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Correlation of Aligned Angular Momentum with Scattering Angle and Energy Loss in Deeply Inelastic Collisions

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ABSTRACT

γ-ray in-plane to out-of-plane anisotropy and multiplicity are determined for the ^{100}Mo + ^{165}Ho reaction at E_{cm} = 450 MeV. The measurements are made as functions of Q-value and θ_{cm} for the coincident quasi or deeply inelastically scattered ions. Strong correlations of the aligned angular momentum with both energy loss and scattering angle are observed.

DISCLAIMER

An important aspect of quasi- and deeply inelastic collisions between two heavy ions is the correlation between the observable quantities, such as the inelasticity or the scattering angle, and the initial impact parameter, or, equivalently, the orbital angular momentum involved in the collision. Most frictional[1-3] or mean field theories[4] for the dynamics of such collisions give a unique dependence of the energy loss and scattering angle on impact parameter. There is considerable experimental evidence suggestive of such correlation, as for example obtained in a "Wilczynski" plot of the double differential cross section as a function of total kinetic energy (TKE) and scattering angle.[5] The ridge line of such a plot can be qualitatively reproduced in theoretical calculations. It has been suggested[6], however, that there may be strong fluctuations in the dependence of the energy loss and scattering angle on initial orbital angular momentum due to the effects of zero- point shape vibrations on the dynamics of the collision. The experiment discussed here is addressed to this question.

During quasi- and deeply inelastic collisions a portion of the initial orbital angular momentum is transferred to the reaction products, resulting in angular momentum aligned perpendicular to the reaction planes. The magnitude of this aligned component of the angular momentum can be deduced from fission fragment[7-9] and gamma ray[10,11] in-plane to out-of-plane anisotropies. For small energy losses the anisotropy increases rapidly with increasing energy loss. An eventual decrease in the aligned angular momentum with increasing inelasticity has been observed in some fission fragment experiments for some systems[7] but not in others[8,9]. A determination of the continuum gamma ray anisotropy in the $^{86}Kr + ^{166}Er$ system showed the expected rise of the anisotropy with energy loss in the quasielastic region and a decrease in anisotropy for the most inelastic events[10]. Similar results have been obtained more recently for the $^{165}Ho + ^{165}Ho$ system[11]. All of these measurements have been performed at a fixed laboratory scattering angle setting of the detector for the inelastically scattered particle.

We report here on the first measurement of γ-ray in-plane to out-of-plane anisotropy and γ-ray multiplicity as a function of both reaction Q-value and scattering angle. Products from the reaction $^{165}Ho + ^{100}Mo$ at E_{cm} = 450 MeV are detected over the angular range from $55^{o} \leq \theta_{c.m.} \leq 140^{o}$. Our previous study of the $^{86}Kr + ^{166}Er$ reaction at a fixed angle revealed a decrease in the anisotropy of the continuum γ-ray spectrum with increasing inelasticity. In our present work we wished to extend these measurements to backward angles for a system similar to $^{86}Kr + ^{166}Er$. Considerations of experimental details led us to use an inverse reaction of a heavy beam and a lighter target; with these constraints the $^{165}Ho + ^{100}Mo$ system ws chosen. A charged particle telescope (solid angle approximately 0.3 msr) consisting of a 10 μm surface barrier ΔE and a 100 μm surface barrier E detector was used to measure both target-like and projectile-like fragments. In this manner both forward and backward scattering in the c.m. could be simultaneously observed. γ-rays were detected in three 3" x 3" NaI(Tl) crystals. One of these detectors (out-of-plane) was placed in a direction perpendicular to the reaction plane defined by the beam and the particle detector. The other detectors were placed in the plane at angles of 45° and 135° with respect to the beam direction.

Efficiency calibrations for the γ-ray detectors were made before and after the experiment. A graded absorber consisting of 1.5 mm Cu and 2 mm Pb served to make the total detection efficiency for γ-rays for $E_\gamma \geq 120$ keV energy independent. The analysis began with a mapping of the double differential cross section, $d^2\sigma/d\Omega dQ$, in the TKE-$\theta_{c.m.}$ plane from the particle detector data. At each laboratory angle five two-dimensional gates in the ΔE-E plane were defined, corresponding to Z bins 4 units wide with the central bin centered on the Z of the projectile-like or target-like product. The width of the Z bins were determined by considering the experimental Z resolution as well as the need for adequate statistics in these bins. To each gate, a mean mass, M, was assigned corresponding to the heaviest stable isotope for the Z in question. Using this procedure, two-body kinematics were used to determine the c.m. scattering angle and reaction Q-value on an event by event basis. For each mass, M, observed at a fixed laboratory angle, one obtains the double differential cross section along a conic curve which cuts through the TKE-$\theta_{c.m.}$ plane. With varying mass and laboratory angle, then, one obtains a family of nested curves. From these curves the ridge points in the TKE vs $\theta_{c.m.}$ contour plot can be located. These are shown in Fig. 1. The reaction Q-values are corrected for neutron evaporation from the observed fragments. The apparent rise in TKE at the most backward angles is not understood. The magnitude the rise is however not outside of the experimental uncertainties. Also shown is the predicted ridge line from trajectory calculations employing a one-body dissipation mechanism based on a model of Randrup[12] which includes a neck degree of freedom. This model has been shown[13] to be qualitatively successful in reproducing some features of the ^{86}Kr + ^{139}La quasi and deeply inelastic scattering, although it fails to account for the full magnitude of the energy loss for the most deeply inelastic events because of the neglect of fragment deformations. We will use the theoretical correspondence between orbital angular momentum, ℓ, and ($\theta_{c.m.}$, TKE) values as a convenient way to label the location of our measured points along the ridge of the TKE-$\theta_{c.m.}$ contour plot. For the purposes that follow we will not depend on the absolute values of the corresponding ℓ values but only their relative location.

We next selected bins along the experimental ridge line of maximum differential cross section. These bins were 60 MeV wide in Q (or TKE) value in the deeply inelastic region and 30 MeV wide in the quasielastic region. A Z window, six units wide centered on the entrance channel was used. These bins were labeled by the ℓ value for which the theoretical TKE-$\theta_{c.m.}$ values most closely corresponded to the experimental location of the bin. The γ-ray multiplicity was determined by the ratio of the yield for charged particles in coincidence with γ-rays of E_γ > 100 keV to the single yield for charged particles. The gamma ray multiplicity and out-of-plane anisotropy are plotted vesus ℓ value in Fig. 2. The anisotropy values are based on the θ_γ = 45° in-plane detector and are integrated over γ-ray energies between 320 keV and 2600 keV. The anisotropy for the θ_γ = 135° detector exhibits a similar dependence on TKE and θ but suffered from a small normalization factor discrepancy.

The anisotropy is seen to initially increase with increasing energy loss and decreasing ℓ value. As one continues along the bend in the Wilczynski plot (to smaller ℓ values) the anisotropy reaches a maximum and then decreases. It is important to note that the anisotropy continues to decrease significantly even after the energy loss has saturated and that only the angle is changing as one progresses along the ridge line of the Wilczynski plot. In this region the gamma ray multiplicity however is practically constant.

We interpret these results in the following way. For small energy losses the anisotropy and gamma ray multiplicity increase with increasing inelasticity. This dependence has been seen in previous studies both by gamma ray de-excitation and sequential fission probes. It has a natural explanation in energy loss mechanisms based on nucleon exchange, wherein each particle transfer contributes to the component of angular momentum aligned perpendicular to the reaction plane.[14,15] The alignment initially increases rapidly with the number of exchanges because the aligned component grows approximately linearly with the number of exchanged particles whereas the randomly oriented component of angular momentum associated with the Fermi motion grows only with the square root of the number of exchanged particles.[15] As one progresses to larger energy losses the relative motion of the nuclei has decreased at the time of the later exchanges for a given collision due to the deceleration associated with the energy losses from previous exchanges. The aligned component per exchange decreases while the random contribution from the Fermi motion remains at the same rate per exchange. In this domain the anisotropy will stop increasing while the gamma ray multiplicity can continue to increase. Eventually for the largest energy losses and increasing scattering angles the orbital angular momentum of the contributing partial waves decreases and the aligned component decreases. Thus the anisotropy, sensitive to the aligned component, decreases, while the multiplicity, sensitive to the total angular momentum transfer, can remain approximately constant due to the continuing buildup of the randomly oriented component from the Fermi motion of each exchanged nucleon. An additional randomly oriented component can arise from collective excitations such as excitation of the bending mode or of collective excitations of the fragments. Crucial to an understanding of the decrease in anisotropy with increasing angle is a corresponding decrease in the ℓ-value of the dominant contributing partial waves. We conclude from the observation of a sizeable decrease in anisotropy with increasing angle that a strong correlation between scattering angle and impact parameter survives the effects of any fluctuation phenomena present. The establishment of the correlation between both the observed energy loss and scattering angle and the initial impact parameter will enable future determinations of the dependence of other interesting quantities such as the mean values and the widths of the charge and mass distributions on impact parameter.

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Fig. 1 Deflection function for Mo + Mo System. The full curve is a theoretical prediction based on the one-body dissipation model of Randrup. The numbers by full dots along the curve indicate ℓ-values. The experimental values are the most probable Q-values for selected Z and θ cuts.

Fig. 2 Continuum gamma ray anisotropies (bottom) and multiplicities (top) for selected Q bins as a function of location along the deflection function. The lower scale gives the ℓ-value of the closest point on the theoretical curve, and the two rows above the figure give the $\theta_{c.m.}$ and Q values for each point.

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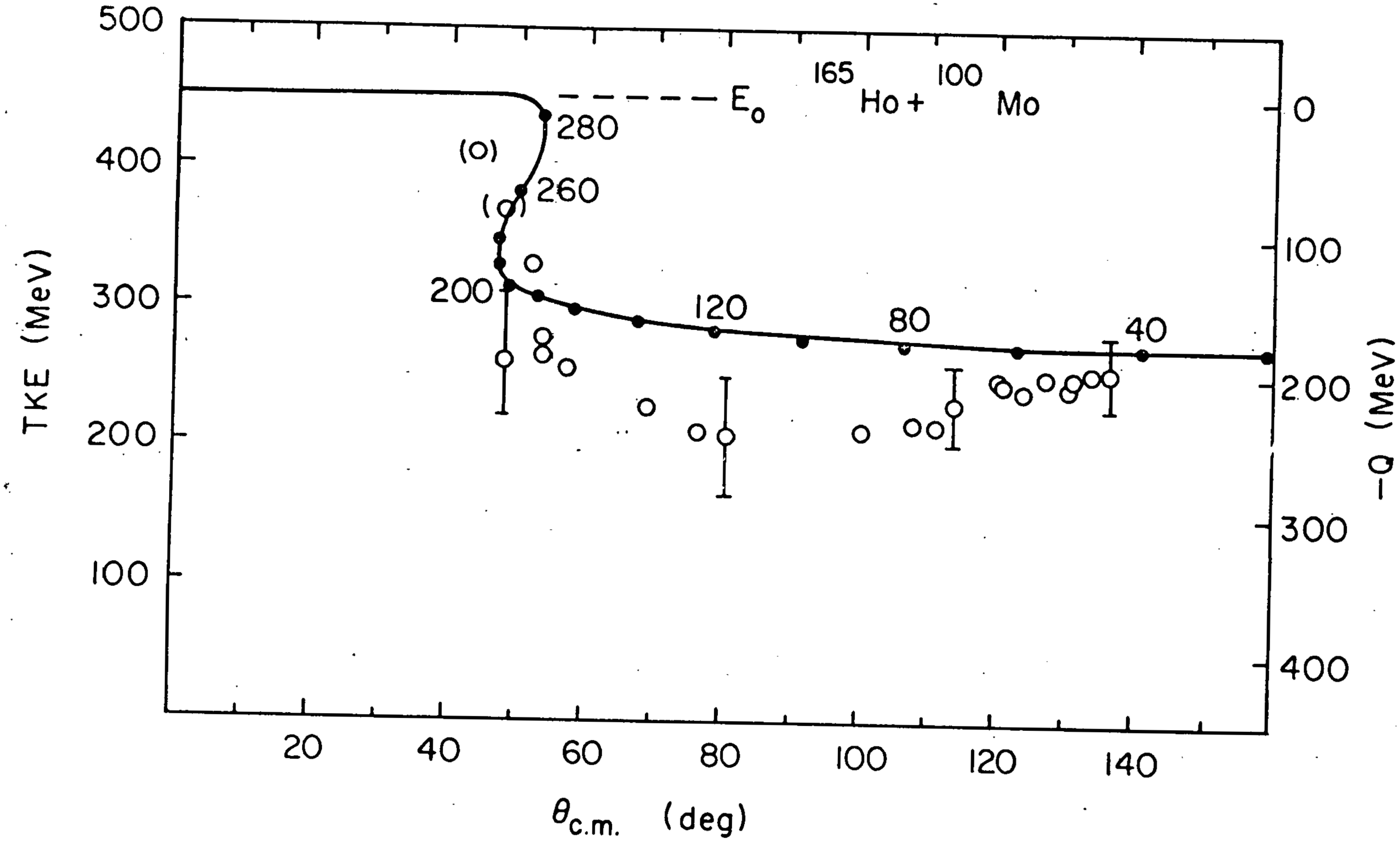

500
400
300
200
100
TKE (MeV)
E$_o$
^{165}Ho + ^{100}Mo
280
260
200
120
80
40
(o)
(o)
0
100
200
300
400
−Q (MeV)
20
40
60
80
100
120
140
$\theta_{c.m.}$ (deg)

Fig 1

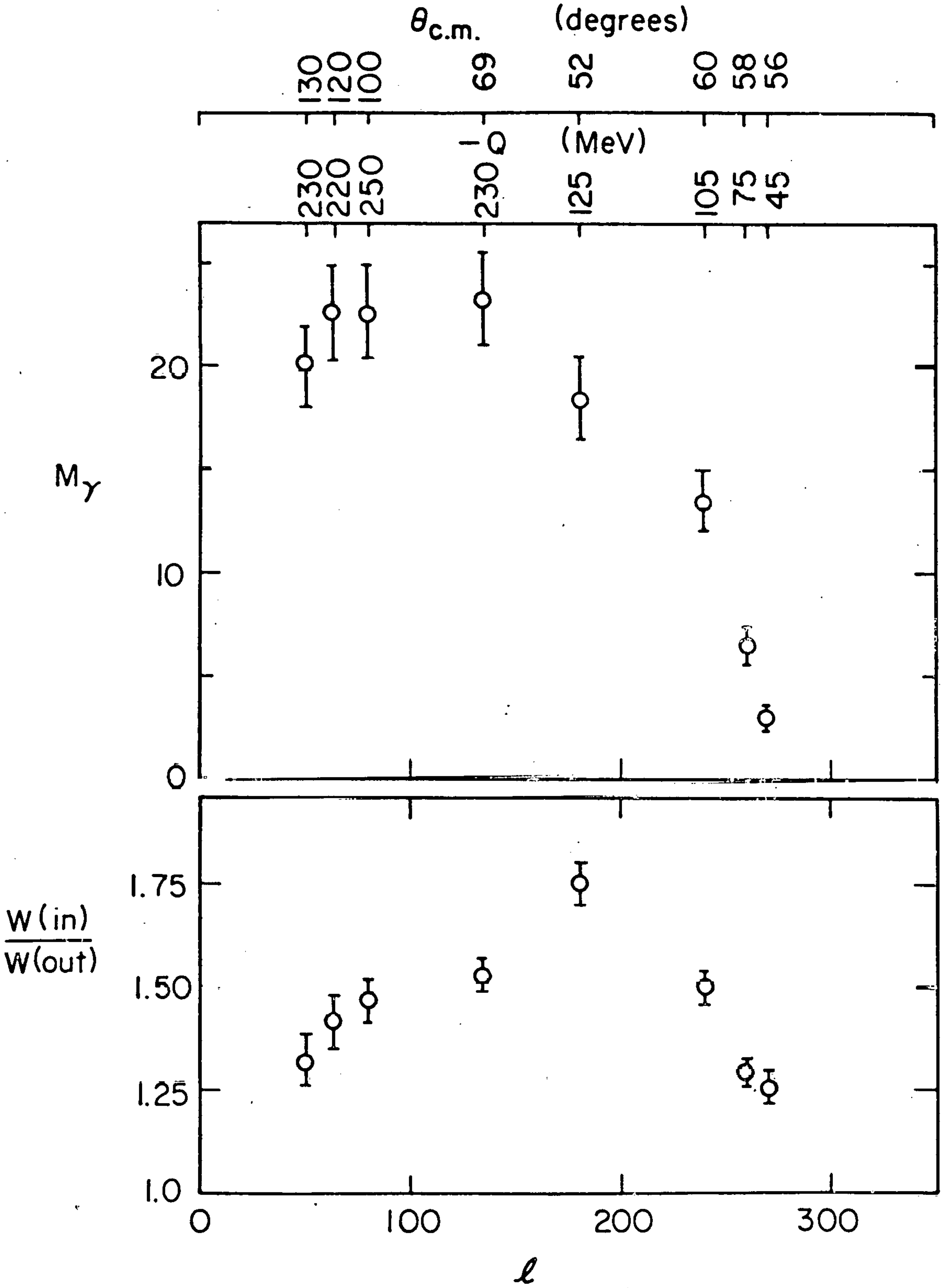
θc.m. (degrees)
130 120 100 69 52 60 58 56
−Q (MeV)
230 220 250 230 125 105 75 45
Mγ
20
10
0
W(in)/W(out)
1.75
1.50
1.25
1.0
0 100 200 300
ℓ

Fig. 2