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MUON INDUCED PHOTOFISSION IN ^{235}U AND ^{238}U *

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Abstract

Nonradiative nuclear excitation resulting in muon-induced prompt fission was studied by measuring fissions in coincidence with muonic X-rays. Both 2→1 and 3→1 nonradiative transitions appear to contribute significantly to prompt fission. In contradiction to recently reported results, it was found that at least 60% of the prompt fissions are induced by dipole transitions.

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A negative muon captured into an atomic orbit of an actinide nucleus cascades eventually to the muonic 1s state either by emission of an X-ray or by the nonradiative transfer of a virtual photon to the nucleus. In uranium, such nuclear excitation is sufficiently energetic to lead to fission in prompt time with the muon stop. The theory of the nonradiative excitation process, and its relationship to photoabsorption, was developed by Zaretski and Novikov [1], who considered the prompt nuclear excitation only through the dipole interaction between the atomic muon and the nucleus. It has been suggested more recently [2] that, in addition to the 2p→1s dipole, the 3d→1s quadrupole and 3p→1s dipole transitions might make some contribution to the prompt fission yield. The present experiment was undertaken to investigate the role of specific nonradiative transitions in inducing prompt fission.

The measurement was made using the velocity-separated cloud muon beam from the TRIUMF M9 channel. The signal for a muon stopping in the multiplate fission chamber was obtained from a conventional four-scintillator telescope, and a time-of-flight gate was used to identify muons in the beam from the small pion and electron contaminations. The multiplate fission chambers each consisted of a stacked sandwich of propane-filled parallel-plate avalanche chambers and aluminum foils on which UF_4 had been evaporated [3,4].

The complete time correlation of the muon stop, fission and muonic X-rays detected with three NaI(Tℓ) detectors (15.2 cm × 12.7 cm diam) was measured. Typical fission time distributions with and without X-ray conicidences are shown in fig. 1. In the fission X-ray coincidence data there is, of course, a background from nuclear gamma rays. It is reasonable to suppose that this gamma spectrum is independent of whether the fission is prompt or delayed. Therefore, we have applied a background correction to the prompt fission X-ray spectrum derived from the gamma rays in coincidence with delayed fissions.

Following a K_α X-ray, the muon reaches the 1s state and only delayed fissions are possible from nuclear muon capture. As expected, the yields of prompt fissions [(0±14)% for ^{235}U and (9±9)% for ^{238}U] observed in coincidence with K_α X-rays were consistent with zero. The yield of prompt fissions in coincidence with 3d→2p (L_α) X-rays was considered to be produced via the 2p→1s nonradiative E1 transition. It was observed that

(60±13)% and (60±10)% of the prompt fissions in ^{235}U and ^{238}U, respectively, were produced from the muonic 2p→1s dipole nonradiative nuclear excitation. The rest, (40±13)% in ^{235}U and (40±10)% in ^{238}U, were therefore produced from the 3p→1s dipole and 3d→1s quadrupole excitations (neglecting the very small contribution from higher-order transitions).

In the recent SIN measurement [5], it was found that only about (26±15)% of the prompt fissions in ^{238}U were produced by 2p→1s dipole nonradiative nuclear excitation, whereas the rest, (74±15)%, were attributed only to the 3d→1s transitions. For the prompt fissions that originate from the 3d→1s transition, the muons in the 3d states would make radiationless transitions by exciting the nucleus via the E2 giant resonance [2]. Although this resonance has been seen in heavy ion scattering and electron-induced fission experiments, the probability with which it leads to fission is controversial [6-8].

To determine the absolute prompt fission yield, the delayed fission yield per muon stop must be known. Since the previous results [9-12] for this yield exhibit a large variation up to a factor of five, we have used the most recent value [4,9] in our calculation. A summary of the absolute fission yields and lifetimes obtained from the present data [4] are shown in table 1.

In the present measurement, the absolute yield of prompt fissions originating from the 2p→1s transition was found to be about 1%. Using the ratio of nonradiative to total width [2], the photofission probability [13-15] at the energy of the muonic 2p→1s transition (~6-6.5 MeV), and assuming unit probability for the population of the 2p state during the muon cascade, one calculates a fission yield per muon stop of about 5%. As has already been pointed out, however [1,16], the presence of a 1s muon raises the fission barrier by about 0.6 MeV over the normal barrier of 6 MeV. This enhancement of the barrier is undoubtedly the principal reason for the sharp inhibition in the experimental prompt fission yield [4,9,11,12].

In our X-ray spectrum from the NaI detectors, we could not resolve the relative contributions of the 3p→1s and the 3d→1s transitions. Based on the estimated population of the non-circular 3p orbit [2], the photofission yield at 9-12 MeV [15], and the nonradiative-to-total width [2], we calculated the fission yield for the 3p→1s transition to be twice the total measured yield for the 3→1 transition. Furthermore, because the 3→1 transition energy is far above the fission barrier, we would expect little, if any, inhibition due to the muon-induced barrier shift. If we consider the uncertainties present in the calculation and the measurement, the calculated fission yield from the 3p→1s transition is consistent with our measured value for the 3→1 transition. Therefore, we conclude that there is no clear evidence for the significant contribution of the 3d→1s transition in inducing prompt fission as was claimed in recent results from SIN [5].

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Table 1

Results of fission yields and lifetimes of ^{235}U and ^{238}U.

Measurements	^{235}U	^{238}U
Mean lifetime (ns)	71.6 ± 0.6	77.2 ± 0.4
$\frac{\text{Prompt}}{\text{Delayed}}$ fission yield	0.133 ± 0.006	0.093 ± 0.005
Absolute fission yield per muon stop (%)	14.8 ± 2.6	7.5 ± 1.0
Delayed fission yield per muon stop (%)	13.1 ± 2.6	6.9 ± 1.0
Prompt fission yield per muon stop (%)	1.74 ± 0.36	0.64 ± 0.10
$\frac{\text{Prompt fission} * K_\alpha \text{ X-ray}}{\text{Prompt fission}}$ (%)	0 ± 14	9 ± 9
$\frac{\text{Prompt fission} * L_\alpha \text{ X-ray}}{\text{Prompt fission}}$ (%)	60 ± 13	60 ± 10
$\frac{\text{Prompt fission} * 2\to1_{nr}}{\text{Muon stop}}$ (%) where $2\to1_{nr}$ = [2p→1s(E1)]	1.04 ± 0.31	0.38 ± 0.09
$\frac{\text{Prompt fission} * 3\to1_{nr}}{\text{Muon stop}}$ (%) where $3\to1_{nr} = \frac{3d\to1s(E2)}{3p\to1s(E1)}$	0.70 ± 0.27	0.26 ± 0.08

Figure caption.

Fig. 1. Muon induced fission time distributions in ^{238}U;

(a) with L_α X-ray coincidence

(b) with K_α X-ray coincidence

(c) without X-ray coincidence.

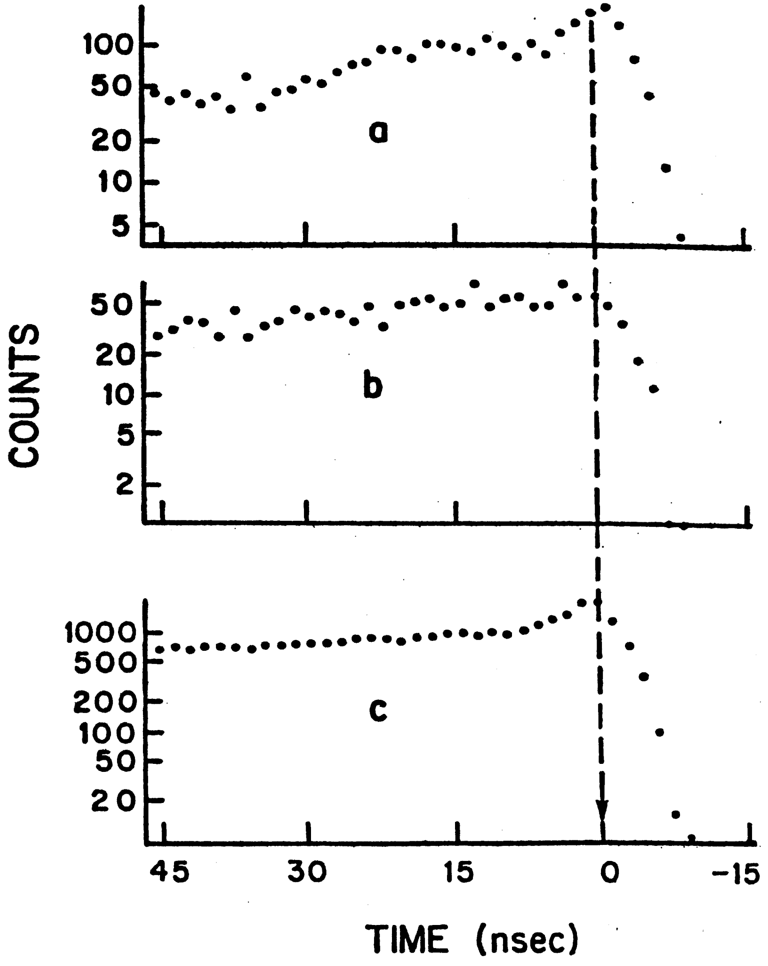

Fig. 1