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TOTAL MUON CAPTURE RATES IN ACTINIDE NUCLEI*

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ABSTRACT

Lifetimes of negative muons bound to ^{232}Th, ^{235}U, ^{238}U and ^{239}Pu have been determined to be 80.4 ± 2.0 ns(^{232}Th), 78 ± 4 ns(^{235}U), 81.5 ± 2.0 ns(^{238}U) and 77.5 ± 2.0 ns(^{239}Pu) by observing decay electrons from muons. Systematics of total muon capture rates is discussed. They are also compared with the lifetimes determined by fission fragments in view of possible fission-isomer excitation by muons.

In actinide nuclei several lifetime measurements of bound muons have been reported [1-6], but there are significant disagreements among them. They were carried out mostly by observing fission fragments after muon capture, except in ^{238}U where the lifetime was determined also through the detection of electrons emitted from muons. In order to study the systematics of total muon capture rates in this actinide region in more detail we have measured lifetimes of muons bound to ^{232}Th, ^{235}U, ^{238}U and ^{239}Pu through the detection of electrons. Another intention of this experiment is to look for any difference between τ_e (lifetime viewed through the electron decay mode) and τ_f (lifetime viewed through the fission mode) , since recently Bloom [7] pointed out that there could be a difference between τ_e and τ_f for ^{238}U due to the presence of a fission isomer ($\tau \sim 195$ ns) in ^{238}U which might be populated by the radiationless muonic 2p → 1s transition.

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The experimental set-up and the procedure of measurements were the same as those reported before [8]. Muons from the 184" Cyclotron at LBL were stopped in a metallic target of 6.3 cm height, 7.6 cm width and thickness of 7.3 g/cm^2 for ^{232}Th, 6.7 g/cm^2 for ^{235}U, 12.4 g/cm^2 for ^{238}U and 10.1 g/cm^2 for ^{239}Pu. The target was placed in an external magnetic field of 9.4 kOe (^{235}U and ^{238}U) or 6.8 kOe (^{232}Th and ^{239}Pu) to wipe out possible angular-distribution effects of decay electrons on the time spectrum. In order to reduce random coincidence rate, the beam intensity was kept sufficiently low; the stopped muon events were about 3000 /sec and the decay electron events were 10-30 /sec. The time interval between stopped muon and its decay electron was measured by a digitized clock counter (HP 5360A) and recorded by a PDP-15 computer. In the fast logic the decay electron signal, which was anti-gated at time zero by many counters, might be slightly suppressed in the early part of the time spectrum up to a few 10 ns. Therefore, in the case of ^{238}U, we measured time spectra for a carbon target and the ^{238}U target alternately every few hours in order to correct for possible distortion in the early part of the time spectrum.

A typical time spectrum for ^{238}U is shown in Fig. 1. It involves two components of exponential decays, the short-lived component from muons bound to ^{238}U and the long-lived one from those stopped in surrounding counters. The latter component is one tenth the true signal of μ^-U. We fitted the raw time spectrum by a function of $N_1\exp(-t/\tau) + N_2\exp(-t/\tau_L) + B$, and obtained $\tau =$ 81.5 ± 1.5 ns as a preliminary value. Furthermore, we have done a more extended analysis. First, the time spectrum was analyzed from t_0 to t_0+4 μs with various values of t_0 (from 20 ns to 160 ns) in order to exclude possible distortion effect on the time spectrum. Second, the time spectrum for the ^{238}U was divided by the time spectrum for the carbon target to obtain a normalized time spectrum. Third, the effect of the long-lived component was examined by artificially changing τ_L between τ_L(best fit) ± 100 ns. Even after these analyses the value of τ stayed within ± 1.0 ns. Taking into account these possible systematic errors we finally obtained $\tau_e(^{238}\text{U}) = 81.5 \pm 2.0$ ns, which is shorter than the lifetime reported by Sens [5] ($\tau_e = 88 \pm 4$ ns). Similar analyses were done for ^{232}Th, ^{235}U and ^{239}Pu, and the results were summarized in Table 1 together with several reported values of τ_f.

The total muon capture rate, $\Lambda_c(A,Z)$, which is equal to $1/\tau - 1/\tau_{free}$, is given by the Primakoff gross theory [9] as

$$\Lambda_c(A,Z) = \text{const.} \langle\rho\rangle[1 - \delta(A-Z)/2A] \qquad (1)$$

where δ is the nuclear correlation parameter and $\langle\rho\rangle$ is an overlap of muon and nuclear charge. Reduced capture rates, $\Lambda_c/\langle\rho\rangle$, are tabulated in the last column of Table 1, and they are plotted in Fig. 2 as a function of $(A-Z)/2A$. The solid straight line in Fig. 2 corresponds to $\delta = 3.12$ with $\chi^2/\overline{\chi}^2 = 11.4$ which was obtained from the best fit for relatively high-Z elements from Ca to ^{239}Pu [81 data, $(A-Z)/2A$ ranged from 0.2506 to 0.3068]. We excluded odd-mass elements in light-mass region in order to make systematics free from the hyperfine effect. Roughly speaking, our data fall on a straight line as expected from the Primakoff theory. In actinide nuclei, however, the reduced capture rates in the electronic decay mode are less dependent on $(A - Z)/2A$. In the case of $(A - Z)/2A = 1/\delta \sim 0.32$, the formula (1) may not be physical because it would give a vanishing capture rate. Our observation suggests that $\Lambda_c(A,Z)$ needs to be expressed by including additional terms. Very recently, Goulard and Primakoff [10] derived a new formula which contains an A/Z term as

$$\Lambda_c(A,Z) = \text{const.} \langle\rho\rangle[\ 1 + \delta' A/Z - \delta''(A-Z)/2A] \qquad (2)$$

Using this three-parameter formula, we obtained a better agreement with the experimental data with $\delta' = 0.18$, $\delta'' = 4.66$ and $\chi^2/\overline{\chi}^2 = 9.3$. The result is plotted by dashed line in Fig. 2.

Next, let us discuss a possible difference between τ_e and τ_f for the ^{238}U case. The average value of τ_f so far reported is 75.8 ± 0.8 ns, which is a a little smaller than the present value of τ_e. Bloom [7] considered possible population of the fission isomer of ^{238}U ($t_{1/2} = 195$ ns) through the radiationless $2p \rightarrow 1s$ muonic transition of about 6 MeV, probability of which is known to be 0.23 ± 0.04 from the missing K x-ray intensity [11]. Population of this isomer would affect the apparent lifetimes of both fission and electron decay modes, because the isomer undergoes both spontaneous fission and muon capture and also populates the ground state which then decays into electron and fission. Taking into account these processes, Bloom derived a simple formula of ω_d defined by $\omega_d \equiv 1/\tau_f - 1/\tau_e$ to be

$$\omega_d = \frac{P}{1 - P} \frac{1}{\alpha} \frac{\omega_i}{\omega_c} \omega_i^f \tag{3}$$

where α is the fission probability per muon capture, P is the population probability of the fission isomer per stopped muon, ω_i is the isomeric decay rate, ω_c is the muon capture rate and ω_i^f is the spontaneous fission rate from the isomer. Using the experimental values of $\omega_i = 5 \times 10^6$ /sec [12], $\omega_c = 12 \times 10^6$ /sec (derived from our result of τ_e) and $\omega_i/\omega_i^f = 5 \sim 25$ [12], and assuming that all the radiationless transition populates the fission isomer (P = 0.23), we obtain an upper limit of ω_d which is $(0.36 \sim 1.8) \times 10^6$ /sec for $\alpha = 0.07$ [13], $(0.83 \sim 4.1) \times 10^6$ /sec for $\alpha = 0.03$ [3]. These expected values of ω_d are of the same order of magnitude as the experimental value of $\omega_d = (0.92 \pm 0.33) \times 10^6$ /sec. However, it is expected that prompt fission is dominant at the excitation energy which corresponds to the muonic transition (∿ 6 MeV), and thus the population probability of the fission isomer by the muonic radiationless transition would be a few order of magnitude smaller than the prompt fission probability. Therefore, the experimental value of ω_d seems to be too large to be accounted for from the present knowledge. We may suspect whether the experimental difference between τ_f and τ_e is real or not in view of the fact that the observed values of τ_f are considerably scattered compared with τ_e. Further extended measurements would give more clear information whether the fission isomer could be excited by negative muons.

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TABLE I

Lifetimes and reduced capture rates of muons bound to actinide nuclei

Nucleus	(A-Z)/2A	Mode[a)]	Mean lifetime (nsec)	$\Lambda_c/\langle\rho\rangle$[b)] ($sec^{-1} fm^3 10^7$)
^{232}Th	0.3060	f	74.2(56)	4.50(34)[1)]
		f	87(4)	3.81(18)[3)]
		e	80.4(20)	4.14(11)[c)]
^{233}U	0.3026	f	61.7(38)	5.24(33)[2)]
^{235}U	0.3043	f	65.3(28)	4.98(22)[2)]
		f	66.5(42)	4.89(31)[1)]
		f	84(6)	3.84(28)[3)]
		e	78(4)	4.14(22)[c)]
^{238}U	0.3067	f	75.6(29)	4.32(17)[1)]
		f	74.1(28)	4.41(17)[2)]
		f	76.0(10)	4.30(6)[3)]
		e	88(4)	3.69(17)[5)]
		e	81.5(20)	3.99(10)[c)]
^{237}Np	0.3038	f	72(2)	4.44(13)[6)]
^{239}Pu	0.3033	f	74(14)	4.26(87)[4)]
		f	70(3)	4.51(19)[6)]
		e	77.5(20)	4.06(12)[c)]
^{242}Pu	0.3058	f	79(5)	4.02(25)[6)]

a) The detection of fission fragments and that of decay electrons are denoted by f and e, respectively.

b) Λ_c defined by $\Lambda_c \equiv 1/\tau - 1/\tau_{free}$. The value $\langle\rho\rangle$ was calculated by solving the Dirac equation for a spherical nucleus.

c) Present result.

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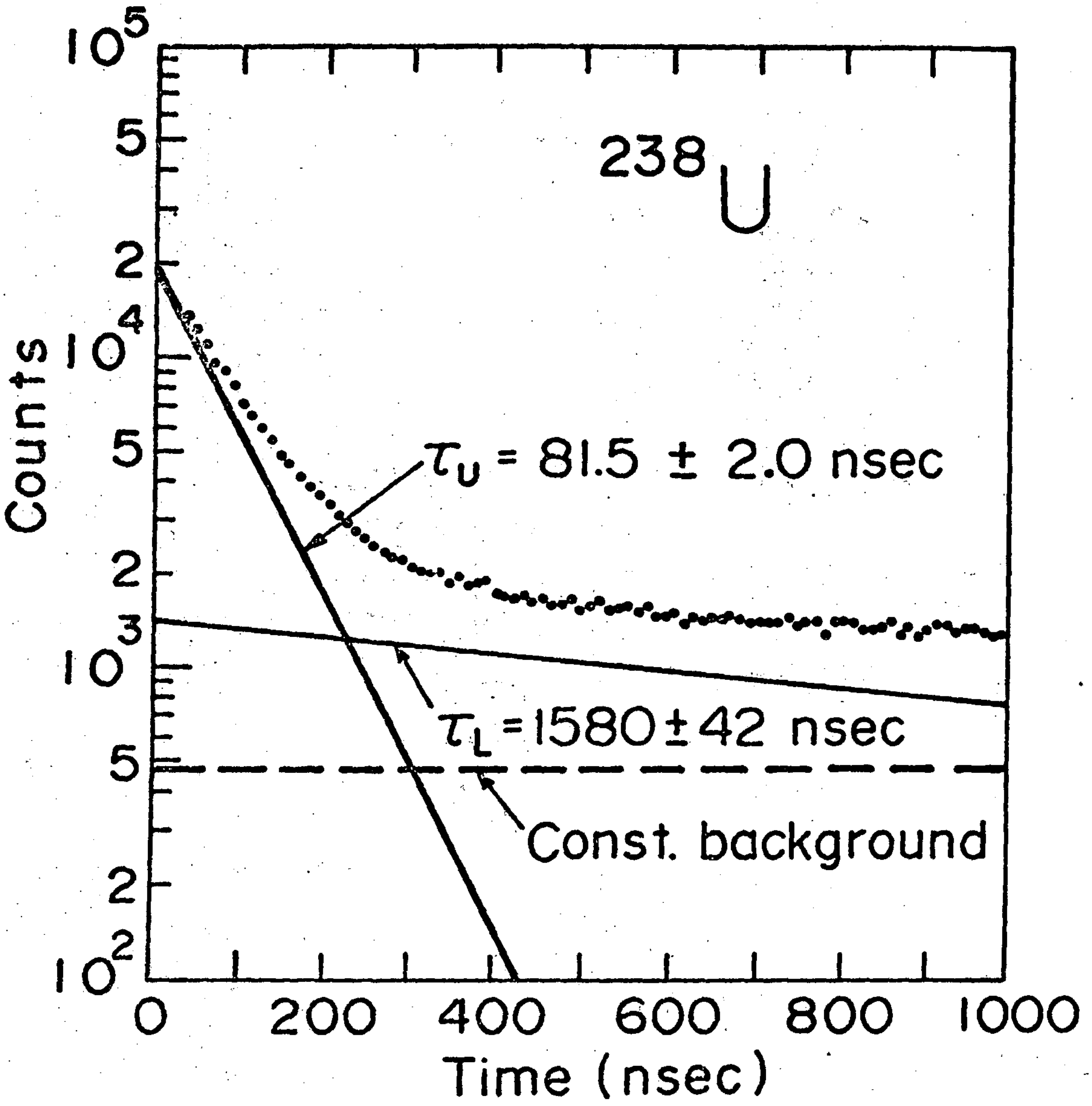
Figure captions

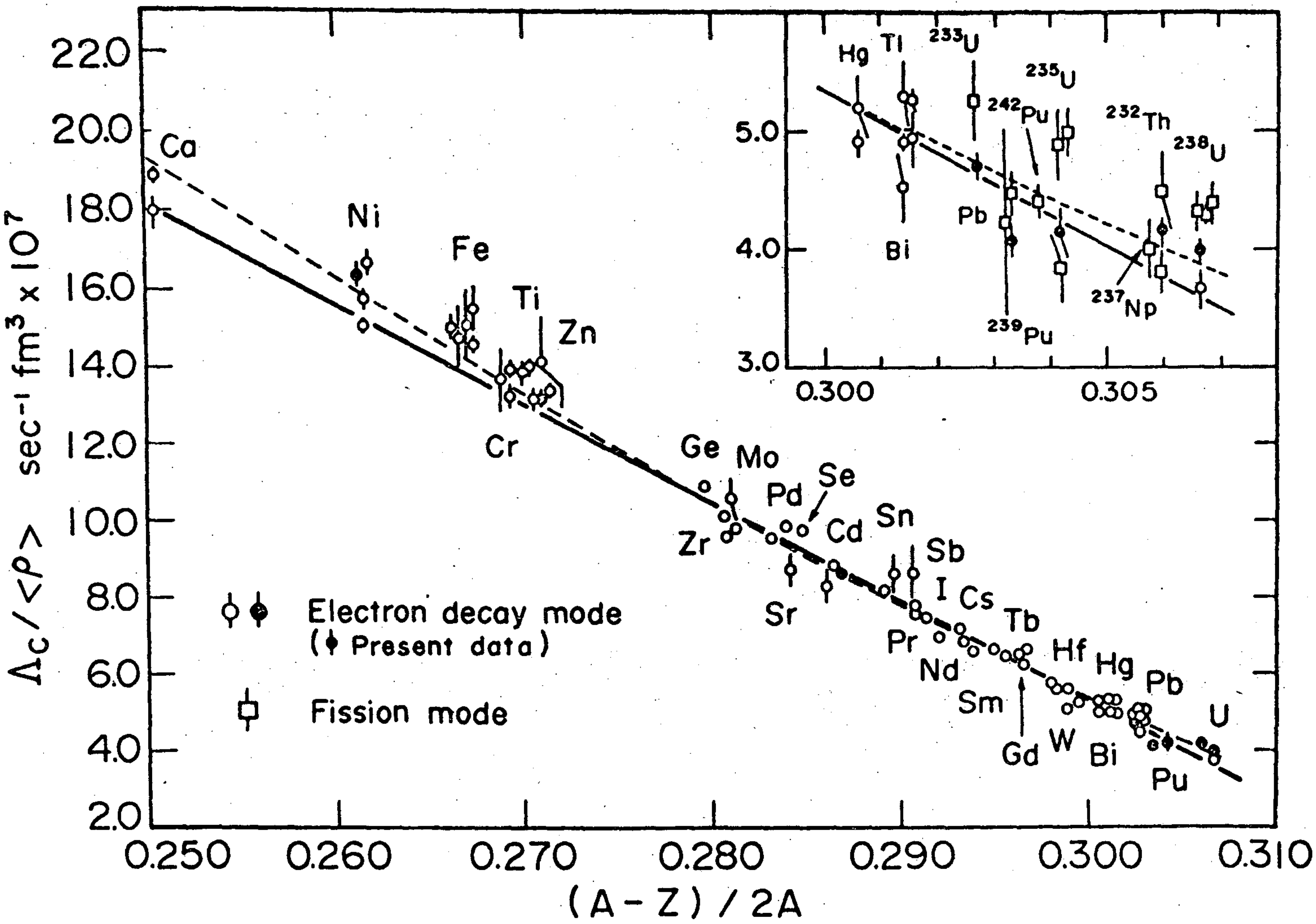
Fig. 1 The time spectrum of decay electrons from muons bound to ^{238}U.

Fig. 2 Reduced muon capture rate plotted as a function of (A - Z)/2A. 72 available data from Ca to ^{239}Pu are shown, where the black circles are the present results (Ni : 165.6 ± 2.0 ; Zn : 158.3 ± 2.0 ; Cd : 91.5 ± 1.5 ; Pb : 77.5 ± 2.0 nsec). Data of odd-mass nuclei are excluded to obtain systematics free from the hyperfine effect. In the inset, data of heavy nuclei ($(A - Z)/2A > 0.3$) are presented together with fission data in actinide region. The solid lines are the best fit by the equation (1) and the dashed lines were obtained by assuming the formula of Goulard and Primakoff [10].



^{238}U
τ_U = 81.5 ± 2.0 nsec
τ_L = 1580 ± 42 nsec
Const. background
Counts
10^5
5
2
10^4
5
2
10^3
5
2
10^2
0
200
400
600
800
1000
Time (nsec)

Fig. 1



$\Lambda_c / \langle\rho\rangle$ sec^{-1} fm^3 x 10^7
(A - Z) / 2A
22.0
20.0
18.0
16.0
14.0
12.0
10.0
8.0
6.0
4.0
2.0
0.250
0.260
0.270
0.280
0.290
0.300
0.310
Ca
Ni
Fe
Ti
Zn
Cr
Ge
Mo
Zr
Pd
Se
Cd
Sn
Sb
Sr
I
Cs
Tb
Pr
Nd
Sm
Gd
Hf
Hg
W
Bi
Pb
Pu
U
Electron decay mode
(♦ Present data)
Fission mode
Hg
Tl
^{233}U
^{235}U
^{242}Pu
^{232}Th
^{238}U
Pb
Bi
^{239}Pu
^{237}Np
5.0
4.0
3.0
0.300
0.305

Fig. 2