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SUBCOULOMB FISSION INDUCED BY Xe AND Kr IONS*

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ABSTRACT

Excitation functions have been measured for fission of ^{232}Th and ^{238}U induced by ^{86}Kr and ^{136}Xe beams at energies around the Coulomb barrier. Fission events were detected in coincidence with the backscattered projectiles. The results suggest that Coulomb fission is occurring in the Xe + U reaction.

Coulomb fission is one possible consequence of the excitation of nuclei by the Coulomb interaction between two very heavy ions. Observation of this phenomenon would be very interesting since it can provide information on the variation of the collective potential energy surface as a function of deformation up to the saddle point. Coulomb fission could occur in the presence of the projectile if the target nucleus is distorted in a sufficiently adiabatic process (for example the excitation of high frequency modes like the giant quadrupole resonance). The process would be less adiabatic if low frequency modes (like β vibrations) are excited. For these latter processes, however, the collective motion would probably be damped,[3] and the fission probabilities would be reduced. Most theoretical calculations[1-4] assume E2 excitation of low-lying β vibrational states, but do not take damping into account. They indicate that Coulomb fission is likely to occur only when heavy projectiles (e.g., Xe) interact with easily fissionable targets. Predicted values of fission cross-sections near the Coulomb barrier for Xe + U range from 0.1 to 100 mb/sr for back-scattered projectiles. Previous attempts to observe Coulomb fission with Kr and lighter ions have failed.[5-7]

This paper gives the results of a study of the fission of ^{238}U and ^{232}Th by Xe and Kr ions at incident energies close to the Coulomb barrier. At these energies processes acting through the tail of the nuclear force (e.g., nuclear inelastic scattering, quasi-elastic transfer, quasi-fission) can supply enough excitation energy to induce fission. In order to differentiate Coulomb fission from these processes, we have compared the excitation functions of Xe- and Kr-induced reactions on ^{238}U and ^{232}Th, since for incident energies below the Coulomb barrier the excitation functions are expected to be sensitive to the admixture of Coulomb fission. The Coulomb fission cross-section is also expected to depend strongly on the fission barrier, and thus a comparison of these two targets with different barriers (e.g., the barrier height is ≃5.8 MeV for ^{238}U, ≃6.0 MeV for ^{232}Th)[8] may give additional information. In a control experiment, a ^{197}Au target was irradiated since in this case, the height of the fission barrier (≃20 MeV) makes fission much less likely.

The experimental detection system was designed so as to maximize the geometric efficiency for detecting two correlated fission fragments in coincidence with the backscattered projectile. This projectile was detected in an annular silicon counter subtending a solid angle of about 0.5 sr, and for all reactions the average detection angle was 164° in the center of mass system. The fission products were detected in another annulus composed of four 70° sectors, centered on the beam axis, each sector consisting of a 1.5×1 cm Si(P) detector. All detectors were covered with a 1.1 mg/cm^2 Au foil. The detectors subtended at the target a range in θ from 24 to 38° for Xe + U and from 28° to 42° for Kr + U. The wide acceptance angle in θ and ϕ of each fission counter ensured that the probability of detecting both fission fragments was high, even though the fissioning heavy product does not recoil exactly along the beam axis. Assuming asymmetric fission and an isotropic angular distribution of the fragments, the overall fission detection efficiency was ≈5% for a Xe + U reaction, ≈8% for Kr + U. Both timing and energy related signals from the fission detectors were recorded event by event following coincidences between each pair of fission detectors (six combinations in all). The corresponding signals from the backscatter counter were recorded whenever there was a triple fission-fission-backscatter coincidence.

The ^{136}Xe and ^{86}Kr beams were produced by the Lawrence Berkeley Laboratory SuperHILAC accelerator. Excitation functions were measured for all reactions at energies ranging from 90 to 105% of the Coulomb barrier E_c, calculated with an interaction radius $R_c = 1.16\ (A_1^{1/3} + A_2^{1/3} + 2)$ fm. The ^{238}U targets were 1.3 mg/cm^2 thick on a 0.6 mg/cm^2 Al backing, The ^{232}Th targets were 2 mg/cm^2 thick, self-supporting. The energy loss in the target for a 700 MeV Xe beam was ≈30 MeV for U and ≈45 MeV for Th.

Typical energy spectra of events observed in the fission counters, in coincidence with the opposite one and the backscatter detector, are shown on Fig. 1 for the reaction Xe + U at 750 MeV. (For comparison the singles spectrum of the forward-scattered Xe ions is shown also in Fig. 1.) The following facts indicate that the observed events are due to fission: (1) The energy spectrum from each fission detector (Figs. 1a,b) is very broad. (2) The spectrum of the sum of the energies for correlated events (Fig. 1c) is much narrower, and the mean energy is consistent with the total energy expected from the fission of a heavy nucleus like ^{238}U after a quasi-elastic collision with a Xe ion. (3) Almost all observed triple coincidences were detected in opposite detectors. Such triple coincidences were observed with both projectiles on ^{238}U and ^{232}Th, with the same characteristic features of fission events. However, very few events were observed with the ^{197}Au target; for example, only 2 at 691 MeV, 1 at 665 MeV for Xe + Au. Assuming these few events are due to fission, the cross-sections are about a factor of 50 smaller than for Xe + U. Similarly the cross-sections for the Kr + Au reaction are a factor of 100 smaller than for Kr + U. These results are consistent with the lower fissility of Au and the neighboring nuclei which can be reached by transfer reactions.

The differential cross-sections for the triple events can be calculated if the angular distribution and the mass asymmetry of the fission fragments are specified. Since triple coincidence events were observed with both Kr and Xe, one can assume that processes involving nuclear forces are predominant. The angular distribution of the fission fragments emitted in such processes is likely to be approximately $1/\sin\theta$ with respect to the symmetry axis of the collision.[9] Furthermore, it seems reasonable to assume a mass asymmetry similar to the one observed for the fission of ^{238}U at low excitation energy. The cross-sections for Xe + U, Xe + Th, Kr + U, Kr + Th were calculated according to these assumptions. Corrections for the target thickness and the beam energy spread were made. The absolute cross-sections were estimated by normalizing to the Rutherford scattering observed in the backscattered detector at the lowest energy for each reaction, and then scaling to higher energies according to the integrated beam current collected during each experiment.

Figure 2 shows the excitation functions at 164° (c.m.) for the different reactions. The most striking feature is the very large cross-section observed below the barrier for Xe + U, as compared to Kr + U. A smaller difference is observed between Xe + Th and Kr + Th. In contrast, cross-sections for Kr + U and Kr + Th look similar in the whole energy range. These features of the excitation functions suggest that a process strongly dependent on the charge of the projectile and the fission barrier is taking place. This cannot be explained easily by consideration of the effects of nuclear interactions. For example, the Q values for one- or two-nucleons transfer reactions induced by Xe on U and Th are very similar, and this is also true for the Kr induced reactions. Therefore, one cannot explain by such considerations why the Xe cross-sections on U and Th are so different whereas the Kr ones are not. On the other hand, the dependence on the strength of the Coulomb interaction and the fission barrier are quite consistent with the suggestion that some Coulomb fission occurs for the Xe + U reaction.

The cross-section for the Xe + U reaction at 668 MeV (92% of the barrier calculated with our choice of R_c) is 2.2 mb/sr at 164° (c.m.) and from comparison with the Kr + U cross-section it is apparent that most of it could be due to Coulomb-induced fission. If Coulomb fission occurs in the presence of the projectile, the angular distribution of fission fragments would, however, not have a $1/\sin\theta$ form, but would probably be peaked at 90°. In this case our detection efficiency would be about three times larger, leading to a cross-section of about 0.6 mb/sr at 668 MeV. The fission cross-sections for Kr + U are in disagreement with the upper limit given in Ref. 6. This discrepancy is probably due to the very low efficiency of their set up.

It is evident from our data that the cross-sections obtained are due to fission following an almost elastic collision. The data are consistent with the suggestion that Coulomb fission is occurring for the Xe + U reaction, although we cannot completely exclude all other processes leading to fission. These cross-sections are of interest since they are at least a factor of five smaller than the most recent theoretical estimate,[4] which predicts $d\sigma/d\Omega$ (180°) ≃ 10 mb/sr for Xe + ^{238}U at an incident energy of ≃670 MeV. The next step would be to prove beyond any doubt that these events do correspond to Coulomb-induced fission. This might be done either by measuring the angular distribution of the fission fragments or by identifying the backscattered projectile (e.g., by observing a radiative transition in the projectile following Coulomb excitation). Such experiments are feasible despite the low observed cross sections.

FOOTNOTES AND REFERENCES

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FIGURE CAPTIONS

Fig. 1. Energy spectra in the forward fission detectors for the reaction $^{136}Xe + ^{238}U$ at 750 MeV. (a) Spectrum of events in a single detector in coincidence with the opposite detector and the backscatter detector. (b) The corresponding spectrum in the opposite detector. (c) Spectrum of the sum of the fission energies for correlated events. (d) Singles spectra showing the elastic peak from the forward scattered Xe ions.

Fig. 2. Differential cross-sections (in c.m.) at 164° (c.m.) for ^{86}Kr, ^{136}Xe induced fission of ^{232}Th and ^{238}U as a function of the bombarding energy. The incident energy E is expressed as a fraction of the Coulomb barrier E_c (E_c(lab) is 439 MeV for $^{86}Xe + ^{232}Th$, 444 MeV for $^{86}Kr + ^{238}U$, 720 MeV for $^{136}Xe + ^{232}Th$, 727 MeV for $^{136}Xe + ^{238}U$). The cross sections were calculated assuming the fission fragments have an asymmetric mass distribution and their angular distribution has a 1/sinθ form. The curves are drawn only to guide the eye.

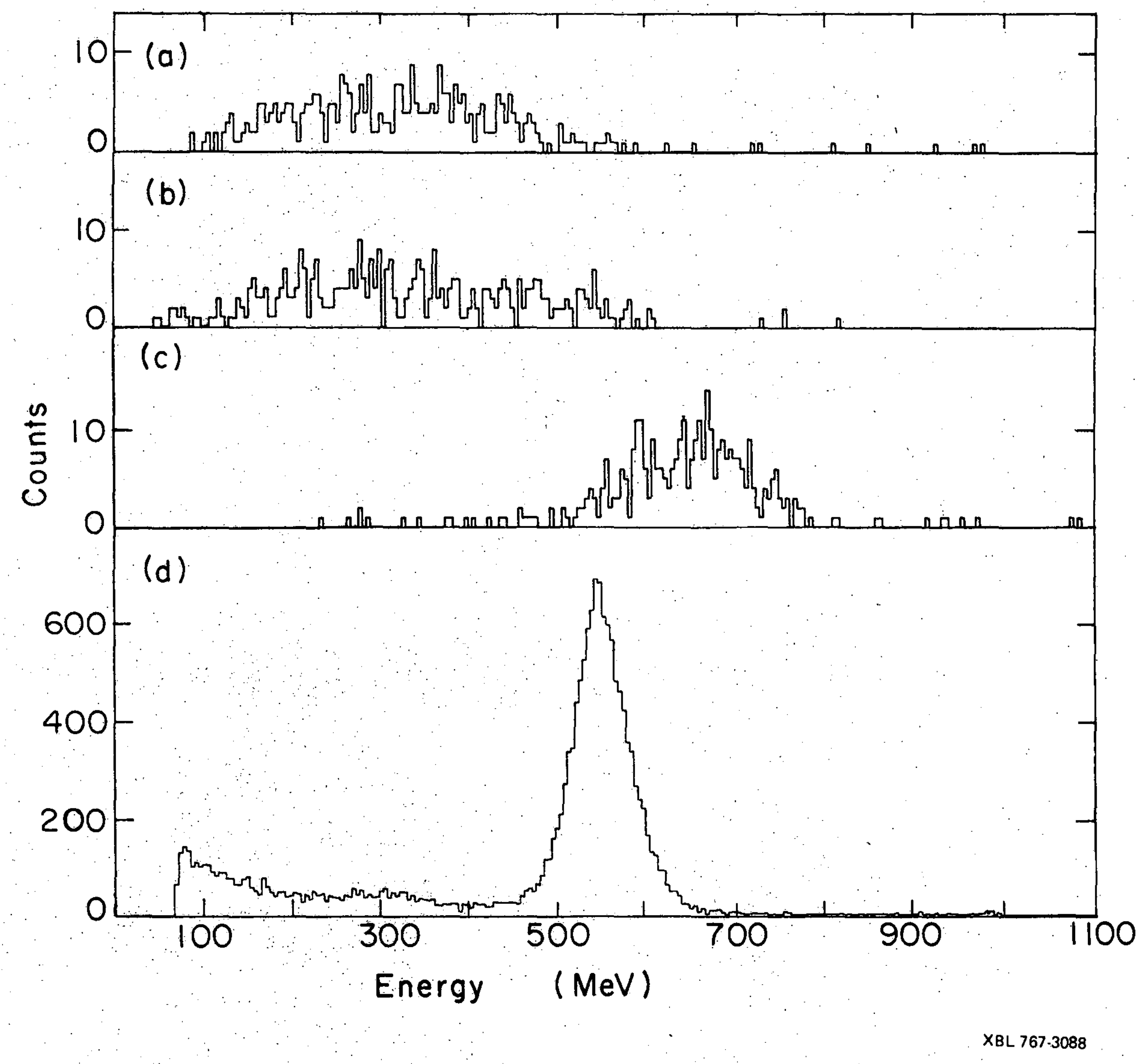
(a)
(b)
(c)
(d)
10
0
10
0
10
0
600
400
200
0
Counts
100
300
500
700
900
1100
Energy (MeV)
XBL 767-3088

Fig. 1

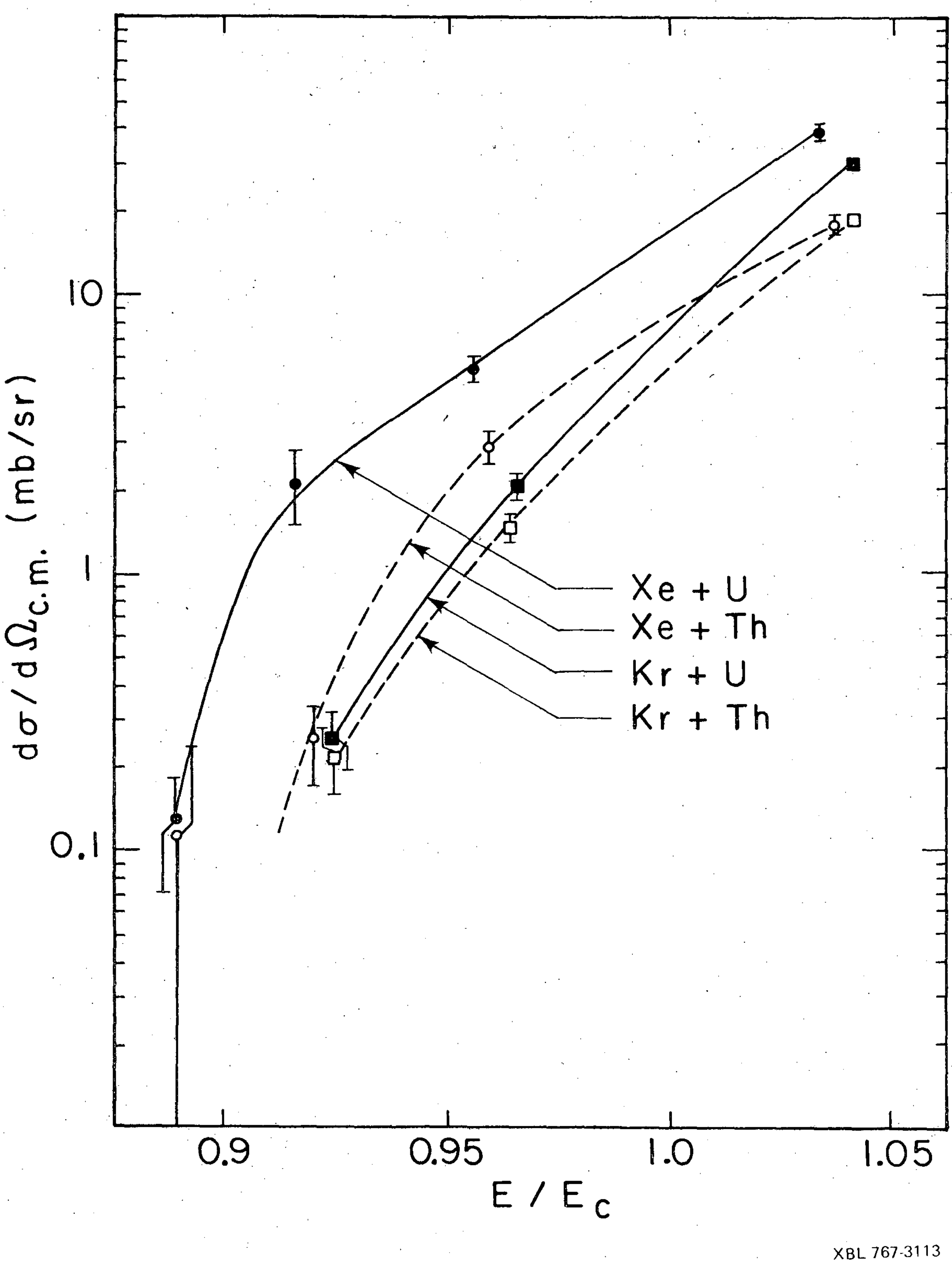
10
1
0.1
dσ / d Ω c.m. (mb/sr)
0.9
0.95
1.0
1.05
E / Ec
Xe + U
Xe + Th
Kr + U
Kr + Th
XBL 767-3113

Fig. 2

0 0 3 0 4 5 0 4 4 2 4

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