MUON INDUCED QUADRUPOLE PHOTOFISSION

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ABSTRACT

Muonic X-rays were measured in coincidence with prompt fission in ^{238}U induced by radiationless transitions. The results demonstrate the dominating role of $3d \rightarrow 1s$ transitions.

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As pointed out first by Wheeler¹⁾ and later considered in more detail by Zaretsky and Novikov²⁾, the excitation of heavy nuclei due to radiationless transitions in muonic atoms can lead to fission. This process, which is normally treated as photoabsorption with subsequent fission, was first observed by Diaz et al.³⁾ for ^{238}U . Later some other actinides were studied^{4,5)}.

Hargrove et al.⁶⁾ studied the emission of neutrons when Pb and Bi were irradiated by muons. In their analysis of the neutron energy spectrum, it was shown that neutrons are emitted after the radiationless transitions $3d \rightarrow 1s$ or $3p \rightarrow 1s$ with a probability in Bi of about 0.07. Schneuwly et al.⁷⁾, as well as Lohs et al.⁸⁾, state more definitely that for Bi the $3d \rightarrow 1s$ radiationless transition is dominant. For the actinides the experimental data have so far been analysed neglecting all possible radiationless transitions except for $2p \rightarrow 1s$. This is certainly not justified.

The experiment to be reported here was designed to investigate the role of the different radiationless transitions. The results demonstrate for the first time that the $3d \rightarrow 1s$ radiationless transition is the dominant one for inducing fission. This conclusion is based on a comparison between the intensities of muonic X-rays measured in coincidence with fission. What we have seen is a weakening of some lines in the muonic X-ray spectrum for prompt fission induced by a radiationless transition. In the case of delayed fission due to nuclear muon capture, the X-ray spectrum is not influenced by the radiationless transitions and can thus be used for normalization.

The experiment was done in a muon beam at SIN. A conventional beam telescope was used for the muons which then entered a multiplate ionization chamber loaded with ^{238}U . For triple events ($\mu\gamma f$), the complete time correlation was measured as well as the energy spectrum of γ -rays, using a germanium detector. The energy spectra of muonic X-rays are shown in Fig. 1 for delayed and prompt fission, respectively. The spectra clearly exhibit lines which can be unambiguously identified as muonic X-rays of ^{238}U . In the spectrum of Fig. 1 the $2p \rightarrow 1s$ transition shows up as a bump at around 6 MeV. Although there can be no $2p \rightarrow 1s$ radiative transition in coincidence with prompt fission, it still appears in the spectrum. The

reason is that a certain fraction of delayed fission events fall into the time interval (± 5 ns) chosen to select prompt fission. The intensity in this bump is used to correct the other components in the X-ray energy spectrum accompanying prompt fission. The analysis is performed by taking the intensity ratio of prompt to delayed coincidences for the various X-ray transitions. In this way the γ -ray efficiency was eliminated and made the analysis straightforward. About 40% of the events for the $8 \rightarrow 7$, $7 \rightarrow 6$, $6 \rightarrow 5$, $5 \rightarrow 4$, and $4 \rightarrow 3$, and 70% of those for the $3d \rightarrow 2p$ transitions, were due to delayed fission.

Table 1 presents the ratios of the muonic X-ray intensities for prompt and delayed fission. The normalization made for the $6 \rightarrow 5$ transition assumes that radiationless transitions from $n \geq 6$ can be neglected. In fact, on the present level of statistics, such higher transitions cannot be excluded. One can see that the intensity of the $3d \rightarrow 2p$ transition is suppressed strongly in contrast to $4 \rightarrow 3$ and $5 \rightarrow 4$. This in fact means that for ^{238}U essentially the $3d \rightarrow 1s$ transition is responsible for prompt fission, since the contribution from the $3p \rightarrow 1s$ transition populated via the $3d$ level is negligible.

The intensity of the $3d \rightarrow 2p$ transition which populates the $2p$ state indicates how strongly the $2p \rightarrow 1s$ radiationless transitions contribute to the prompt fission events. The present data show that $(26 \pm 15)\%$ of all these events are due to these transitions. The remainder, $(74 \pm 15)\%$, can be attributed to $3d \rightarrow 1s$ radiationless transitions. If $4 \rightarrow 1$ or higher transitions should be taken into account, there would only be a small correction to this number.

The $3d \rightarrow 1s$ radiationless transition is a pure quadrupole photoabsorption, usually masked in experiments with photons by dipole photoabsorption. It is thus of interest to compare the fission probability for this type of muon-induced nuclear excitation to that known from experiments using photons.

In muon-induced fission the yield of prompt fission for ^{238}U is about 7% of that for delayed fission⁹⁻¹¹⁾. The values for the total fission yield per stopping muon are scattered in a broad range from 0.03 to 0.15⁹⁻¹²⁾. The most recent value, 0.068 ± 0.013 , obtained by Ahmad et al.¹¹⁾, gives a prompt fission probability per stopping muon of 0.0048 ± 0.0011 . Consequently, the fission probability for quadrupole photoabsorption $3d \rightarrow 1s$ is equal to 0.0036 ± 0.0013 per

stopping muon. This value is determined both by the probability of the radiationless transition $3d \rightarrow 1s$ and the competition between fission and neutron emission. In order to estimate the probability of the $3d \rightarrow 1s$ radiationless transition one can use the data on the yield of neutrons when ^{238}U is irradiated by muons¹³⁾. It should be noted that the analysis of Wilcke et al.¹³⁾ was based on the assumption that the emission of neutrons is mainly due to the $2p \rightarrow 1s$ transition. Assuming instead that all prompt neutrons are emitted due to $3d \rightarrow 1s$ radiationless transitions, which seems more plausible, this probability becomes about 0.15. Thus, the fission probability normalized to the $3d \rightarrow 1s$ radiationless transition is equal to $(2.4 \pm 0.6) \times 10^{-2}$. That gives a ratio of neutron to fission widths $\Gamma_n/\Gamma_f \approx 42$ which is about 10 times larger than Γ_n/Γ_f measured with monoenergetic photons, in the energy range 7-11 MeV¹⁴⁾.

The energy of the $3d \rightarrow 1s$ transition of about 9.6 MeV is on the tail of the very broad giant quadrupole resonance, centred for ^{238}U at 10.5 MeV. It is thus tempting to explain the small values of Γ_f observed in the experiments with muons as due to the hindrance of fission claimed by van der Plicht et al.¹⁵⁾. However, one has to keep in mind the augmentation of the fission barrier in the presence of the negative muon in the $1s$ orbit. As was shown by Leander and Möller¹⁶⁾, the outer fission barrier is increased by 0.8-1.2 MeV in the presence of a muon, for ^{236}U . The fission width, being proportional to the level density at the saddle point where it depends exponentially on the excitation energy, will be much smaller in the presence of a muon. The situation is different for $2p \rightarrow 1s$ radiationless transitions in muonic atoms. Since for dipole photoabsorption in the energy range 6.1-6.5 MeV only a few fission channels are open, fission would be suppressed by the exponential decrease of the fission barrier penetrability. For ^{238}U , Zaretski and Novikov²⁾ give an estimate of 0.24 for the probability of the radiationless $2p \rightarrow 1s$ transition. The corresponding fission probability then becomes 0.005 ± 0.004 , compared to 0.2-0.4 measured with monoenergetic photons. The statistical accuracy is not yet good enough to make it possible to evaluate the fission barrier augmentation due to the presence of the negative muon in the $1s$ orbit.

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Table 1

Ratios of muonic X-ray intensities
for prompt and delayed fission.
The normalization was made to the
6 → 5 transition.

Transition $n_i \rightarrow n_f$	Intensity ratios $I_{pr.f.}/I_{del.f.}$
8 → 7	1.01 ± 0.25
7 → 6	1.03 ± 0.16
6 → 5	1.00
5 → 4	1.02 ± 0.11
4 → 3	0.88 ± 0.13
3 → 2	0.26 ± 0.15
2 → 1	0

Figure caption

Fig. 1 : Muonic X-ray spectra from ^{238}U measured in coincidence with a) delayed fission induced by nuclear muon capture (black dots), and b) prompt fission induced by radiationless transitions (black triangles). The $2p \rightarrow 1s$ region is plotted with ten channels added, while in the other regions only two channels are added.

Fig. 1

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