NUCLEAR DE-EXCITATION FOLLOWING MUON CAPTURE AND THE BOUND MUON DECAY ANOMALY*

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Experiments have been performed[1-3] to measure the rate of negative muon decay,

$$\mu^- \rightarrow e^- + \nu + \bar{\nu},$$

when the muon is bound in the Coulomb field of a nucleus. Figure 1 presents the data of Yovanovitch[1] for the ratio of the bound decay rate to the free decay rate (rate for μ^+ decay or rate for muons bound to a low-Z nucleus),

$$R = \Lambda_d^- / \Lambda_d^+.$$

The curve is a theoretical curve.[4] While the theoretical predictions are always less than $R=1$ the experimental results rise well above $R=1$ in the iron region, yet return quickly close to theory for $_{30}$Zn, and fall well below the theoretical curve for very large Z. The presence of this anomaly has been verified in detail by combining measurements by Lederman and Weinrich[2] of Λ_d^-/Λ_t and measurements of Λ_t,[3] the total disappearance rate. These points are not included in Fig. 1 simply to avoid clutter.

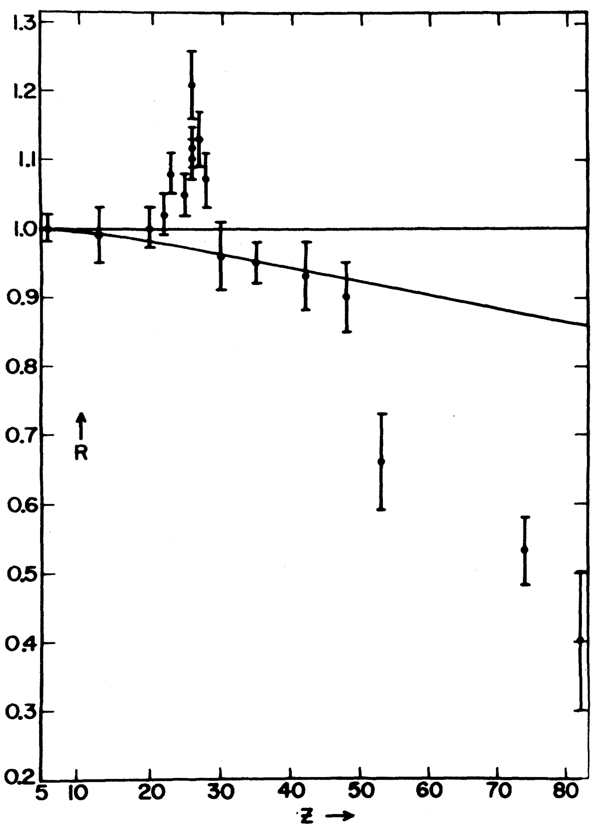

FIG. 1. Data of Yovanovitch (reference 1) on bound muon decay.

The other mode of disappearance of negative muons in matter is muon capture for which the basic reaction is

$$\mu^- + p \rightarrow n + \nu.$$

To determine whether the bound muon decay anomaly is really due to detection of γ rays associated with muon capture rather than electrons from muon decay, we can take the difference between the experimental and theoretical values for R and divide by Λ_c/Λ_d^+. Table I presents the values of $(R_{\rm exp} - R_{\rm th})\Lambda_d^+/\Lambda_c$ calculated using experimentally determined capture rates.[5] The near constancy of the values in Table I makes it appear that the anomaly is due to the detection of 1% of the muon capture events and that this sensitivity to muon capture mysteriously stops at Zn. The initially sharp Z dependence of the anomaly is just the Z dependence of muon capture rates $\sim Z^4$.

To understand how background due to muon capture could appear in such careful experiments, let us consider some of the nuclear processes

Table I. Proportionality of the bound muon decay anomaly to the capture rate.

Z	Element	$(R_{\rm exp}-R_{\rm th})\Lambda_d^+/\Lambda_c$ ($\times 10^2$)
20	Ca	0.4 ±0.5
22	Ti	0.7 ±0.5
23	V	1.5 ±0.4
25	Mn	1.0 ±0.4
26	Fe	1.4 ±0.3
26	Fe	1.7 ±2.0[a]
27	Co	1.3 ±0.3
28	Ni	0.8 ±0.3
29	Cu	1.2 ±0.9[a]
30	Zn	-0.1 ±0.2

[a]From measurements of Λ_d^-/Λ_t by Lederman and Weinrich (reference 2).

accompanying muon capture in complex nuclei. For capture by a free proton the recoil neutron has an energy of 5 Mev. In complex nuclei the average nuclear excitation is 10 to 15 Mev depending on the nuclear model.[6-8] All but about 2 Mev is imparted to the neutron.

When the neutron excitation is greater than the neutron separation energy, neutron emission is usually most likely. From the experimental cross sections for (n,γ) reactions, which are typically a few millibarns,[9] and from experimental cross sections for neutron scattering, which are typically a few barns, the ratio of the photon to neutron emission rates is

$$\Gamma_\gamma/\Gamma_n \sim 10^{-3},$$

when the excitation is a few Mev above the neutron separation energy. In particular this indicates that in this energy region the emission of photons with $E_\gamma > 10$ Mev is unlikely.[10,11] Other properties of neutron emission have been considered in connection with the problem of the neutron asymmetry from the capture of polarized muons.[7,12,13]

When the neutron excitation energy is less than the separation energy, only de-excitation by photon emission is possible. Note that this situation can occur as the second stage of compound nuclear decay even when the initial excitation is greater than the separation energy. Also note that compound nuclear processes are expected to prevail over direct neutron emission.[13] While it would certainly be difficult to calculate the photon spectrum that results from muon capture, a great deal of qualitative information can be obtained from experimental data on the γ-ray spectra resulting from thermal neutron capture.[14] This corresponds to an excitation close to the separation energy, the highest excitation resulting only in photon emission. We have already seen that this situation occurs with sufficient probability.

The first thing to be learned from thermal neutron capture is an estimate of the mean multiplicity of photons. This varies between 2.5 to 4 photons per capture for the medium-weight nuclei, depending on the nucleus involved. The mean multiplicity for muon capture might be expected to be slightly higher for each nucleus than its thermal neutron counterpart since the excitation takes place in such a different way and because the more favored states in muon capture differ from those of photon emission. The "allowed" and "first forbidden" transitions in muon capture correspond to 0+, 1+ and 0-, 1-, 2- transitions, respectively.[15] However, since $k_\nu R \sim 2.5$ for medium nuclei, a change of two units of forbiddenness should make a difference of no more than about 10^{-2} in the transition probability.[15] The most important consideration is which states are available.

Another thing to be learned from neutron capture is the presence of strong direct transitions in certain regions of the periodic table. In the iron region there are strong direct $s \rightarrow 2p_{3/2}$ transitions. An example, the thermal neutron capture spectrum of Fe^{57}, is shown in Fig. 2. The $E_\gamma = 7.65$ Mev, 40% frequency peak corresponds to a transition to the $2p_{3/2}$ single-particle state. The smaller $E_\gamma = 6.0$ Mev peaks correspond to the $2p_{1/2}$ state. For reasons discussed below, the bound muon decay anomaly seems to be due to γ rays with 5 Mev $\leq E_\gamma \leq$ 10 Mev. The experimental anomaly in muon decay found in the iron region suggests that these same p states seem to play an important role in the γ-ray transitions that cause the anomaly. This is illustrated by the

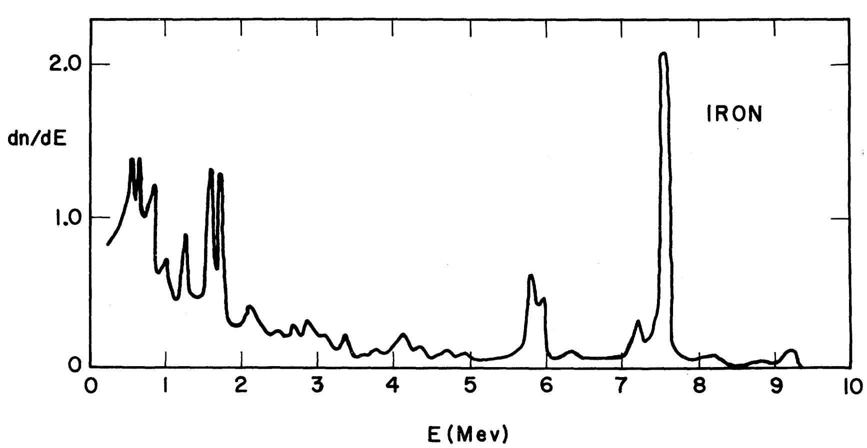

FIG. 2. Thermal neutron capture γ-ray spectrum of Fe (from reference 14).

cases

$$_{28}Ni^{58,60}(\mu^-,\nu)_{27}Co^{58,60*},$$

and

$$_{30}Zn^{64,66,68}(\mu^-,\nu)_{29}Cu^{64,66,68*},$$

for which the final nuclei have the $p_{3/2}$ states essentially full.[16] Table I indicates that the bound muon anomaly is diminished for $_{28}$Ni and gone for $_{30}$Zn, but not for $_{27}$Co or $_{29}$Cu for which the daughter nuclei have empty $p_{3/2}$ states. The single-particle states which would seem most favorable to production of such γ rays in muon capture are listed in Table II for a few nuclei. This is based on the fact that the outermost proton shells are the most important in muon capture,[12] and on considerations of the relative contributions of the various states involved.[17,18] Configuration mixing is apparently responsible for making the p states important, which is consistent with evidence[19] for the applicability of the Nilsson model[20] in the iron region. It is clear from Table II that the yield of higher energy γ rays resulting from muon capture in Ni and Zn will be less than that in the remainder of the iron region. It is also understandable why the anomaly disappears at $_{30}$Zn; the $2p_{3/2}$ proton shell is being filled but the $2p_{3/2}$ neutron shell is already full. However, note that the anomaly might still be expected to be present for $_{29}$Cu although in possibly reduced intensity because the shells are partially filled. The data of Lederman and Weinrich[2] are consistent with this (see Table I).

The experimental arrangement of Yovanovitch[1] included a thick target and an electron telescope consisting of three thin plastic scintillators with two aluminum absorbers sandwiched between the scintillators. The absorber thickness was equal to the range of a 4-Mev electron. The arrangement of Lederman and Weinrich was similar.[2] A 5- to 10-Mev γ ray can produce either a pair or a Compton electron with energy >4 Mev in either the target or the first absorber which will be detected by two counters. In coincidence, a Compton electron from a low-energy γ ray can be detected in the remaining counter. From the known cross sections[21] the total efficiency for such a high-low combination as that above is probably close to 1%, primarily because there are several different ways in which this event can take place. The discrepancy for large Z is evidently due to the different effect of thick targets and absorbers on the altered electron spectrum for bound muon decay as opposed to the spectrum for free decay.[22]

Whether or not the above mechanism is responsible for the bound muon decay anomaly can be tested experimentally. Use of an experimental method which absolutely guarantees exclusion of electrons and photons with $E < 10$ Mev would demonstrate whether the anomaly must be due to other effects than muon decay. This seems to be the case.[23] Anderson et al.[11] have measured the γ-ray spectra from muon capture in Fe and Cu. The part of the spectrum with $E_\gamma > 5$ Mev does not seem inconsistent with the above ideas. The contrast in the γ-ray spectra in the iron region with that in and after Zn should be particularly interesting. Whether the high-low combination of γ rays is likely following muon capture could be determined by a coincidence experiment. Performing an experiment similar to that of Yovanovitch[1] and Lederman and Weinrich[2] with an electron telescope consisting of many counters would be particularly enlightening if all events were stored in which, for instance, the first and last counters register. Such an experiment would permit measurement of bound decay rates and examination of the detailed effects of photons from muon capture simultaneously.

It might also be expected that strong direct γ-ray transitions following muon capture show up

Table II. Expected dominant single-particle transitions resulting in γ rays with $E_\gamma > 5$ Mev.

Nuclei	Initial proton state	Excited neutron state	Configuration mixing	Final neutron state	Comment
$_{26}Fe^{56}(\mu^-,\nu)_{25}Mn^{56*}$	$\{1f_{7/2}$ $\{1f_{7/2}$	$1g_{7/2}$ $1g_{7/2}$	$2d_{3/2}$ ⋯	$2p_{3/2}$ $1f_{5/2}$	
$_{28}Ni^{58,60}(\mu^-,\nu)_{27}Co^{58,60*}$	$1f_{7/2}$	$1g_{7/2}$	⋯	$1f_{5/2}$	$\{Co^{60}, p_{3/2}$ full $\{Co^{58}, (p_{3/2})^3$
$_{30}Zn^{64,66,68}(\mu^-,\nu)_{29}Cu^{64,66,68*}$	$2p_{3/2}$	$2d_{3/2}$	⋯	$2p_{1/2}$	$p_{3/2}$ full

in other regions of the periodic table. This should be most likely in the light nuclei and near closed shells as is the case in thermal neutron capture.

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