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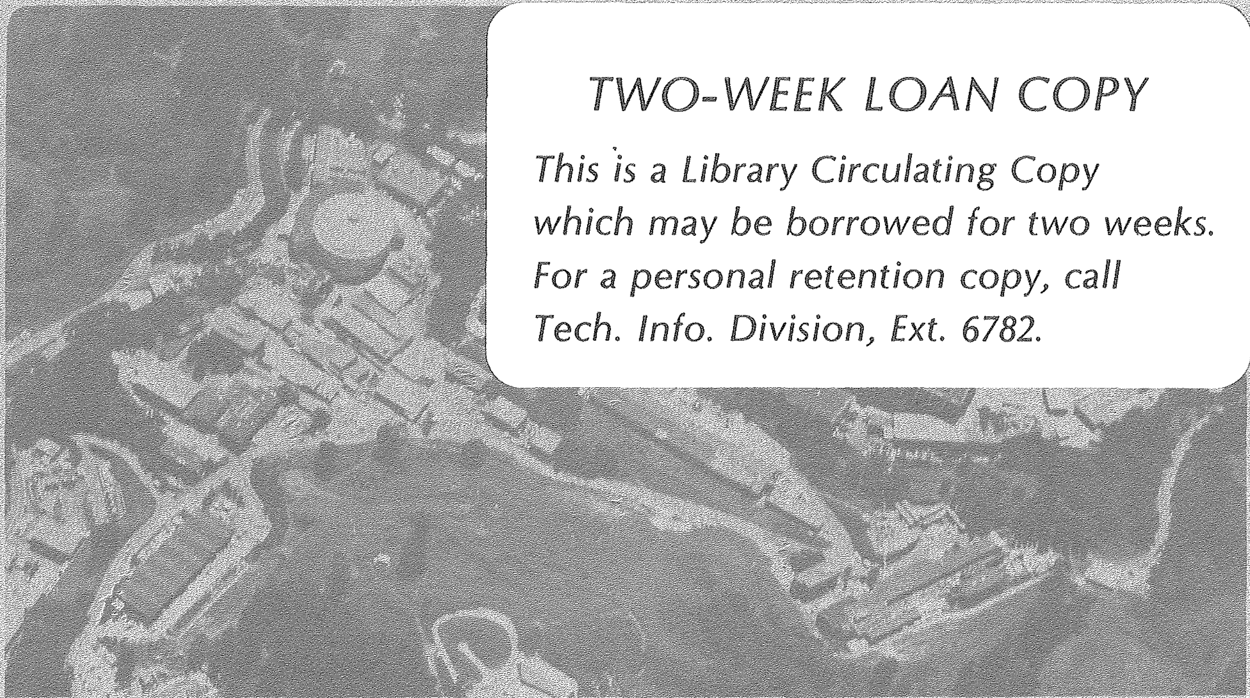

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FISSION YIELDS AND LIFETIMES FOR MUON INDUCED FISSION IN ^{235}U AND ^{238}U

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The absolute yields of prompt and delayed fission induced by negative muons stopping in ^{235}U and ^{238}U have been measured. A coincidence with muonic K_α 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 λ ($\simeq(75\ \mathrm{ns})^{-1}$), 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 γ 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$^{1,2)}$. 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$^{3-5)}$, whose decay rate contains components for fission and for γ back decay to the less deformed ground state.

The prompt fission process was discussed in the pioneering work of Zaretski and Novikov$^{6)}$, 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 1s 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 fisson yields have also been calculated from photofission and neutron-induced fission cross sections$^{8)}$.

Previous measurements$^{9-12)}$ 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_α 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_α x rays. In addition, we have observed the time distributions for fission of muonic ^{235,238}U, without coincidence, to determine the mean lifetimes τ_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 μs 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}U chamber contained 10 foils of 2 mg/cm^2 uranyl nitrate, depleted to 0.0276±0.0013% ^{235}U, and deposited on an aluminized mylar substrate. The ^{235}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 efficiences of (78+12)% for the ^{235}U, and of (47±9)% for the ^{238}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 π^--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_α x ray of $y_d = 0.125 \pm 0.023$ for ^{235}U and $Y_d = 0.062 \pm 0.013$ for ^{238}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 exponentally decaying components, and a constant background, all convoluted with the Gaussian fission chamber resolution function. The ^{235}U data were well fitted over the full time range with a single mean lifetime, $\tau = (71.5 \pm 0.9)$ ns. However in ^{238}U, in addition to the dominant component with $\tau = (76.0 \pm 1.3)$ ns, an additional component, $\tau' = (18 \pm 5)$ ns, with an integrated intensity of (8±2)% of the delayed fission, was required to obtain a satisfactory fit. The contribution from π^--induced fission to the prompt peak is <0.002 per μ^- stop.

An additional analysis for ^{238}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.[13]. A short-lived component of similar intensity and lifetime (12±2 ns) was observed in the γ decay of muonic ^{238}U by Fromm et al.[5] who ascribed it to isomer excitation; yet its contribution to the fission mode should be suppressed by several orders of magnitude[5]. Further experiments are planned to investigate the origin of the short-lived component in the fission of muonic ^{238}U.

In Table 1 we compare the yield ratios for prompt and delayed fission y_p/y_d, and the absolute fission yields y_f with those from previous experiments[9-16]. In ^{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.[9] is low by a factor of four. In ^{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.[11]. A calculation of y_d in ^{238}U by Hadermann and Junker[8] predicts a value that is between our value and Baertschi's. The increased delayed yield in ^{235}U follows their trend in y_d vs fissility. The factor of three increase in y_p from ^{238}U to ^{235}U is in contrast to the nearly equal photofission cross sections at the μ 2p-1s energy[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 ^{235,238}U from the present and previous experiments [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

$$\tau_e = \tau + \beta_e y_p(\tau' - \tau),$$

where τ is the μ-capture lifetime on uranium, $\tau' \simeq 130$ 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 ± 0.2) ns in ^{238}U. Lifetimes measured in the neutron or γ-ray modes may be calculated by using for $\beta_{n,\gamma}$ the ratios of the neutron or γ-ray multiplicities from fragment μ capture to those from uranium capture. Since we would expect $\beta_{n,\gamma} \lesssim 1$, 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.

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Table 1

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

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

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 $^{235,238}U$

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

a) a short lifetime component (τ = 12±2 ns) was also observed
b) a short lifetime component (τ = 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.)

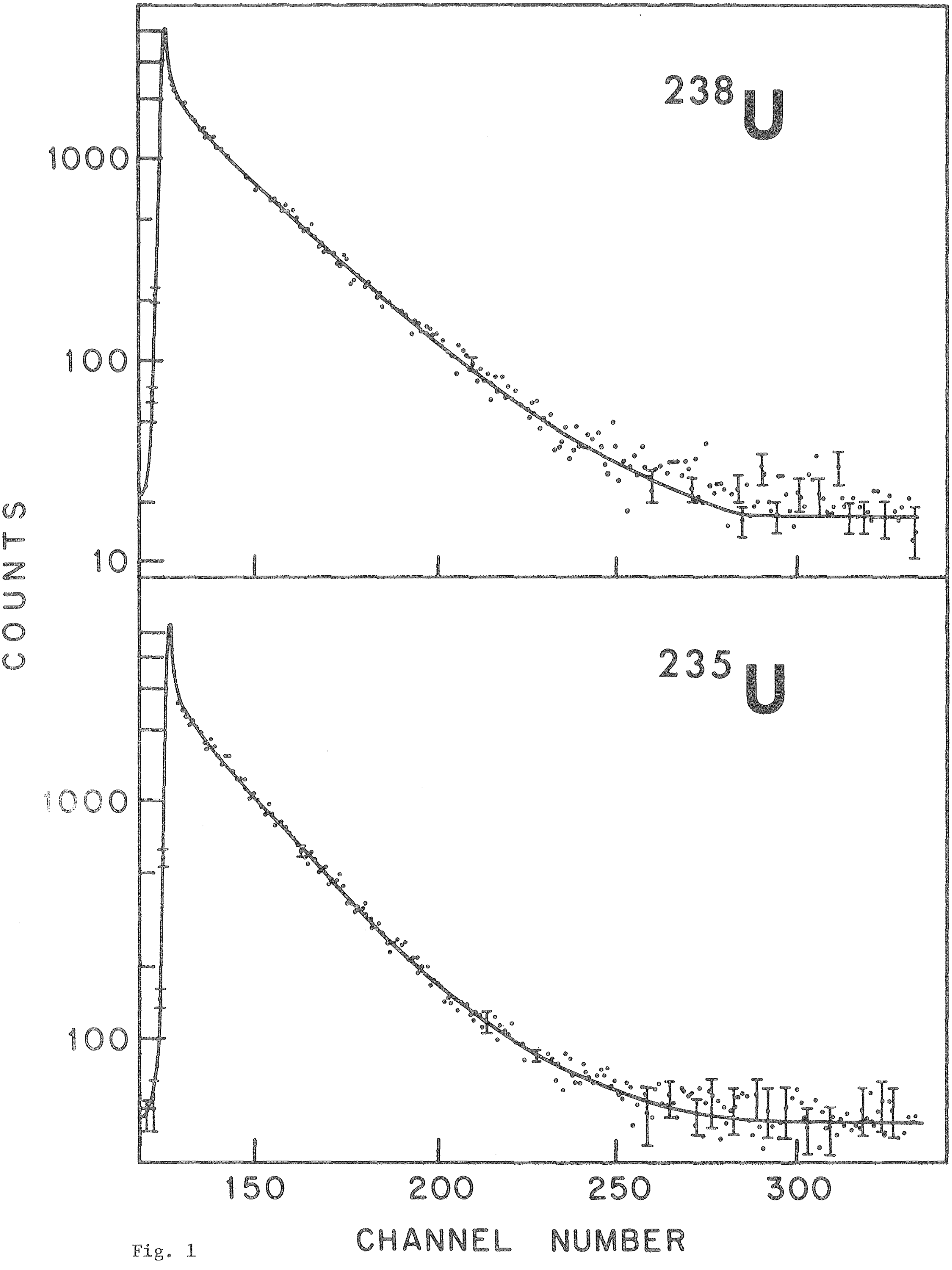
238U
235U
1000
100
10
1000
100
COUNTS
150
200
250
300
CHANNEL NUMBER

Fig. 1