OBSERVATION OF RADIATIVE CAPTURE OF NEGATIVE MUONS IN IRON

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The interest of an experimental investigation of the radiative muon capture

$$\mu^- + N = N' + \nu + \gamma \qquad (1)$$

was first pointed out by Huang, Yang, and Lee.[1] The process has been further considered on theoretical ground by various authors,[2-5] but it has not been observed as yet,[6] though it is expected to occur in medium nuclei with a branching ratio R of about 10^{-4} relative to ordinary muon capture.[4] Its observation is made difficult, in practice, by the fact that decay electrons from μ^-, which have escaped nuclear capture (~10^3 per radiative capture in Fe), can simulate reaction (1) via bremsstrahlung and pair-production processes.

First aim of an experimental program on the subject is merely the detection of this hitherto unobserved process and a measurement of the rate at which it occurs under given experimental conditions. Such a measurement is indeed of practical importance to estimate the feasibility of the more difficult experiments (both capable of yielding relevant information on the coupling constants[1]) on the circular polarization and/or on the asymmetry of γ-ray emission from radiative capture of polarized muons by spinless nuclei.[7] The present experiment, carried out with this in mind, gives evidence for the occurrence of process (1) in Fe with a branching ratio R of about 10^{-4}.

The experiment was carried out at the CERN synchrocyclotron. The machine was operated with an internal vibrating target at a duty cycle of ~30%. Negative muons from the muon channel of ~90-MeV kinetic energy were transported by four additional quadrupoles[8] onto the apparatus shown in Fig. 1. After crossing counters 1, 2, 3, and the "Cu moderator," the muons stopped (at a rate of about 6300 per second) in the five steel plates, 1.5 mm thick, of spark chamber SC1. The first three and the last plates of this chamber were thin Al foils 0.025 mm thick. If a μ^- stop (anticoincidence $123\bar{4}$) was followed by radiative capture and the γ ray converted into an electron pair in the 2-mm thick "W converter," both electrons reached, in general, counter 5(sensitive area 20×20 cm^2) after crossing spark chamber SC2 which contained seven Al foils 0.025 mm thick.

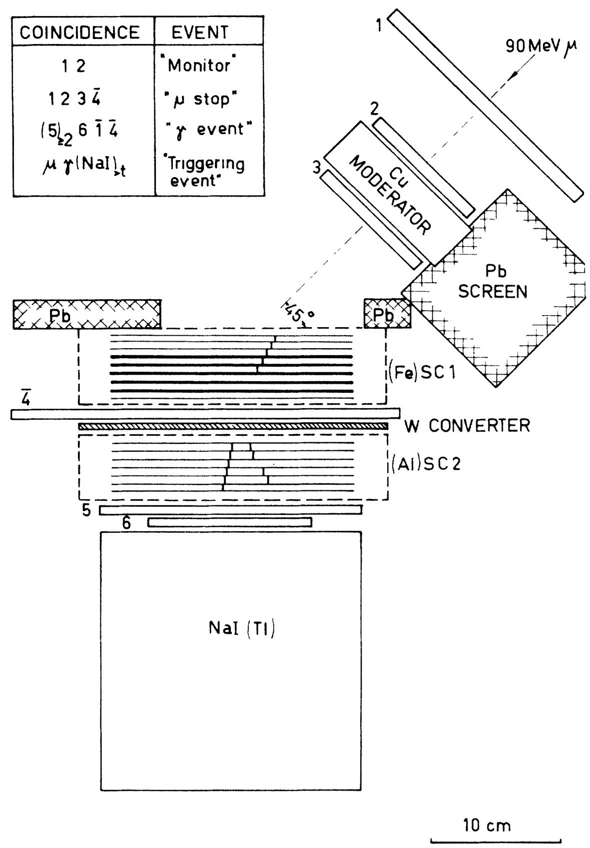

FIG. 1. Layout of experimental setup with, superimposed, the view of one event possibly due to process (1). In this event the μ^- stops in the third of the five steel plates of spark chamber SC1 (other plates are thin Al foils). An electron pair originated in the W converter is clearly seen in the thin Al foil spark chamber SC2, though two gaps are missing in one of the two electron tracks.

At least one of the two electrons had to reach counter 6 and the large NaI(Tl) proportional counter to produce the final coincidence pulse used to trigger both spark chambers. To reduce to a reasonably small value the rate of these "triggering events" (see also insert in Fig. 1), the final coincidences were actually formed only if: (a) the pulse height of counter 5 was nearly twice or more that corresponding to a minimum ionizing particle crossing the counter normally; (b) the pulse height of the NaI counter exceeded a given threshold t. During the main run, t corresponded to an energy release of ~37 MeV in the NaI crystal. Since 6.7 MeV is the energy that an electron, formed at the center of the W plate, loses by ionization before reaching the NaI counter, the minimum γ-ray energy corresponding to the chosen threshold was about 50 MeV. Calibration of the NaI system was made using γ rays of well-known energies.[8]

Pulses from counters 1, 5, and NaI (the latter through an artificial delay of 100 nsec with respect to 5) were displayed on the sweep of an oscilloscope (sweep speed 100 nsec/cm) triggered also by the "triggering events." The necessary information concerning the time relationship among these pulses and the height of the NaI pulse was obtained through inspection of the oscilloscope pictures.[8] 90° stereo-pictures of both spark chambers were taken on another film. Oscilloscope and spark chamber film advancement systems were both operated by the "triggering events."

In ~20 hours of effective measurements N_μ (=4.54 $\times 10^8$) μ^- mesons were stopped in the five steel plates of SC1 and 2299 spark chamber and oscilloscope pictures were taken. These were analyzed and retained as possibly representing radiative capture events if: (a) two tracks were present in SC2 with lines meeting inside the W plate converter; (b) pulse due to counter 1 on the oscilloscope pattern was followed by pulse of counter 5 and, with a further fix delay of ~100 nsec, by the NaI pulse. As a result of this analysis (estimated scanning efficiency ~100%), 33 events were retained of which 24 showed a μ stop (category I) and 9 had no visible track (category II) in the SC1 picture. One of the events of category I is reproduced in Fig. 1.

The energy distributions of the events for both categories are given in Fig. 2, taking into account the energy resolution of our apparatus and the error in the measurement (±6.5%) of the NaI pulse height at the oscilloscope.[8] Some of the events of category I come from the random superposition of a μ stop with an event of category II. In order to subtract these random events from category I, we need to use the normalizing ratio

$$\frac{\text{anticoincidences } 123\bar{4} \text{ with } \mu^- \text{ stop in SC1}}{\text{anticoincidences } 1234 \text{ with no track in SC1}} = 0.61,$$

which is directly known (with negligible statistical error) from our measurements. Subtracting the normalized distribution II of Fig. 2 from histogram I we obtain the correct distribution reported in the same figure (histogram III).

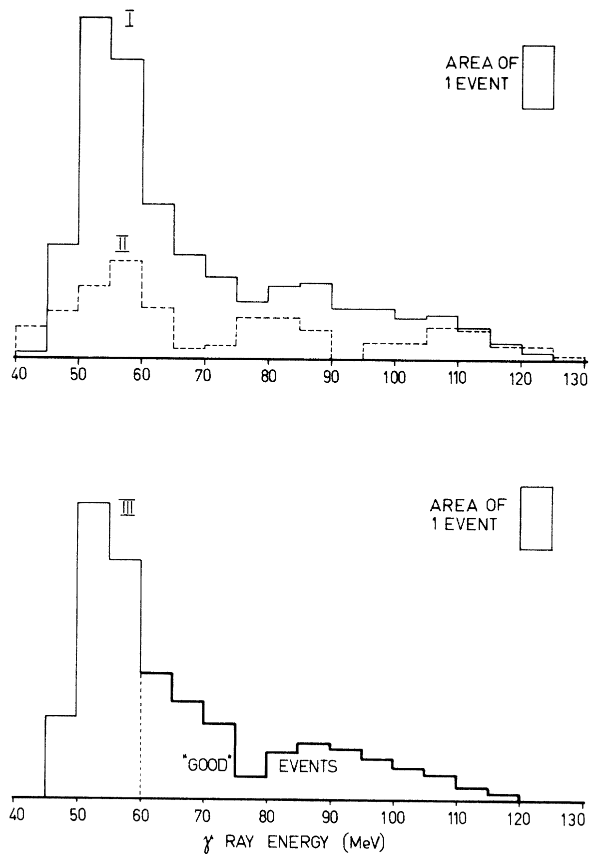

FIG. 2. Energy distribution: (I) of the 24 events fulfilling our selection criteria and showing (as in the event reproduced in Fig. 1) a μ^- stop in SC1; (II) of the 9 events fulfilling the selection criteria but with no track in SC2; (III) of events of category I (24) after subtraction of the contribution (~5.5 events) due to accidental superposition of a μ^- stop with an event of category II. The overall resolution in the energy determination is included in these hystograms, since each event was displayed as a rectangle of constant area with the basis, centered at the measured energy, equal to twice the standard deviation. This standard deviation was evaluated as in reference 8.

Some of the low-energy events in histogram III are originated by decay electrons which have irradiated an energetic γ ray in the steel plate where the μ^- stop occurred or in the next one.[9] The energy distribution of this "spurious" contribution can be calculated starting from the energy spectrum of decay electrons from μ^- mesons stopped in Fe, recently determined[10] using the same NaI spectrometer employed in the present experiment. The results of this calculation (performed taking into account, of course, the effect

Table I. Results of calculations on the expected γ-ray spectra from decay electrons $[F_d(E)]$ and from process (1) $[F_{rc}(E)$, for three different models (see text)]. All spectra are normalized to 1 μ^- stop. The functions $F_{rd}(E)$ are multiplied by R, assuming $R = 10^{-4}$.

E (MeV)	$F_d(E) \times 10^6$	$R \times F_{rc}^{(1)}(E) \times 10^6$	$R \times F_{rc}^{(2)}(E) \times 10^6$	$R \times F_{rc}^{(3)}(E) \times 10^6$
30	8.70	1.75	1.90	1.97
35	7.45	1.77	1.85	1.90
40	5.90	1.74	1.77	1.80
45	4.25	1.65	1.62	1.60
50	1.76	1.52	1.43	1.40
55	0.48	1.35	1.20	1.15
60	<0.01	1.15	0.97	0.90
65	...	0.95	0.75	0.65
70		0.75	0.55	0.42
75		0.56	0.32	0.25
80		0.40	0.20	0.10
85		0.22	0.10	0.05
90		0.10	0.05	0.02
95		0.04	0.02	0.01
100		...	...	...

of the "anticounter" $\bar{4}$ which rejects a γ ray if accompanied by an electron reaching it) are given in Table I, 2nd column. The calculated distribution $[F_d(E)]$ is normalized to one μ^- stop.

The spectra of γ rays from radiative capture $[F_{rc}(E)]$ have also been computed for three different models:

(1) adapting to process (1) the Morrison-Schiff (M-S) formula,[11] which was derived a long time ago for the allowed transitions following the atomic K capture of an electron[12];

(2) using for the Fe nucleus a Fermi model with an "effective mass"[13,14] $M^* = M$ (nucleon mass) to obtain the distribution of the nuclear excitation energies,[15] and assuming that the M-S formula can be applied to all transitions from the ground state of the parent nucleus to the final states of the product nucleus[16];

(3) maintaining the assumptions of case (2) but using $M^* = M/2$.

For a comparison with the photon spectrum from decay electrons $[F_d(E)]$, the three spectra thus calculated are also given in Table I, normalized to one μ^- stop and multiplied by R, assuming $R = 10^{-4}$. It is seen from the table that $F_d(E)$ becomes entirely negligible for $E > E^* = 60$ MeV. Since $F_d(E)$ was derived from the experimental decay electron spectrum which includes the resolution of the NaI spectrometer,[10] we conclude that for $E > E^*$ no appreciable contribution is given to the events of histogram III (Fig. 2) by decay electrons irradiating γ rays in SC1.

The "good" events, i.e., events to be interpreted as due to process (1), are then $n = 9.5 \pm 3.8$ (12.5 of category I from which 4.8×0.61 events of category II must be subtracted), with the energy distribution shown by the thick line in histogram III.

If we want to use this result to get a value of R for each of the three models assumed, we need to know the average detecting efficiencies ϵ of our apparatus for the γ rays of the three corresponding spectra $F_{rd}(E)$. If $f = 0.91$ is the fraction of μ^- undergoing nuclear capture in iron[17] and $u = 0.69$ is the fraction of events accepted by our electronics,[18] then

$$R = n/N_\mu fu\epsilon = (3.3 \pm 1.3)10^{-8}/\epsilon. \qquad (2)$$

The efficiencies ϵ have been computed by a Monte Carlo calculation taking into account the requirement of seeing two electrons in SC2, one at least of which crossed counter 6, as well as the actual distribution of μ^- stops over the Fe plates of SC2 obtained in a special run. The Fe plates have been subdivided into 30 equal squares and for any chosen energy 2000 γ rays have been imagined to come out isotropically from the centers of these squares. The Monte Carlo calculation then takes into account also the possible directions of γ-ray emission from the point at which the μ^- stops in the useful region of SC1, and, of course, all processes which an electron, produced at a given depth of the W converter, may undergo in crossing the remaining thickness of the W plate. Allowance has been made also for the possibility that the γ-ray conversion occurs in the Fe plates

Table II. Average detection efficiencies of apparatus and corresponding values of R for the three models (1), (2), (3) considered in the text. Errors in the values of R include also those of the Monte Carlo calculation.

Model	ϵ	R
(1)	$(4.48 \pm 0.28) \times 10^{-4}$	$(0.73 \pm 0.34) \times 10^{-4}$
(2)	$(3.29 \pm 0.21) \times 10^{-4}$	$(1.00 \pm 0.43) \times 10^{-4}$
(3)	$(2.68 \pm 0.17) \times 10^{-4}$	$(1.23 \pm 0.54) \times 10^{-4}$

of SC1. The results of the calculation are given in Table II, together with the corresponding values of R deduced from Eq. (2). Consistent values of R are obtained choosing 65 MeV rather than 60 MeV for E^*.

We conclude, therefore, that process (1) exists and it occurs with a branching ratio,

$$R \sim 1 \times 10^{-4},$$

in agreement with the theoretical predictions relative to the whole γ-ray spectrum from radiative capture in copper.[4] A greater accuracy in the experimental and theoretical determinations of R would be necessary, however, to infer from such an agreement which, of the models adopted for the capturing nucleus, has to be preferred.

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[1]K. Huang, C. N. Yang, and T. D. Lee, Phys. Rev. 108, 1340 (1957); see also R. Cutkosky, Phys. Rev. 107, 330 (1957).

[2]J. Bernstein, Phys. Rev. 115, 694 (1959).

[3]G. K. Manacher and L. Wolfenstein, Phys. Rev. 116, 782 (1959); see also H. Obayashi and B. Sakita, University of Nagoya Report, 1955 (unpublished).

[4]H. Primakoff, Revs. Modern Phys. 31, 802 (1959).

[5]G. K. Manacher, Carnegie Institute of Technology Report NYO-9284, 1961 (unpublished).

[6]A first attempt to detect process (1) was carried out at the Nevis cyclotron by W. F. Baker and C. Rubbia (private communication of Dr. C. Rubbia).

[7]Considering only the main diagram in which the photon is attached to the μ^-, it has been shown in reference 1 that opposite values of the asymmetry parameter are expected for the two extreme cases of pure V-A and S-T couplings, provided that μ^- capture occurs in nuclei with $Z \ll \hbar c/e^2 = 137$.

[8]See G. Conforto, M. Conversi, L. di Lella, G. Penso, C. Rubbia, and M. Toller, Nuovo cimento (to be published); also Phys. Rev. Letters 8, 125 (1962).

[9]Looking at the SC1 pictures, events produced by decay electrons cannot be recognized from those searched for if the γ ray is radiated in the plate where the muon is stopped or in the following one. In all other instances, however, the radiating electron will, in general, be recognized as being emitted by the stopping muon, since the muon and electron tracks make an average angle of about 45°. This has been taken into account in the calculation mentioned later in the text.

[10]G. Culligan, D. Harting, N. H. Lipman, and G. Tibell, Proceedings of the Aix-en-Provence Conference on Elementary Particles, 1961 (C.E.N. Saclay, France, 1961), Vol. 1, p. 143.

[11]P. Morrison and L. I. Schiff, Phys. Rev. 58, 24 (1940).

[12]The M-S formula $[x(1-x^2)$ with x = photon energy/max photon energy] agrees well with the high-energy side of the experimental photon spectrum from atomic K capture. [See R. J. Glauber, P. C. Martin, T. Lindqvist, and C. S. Wu, Phys. Rev. 101, 905 (1956).] The interpretation of the low-energy side requires, however, more refined calculations. [See P. C. Martin and R. J. Glauber, Phys. Rev. 109, 1307 (1958).]

[13]K. A. Brueckner, Phys. Rev. 97, 1353 (1955).

[14]See, for example, S. A. Moszkowski, Handbuch der Physik, edited by S. Flügge (Springer-Verlag, Berlin, 1957), Vol. 39, p. 421.

[15]See, for example, S. N. Kaplan, B. J. Moyer, and R. W. Pyle, Phys. Rev. 112, 968 (1958).

[16]Because of the large muon mass, many final excited states are possible for the product nucleus. This is why sizeable departure from the atomic K capture spectrum may occur in spite of the close similarity of the two processes.

[17]Using for the lifetime of μ^- mesons in Fe the value (207 ± 3) nsec recently obtained by I. M. Blair, H. Muirhead, T. Woodhead, and J. M. Woulde, ULDP Report No. 10, March, 1962 (unpublished).

[18]Minimum and maximum accepted γ-μ delays were 32 and 392 nsec, respectively. In order to eliminate "triggering events" possibly originated by μ^-'s stopping after counter 4, it was furthermore required that the final coincidences $[\mu\gamma(\mathrm{NaI})_{>t}]$ did not follow a coincidence 1234 within $\sim 1\ \mu$sec. This requirement caused $\sim 5\%$ accidental loss of events. Hence $u = 0.95 \exp(-0.155) \times [1-\exp(-1.9)] = 0.69$.