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G. J. Wozniak, R. P. Schmitt, P. Glässel,
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EVIDENCE FOR ANGULAR MOMENTUM DEPOLARIZATION AND FOR ENHANCED

SEQUENTIAL FISSION IN THE REACTION $^{197}\text{Au} (^{86}\text{Kr}, Z_3f)$

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ABSTRACT:

At 618 MeV bombarding energy, large fission probabilities have been observed for recoil fragments heavier than the target. The probability of sequential fission seems to depend very strongly upon angular momentum as well as excitation energy. The out-of-plane widths of the fission fragments together with the above observations imply that a depolarization of the heavy fragment angular momentum may occur during the deep-inelastic process. This interpretation is consistent with the γ -ray angular distributions observed for similar systems.

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An interesting phenomenon, accompanying the deep-inelastic process, namely the fission of the heavy partner, has recently been observed¹ in the reaction $^{197}\text{Au} + 979 \text{ MeV } ^{136}\text{Xe}$. This special kind of decay can potentially provide information on: a) the transfer of energy from the entrance channel to internal degrees of freedom; b) the transfer of angular momentum from orbital to intrinsic rotation; and c) the possibility of prompt fission of the heavy partner in the Coulomb and nuclear fields of the light fragment.

Of the above possibilities only b) has received serious attention experimentally. From in- and out-of-plane fission-fragment angular distributions, the authors of ref. 2 have deduced a value for the average intrinsic angular momentum $\bar{I}$ of the heavy fragment. Their assumptions were: 1) that $\bar{I}$ is essentially aligned perpendicular to the reaction plane; 2) that all I -values contribute to fission in accord with a $2I+1$ weight; and 3) the rms out-of-plane angle ϕ is given by

$$\phi = \sin^{-1}(K_0/\bar{I}),$$

where K_0 is the rms projection of $\bar{I}$ on the fission axis estimated from light particle induced fission data.

While this approach leads to reasonable agreement with the data of ref. 2, the first assumption seems to be in conflict with measurements³ of the γ -ray angular distribution which are isotropic to 5-20%. Secondly, one expects that the fission process should preferentially occur for the highest angular momenta in contrast to assumption 2. Furthermore in ^{252}Cf ($J^\pi = 0^+$) spontaneous fission, the resulting fragments each have 7 to 8h of angular momentum which is aligned perpendicular to the fission

axis. This angular momentum is most likely generated by the bending oscillations of the fissioning nucleus. Recently, Perrin and Peter³ proposed that the same effect could arise in the primary deep-inelastic process, thus shedding some doubt on assumption 1.

In order to clarify the above situation, we have studied a similar system ($^{197}\text{Au}+620\text{ MeV }^{86}\text{Kr}$) with a special experimental configuration. This setup consists of a $\Delta E(\text{gas}), E(\text{solid state})$ telescope to identify the atomic number Z_3 and energy E_3 of the light partner, and a large solid angle, X-Y position-sensitive counter⁴ to simultaneously detect either the heavy partner (Z_4) or one of its fission fragments. The latter detector, which has a position resolution of 1° and subtends 24° both radially and vertically, provides information on both the energy E_4 and the in- and the out-of-plane angular distributions of the correlated fragments.

Figure 1a depicts cross section contour lines in the E_4 - Z_3 plane and illustrates the clear separation between the non-fissioning binary events and the sequential fission events. The fission distribution peaks at smaller values of Z_3 than the non-fission one due to the fission probability which increases with Z_4 . To obtain the fission probability of the heavy fragment (Z_4), the number of singles events for the corresponding Z_3 value were compared with the number of coincidence, non-fission events (after correction for the coincidence efficiency which was measured with elastic scattering). In Fig. 1b, this fission probability, integrated over the deep-inelastic region⁵ of E_3 , is shown as a function of Z_3 . Although the fission probability is quite small

around $Z_3 = 40$ ($Z_4 = 75$), it rises very rapidly and approaches 100% for $Z_3 < 30$ ($Z_4 > 85$).

In Fig. 2 the fission probabilities for the heavy recoils are shown as function of the light fragment kinetic energy for representative atomic numbers. For all cases, the fission probability increases with decreasing kinetic energy E_3 . This increase starts rather sharply at low E_3 values for fragments lighter than the target ($Z_4 = 79$). Since nuclei heavier than the target are more fissile, the fission probabilities start to rise at higher values of E_3 and saturate at rather large values. Qualitatively, these features can be understood in terms of a fission barrier which decreases with increasing Z_4 and an excitation energy E_4^* which increases with decreasing E_3 .

It is important to note that these fission probabilities reach astoundingly large values at the highest excitation energies, namely 80%, even for recoils with an atomic number of 79. For sake of comparison the fission barrier for $\ell = 0$ is ~ 22 MeV in this mass region and the total fission probability at comparable excitation energies for a light-ion reaction ${}^6_{130}\text{MeV } {}^4\text{He} + {}^{197}\text{Au}$ barely reaches 10%. The dramatically different fission probabilities indicate that the broader partial wave distribution may allow sequential fission to select out the very highest angular momentum transfers which enhances the fission probability.

Thus the ℓ -distribution of the sequential fission channel may not at all reflect the overall ℓ -distribution for the deep-inelastic process as a whole. This is borne out independently by the γ

multiplicities⁷ which are the same whether or not the heavy recoil undergoes fission. Since fission removes $\sim 5/7$ of the heavy fragment spin, one is again led to the conclusion that the sequential fission channel is indeed associated with higher than average angular momenta. Still, even allowing for this effect, the total fission probability is so high that one wonders whether or not a more direct mechanism, like contact fission^{8,9} is occurring (which would be caused by the heavy partner being held close to the light fragment by the short range proximity force and being stretched beyond the saddle point by the long range Coulomb force).

The out-of-plane angular distributions of the fragments from sequential fission are nearly Gaussian and peaked on the reaction plane. The FWHM¹⁰ of these distributions in the laboratory and in the c.m. of the recoiling heavy fragment are shown as a function of Z_3 in Fig. 3. For fission fragments originating from elements heavier than the target ($Z_3 < 36$) the c.m. width is 27° in agreement with the previously measured value² which is an average over the entire Z-distribution. One should note that the out-of-plane angular distribution for a binary reaction not followed by fission (see Fig. 3) appears to be completely consistent with the de-excitation of both fragments mainly by neutron emission.¹¹

Of central importance to ref. 2's analysis of the out-of-plane distributions are the assumptions that the angular momentum of the heavy fragment is oriented essentially perpendicular to the reaction

plane, and that the out-of-plane width is inherent to the fission process and not to the deep-inelastic process. If the γ -rays are stretched E2 decays they should show a strong anisotropy of the limiting form

$$W(\theta) = (5/4)(1 - \cos^4\theta)$$

where θ is the angle of emission with respect to the angular momentum direction.

However, the evidence³ is that the γ -ray angular distribution is isotropic to within 5-20%. This fact cannot be explained away by invoking E1 decay. The latter is not expected to be stretched, but, even if it were, a very unlikely 50-50 contribution from E1 and E2 would lead to an anisotropy of only 1.33, which would still be contrary to the experimental evidence. This dilemma forces one to either abandon the assumption of stretched E2 decays, which is disastrous because it compromises all our understanding of yrast decay, or to seek another explanation.

If we assume the depolarization mechanism proposed in ref. 3, simple statistical considerations lead to the following distribution (for symmetric splitting):

$$P(I) \propto \exp(-E_1^{\text{rot}}/T - E_2^{\text{rot}}/T) \cong \exp(-I^2/\mathcal{J}T)$$

where $\mathcal{J}$ is the moment of inertia of one fragment and T is the temperature. The resulting rms angular momentum per fragment is:

$$\bar{I}^2 = \frac{1}{2} \mathcal{J} T.$$

For the present reaction of 618 MeV $^{86}\text{Kr} + \text{Au}$, $\bar{I}$ is estimated to be about 8 to 9 $\hbar$.

By randomly coupling this angular momentum to that arising from rigid rotation, which is borne out by γ -ray multiplicity data⁷, one obtains a rms angular momentum misalignment ϕ' of the order of 15° to 20° . This misalignment comes from the deep-inelastic process itself and can explain the γ -ray near isotropy (with the help of $\sim 20\%$ E1 decay). If this is the case, the explanation of the fission fragment out-of-plane distribution lies in a depolarization inherent to the deep-inelastic process and not in the fission mechanism.

This explanation does not contradict the existence of the fluctuations in the fission direction as described above. However, it suffices to recognize that if fission selects the largest angular momenta, the angle $\phi \approx K_0/\bar{I}$ may be rather small ($< 10^\circ$). By coupling this angle to the possibly larger random misalignment ϕ' ($15^\circ - 20^\circ$) arising from the deep-inelastic process one obtains that

$$\phi_{\text{total}} = \sqrt{\phi^2 + \phi'^2} \approx \phi'.$$

In summary, the sequential fission process is more intriguing than expected and its use to elucidate the angular momentum transfer in deep-inelastic processes is not straightforward. A possible biasing of the ℓ -distribution due to fission, and a primary depolarization of the heavy

fragment's intrinsic angular momentum provides us with an alternative interpretation which not only explains the out-of-plane angular distribution of the sequential fission fragments but also resolves the dilemma presented by the γ -ray angular distributions.

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Figure Captions

- Fig. 1 Top. Cross section contour lines in the $E_4 - Z_3$ plane for events detected in coincidence at $\theta_3 = 40^\circ$ and for two PSD settings of $\theta_4 = 45^\circ$ and 53° . The contour lines correspond to values of 20000, 2000, 200, 10 and 5 events for the non-fission component and 60, 40, 10 and 5 events for the fission component.
- Bottom. Measured fission probabilities of the heavy recoils ($Z_4 = 115 - Z_3$) integrated over the deep inelastic region of E_3 as a function of Z_3 . Only statistical errors are shown for the data points in this and the following figures.
- Fig. 2 Measured fission probabilities of the heavy fragment ($Z_4 = 115 - Z_3$) as a function of the lab energy E_3 of the light fragment Z_3 .
- Fig. 3 Corrected FWHM^{10} of the measured out-of-plane angular correlation (ϕ_4) as a function of Z_3 .

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Fig. 1

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Fig. 2

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Fig. 3

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