Fission Following Transfer to ^{232}Th at Energies below the Coulomb Barrier

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We have observed fission induced by transfer to ^{232}Th from ^{16}O and ^{19}F projectiles at sub-Coulomb energies. The cross sections for the stronger reactions are in qualitative agreement with simple theoretical estimates. They are of the same magnitude as those found earlier by bombardment with Kr and Xe where the Q windows are considerably less favorable. In those cases, transfer involving Coulomb excitation is proposed as an explanation.

Fission induced by the Coulomb interaction of a target and projectile (Coulomb fission) has been considered theoretically for several years.[1-4] Attempts to observe Coulomb fission using Kr and Xe projectiles on actinide targets have been reported.[5,6] Fission events were indeed observed in coincidence with back-scattered particles but the characteristics found are not wholly consistent with Coulomb excitation being the dominant process. At bombarding energies between 0.85 and 1.0 times the Coulomb barrier (V_{CB}) the differential cross sections are the same, within about a factor 2, for both Kr and Xe ions, while all theoretical approaches to Coulomb fission indicate a very strong dependence on the charge of the projectile. Also some variation with the target might be expected, but experimental yields are similar for ^{232}Th and ^{248}Cm, even though the latter has an 11% spontaneous-fission decay mode.

An alternative process which might lead to the observed results is particle-transfer–induced fission. If the Q values for transfer reactions were such that transfer to states above the fission barriers of the product nuclei were likely, there would be little dependence on the projectile or on the target since all have fission barriers (V_F) around 6 MeV.[7] Currently one cannot identify the scattered particles in Kr- and Xe-induced reactions and therefore we have made similar studies with lighter projectiles.

The present experiment was performed using the 14UD Pelletron accelerator at the Australian National University. Targets of ^{232}Th, ~50 μg/cm^2 thick, were bombarded by beams of ^{16}O and ^{19}F in the energy ranges $E_{\rm lab}=75-95$ and 85–95 MeV, respectively. Singles transfer data were obtained using an annular detector at a mean angle of 172° to the beam direction. Transfer-induced fission was identified by requiring triple coincidences between this counter and two fission-fragment detectors located at ±70°. Coincidences between the annular counter and either of the fission detectors were also recorded to ensure that all fission events were observed. Comparison, for $E_{\rm lab} \ll V_{CB}$, of the elastic yields in the annular and fission fragment detectors with those in two monitor counters at ±25° allowed determination of counter efficiencies and hence absolute cross sections. The transfer-induced fission cross sections were evaluated assuming a $1/\sin\theta$ dependence for the fission-fragment angular distributions as in Ref. 5. The opposite extreme of isotropy would only reduce the cross sections by 36%.

By replacing the annular detector with a two-detector particle telescope at 154°, Z-specific reaction products were identified. Singles measurements using an Enge spectrograph at 154° were also performed and the superior mass resolution allowed still weaker reactions to be identified. Details of these measurements will be published.[8] The dominant reactions leading to fission are ^{232}Th(^{19}F, ^{18}O)^{233}Pa ~ 60%, ^{232}Th(^{19}F, ^{15}N)^{236}U ~ 25%, ^{232}Th(^{16}O, ^{14}C)^{234}U ~ 45%, ^{232}Th(^{16}O, ^{12}C)^{236}U ~ 25%, and ^{232}Th(^{16}O, ^{15}N)^{233}Pa ~ 20%.

The measured excitation functions are shown in Fig. 1, where they are compared with the results for ^{86}Kr and ^{136}Xe projectiles.[5] Cross sections are plotted against bombarding energy expressed as a fraction of V_{CB}, defined as $1.44Z_1Z_2f(\varphi)/1.16(A_1^{1/3}+A_2^{1/3}+2)$ MeV where φ is the mean observation angle of the scattered particles, in the c.m. system, and $f(\varphi)$ is $0.5[1+\csc(\frac{1}{2}\varphi)]$. The obvious features are that the excitation functions are all of similar shape and magnitude except that for ^{19}F which is somewhat higher with a less-steep gradient. In this instance the (^{19}F, ^{18}O) single-nucleon transfer reaction has a Q value favoring transfer to states above V_F, and thus the data are dominated by single- rather than two-proton stripping as with ^{16}O. One expects, and our data confirm, that

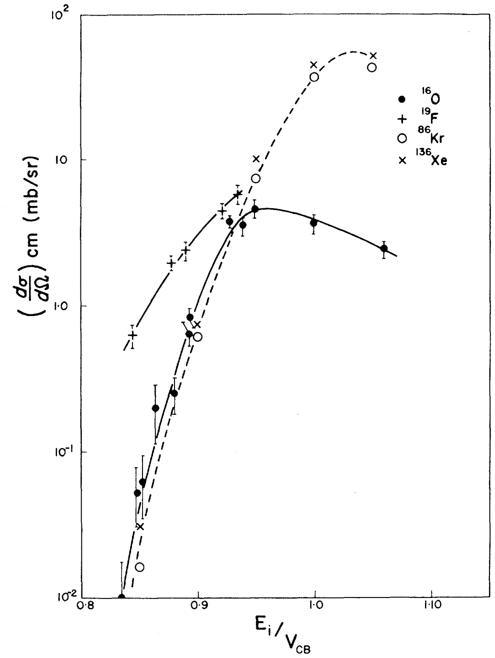

FIG. 1. Comparison of the excitation functions for fission induced by ^{16}O, ^{19}F, ^{86}Kr, and ^{136}Xe. The data for the two lighter projectiles are from the present work and those for the heavier ions are taken from Ref. 5. The errors shown do not include a possible contribution associated with the choice of a $1/\sin\theta$ dependence for the fission-fragment angular distirubtions; the assumption of isotropy reduces the cross sections by 36%. The lines are drawn to guide the eye.

single nucleons tunnel more easily through the barrier than heavier clusters, thus giving rise to larger cross sections and less-steep excitation functions.

The similarity of the excitation functions in Fig. 1 suggests that similar processes might be involved in all cases. However, transfer reactions near the Coulomb barrier are generally dominated by Q-value effects. Therefore it is surprising that the cross sections are so similar, since the Q windows associated with the various projectiles differ considerably. Values of $Q_{gg} - Q_{\text{opt}}$ are shown in Fig. 2 for the most likely stripping and pickup reactions; Q_{gg} is the Q value for ground-state transfer and $Q_{\text{opt}} = E_i(z'Z'/zZ - 1)$, where z (z') and Z (Z') are the atomic numbers of the incoming (outgoing) particle and the target (residual) nucleus and E_i is the bombarding energy in the center-of-mass system taken as $0.94V_{\text{CB}}$. This simple estimate of Q_{opt} matches the distance of closest approach for the incoming and outgoing orbits; the value of $Q_{gg} - Q_{\text{opt}}$ is the excitation energy in the residual nucleus to which transfer is favored.

For the light projectiles (^{16}O and ^{19}F) the spread in the centroids of the Q windows ($Q_{gg} - Q_{\text{opt}}$) for the different reactions is considerable, and only those with values near a minimum excitation energy of V_F, taken to be 6 MeV, are observed to

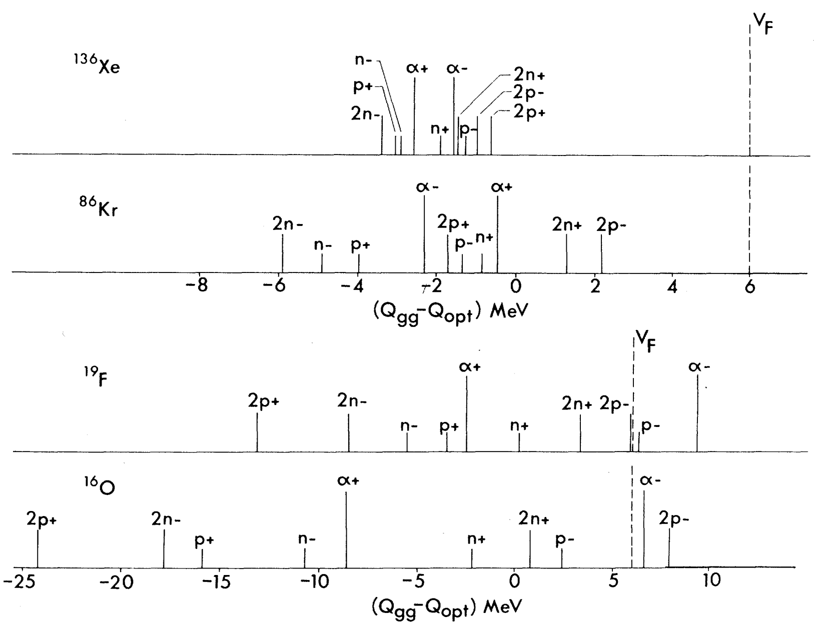

FIG. 2. Preferred excitation energy in the residual nucleus following transfer reactions with ^{16}O, ^{19}F, ^{86}Kr, and ^{136}Xe. The nucleons transferred are indicated and the symbols "+" and "−" refer to pickup and stripping, respectively. Q_{opt} has been evaluated at $E_i = 0.94V_{\text{CB}}$. The excitation energy required to produce fission (V_F) is indicated at 6 MeV.

contribute to transfer fission. This implies a Q-window width which is smaller than the spread in centroid energies. A quantitative estimate can be obtained by assuming that the widths of the singles energy spectra for reactions with $(Q_{gg} - Q_{\rm opt}) \gg 0$ MeV are dominated by Q-window effects. This gives widths [full width at half maximum (FWHM)] which are around 5 MeV. Theoretical results for subbarrier energies[9] are also consistent with this value and suggest little variation over the range of projectiles discussed here. A semiquantitative estimate of the transfer probabilities can be obtained by assuming a Gaussian distribution $P_{\rm trans} = (K/\sigma\sqrt{2\pi}) \exp[-(Q - Q_{\rm opt})^2/2\sigma^2]$ with FWHM of $2.35\sigma = 5$ MeV; this form is in good agreement with that predicted by theory[9,10] for a wide range of reactions. Though K may decrease with increasing numbers of nucleons transferred and might depend on bombarding energy, we have taken $K = 1$ for simplicity. Integration of $P_{\rm trans}$ for states with energies above V_F in the residual nuclei thus gives relative transfer fission probabilities as shown in Table I. Considering the neglect of spectroscopic information, different form factors, etc., the results are in qualitatively good agreement with the ^{16}O and ^{19}F data. However, even allowing for these factors, it seems that much smaller transfer fission probabilities would be expected for ^{86}Kr and ^{136}Xe than for the lighter ions. Yet, it is extremely unlikely that the observed fission cross sections for the ^{86}Kr projectiles are due to Coulomb fission, because theory[2,3] predicts that these cross sections should be more than an order of magnitude lower than those for ^{136}Xe. One would expect the predicted relative Coulomb-fission cross sections to be much more reliable than the absolute values. Moreover the observed cross sections for ^{136}Xe are only upper limits to those for Coulomb fission. Hence we are forced to conclude that the observed ^{86}Kr cross sections are due almost entirely to transfer fission and are not explained in terms of simple Q-value effects. An obvious difference between light- and heavy-projectile systems is the much stronger Coulomb interaction in the latter. Effects of Coulomb excitation on transfer using light ions have been observed[11] and will be much stronger with Kr ions. Possibly these effects are responsible for the discrepancy we have noted.

TABLE I. Calculated transfer fission probabilities ($\times 10^4$) for the most likely pickup (+) and stripping (−) reactions evaluated using a Gaussian Q window. The values are obtained using $E_i = 0.94V_{\rm CB}$ and $V_F = 6$ MeV. Probabilities less than 10^{-4} are not shown.

Transferred nucleons	^{16}O	^{19}F	^{86}Kr	^{136}Xe
$p-$	430	5500	3	3
$p+$	···	···	···	···
$n-$	···	···	···	···
$n+$	···	33	6	···
$(2p)-$	8300	4700	380	5
$(2p)+$	···	···	1	9
$(2n)-$	···	···	···	···
$(2n)+$	65	980	130	2
$\alpha-$	6100	9400	···	2
$\alpha+$	···	···	11	···

Coulomb excitation can occur both before and following transfer and the effects would be to make $Q_{gg} - Q_{\rm opt}$ in Fig. 2 appear more positive and broaden the Q window. Both effects enhance the probability of transfer-induced fission although all of the Coulomb excitation is not useful in surmounting the fission barrier, as increased angular momentum of the product nucleus ties up part of the energy even at the saddle point. Coupled-channel codes of the required complexity are not yet available. However, particle transfer and Coulomb excitation together clearly yield more excitation energy than either alone, and so the resulting fission is neither a single transfer process nor "pure" Coulomb fission, but a hybrid. Since this hybrid excitation seems necessary to explain the ^{86}Kr data, it seems most plausible that it can also explain that for ^{136}Xe, at least down to $E_i + 0.85V_{\rm CB}$, where ^{86}Kr and ^{136}Xe still give similar results; for ^{136}Xe, $Q_{gg} - Q_{\rm opt}$ is even more negative but the Coulomb interaction is stronger than for ^{86}Kr.

The radiochemical excitation-function measurements of Franz *et al.*[12] for ^{132}Xe on ^{238}U extend to significantly lower energies ($\sim 0.75V_{\rm CB}$). These results suggest different slopes for the fission-product excitation function compared to neutron-transfer reactions below about $0.85V_{\rm CB}$. Thus, there remains the possibility that at the larger distance of closest approach corresponding to such low bombarding energies, "pure" Coulomb-induced fission becomes observable with very low cross sections. Since Kr should lead to much less Coulomb fission it would be most informative to have similar radiochemical data for this projectile.

We report for the first time heavy-ion transfer-induced fission in experiments at subbarrier energies. Our results with ^{16}O and ^{19}F projectiles on ^{232}Th at energies of $(0.83-0.95)V_{CB}$ show predominantly two-proton and one-proton stripping, respectively, and the relative yields are in qualitative agreement with a simple calculation. Similar calculations for ^{86}Kr and ^{136}Xe projectiles suggest little transfer-induced fission because of the near-zero or negative Q-windows involved, while there is little probability of pure Coulomb fission with Kr particles. Yet the fission cross sections observed are similar for ^{16}O, ^{86}Kr, and ^{136}Xe. We would like to suggest that with the heavy ions, fission occurs as a result of the combination of Coulomb excitation and excitation from the tail of the Q window for particle transfer, the relative amounts changing toward more Coulomb excitation as one goes from light to heavy projectiles and to lower bombarding energy. For oxygen the process is primarily transfer induced; it would seem both processes are necessary with Kr, and the same is probably true with Xe. At least it seems difficult with Xe to speak of a pure Coulomb-induced or transfer-induced fission in the range $(0.85-1.0)V_{CB}$.

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Influence of Deformation upon Light-Particle Emission from High-Spin States in Nuclei

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We examine changes in light-particle emission from high-spin states in nuclei arising from a deformation dependence of the transmission coefficients. These changes are large enough to have measurable influences upon decay-product characteristics; consequently, the use in statistical models of transmission coefficients representative of spherical nuclei is probably inadequate.

Many investigations are in progress involving analyses of heavy-ion–reaction decay-product characteristics such as γ-ray multiplicities, particle multiplicities, total fusion cross sections, and the division of the fusion cross section between the formation of fission and evaporation-residue products (see, e.g., Hillis *et al.*,[1] Eyal *et al.*,[2] Gould *et al.*,[2] and Britt *et al.*[3]). The decay products of greatest current interest are those resulting from de-excitation from high-spin states. Nuclei at high angular momenta are predicted[4] to be highly deformed, and this has been incorporated in part into descriptions of the statistical rotating-liquid-drop model (see, e.g., Beckerman and co-workers[5-8]) of the decay process through the introduction of rotational energies of saddle-point and equilibrium deformed nuclei. While considerable attention[5-8] has been

