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Author
Kaplan, S.N.

Publication Date
1976-07-01

Submitted to Physics Letters B

LBL-5334
Preprint c.1

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S. N. Kaplan, J. A. Monard and S. Nagamiya

July 1976

Prepared for the U. S. Energy Research and
Development Administration under Contract W-7405-ENG-48

SHAPE ISOMER EXCITATION BY MU-MINUS ATOMIC CAPTURE?[*]

S.N. Kaplan, J.A. Monard[+] and S. Nagamiya[++]

Lawrence Berkeley Laboratory, University of California,
Berkeley, California 94720, U.S.A.

ABSTRACT

The possibility of excitation of the ^{238}U shape-isomer by the atomic cascade of a negative muon has been investigated by a search for back-decay γ-rays. No candidates for such γ-rays have been found with yields greater than 1% per stopping muon, indicating that the probability of the isomer excitation by muons is less than 3%. The lifetime of a μ^- bound to ^{238}U has been determined from capture γ-rays to be 79.1 ± 0.5 ns,which also set the upper limit of this probability to 7-15%.

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[*] Work performed under the auspices of the U.S.Energy Research and Development Administration.

[+] Present address: General Electric Co, NED, San Jose, CA 95125

[++] On leave from the Dept. of Physics, University of Tokyo, Tokyo, Japan

Recently Bloom [1] proposed a rather intriguing alternative to the accepted picture of nuclear fission following mu-minus (μ^-) capture in ^{238}U to explain an apparent discrepancy between μ^- lifetimes measured by decay electrons (τ_e) [2] and by fission fragments (τ_f) [3]. He hypothesized that a significant fraction of the 2p-1s muonic transitions excites, nonradiatively, the shape isomeric state in ^{238}U and that the apparently lower μ^- lifetime as measured from fission fragments is due to the combined effect of the alternative pathways to fission, μ^- capture and isomer decay. Other available evidence is not inconsistent with this hypothesis. The isomer can be dipole excited at the available energy [4], and it is known that ^{238}U 2p-1s mu-mesic x-rays have an anomalously low yield (by more than 20%) [5].

In Bloom's picture, the muonic atom exists in one of two states: a normal state, with the muon in a 1s orbit about the ground-state nucleus, and an abnormal state, in which the muon orbits the shape isomer. In the abnormal state, the isomer then may capture the muon, spontaneously fission, or back-decay to the normal state by γ-ray emission. The reciprocal lifetime of the isomer is expressed as

$$\frac{1}{\tau^i} = \omega_c^i + \omega_\gamma^i + \omega_f^i \,, \tag{1}$$

where ω_c^i is the capture rate, ω_γ^i is the back-decay rate, and ω_f^i is the rate of isomeric fission. If one assumes the capture rates by the isomer and the ground state are the same, then $\omega_c^i \simeq 1.2\text{x}10^7\text{s}^{-1}$ [2]

for ^{238}U. In the absence of a μ^-, the other two transition rates are $\omega_\gamma^i \simeq 5 \times 10^6 s^{-1}$ and $\omega_\gamma^i/\omega_f^i \simeq 5$ to 25 [6]. Thus $\tau^i \simeq 60$ns which is shorter than the lifetime (~ 80ns) of a μ^- in the 1s orbit. Therefore, if an appreciable fraction of the fission fragments arise from isomer decays, then the measured τ_f could be observably shorter than τ_e. The previous μ^- lifetime measurements known to us are shown in Table 1. The possible discrepancy lies in the somewhat higher average of τ_e compared to τ_f.

The main purpose of this work was to find more convincing evidence for such isomer excitation, or to set limits on its yield by identifying and making lifetime measurements of γ-rays observed following μ^- capture by ^{238}U. In particular, Bloom's calculations together with the experimental results of Russo et al [6] suggested that there could be a yield of back-decay γ-rays from the isomer sufficient for such a measurement. If P is the probability of isomer excitation per μ^- stopping, then the γ-ray intensity is:

$$I_\gamma \text{ (per } \mu^- \text{stop)} = P \cdot \omega_\gamma^i/(\omega_c^i + \omega_\gamma^i + \omega_f^i) \simeq 0.3 \text{ P.} \qquad (2)$$

Hence, if a 10% fraction of stopped μ^- excite the isomer, the yield of the back-decay γ-rays would be 3% of the stopped μ^-, which can be clearly identified by a Ge(Li) detector. (Bloom's optimistic estimate was P $\simeq$ 50% !). The lifetime of these γ-rays is equal to τ^i, given by Eq. (1). A determination of τ^i, and therefore ω_γ^i gives information on the interior fission barrier as perturbed by the Coulomb field of the μ^-.

Additional, but less direct, information on P can be obtained from the lifetime measurement of capture γ-rays. It is expected that most γ-rays are emitted after the normal muon capture with their lifetime, τ_γ, being equal to τ_e. The experimental accuracy of τ_γ could be much higher than that of τ_e, because the electron measurements suffer both from low yield and long-lived background (∿1.8 μs) from surrounding low-Z counters [2]. For γ-ray measurements, such background is reduced more than a factor of 100 because of the higher capture rate for the higher-Z nucleus. The normalized difference between τ_γ and τ_f is related to P through the following equation [1]:

$$\frac{\tau_\gamma - \tau_f}{\tau_\gamma} = \frac{P}{1-P} \cdot \frac{1}{\alpha} \cdot \frac{\omega_\gamma^i \, \omega_f^i}{\omega_c(\omega_c + \omega_e^{free})} \tag{3}$$

where α is the fission probability per muon capture, ω_c is the muon capture rate, and ω_e^{free} is the free muon decay rate. Simple substitution into the above expression cannot be expected to yield a precise value for P because there are large ambiguities (possibly over 100%) in the values of α [3] and ω_f^i [6]. In addition, the possibility of systematic error causing the observed difference between τ_γ and τ_f cannot be completely excluded since the set-ups of the two experiments are quite different.

Measurements have been made with nearly the same set-up as previously reported [7]. Muons from the 184-inch Cyclotron at LBL were stopped in a metallic ^{238}U target. The target was a 13 cm. x 13 cm. x 0.32 cm. plate and was placed at an angle of 45° with respect to the beam. Target thickness along the beam line was 9 g/cm^2. Stopped μ^- events were signalled by a set of plastic counters, and γ-rays were detected at 90° with a Ge(Li) detector. Energy (E) and time (T) spectra of γ-rays were recorded in a PDP-15 computer. The principal configuration was 1024 E x 16 T channels, covering an energy range of 0 to 4 MeV and a time range of -100 to 250 ns. Measurements were also made with a 16 E x 1024 T configuration, covering the same energy range and a time range up to 1 μs. The stopped μ^- rate was $\sim 2 \times 10^4 s^{-1}$ in the first configuration, but it was reduced by a factor of 5 in the second configuration in order to lower the periodic background associated with 20 MHz beam spikes.

Prompt, delayed and background (measured at negative time) spectra of γ-rays are shown in Fig. 1. In the delayed spectrum, no prominent peaks associated with μ^- stoppings in ^{238}U have been observed. The energy region of particular interest is the neighborhood of 2.5 MeV where Russo, Pederson and Vandenbosch [6] have reported a prominent γ-ray transition at 2.514 MeV, attributed to back-decay from the shape isomer. Unfortunately, because of Coulomb perturbations of the barrier due to the presence of the muon, the energy of the back-decay γ-ray not necessarily identical to the 2.514 MeV, and could be as much as 400 keV greater [8]. Near 2.5 MeV there is only one significant peak at 2614 ± 2 keV which has a net γ-ray yield of 2.0 ± 0.5% of μ^- stoppings. However, this energy is within experimental precision equal to the well-known first excited state in ^{208}Pb (2614.5 keV). Therefore, it is more likely that this peak is due to the (n, n'γ) inelastic scattering in the ever-present Pb shielding of neutrons emitted from target nuclei after μ^- captures. (Since the peak does not appear in the background spectrum, it is not a simple background but time-correlated!) Rough estimates of neutron intensity after μ^- capture together with expected γ-ray intensity following (n, n'γ) support the above conjecture. After dismissing the 2614-keV peak as being from ^{208}Pb, the non observation of a distinguishable peak in this energy region sets an upper limit on the intensity of the back-decay γ-rays to be less than 1% per μ^- stop. Using Eq. (2), the probability of the shape-isomer excitation by a μ^- is then

$$P < 3\%, \tag{4}$$

much smaller than the upper range of Bloom's early estimates [1].

The delayed spectrum is almost continuous and shows no peaks. It was rather surprising to us that no single γ-rays were observed even after muon capture. This is presumably because the levels of the product Pa nuclei are very densely distributed, thereby discriminating against prominent peaks. Nevertheless, it is reasonable to assume that the observed continuous γ-rays arise mainly from the normal μ^- capture. Over 16 pulse height ranges, time spectra were analyzed in 1024 time channels, over the time interval from -100 ns to 1 μs. Each time spectrum showed a clean decay pattern, but it was carefully analyzed by the following procedures: First, the background spectrum determined in the negative time region was frequency analyzed and ~~ex~~trapolated to the positive time region, and such a background spectrum was subtracted from the raw data. Second, the spectrum thus obtained was fitted with the functions $A\exp(-t/\tau_\gamma)$, $A\exp(-t/\tau_\gamma) + B$, and $A\exp(-t/\tau_\gamma) + B\exp(-t/\tau_L) + C$. The three different fits always gave the same value of τ_γ (within ± 0.5 ns), and the final results of τ_γ are listed in Fig. 2. As an average we have obtained:

$$\tau_\gamma = 79.1 \pm 0.5 \text{ ns}, \qquad (5)$$

which is consistent with τ_e reported by Hashimoto et. al. [2] ($\tau_e = 81.5 \pm 3.0$ ns), but is still larger than the average of τ_f [3] (τ_f (average) = 75.8 ± 0.8 ns). The use of Eq. (3) gives the upper limit of P to be $P < 7$ to 15% , which is consistent with the value (4) obtained from the intensity measurements of back-decay γ-rays.

It is known [5] that the radiationless transition probability of the $2p \rightarrow 1s$ x-ray is 23%. From our result of Eq. (4), the isomer population probability is less than 1/8 of the radiationless transition. Although the apparent production rate of the shape isomer by this mechanism is, disappointingly, much lower than hoped for, Bloom's basic hypothesis remains interesting, and his more detailed quantitative arguments are still open to further investigation.

We would like to express our thanks to Dr.S.D. Bloom for valuable discussions, and to the 184-inch Cyclotron crew for their heroic support; also to express a note of remorse for the demise of this noble instrument of physics. One of us (S. Nagamiya) expresses his thanks to the Nishina Memorial Foundation and the Mitsubishi Foundation for their financial support and to Professor Owen Chamberlain for his continuous encouragement.

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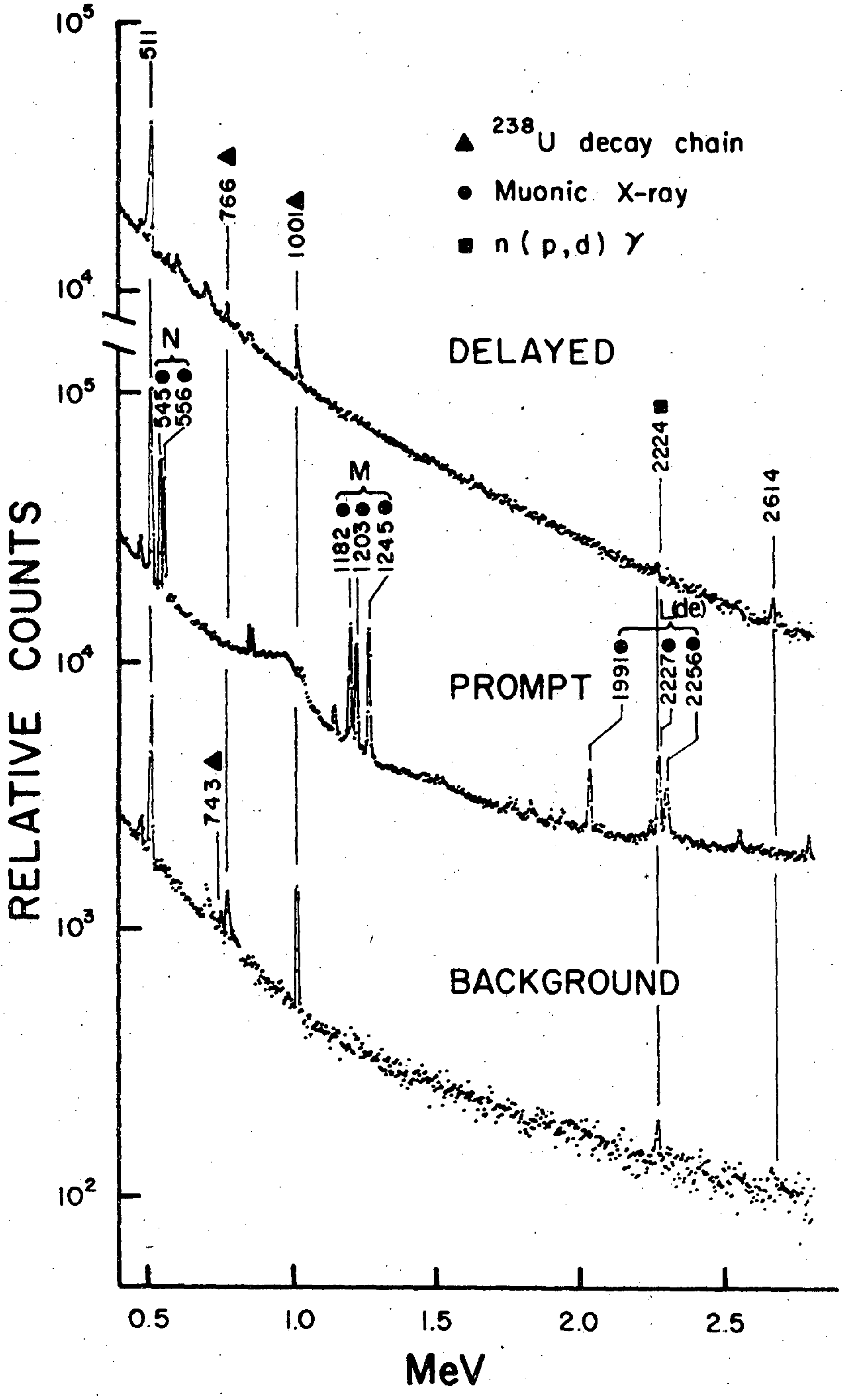
Table 1 Previously measured μ^- lifetime in ^{238}U

Lifetimes	Year	Reference
$\tau_e = 88 \pm 4$	1959	Sens [2]
$\tau_f = 75.6 \pm 2.9$	1963	Diaz et al. [3]
$\tau_f = 74.1 \pm 2.8$	1970	Budick et al [3]
$\tau_f = 76.1 \pm 1.0$	1975	Chultem et al. [3]
$\tau_e = 81.5 \pm 3.0$	1976	Hashimoto et al. [2]

FIGURE CAPTIONS

Figure 1 Energy spectra obtained in 1024E x 16T analysis. The spectra labeled BACKGROUND, PROMPT, and DELAYED have been summed over time channels 1-3, 4-5, and 6-15 respectively. The identifications of the prominent x-ray peaks in the PROMPT spectrum are from Cote et al. (Phys. Rev. 179 (1969) 1134). The broad peaks below 1 MeV in the DELAYED spectrum are from inelastic neutron scattering, Ge(n,n')Ge*, in the Ge(Li) spectrometer. The only other DELAYED peaks with significant yields above background are the ubiquitous 511-KeV annihilation γ-ray and the 2614-KeV peak discussed in the text.

Figure 2 Mean lives determined from analysis of the 16E x 1024T spectrum. The lifetimes determined separately for each 0.25-MeV energy band, as well as their weighted mean are shown.



XBL 767-3137

Fig. 1

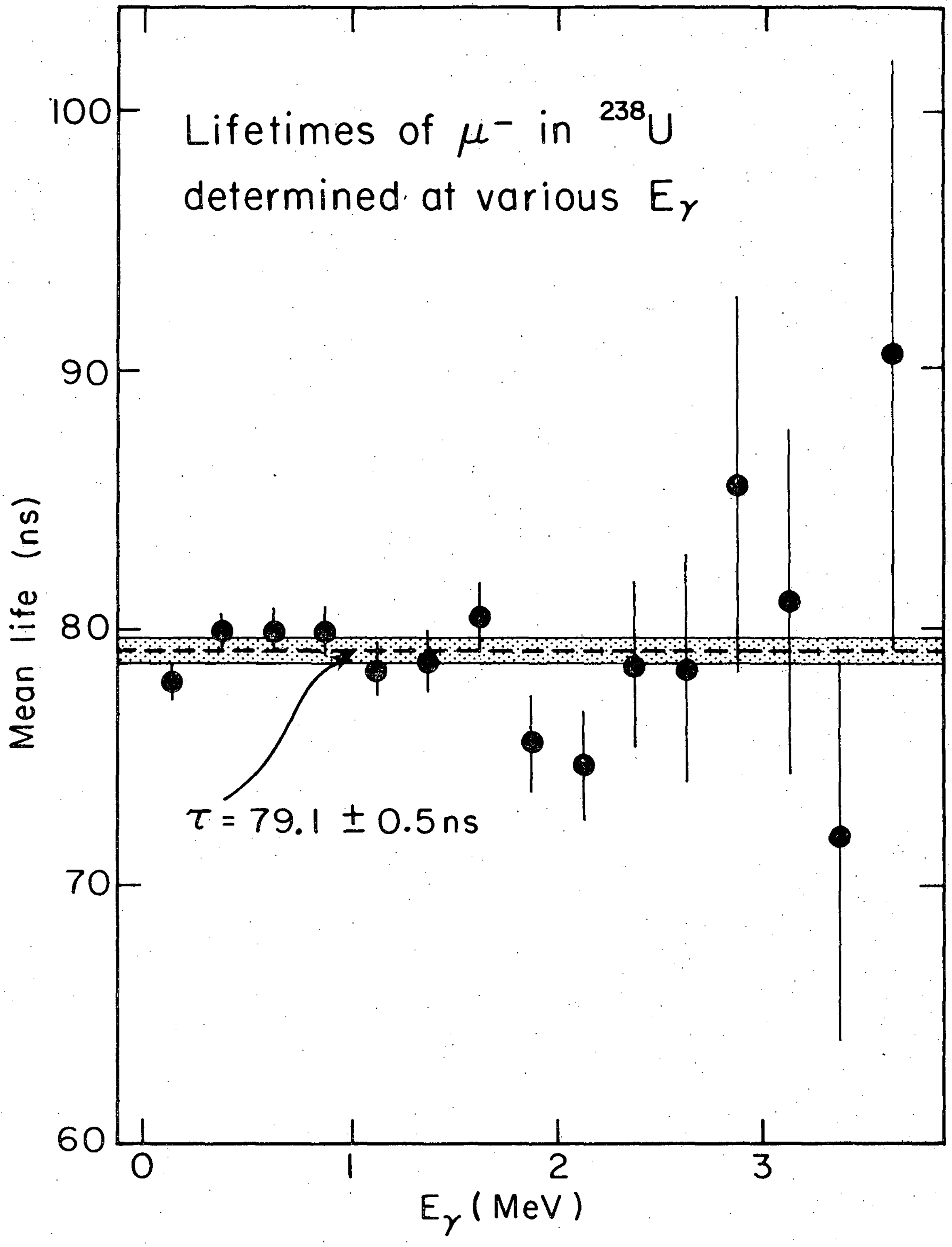


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Fig. 2

TECHNICAL INFORMATION DIVISION
LAWRENCE BERKELEY LABORATORY
UNIVERSITY OF CALIFORNIA
BERKELEY, CALIFORNIA 94720