Evidence for Angular Momentum Depolarization and for Enhanced Sequential Fission in the Reaction $^{197}Au(^{86}Kr, Z_3 f)$

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(Received 13 January 1978)

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 upon excitation energy. The out-of-plane widths of the fission fragments together with the above observations imply that a nearly random depolarization of the heavy-fragment angular momentum may occur during the deep-inelastic processes.

An interesting phenomenon accompanying the deep-inelastic process, namely the fission of the heavy partner, has recently been observed[1] in the reaction ^{197}Au + 979-MeV ^{136}Xe. This special kind of decay can potentially provide information on (a) the transfer of angular momentum from orbital to intrinsic rotation; (b) the transfer of energy from the entrance channel to internal degrees of freedom; and (c) the possibility of prompt fission of the heavy partner in the Coulomb and nuclear fields of the light fragment.

Although point (a) has recently been investigated via measurements of the in-plane and out-of-plane sequential fission-fragment angular distributions,[2] which provide complementary information to γ-multiplicity measurements,[3-5] the latter two points have not been explored. A global approach which may lead to a better understanding of all these points involves studying the sequential fission process as a function of the mass and energy of the deep-inelastic fragments as well as simultaneously measuring the fission-fragment angular correlation. In this Letter we report on the first such detailed study of the sequential fission process.

Our experimental apparatus consisted of a ΔE (gas), E(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 counter[6] to detect simultaneously 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-plane and the out-of-plane angular distributions of the correlated fragments.

Figure 1(a) depicts cross-section contour lines in the E_4-Z_3 plane and illustrates the clear separation between the nonfissioning binary events and the sequential fission events. The fission distribution peaks at smaller values of Z_3 than the nonfission one because of 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, nonfission events (after correction for the coincidence efficiency which was measured with elastic scattering). In Fig. 1(b), this fission probability, integrated over the deep-inelastic region[7] 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 $Z_3 < 30$ ($Z_4 > 85$).

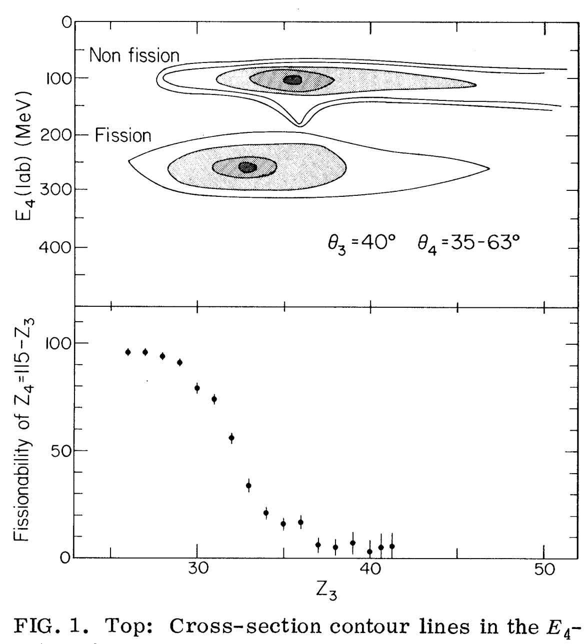

FIG. 1. Top: Cross-section contour lines in the E_4-Z_3 plane for events detected in coincidence. The contour lines correspond to values of 20 000, 2000, 200, 10, and 5 events for the nonfission component and 60, 40, 10, and 5 events for the fission component. Bottom: Measured fission probabilities of the heavy recoils ($Z_4 = 115 - Z_3$) integrated over the deep-inelastic region (Ref. 7) of E_3. Only statistical errors are shown for the data points in this and the following figures.

In Fig. 2 the fission probabilities for the heavy recoils are shown as a 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 the sake of comparison, the fission barrier for $l=0$ is ~ 22 MeV in this mass region, and the total fission probability at comparable excitation energies for a light-ion reaction,[8] 130-MeV $^4He+{}^{197}Au$, barely reaches 10%. The dramatically different fission probabilities indicate that the broader partial-wave distribution in heavy-ion reactions may allow sequential fission to select out the very highest angular momentum transfers, which enhances the fission probability.

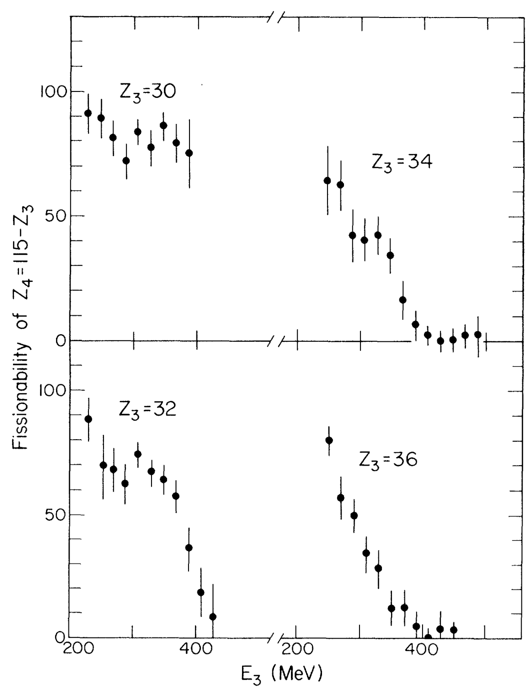

FIG. 2. Measured fission probabilities of the heavy fragment ($Z_4=115-Z_3$) as a function of the lab energy E_3 of the light fragment Z_3.

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 multiplicities[4] which are the same whether or not the heavy recoil undergoes fission. Since fission removes $\sim \frac{5}{7}$ 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,[9,10] 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 full widths at half-maxima[11] (FWHM) 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 47°–50° in agreement with the previously measured value[2] which is an average over the entire Z distribution. One should note

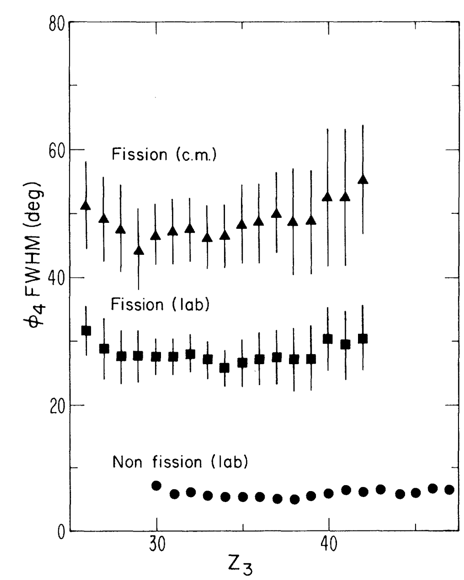

FIG. 3. Corrected FWHM (Ref. 11) of the measured out-of-plane angular correlation (φ_4) as a function of Z_3.

that the out-of-plane angular distribution for a binary reaction not followed by fission (see Fig. 3) appears to be consistent with the deexcitation of both fragments mainly by neutron emission.[12]

To explain the comparable out-of-plane fission angular distribution observed in a similar reaction (610-MeV ^{86}Kr + ^{209}Bi), the authors of Ref. 2 presented calculations which assumed that the angular momentum is essentially aligned perpendicular to the reaction plane and that the fission width arises from the fission process itself. In addition, preliminary calculations were also presented which assumed a Gaussian distribution ($\sigma = 27°$) of angular momentum *perpendicular to the recoil direction.* The latter system is highly aligned and would create an out-of-plane angular distribution which is strongly dependent on the in-plane angle. Although both of these calculations reproduced the data presented in Ref. 2, both seemed to attribute the out-of-plane angular distribution to the fluctuation of the fission axis with respect to the plane perpendicular to the angular momentum. This conclusion could be doubtful in view of a lack of a Γ_f/Γ_T weight of the l distribution and in view of recent measurements[3,5] of the γ-ray angular distributions. If the γ rays emitted by an aligned system ($M = J$) are stretched $E2$ decays, they should show a strong anisotropy, though attenuated by the presence of $E1$ decays. The expressions for the angular distributions arising from completely aligned systems are,[13] for $E2$,

$$W(\theta) = \tfrac{5}{4}(1 - \cos^4\theta),$$

and for $E1$,

$$W(\theta) = \tfrac{3}{4}(1 + \cos^2\theta),$$

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

However, the evidence[3,5] is that the γ-ray angular distribution is *isotropic* to within 5–35%. This fact can, to some extent, be explained away by invoking $E1$ decay. However, a very unlikely 50-50 contribution from $E1$ and $E2$ is barely sufficient to explain the largest measured anisotropy of 1.35. This dilemma forces one either to abandon the assumption of stretched $E2$ decays, which is disastrous because it compromises all our understanding of the yrast decay, or to seek another explanation.

In ^{252}Cf ($J^\pi = 0^+$) spontaneous fission, the resulting fragments each have $(7-8)\hbar$ 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, Berlanger *et al.*[3] proposed that the same effect could arise in the primary deep-inelastic process. Along the same line, but more generally, we suggest that collective modes like bending (doubly degenerate) and twisting (nondegenerate) may be thermally excited, thus generating *random* components in the angular momentum.

If we assume such a depolarization mechanism, simple statistical considerations lead to the following partition function (for simplicity a two-equal-touching-sphere model is assumed):

$$Z = (4\pi)^2 \int I^2 \exp(-I^2/\mathscr{I}T)\, dT\ ,$$

and

$$\ln Z = a + \tfrac{3}{2}\ln(\mathscr{I}T),$$

where $\mathscr{I}$ is the moment of inertia of one fragment, T is the temperature, and a is a constant. The resulting mean-square angular momentum per fragment is

$$\langle I^2\rangle = -\partial \ln Z/\partial[1/\mathscr{I}T] = \tfrac{3}{2}\mathscr{I}T.$$

For the present reaction of 618-MeV ^{86}Kr + ^{197}Ar and with use of $r_0 = 1.22$ fm and $T = 2-3$ MeV, $\langle I^2\rangle^{1/2}$ is estimated to be about (13–16$\hbar$ per fragment,[14] randomly oriented, rather than perpendicular to the recoil direction. (These results are not very sensitive to small deviations from symmetric splitting.)

By randomly coupling this angular momentum to that transferred from orbital motion (~ 30$\hbar$, as is inferred from γ-ray multiplicity data),[4] one obtains a rms angular momentum misalignment φ' of the order of 24° to 28°, more than adequate to explain *by itself* the sequential-fission out-of-plane distribution. This misalignment comes from the deep-inelastic process itself. 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 fluctuations in the fission direction as described in Ref. 2. However, one should note that the $\langle I^2\rangle^{1/2}$ generated by these bending and twisting modes may be larger than K_0 and thus should be the dominant effect in producing the out-of-plane fission widths. The presence of such a depolarization substantially helps to explain the γ-ray anisotropy with a much smaller amount of $E1$ transitions.

In summary, the Q and Z dependence of sequential fission following a deep-inelastic process has been presented. Large fission probabilities have been observed at high excitation energies. These data may serve as a basis for judging the validity of models which treat the equilibration of the entrance-channel energy between the fragments as well as models of the direct-fission process. As far as the angular-momentum transfer process is concerned, possible biasing of the l distribution due to fission, and a primary depolarization of the heavy fragment's intrinsic angular momentum, provide us with an alternative explanation of the measured out-of-plane fission widths which seems more consistent with γ-anisotropy data. Thus the sequential-fission process following a deep-inelastic collision seems to be more intriguing than expected insofar as the population of new modes in deep-inelastic collisions is concerned.

This work was supported by the Division of Nuclear Physics, Nuclear Science Division, U. S. Department of Energy.

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[14]Other modes such as "wriggling" may also contribute to the depolarization and would lead to even higher estimates.

Experimental Test of the Factorization Approximation in the Reaction ^{40}Ca$(p,2p)^{39}$K at 148.2 MeV

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(Received 20 March 1978)

We present data for the reaction ^{40}Ca$(p,2p)^{39}$K at 148.2 MeV. Energy sharing cross sections for the $\frac{3}{2}^+$ ground state and $\frac{1}{2}^+$ excited state are well described by distorted-wave impulse-approximation calculations. An explicit comparison of the results of the factorization approximation with these experimental results provides considerable support for the usual distorted-wave impulse-approximation treatment.

In order to extract precise nuclear structure information from any nuclear reaction, it is essential to understand the accuracy of the reaction theory used. In the present work we take advantage of the kinematic flexibility of the three-body $(p, 2p)$ reaction[1] to make a detailed test of the

