ANOMALY IN THE DECAY OF μ^--MESONS IN MESIC ATOMS OF IRON-GROUP TRANSITION METALS

L. B. EGOROV, A. E. IGNATENKO, A. V. KUPTSOV, and M. G. PETRASHKU

Joint Institute for Nuclear Research

Submitted to JETP editor April 23, 1962

J. Exptl. Theoret. Phys. (U.S.S.R.) 43, 1149-1153 (October, 1962)

By the method of scintillation counters, relative measurements are made of the decay probabilities of μ^- mesons in mesic atoms of iron and zinc, and also of nickel and copper. The results of measurements indicate an absence of the anomaly observed by a number of authors [1-4]. Equality, within the limits of errors of the experiment, of the yield of γ rays from the above-mentioned targets indicates that the instrument effect noted in [7,9] is not the cause of the anomaly observed.

1. INTRODUCTION

ABSOLUTE measurements of the ratio R of the μ^--meson decay probability in mesic atoms to the probability of decay of free μ^- mesons were reported in several papers [1-4]. These values of R point to the existence of an anomaly in the transition metals of the iron group. A theoretical analysis [5-7] of these questions shows that the observed anomaly cannot be explained when all the possible trivial effects in mesic atoms are taken into account. Measurements of the relative electron yields from μ^--meson decay in mesic atoms of the transition metals palladium, titanium, and their hydrides [8] show directly that there are no nontrivial effects due to unpaired electrons in the atoms. Huff and Chilton [7,9] noted that the observed anomalies are more likely to be an apparatus effect than a nontrivial phenomenon. Thus, one of the causes may be that the gamma rays with energy less than 10 MeV, emitted from the nuclei as a result of μ^--meson capture, have a registration efficiency which is one order of magnitude larger than estimated in [1-4]. To check the results of these experimental investigations and the predictions made by Huff and Chilton, we have made relative measurements of R in mesic atoms of iron and zinc, and also of nickel and copper.

2. THE EXPERIMENT

A. The method. The yield y(Z) of decay electrons from a target with atomic number Z can be written in the form

$$y(Z)=\frac{\Lambda_d(Z)}{\Lambda(Z)}\Delta\Omega(Z)\,\varepsilon(Z), \tag{1}$$

where $\Lambda_d(Z)$ is the μ^--meson decay probability, $\Lambda(Z)$ is the total probability of annihilation of the μ^- mesons in the mesic atom, $\Delta\Omega(Z)$ is the solid angle subtended by the electron detector, and $\epsilon(Z)$ is the decay electron registration efficiency.

The ratio ξ of the probabilities of the μ^--meson decay in mesic atoms with atomic numbers Z and Z′ is

$$\xi=\frac{\Lambda_d(Z)}{\Lambda_d(Z')}=\frac{y(Z)}{y(Z')}\frac{\Lambda(Z)}{\Lambda(Z')}\frac{\Delta\Omega(Z')\,\varepsilon(Z')}{\Delta\Omega(Z)\,\varepsilon(Z)}. \tag{2}$$

We use the "sandwich" method to measure the values of ξ [1,4]. We choose the investigated substances to have close values of Z and Z_0, such as iron and zinc. Then the difference in the values of ϵ due to the difference in the geometry of the experiment and in the decay electron spectra will be insignificant [7]. The expression for ξ in two investigated mesic atoms with Z and Z_0 can be written in the form

$$\xi=\frac{\Lambda_d(Z)}{\Lambda_d(Z_0)}=\frac{y(Z)}{y(Z_0)}\frac{\Lambda(Z)}{\Lambda(Z_0)}=\frac{y(Z)\,\Lambda(Z')\,/\,y(Z')\,\Lambda(Z_0)}{y(Z_0)\,\Lambda(Z')\,/\,y(Z')\,\Lambda(Z)}. \tag{3}$$

It follows from (2) and (3) that if we know the values of Λ for the investigated substances, then the use of a substance with Z′ for calibration purposes makes it possible to find the sought values of ξ. Aluminum was used for calibration in the experiments with iron and zinc.

We maintain all the conditions of experiments with substances in which Z differs by unity (such as nickel and copper) identical. Then, as follows from (2), to determine ξ it is sufficient to measure the ratio of the decay electron yields.

B. Experimental setup. Figure 1 shows a block diagram of the setup. In experiments with iron and zinc, the negative muons stopped in the target

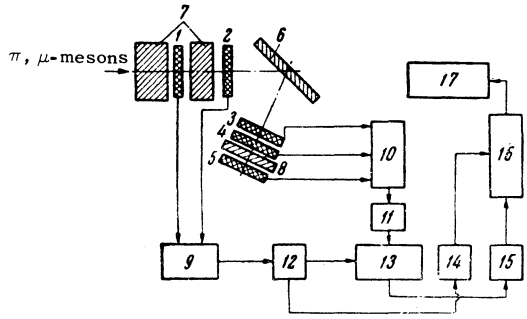

FIG. 1. Block diagram of setup: 1–5 (scintillation counters); 6 – target; 7 – copper absorbers; 8 – aluminum absorber; 9, 10 – coincidence and anticoincidence block; 11 – delay; 12 – gate duration flipflop; 13 – gate; 14–15 – shaping devices; 16 – converter; 17 – pulse height analyzer.

6 were registered by the 1 + 2 coincidences. Pulses from the network 9 triggered flipflop 12, which generated positive rectangular stable pulses of 5 μsec duration. A gate circuit 13 was opened for this length of time. The pulses through the gate from circuit 10 were due to the μ-e decay electrons and the neutral radiation emitted upon capture of the μ^- mesons by the nuclei (4 + 5 coincidences), and were also due to the neutral radiation from the circuit 10 (4 + 5 – 3 anticoincidences), delayed in cell 11 for 0.2 μsec; the latter pulses triggered the shaping unit 15. The delay 11 was introduced to set the zero time between the pulses on the screen of analyzer 17. The pulses intended to trigger the converter 16 were fed to its first input from circuit 15, while the second input received pulses from shaping unit 14, which was triggered by the trailing edge of the pulse from flipflop 12. The converter output pulses, whose amplitude was proportional to the time interval between the two pulses fed to its inputs, were analyzed with a 128-channel pulse-height analyzer.

The targets were assembled in these experiments in the form of sandwiches made of iron and aluminum or zinc and aluminum. Each component of the sandwich consisted of 10 plates measuring 15 × 15 cm. The thicknesses of the plates were 0.8 mm for iron, 1 mm for zinc, and 0.7 mm for aluminum.

In the experiments with the nickel and copper, the scintillation counter 3 was placed on the "axis" of the μ^- meson beam. The negative μ mesons, which were stopped in the target 6, were registered by the 1 + 2 – 3 anticoincidence circuit 9. The pulses from circuit 9, delayed by 0.1 μsec, opened the gates 13 for 1 μsec. The pulses from the decaying electrons were fed through the gates from the circuit 10 (4 + 5 coincidences) and were registered by a separate scaler. The targets employed had an area 15 × 15 cm^2 and a thickness 5 g/cm^2. All the conditions for the experiments with nickel and copper were identical.

Scintillation counters 1—5 were made of plastic and were 10 cm in diameter and 1 cm thick.

The linearity of the apparatus employed in the experiments was checked with the aid of a set of delay lines (in the form of cables). The identity of the delay was checked by a resonance method accurate to 0.5%. The nonlinearity of the apparatus did not exceed 1%. The stability of the calibration of the apparatus over 15 hours of work was better than 1%. To determine the "zero" channel of the analyzer, the scintillation counters 1—5 were located along the "axis" of the meson beam, and the anticoincidence channels were then disconnected.

3. Results, data reduction, and discussion. Figures 2 and 3 show the time distribution of the pulses from the circuit 9 (4 + 5 coincidences) for targets consisting of Fe + Al and Zn + Al sandwiches. The time distribution of the pulses from circuit 10 (4 + 5 – 3 anticoincidences) is shown in Fig. 4. The measured ratio of the yield of electrons from nickel and copper was found to 0.95 ± 0.02.

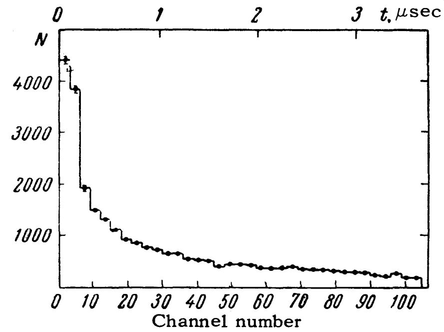

FIG. 2. Time distribution of electrons from μ^--meson decay in a Fe + Al target. Here and throughout N is the sum of the counts in the three analyzer channels.

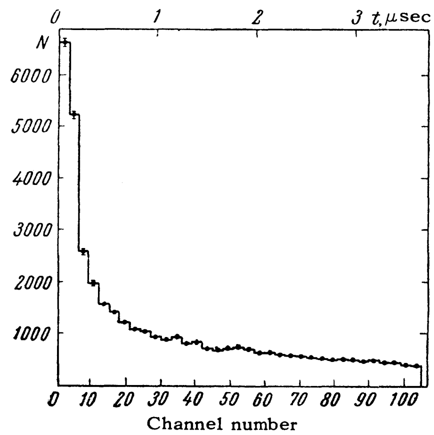

FIG. 3. Time distribution of electrons from μ^--meson decay in Zn + Al target.

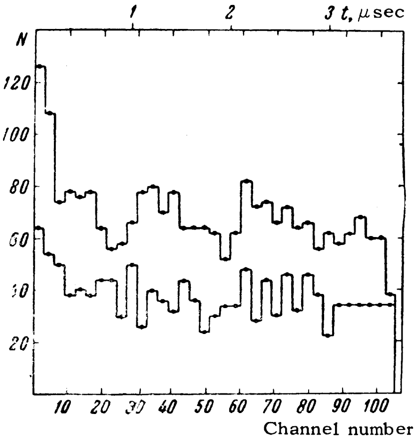

FIG. 4. Time distribution of 4 + 5 − 3 anticoincidence pulses for Zn + Al (upper histogram) and Fe + Al (lower histogram) targets.

The time interval from 0 to 3.71 μsec, corresponding to 105 channels of the analyzer, was used in the reduction of the results presented in Figs. 2 and 3. The time interval from 2.43 to 3.71 μsec was used to calculate the background. In calculating the quantities

$$S = \sum t_i n_i \Big/ \sum n_i$$

(here n_i is the number of pulses at the instant of time t_i), the pulses from three channels were summed, i.e., over a time interval 0.106 μsec. The measured values of S were:

Target:	Fe + Al	Zn + Al
S, μsec:	0.485 ± 0.009	0.463 ± 0.008

It is easy to see that any distribution which results from the superposition of two processes characterized by τ_1 and τ_2 obeys the relation

$$S = n_1 S_1 + n_2 S_2, \qquad S_1 = \sum n_{1i} t_i / N_1,$$
$$S_2 = \sum n_{2i} t_i / N_2, \tag{4}$$

where the sums S_1 and S_2, calculated in the time interval from 0 to t, correspond to the exponentials $\exp[-t/\tau_1]$ and $\exp[-t/\tau_2]$, while $n_1 = N_1/N$, $n_2 = N_2/N$, and $N_1 + N_2 = N$.

For Fe + Al and Zn + Al targets, the values of S can be written in the form

$$S\,(\mathrm{Fe + Al}) = n_1 S\,(\mathrm{Fe}) + n_2 S\,(\mathrm{Al}),$$
$$S\,(\mathrm{Zn + Al}) = n_1' S\,(\mathrm{Zn}) + n_2' S\,(\mathrm{Al}). \tag{5}$$

In the time interval employed from 0 to 2.43 μsec, we obtained on the basis of the tables of coefficients given by Peierls [10] and the experimental data for τ given in [11,12] the following values of S (in μsec):

$$S\,(\mathrm{Fe}) = 0.201 \pm 0.004, \qquad S\,(\mathrm{Zn}) = 0.161 \pm 0.004,$$
$$S\,(\mathrm{Al}) = 0.707 \pm 0.002.$$

The agreement between the values of τ for phosphorus, as measured in our previous investigation [3] and by Lathrop et al [11], indicates that the time scale used in conjunction with the present apparatus has been correctly calibrated.

On the basis of expressions (3) and (5), the ratio of the decay probabilities of the μ^- mesons in the mesic atoms of iron and zinc can be written in the form

$$\xi = \frac{\Lambda_d(\mathrm{Fe})}{\Lambda_d(\mathrm{Zn})} = \frac{n_1}{n_1'}\frac{n_2'}{n_2}\frac{\Lambda\,(\mathrm{Fe})}{\Lambda\,(\mathrm{Zn})} k_1 k_2, \tag{6}$$

where k_1 is a correction that takes into account the difference in the layer thicknesses (in g/cm^2) of the zinc and the iron in the sandwich, and k_2 is a correction that takes into account the difference in the angular distributions of the μ-e decay electrons in iron and in zinc [14].

We have also analyzed the corrections necessitated by the absorption in the target of electrons from the μ^--meson decay, with allowance for the fact that the thicknesses of the Fe + Al and Zn + Al targets were not much different from each other. These corrections turned out to be less than 1%. The probability of registration of the beam electrons scattered in the targets was likewise insignificant.

The value obtained for ξ was

$$\xi = \Lambda_d(\mathrm{Fe}) / \Lambda_d(\mathrm{Zn}) = 0.94 \pm 0.05.$$

In the experiments with nickel and copper, the measured value was

$$\xi = \Lambda_d(\mathrm{Ni}) / \Lambda_d(\mathrm{Cu}) = 0.98 \pm 0.05.$$

The data for Λ used in the calculations of ξ were taken from [11,12].

In the reduction of the measurement results shown in Fig. 4, the data in the time interval from 0.64 to 3.71 μsec, used for the calculation of the background, were subtracted from the data for the interval from 0 to 0.64 μsec. This was followed by summation and normalization to equal background in both histograms. For the Zn + Al target the number of 4 + 5 − 3 anticoincidence counts was 150 ± 20, while for the Fe + Al target the number was 117 ± 32. The efficiency of the anticoincidence circuit 10 was 99.95%.

The results of the relative measurements of ξ show that within the limits of statistical errors of the experiment the μ^--meson decay probabilities are the same in iron and in zinc, and also in nickel and copper. The fact that there are no anomalies in the μ^--meson decay in the mesic atoms of the ferromagnetic iron triad contradicts the results of several authors [1-4], but agrees with the results of the absolute measurements of the value of R, given by Culligan et al [15], and also by Muirhead et al [16].

It is reasonable to assume that the number of 4 + 5 − 3 anticoincidences is due essentially to γ rays emitted from the target as a result of absorption of μ^- mesons by the nuclei. The thickness of the aluminum absorber 8 located between counters 4 and 5 was the same as in [1-4]. The equal emission of γ rays from Fe + Al and Zn + Al targets (within the limits of experimental error) is evidence in favor of assuming that the apparatus effect, indicated by Huff [7] and by Chilton [9] does not cause the anomaly observed experimentally [1-4].

The authors are grateful to V. O. Vyazemskiĭ for valuable advice offered during the course of developing the converter.

[1] Lundy, Sens, Swanson, Telegdi, and Yovanovitch, Phys. Rev. Lett. **1**, 102 (1958).

[2] Astbury, Hussain, Kemp, Lipman, Muirhead, Voss, and Kirk, Proc. Phys. Soc. (London) **73**, 314 (1959).

[3] Barrett, Holmstrom, Keuffel, Phys. Rev. **113**, 661 (1959).

[4] D. D. Yovanovitch, Phys. Rev. **117**, 1580 (1960).

[5] H. Uberall, Phys. Rev. **119**, 365 (1960).

[6] V. Gilinsky and J. Mathews, Phys. Rev. **120**, 1450 (1960).

[7] R. W. Huff, Ann. Physics **16**, 288 (1961).

[8] Egorov, Ignatenko, Kuptsov, and Petrashku, JETP **43**, 873 (1962), Soviet Phys. JETP **16**, 619 (1962).

[9] F. Chilton, Phys. Rev. Lett. **7**, 31 (1961).

[10] R. Peierls, Proc. Roy. Soc. **149**, 467 (1935).

[11] Lathrop, Lundy, Telegdi, Winston, and Yovanovitch, Phys. Rev. Lett. **7**, 107 (1961).

[12] J. C. Sens, Phys. Rev. **113**, 679 (1959).

[13] Egorov, Zhuravlev, Ignatenko, Kuptsov, Li, and Petrashku, JETP **41**, 684 (1961), Soviet Phys. JETP **14**, 494 (1962).

[14] A. E. Ignatenko, Nucl. Phys. **23**, 75 (1961).

[15] Culligan, Harting, Lipman, and Tibell, The Aix-en-Provence, Intern. Conf. on Elementary Particles, C.E. N. Saclay, France, 1961, **1**, p. 143.

[16] Blair, Muirhead, Woodhead, and Woulds, Preprint, University of Liverpool, ULDP 10, (1962).

Translated by J. G. Adashko
203