5.3 Fission Fragment Angular Distributions from Intermediate-Energy 4He-Ion-Induced Reactions (V.E. Viola, Jr., C.T. Roche, W.G. Meyer and R.G. Clark)

The measurement of fission fragment angular distributions at moderate excitation energies provides an important means of deducing information concerning the nuclear shape which characterizes the fission transition state. By selection of appropriate projectile-target combinations and projectile energies it is possible to study the dependence of saddle point shapes upon the fissility parameter \( Z^2/A \) and on excitation energy and to compare these results with the predictions of fission theory. The angular distribution of fragments in binary fission depends upon (1) the total angular momentum \( I \) of the fissioning nucleus — which is approximately equal to the reaction orbital angular momentum \( I \) in these reactions — and (2) the projection of \( I \) on the nuclear symmetry axis, \( K \). The variance in the distribution of \( K \)-states, \( K_o^2 \), is given by the expression

\[
K_o^2 = T J_{\text{eff}} / h^2
\]

where \( T \) is the nuclear temperature and \( J_{\text{eff}} \) is an effective moment of inertia which characterizes the nuclear shape at the fission transition state.

Reising-[1] et al have shown that the agreement between experimental and theoretical values of \( J_{\text{eff}} \) as a function of \( Z^2/A \) is generally good. However, the behavior of \( J_{\text{eff}} \) as a function of excitation energy remains poorly understood. Theoretical calculations indicate that \( J_{\text{eff}} \) should be approximately independent of excitation energy and hence the ratio \( K_o^2/T \) should be constant for a given fissioning system. However, the
results of Kapoor et al [2] have shown that $K^2/T$ increases by a factor of two for $^{238}\text{U}$ fission with $^4\text{He}$ ions between the energies of 23 and 115 MeV. Kapoor concluded from his data that either the theoretical calculations of $J_{\text{eff}}$ must be in error or that the results implied a breakdown in the statistical assumptions used in the angular distribution theory. Vandenbosch [3] has suggested that this behavior may represent a possible transition from the second barrier to the liquid drop barrier in higher excitation energy fission.

The purpose of the present research has been to investigate the behavior of $J_{\text{eff}}$ on excitation energy by performing studies of fission induced in $^{238}\text{U}$, $^{209}\text{Bi}$ and $^{197}\text{Au}$ by 140 MeV $^4\text{He}$ ions. Semiconductor detectors were used to measure the angular distributions, using techniques described in earlier reports. The center-of-mass angular distributions for 140 MeV $^4\text{He}$ ion-induced fission of $^{197}\text{Au}$, $^{209}\text{Bi}$ and $^{238}\text{U}$ are shown in Fig. 5.3a. The $^{209}\text{Bi}$ data were taken in both forward and backward reaction planes and transformation from the laboratory to the center-of-mass systems was accomplished using a value for the transformation parameter, $X^2$, equal to the value calculated for compound nucleus formation, $X_{\text{CN}}^2$. For $^{209}\text{Bi}$ the forward-backward symmetry required for binary processes is met with this assumption, thus confirming the conclusion based on the angular correlation data that $^{209}\text{Bi}$ fission proceeds almost entirely via a compound nucleus mechanism at these energies. Consequently, the angular distribution for the less fissionable gold target was transformed assuming $X^2 = X_{\text{CN}}^2$. The $^{238}\text{U}$ data were transformed into the center-of-mass system under two assumptions. First, $X_{\text{CN}}^2$ was used -- which does not yield an angular distribution that is symmetric about 90 deg, as shown in Fig. 5.3a.
However, the value for the anisotropy, \( W(175)/W(90) \), obtained from this procedure does serve as a lower limit for the anisotropy that would be observed in the absence of an NCN fission and has been treated as such in subsequent calculations. Second, a search was made to determine the transformation parameter that would yield the best forward-backward symmetry for the angular distribution. A value of \( X^2 = 0.0098 = 0.74 X_{CN}^2 \) was obtained in this way, in excellent agreement with the value of \( X^2 = 0.743 X_{CN}^2 \) determined from the linear momentum distribution obtained in the angular correlation measurements discussed elsewhere in this report. In Table 5.3a the values for the anisotropy are listed along with the corresponding transformation parameters.

In order to derive \( K_0^2 \) values appropriate to fission following compound nucleus fission from these systems, it was necessary to make appropriate assumptions concerning the distribution of orbital angular momenta, \( \ell \), among the fissioning nuclides and also the effects of neutron evaporation prior to fission. The problem of calculating the transmission coefficients, \( T_\ell \), is complicated greatly by the high probability for pre-equilibrium decay in these reactions. In the absence of a detailed theoretical calculation which predicts the orbital angular momentum distribution in a system where direct, pre-equilibrium and compound nucleus reactions occur simultaneously, we have made the following assumptions, illustrated in Fig. 5.3b, which should bracket the true situation. Under assumption I the orbital angular momentum distribution for the compound nuclei formed in these reactions is restricted to the lowest possible \( \ell \)-waves. Thus, all partial cross-sections, \( \sigma_\ell \), up to the point where \( \sigma_{CN} = 0.493 \sigma_R \) (determined from reaction mechanism studies) are considered
to make up the compound nucleus cross section. All higher \( \ell \)-waves are considered to produce MCN reactions. The upper limit on the average angular momentum (assumption II) is then obtained by assuming that the transmission coefficients for compound nucleus reaction products are the same as those calculated for the total reaction cross section, but that only 49.3 percent of each partial cross section results in compound nucleus formation. Transmission coefficients were calculated using the deformed optical model potential of Rasmussen and Sugawara-Tanabe [41] with parameters derived from fitting the experimental excitation function for \( ^{238}\text{U} \) fission. The parameters were: wall-depth, \( V_0 = 130\text{ MeV} \); radius parameter, \( r_o = 1.194\text{ F} \), and diffuseness, \( d = 0.35\text{ F} \). Deformation parameters were \( \beta_2 = 0.261 \) and \( \beta_4 = 0.106 \) for \( ^{238}\text{U} \) and zero for gold and bismuth. The compound nucleus radius parameter for calculations under assumption I above was \( r_o = 0.843\text{ F} \).

In calculating values of the effective moment of inertia from our data, corrections were also made for pre-fission neutron evaporation, the fission barriers and energy tied up in rotation. In Table 5.3b the values of \( K_0^2/T \) — which should be a constant, independent of excitation energy for each nuclide — are compared with the low energy values determined by Reising et al [1]. It is observed that our values bracket the low energy value and consequently, there is no experimental basis for concluding that the effective moment of inertia is a function of excitation energy or that the assumptions of the angular distribution theory are inadequate to describe fission at intermediate excitation energies. Thus, the results of Ref. [3], which led Vandenbosch to suggest the possibility of a transition from the second maximum to the liquid drop value for the saddle point deformation in \( ^{238}\text{U} \) fission, is more an artifact of the reaction mechanism
than of the fission process.

References:
### TABLE 5.3a

Results of fission-fragment angular distribution measurements.

<table>
<thead>
<tr>
<th></th>
<th>$^{197}$Au</th>
<th>$^{209}$Bi</th>
<th>$^{238}$U</th>
</tr>
</thead>
<tbody>
<tr>
<td>Transformation parameter, $X^2$</td>
<td>0.0195</td>
<td>0.0173</td>
<td>0.0133</td>
</tr>
<tr>
<td>Anisotropy, $W(175)/W(90)$</td>
<td>3.04±0.03</td>
<td>2.48±0.03</td>
<td>1.64±0.02</td>
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</tbody>
</table>

### TABLE 5.3b

Comparison of $K_0^2/T = \mathcal{J}/h^2$ values obtained in this work compared with the low-energy results from [3].

<table>
<thead>
<tr>
<th></th>
<th>$^{197}$Au</th>
<th>$^{209}$Bi</th>
<th>$^{238}$U</th>
</tr>
</thead>
<tbody>
<tr>
<td>This work (assumption I)</td>
<td>7.7</td>
<td>10.5</td>
<td>20.3</td>
</tr>
<tr>
<td>This work (assumption II)</td>
<td>16.0</td>
<td>21.9</td>
<td>42.2</td>
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<tr>
<td>Reference [3]</td>
<td>9.0</td>
<td>13.6</td>
<td>25.0</td>
</tr>
</tbody>
</table>
Figure Captions

Fig. 5.3a Angular distributions in the center-of-mass for fission of $^{238}$U, $^{209}$Bi and $^{197}$Au by 140 MeV $^4$He ions. The relative differential cross section, $[d\sigma(\theta)/d\omega]/[d\sigma(90\ deg)/d\omega]$, is plotted as a function of center-of-mass angle. The transformation parameter, $x^2$, is shown for each set of data. For $^{238}$U the transformation is performed using a value of $x^2$ corresponding to (1) compound nucleus formation ($x^2 = 0.0133$) and (2) the best forward-backward symmetry about 90 deg ($x^2 = 0.0098$).

Fig. 5.3b Plot gives transmission coefficients, $T_x$, (upper curves) and partial cross sections, $\sigma_x$, as a function of orbital angular momentum which were used to derive $K_0^2$ values. The curve labelled $\sigma_R$ represents an optical model fit to the total fission cross section for 140 MeV $^4$He ion-induced fission of $^{238}$U. The quantities $\sigma_{CN}(I)$ and $T_x(I)$ represent the low orbital angular momentum extreme for $K_0^2$, whereas $\sigma_{CN}(II)$ and $T_x(II)$ give the upper limit for this quantity.
Figure 5.3a