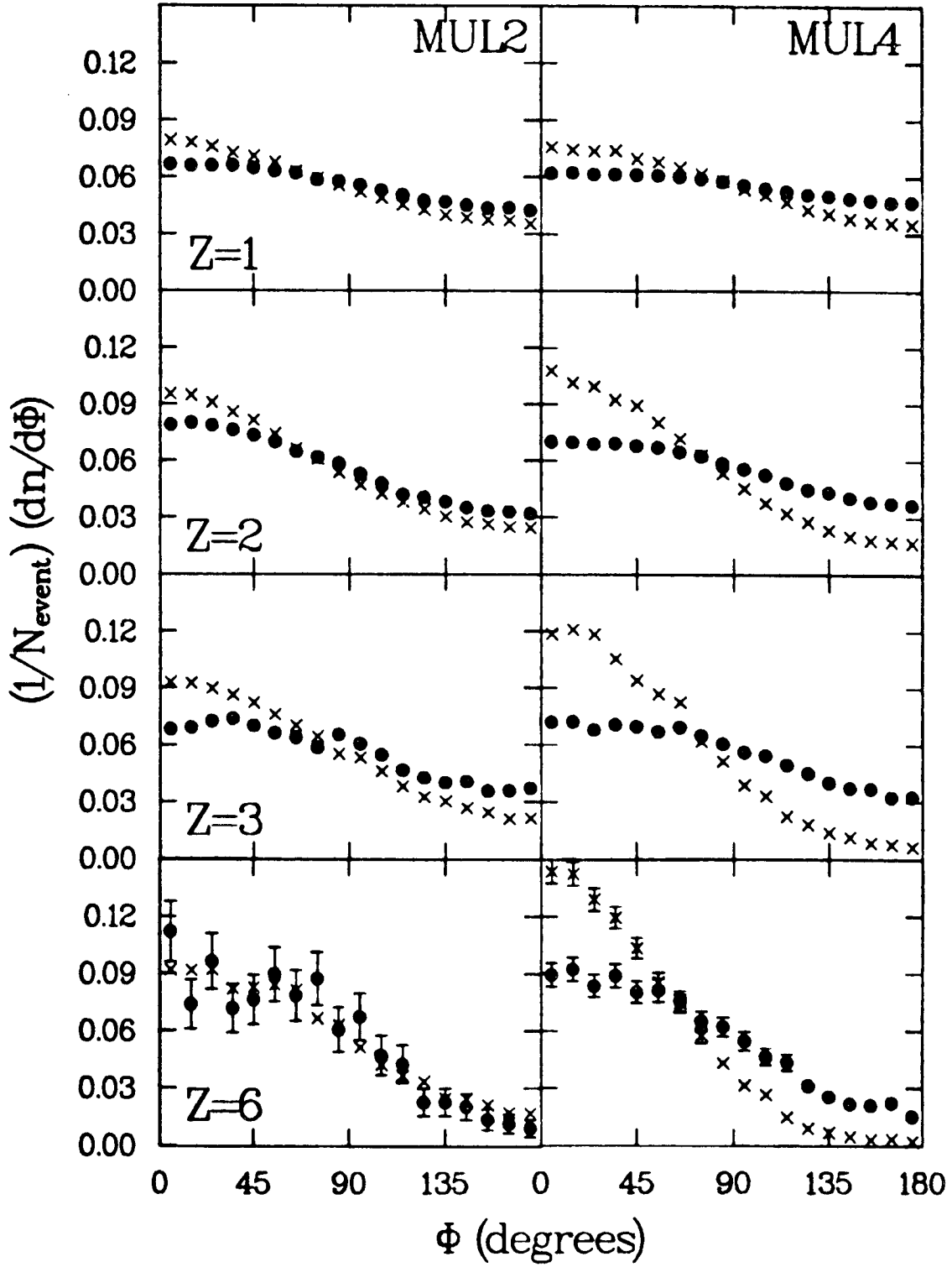


Figure 3



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