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FISSION YIELDS AND LIFETIMES FOR MUON INDUCED FISSION IN $^{235}$U AND $^{238}$U

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The absolute yields of prompt and delayed fission induced by negative muons stopping in $^{235}\text{U}$ and $^{238}\text{U}$ have been measured. A coincidence with muonic $K\alpha$ x-rays was used to identify the muon stop in the target. The time distribution of fissions following the muon stopping were also obtained.

When a negative muon is captured into the atomic orbit of an actinide nucleus it undergoes an atomic cascade, ordinarily reaching the muonic $K$ shell through radiative transitions. The muon then disappears from the $K$ shell at a characteristic rate $\lambda = (75 \text{ ns})^{-1}$, which is the sum of leptonic decay rate and nuclear muon capture rate. The rate can be obtained by measuring the time distributions of emitted decay electrons, neutrons, capture $\gamma$ rays, or fission fragments relative to the muon arrival time at the target. Prompt nuclear excitation also occurs, arising from non radiative atomic transitions by some of the cascading muons. A fraction of these excitations will cause the nucleus to undergo prompt fission, leaving the muon attached predominantly to the heavier fragment. The corresponding disappearance rate of the muon attached to the fragment is observable in all decay channels except that for fission. Another fraction of the prompt excitations may populate an isomeric state of large deformation, whose decay rate contains components for fission and for $\gamma$ back decay to the less deformed ground state.

The prompt fission process was discussed in the pioneering work of Zaretski and Novikov, which related the prompt fission yields to photofission cross sections. They also pointed out that the change in the fission barrier
due to the presence of the ls muon will reduce the prompt yields. In uranium
the fission mode for the isomer is expected to be extremely weak because the
inner potential barrier is more transparent than the outer one\(^7\), especially in
the presence of the muon\(^5\). The delayed fission yields have also been calculated
from photofission and neutron-induced fission cross sections\(^8\).

Previous measurements\(^9\)\textsuperscript{−12} exhibit a large variation in the prompt
fission yield, \(y_p\) (of up to a factor of five), which indicates large systematic
uncertainties. In fission chamber experiments it is often difficult to estimate
the fraction of muons captured onto the thin actinide target, particularly if it
is in the form of a compound or mixture. In the present work we identify muon
capture onto U by requiring a muonic \(K_{\alpha}\) x ray to precede the fission event.
After applying a correction for the detection efficiency of the fission chamber,
the absolute yield for delayed fission is simply the ratio of coincidences to
total \(K_{\alpha}\) x rays. In addition, we have observed the time distributions for
fission of muonic \(^{235,238}\text{U}\), without coincidence, to determine the mean
lifetimes \(\tau_f\) and the prompt relative fission yields.

In the present measurements the muon beam from the M9 channel at the
TRIUMF meson facility was used. The muon-stop signal was obtained from a
four-scintillator telescope. In order to reduce the number of false stoppings a
large pulse was required in the thin scintillator immediately upstream of the
fission-chamber target. The time of flight over the 8 m distance from the meson
production target to the telescope was used to distinguish muons from pions and
electrons. Events for which two muon stops were registered within 1 \(\mu s\) were
rejected. Each of the multiplate fission chambers consisted of a stacked
sandwich of propane-filled parallel-plate avalanche chambers and uranium foils. The $^{238}\text{U}$ chamber contained 10 foils of 2 mg/cm$^2$ uranyl nitrate, depleted to 0.0276±0.0013% $^{235}\text{U}$, and deposited on an aluminized mylar substrate. The $^{235}\text{U}$ chamber contained 17 foils each with 0.6 mg/cm$^2$ of 95% enriched UF$_4$ vacuum sublimed onto a thin Al substrate. The fission detection efficiencies of (78±12)% for the $^{235}\text{U}$, and of (47±9)% for the $^{238}\text{U}$ chamber, were determined using slow neutrons from the University of California Research Reactor at Berkeley. The time resolution of the chambers, measured using a stopping $\pi^-$-beam, was 4 ns FWHM.

The x rays from the cascade of muons captured in U nuclei were detected in a large volume Ge(Li) detector placed 12 cm from the center of the fission chamber. All events in which a muon stopping was accompanied by an x ray or a fission were recorded on magnetic tape with a computer-based data acquisition system. From analysis of the coincidence data, delayed fission yields per $K_x$ x ray of $y_d = 0.125\pm0.023$ for $^{235}\text{U}$ and $y_d = 0.062\pm0.013$ for $^{238}\text{U}$ were obtained. The prompt-to-delayed fission ratios, $y_p/y_d$, were calculated from the time distributions shown in Fig. 1. These distributions were fitted with a function consisting of a prompt component, one or two exponentially decaying components, and a constant background, all convoluted with the Gaussian fission chamber resolution function. The $^{235}\text{U}$ data were well fitted over the full time range with a single mean lifetime, $\tau = (71.5\pm0.9)$ ns. However in $^{238}\text{U}$, in addition to the dominant component with $\tau = (76.0\pm1.3)$ ns, an additional component, $\tau' = (18\pm5)$ ns, with an integrated intensity of $(8\pm2)$% of the delayed fission, was required to obtain a satisfactory fit. The contribution from $\mu^-$-induced fission to the prompt peak is $<0.002$ per $\mu^-$ stop.

An additional analysis for $^{238}\text{U}$ was carried out by fitting, with a
single lifetime, the time ranges starting at 15, 25, 40 and 50 ns after the stop, and extending to 600 ns. The fitted mean lives, (74.6±0.6) ns, (74.9±0.6) ns, (75.7±0.7) ns, and (76.2±0.7) ns, respectively, showed an increase similar to the one reported by Ganzorig et al.\textsuperscript{13}). A short-lived component of similar intensity and lifetime (12±2 ns) was observed in the γ decay of muonic \textsuperscript{238}U by Fromm et al.\textsuperscript{5}) who ascribed it to isomer excitation; yet its contribution to the fission mode should be suppressed by several orders of magnitude\textsuperscript{5}). Further experiments are planned to investigate the origin of the short-lived component in the fission of muonic \textsuperscript{238}U.

In Table 1 we compare the yield ratios for prompt and delayed fission $\frac{y_p}{y_d}$ and the absolute fission yields $y_f$ with those from previous experiments\textsuperscript{9-16}). In \textsuperscript{235}U, where target thickness and efficiency corrections are small, our value for $y_f$ should be particularly reliable, indicating that the only other value, measured by Chultem et al.\textsuperscript{9}) is low by a factor of four. In \textsuperscript{238}U, where our efficiency correction is large and more difficult to measure our yield is still more than a factor of two larger than that of Chultem, but lower than the recent radiochemical determination by Baertschi et al.\textsuperscript{11}). A calculation of $y_d$ in \textsuperscript{238}U by Hadermann and Junker\textsuperscript{8}) predicts a value that is between our value and Baertschi's. The increased delayed yield in \textsuperscript{235}U follows their trend in $y_d$ vs fissility. The factor of three increase in $y_p$ from \textsuperscript{238}U to \textsuperscript{235}U is in contrast to the nearly equal photofission cross sections at the $\mu$ 2p-1s energy\textsuperscript{17}). This behavior can be qualitatively understood if one takes into account the effect of the 1s muon on the fission barrier.

In Table 2 the lifetimes for muonic \textsuperscript{235,238}U from the present and previous experiments \textsuperscript{5,9,13-15,18-22}) are summarized. Apparent differences in
these observed lifetimes as a function of the capture or decay product detected
have been ascribed both to admixtures of isomer-decay products\(^3\)) and to capture
or decay products from prompt-fission fragments\(^4\)). The results of Fromm\(^5\)
indicate that the effect of the isomer would be small. A systematic effect of
prompt fission on measured lifetimes would come about through fitting the muon
disappearance rate to a single exponential.

The mean lifetime measured in the electron mode is given by
\[
\tau_e = \tau + \beta_e \nu_p (\tau' - \tau),
\]
where \(\tau\) is the \(\mu\)-capture lifetime on uranium, \(\tau' \approx 130\) ns is the average lifetime
on the fission fragment, and \(\beta_e = \tau' / \tau\) is the decay-electron yield on the fragment
relative to that on uranium. Using our absolute prompt-fission yields, we obtain
\(\tau_e - \tau = (2.1 \pm 0.4)\) ns in \(^{235}\)U and \((0.6 \pm 0.2)\) ns in \(^{238}\)U. Lifetimes measured in the
neutron or \(\gamma\)-ray modes may be calculated by using for \(\beta_{n,\gamma}\) the ratios of the
neutron or \(\gamma\)-ray multiplicities from fragment \(\mu\) capture to those from uranium
capture. Since we would expect \(\beta_{n,\gamma} < 1\), the values \(\tau_{n,\gamma} - \tau\) will be
considerably smaller than \(\tau_e - \tau\).

The trend in Table 2 is to shorter lifetimes measured in the fission
mode. However, the size of the lifetime differences estimated above is smaller
than some of the measurements would suggest. It should also be noted that Table
2 invites comparisons of experiments with different sensitivities to unwanted
backgrounds, with fissions usually providing the least ambiguous signal. A
future fruitful approach to the observation of lifetime differences in muonic
actinides might be an extension of the present technique, namely the measurement
of the time distribution of the various decay products in coincidence with
x-rays from different stages of the atomic muon cascade. The high beam
intensities available from the present meson facilities should make such experiments feasible.

The authors are indebted to J. Gallant for his preparation of the $^{235}$U foils, to Dr. M. Michel of LBL for performing the mass spectrographic analysis of the U target material. We are grateful to A. Mireshghi for his assistance in the fission chamber calibrations and to Dr. W. C. Sperry for his help with the data collection. One of us (O.H.) wishes to express his appreciation to J.C.D. Milton for his interest and encouragement during the course of this work. This experiment was supported by the Natural Science and Engineering Research Council of Canada under grant IEP-11, and by the U.S. Department of Energy under contract W-7405-ENG-48.
References


Table 1

Fission yields $y_f$ per muon atomic capture and prompt-to-delayed fission ratios

<table>
<thead>
<tr>
<th>Nucleus</th>
<th>Fission probability prompt/delayed per muon stopping</th>
<th>Reference</th>
</tr>
</thead>
<tbody>
<tr>
<td>$^{235}\text{U}$</td>
<td>0.111±0.021</td>
<td>14) Diaz 1963</td>
</tr>
<tr>
<td></td>
<td>0.063±0.025</td>
<td>15) Budick 1970</td>
</tr>
<tr>
<td></td>
<td>0.170±0.010 0.037±0.009</td>
<td>9) Chultern 1975</td>
</tr>
<tr>
<td></td>
<td>0.138±0.009 0.142±0.023</td>
<td>present work</td>
</tr>
<tr>
<td>$^{238}\text{U}$</td>
<td>- 0.150±0.060</td>
<td>10) John 1953</td>
</tr>
<tr>
<td></td>
<td>- 0.070±0.030</td>
<td>11) Belovitskii 1960</td>
</tr>
<tr>
<td></td>
<td>- 0.070±0.008</td>
<td>14) Diaz 1963</td>
</tr>
<tr>
<td></td>
<td>0.072±0.014 0.070±0.008</td>
<td>15) Budick 1970</td>
</tr>
<tr>
<td></td>
<td>0.048±0.025 -</td>
<td>16) Rushton 1972</td>
</tr>
<tr>
<td></td>
<td>0.080±0.024 -</td>
<td>9) Chultern 1975</td>
</tr>
<tr>
<td></td>
<td>0.071±0.003 0.031±0.007</td>
<td>12) Baertschi 1978</td>
</tr>
<tr>
<td></td>
<td>- 0.150±0.030</td>
<td>present work</td>
</tr>
<tr>
<td></td>
<td>0.089±0.017 0.068±0.013</td>
<td>present work</td>
</tr>
<tr>
<td></td>
<td>0.074±0.013</td>
<td>present work</td>
</tr>
</tbody>
</table>

a) assume both delayed components follow K x-ray emission
b) assume only longest lifetime component follows K x-ray emission
## Table 2

Experimental Mean Lifetimes for Muonic $^{235, 238}$U

<table>
<thead>
<tr>
<th>Mode of Registration</th>
<th>$\tau (^{235}$U) (ns)</th>
<th>$\tau (^{238}$U) (ns)</th>
<th>Reference</th>
</tr>
</thead>
<tbody>
<tr>
<td>Decay electron</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>-</td>
<td>-</td>
<td>88±4</td>
<td>18) Sens 1959</td>
</tr>
<tr>
<td>78±4</td>
<td>81.5±2.0</td>
<td>19) Hashimoto 1976</td>
<td></td>
</tr>
<tr>
<td>75.4±2.9</td>
<td>73.5±2.9</td>
<td>20) Johnson 1977</td>
<td></td>
</tr>
<tr>
<td>Capture γ ray</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>-</td>
<td>79.5±0.5</td>
<td>21) Kaplan 1976</td>
<td></td>
</tr>
<tr>
<td></td>
<td>78.6±1.5</td>
<td>5) Fromm 1977</td>
<td></td>
</tr>
<tr>
<td>Neutron</td>
<td>75.0±0.7</td>
<td>78.3±1.0</td>
<td>22) Wilcke 1978</td>
</tr>
<tr>
<td>Fission</td>
<td>66.5±4.2</td>
<td>75.6±2.9</td>
<td>14) Diaz 1963</td>
</tr>
<tr>
<td></td>
<td>65.3±2.8</td>
<td>74.1±2.8</td>
<td>15) Budick 1970</td>
</tr>
<tr>
<td></td>
<td>75.6±2.3</td>
<td>76±1</td>
<td>9) Chultem 1975</td>
</tr>
<tr>
<td></td>
<td>-</td>
<td>77.1±0.2</td>
<td>13) Ganzorig 1978</td>
</tr>
<tr>
<td></td>
<td>71.5±0.9</td>
<td>76.0±1.3</td>
<td>present work</td>
</tr>
</tbody>
</table>

a) a short lifetime component ($\tau = 12±2$ ns) was also observed
b) a short lifetime component ($\tau = 18±5$ ns) was also observed
Figure Caption

Fig. 1. Time distributions of fission events relative to time of muon stopping in $^{238}$U and $^{235}$U. The solid curve is the least square fit to the data. (One channel corresponds to 2.926 ns.)