SPECTRUM OF ELECTRONS EMITTED IN THE DECAY OF NEGATIVE MUONS IN NUCLEAR EMULSION

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The spectra of electrons produced in the decay of μ^- mesons in light (C, N, O) and heavy (Ag, Br) mesic atoms in a nuclear emulsion have been measured. In the first case, the spectrum is identical with the positron spectrum in the μ^+-e decay. In the second case, the spectrum shape seems to be softer. The spectrum of Auger electrons accompanying the μ^--e decay has been obtained. The probability of Auger electron production in light mesic atoms is shown to agree with the theoretical prediction.

1. INTRODUCTION

THE purpose of the present experiment is to compare the spectrum of the electrons produced in μ^--e^- decays of mesic atoms of light (C, N, O) and heavy (Ag, Br) emulsion nuclei with the positron spectra in the μ^+-e^+ decay of "free" μ^+ mesons. The decay probabilities and the spectra in the μ^+ and μ^- decay may differ considerably, and this difference should increase for heavy nuclei. This is due to the decrease in the number of final states of the decay electrons, to relativistic effects caused by the motion of the μ^- mesons in the K orbit of the mesic atom, and to the action of the Coulomb field of the nucleus on the decay electrons.

All these effects, both for a point and an extended nucleus, were investigated theoretically by a number of authors.[1-3] For an illustration of the magnitude of the expected effect, the decay electron spectra for free μ^+ mesons (curve 1) and for the decay of mesic atoms with Z = 7 and Z = 40 (curves 2 and 3, taken from [2]) are shown in Fig. 1. Here and in the following figures, the x axis represents the energy $\epsilon = E\,[\text{Mev}]/52.8$. These curves have been obtained for the four-fermion V-A interaction. Thus, curve 1 corresponds to the Michel parameter $\rho = 3/4$.

In the present experiments, we have measured the following electron spectra: 1) spectrum from 2969 π^+-μ^+-e^+ decays; 2) spectrum from 604 μ^--e^- decays; and 3) spectrum from 207 μ^--e^- decays accompanied by the production of Auger electrons.

The spectra 1) and 2) have been used earlier[4] to determine the Michel parameter ρ and the asymmetry parameter δ. The same reference describes in detail the irradiation of the emulsion chambers in the π^+ and μ^- meson beams using the proton synchrotron of the Joint Institute for Nuclear Research, the method of spectrum measurement, and the selection criteria.

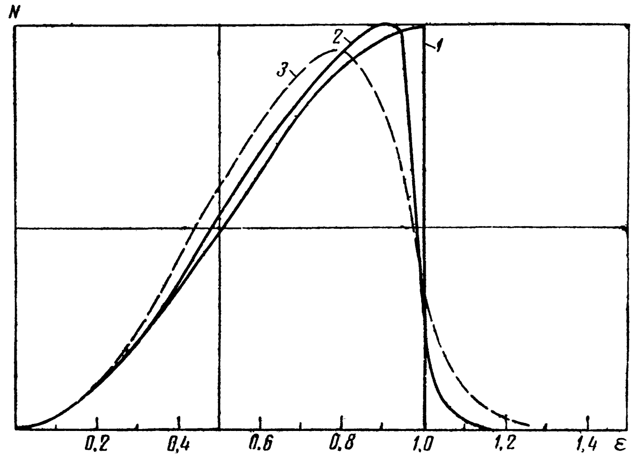

FIG. 1. Spectra of decay electrons for V – A interaction: 1 – Z = 0; $\rho = 3/4$; 2 – Z = 7; 3 – Z = 40. The calculations refer to an extended nucleus.[2]

2. COMPARISON OF THE ELECTRON SPECTRA IN μ^--e^- DECAY IN LIGHT EMULSION ATOMS WITH THE POSITRON SPECTRUM IN μ^+-e^+ DECAY

The positron spectrum obtained from 2969 μ^+-e^+ decays and the spectrum of electrons from 604 μ^--e^- decays in light emulsion atoms is shown in Fig. 2. The solid curve indicates the theoretical spectrum, blurred by the experimental conditions, with a Michel parameter $\rho = 0.68$.[4] An analysis of these spectra leads to the conclusion that the electron spectrum for the decay in light emulsion atoms (C, N, O) is almost in full agreement

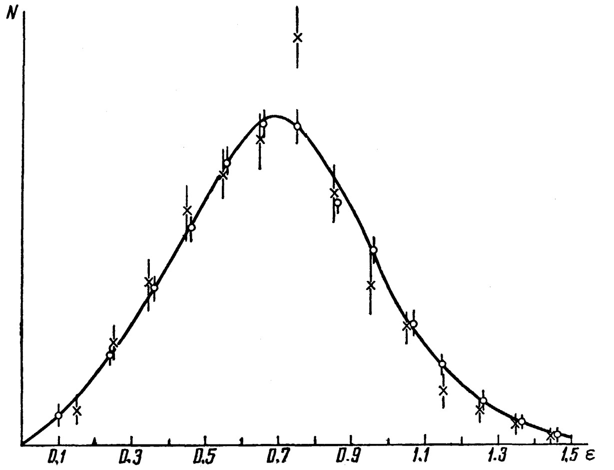

FIG. 2. Electron spectra for the $\mu^+ - e^+$ decay (o) and for the $\mu^- - e^-$ decay (×) in light emulsion atoms.

with the spectrum of positrons from the μ^+-e^+ decay. This result is not unexpected, since the influence of the above-mentioned effects connected with the bound μ^- meson should be small for low Z (see curve 2 in Fig. 1), and the blurring of both spectra due to the dispersion of the measurement makes them even more indistinguishable.

Analogous results have also been obtained by Bloch et al,[5] who compared the electron spectrum in μ^--e^- decays in He with the positron spectrum in the μ^+-e^+ decay.

3. SELECTION OF DECAYS IN HEAVY EMULSION ATOMS

Most μ^- meson decays in emulsion occur in mesic atoms of light nuclei. If we assume that ~ 40% of the μ^- mesons stop in the gelatine and ~ 60% in the silver-halide crystals [6] and use the known values for the μ^- meson lifetime in mesic atoms of C, N, O, Ag, and Br,[7] we find that approximately only one out of 15 μ^--e^- decays in the emulsion occurs in the mesic atoms of silver halides. In order to select such decays, we have used as a selection criterion the presence of a track of an Auger electron in addition to the decay-electron track. Tracks were classified as due to Auger electron if they contained not less than four grains or blobs, with the first not more than $4\,\mu$ from the point were the μ^- meson stopped, and in which, moreover, the large scattering characteristic of slow electron tracks is observed.

The spectrum of Auger electrons selected by such a criterion was estimated in the following way: for each Auger electron track, we count the number of grains or blobs. Then, on plane tracks whose range is easy to measure, we establish the approximate blob density vs. range relation which, in the range of 4 — 50 blobs, is of the form $R(\mu) = 1.85\,N$ (blobs). From this relation we can determine the range of the remaining tracks that are more inclined, for which the number of blobs can be measured while the range can be measured only with great difficulty. After the range has been estimated, the energy is found by using the range-energy relations for slow electrons.[8]

The energy spectrum of Auger electrons accompanying the μ^--e^- decay as obtained by us is shown in Fig. 3. The comparison of this spectrum with the probabilities, calculated in [9], of transitions in C, N, O, Ag, and Br atoms leads to the conclusion that, for our selection criterion, about 85 — 90% of the μ^--e^- decays accompanied by Auger electrons occurred in mesic atoms of Ag or Br.

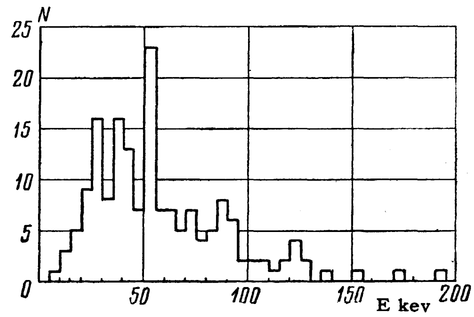

FIG. 3. Spectrum of Auger electrons accompanying the μ^- — e^- decay.

As a direct check of the accuracy of such a selection criterion, we have used the presence of Auger electrons in σ_μ capture stars on light nuclei of the emulsion. The capture by a light nucleus was identified by the presence of a two-prong star, with one prong representing the track of the recoil nucleus with a range less than $10\,\mu$, while the second prong represents the track of an α particle. In scanning 500 such stars, we found an Auger electron track which satisfied our selection criterion, with energy $\gtrsim 25$ kev, in only two cases. In selecting the μ^--e^- decays in the emulsion, we found that, using our selection criterion, about 60 normal μ^- meson decays occurred for each decay event accompanied by an Auger electron. Hence, it follows that, in our spectrum of 202 particles, not more than $(2/500) \times 60 \approx 25\%$ of μ^- meson decays in light atoms may be present as an admixture. This analysis confirms the correctness of our selection criteria for decays in heavy atoms.

4. COMPARISON OF ELECTRON SPECTRA IN μ^--e^- DECAY IN HEAVY EMULSION ATOMS WITH THE POSITRON SPECTRUM

This comparison is shown in Fig. 4, where curve 1 represents the positron spectrum (taken from Fig. 2), while curve 2 represents the theoretical electron spectrum from the μ meson decay in heavy emulsion atoms (Z = 40) calculated by Überall and blurred by our experimental conditions. The circles represent the experimental electron spectrum. A comparison shows that, because of instrumental errors, spectrum 2 is shifted towards lower energies. The parameter of the spectrum sensitive to the low-energy region is the inverse energy averaged over the whole spectrum $\langle 1/\epsilon \rangle$. The values of $\langle 1/\epsilon \rangle$ for the experimental spectrum and for the theoretical spectra are shown in the table.

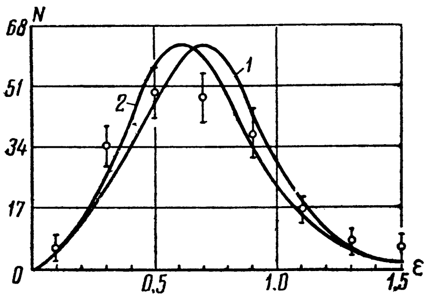

FIG. 4. Comparison of the electron spectra for the $\mu^+ - e^+$ and $\mu^- - e^-$ decays in Ag and Br emulsion nuclei. 1 – experimental spectrum of electrons in the $\mu^+ - e^+$ decay taken from Fig. 2; 2 – electron spectrum calculated by Überall[3] in the $\mu^- - e^-$ decay for Z = 40 and blurred because of our instrumental errors.

Spectrum	$<1/\varepsilon>$
Theoretical spectrum of positrons (ρ = 0.68)	1.79
Experimental spectrum of 2969 positrons	1.77 ± 0.07
Theoretical electron spectrum	
according to Überall[3]	1.91
according to Terent'ev[2]	2.06
Experimental spectrum of 202 electrons	1.92 ± 0.30

It can be seen from the table that the mean values of $\langle 1/\epsilon \rangle$ for the theoretical and experimental positron spectra and for the electron spectra respectively are in good agreement. For an experimental check of the statistical significance of this agreement, we have divided the spectrum of μ^+-e^+ decays consisting of 2969 positrons and the similar spectrum of 604 electrons from μ^- meson decays in mesic atoms of light emulsion nuclei into spectra consisting of 200 particles each, and have compared the number of particles in the low energy range ($\Delta\epsilon = 0 - 0.4$) of these 17 spectra with the number of particles in the same range in the spectrum of μ^- decays in heavy atoms (the latter being equal to 39). In addition, we have also compared the mean values of the inverse energy for each of the spectra. It was found that in none of the 17 spectra is the number of particles in the interval $\Delta\epsilon = 0 - 0.4$ greater than the number of particles in the electron spectrum (39), and all values of $\langle 1/\epsilon \rangle$ are less than 1.92. Thus, the experimental estimate of the probability that the measured spectrum of electrons is a fluctuation of the positron spectrum gives the value of $\sim 1/_{17} \lesssim 10\%$.

5. NEUTRINOLESS DECAY OF μ^- MESONS INTO ELECTRONS

Our experimental data on the electron spectra in the μ^--e^- decay makes it possible to obtain the upper limit for the probability of the neutrinoless decay of μ^- mesons into electrons on the X nucleus: $\mu^- + X \rightarrow X^* + e^-$. This process is forbidden in the first approximation of the four-fermion interaction theory, and is absolutely forbidden if the electron and meson neutrinos are different. It could occur with a μ^- meson captured on the K orbit of the mesic atom: the whole recoil would be absorbed by the X nucleus, and the energy carried away by the electron would be close to the rest energy of the μ^- meson $\sim$ 100 Mev, or somewhat less if the nucleus were excited.

Let us consider the spectra of positrons and electrons in the energy range $\epsilon > 1.0$. For the positron spectrum, we limit ourselves to this range because of the dispersion of the scattering measurements which, under our conditions, amounts to 15 – 25% at the limit of the spectrum.

The analysis carried out by us showed that most of the particles with energy $\epsilon > 1$ correspond to short tracks of length $l \leq 1.5$ mm, for which the dispersion of the measurements is considerable. Thus, the background in the range of large energies ($\epsilon \sim 2$), when we are looking for monochromatic electrons of $\sim$ 100 Mev from the μ^--e^- decay, is determined by the dispersion of the scattering measurements.

The second source of the background in this energy range is due to the fact that the electron spectrum exceeds the limit $\epsilon = 1$ because of the effects of the μ^- meson binding in the mesic atom. The blurring of the spectra in our experiment[4] showed, however, that this background is negligibly small as compared with the first source.

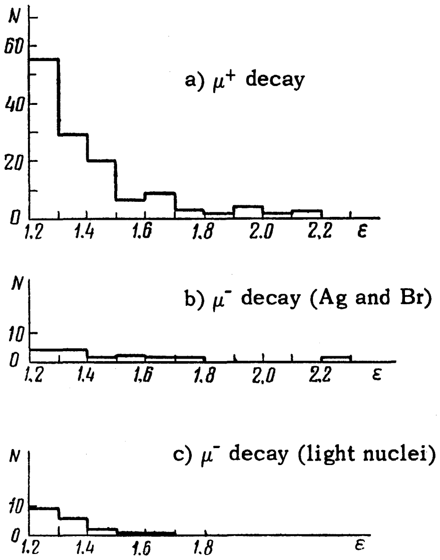

FIG. 5. Comparison of the "tails" of the spectra for $\mu^+ - e^+$ and $\mu^- - e^-$ decays.

Figure 5 shows the spectra for an energy $\epsilon > 1.2$ for a) 2980 positrons, b) 604 electrons originating in the decays in light emulsion atoms, and c) 207 electrons in the decays in heavy emulsion atoms. We shall assume that the particles of the spectrum a) determine the background of the measurement for the spectra b) and c). This background in the energy range $\Delta\epsilon = 1.7 - 2.3$ amounts to $\sim 0.06\%$ of the total spectrum in the energy range $\Delta\epsilon = 0.1$. In the spectrum c) of decays in heavy emulsion nuclei in the range $\Delta\epsilon = 1.6 - 2.3$, two particles are present. It should be added that the tracks of electrons starting with $\epsilon = 1.5$ are very short in this spectrum, namely 1.0, 1.25, 1.1, and 1.0 mm, and their energy is therefore measured with an increased spread. We can therefore maintain that the spectrum of electrons from μ^--e^- decays in heavy mesic atoms in the emulsion as obtained by us does not indicate the presence of electrons in the range of 80 — 120 Mev in numbers greater than that determined by the background.

We shall now estimate the upper limit of the probability of the process $\mu^- + X \rightarrow X^* + e^-$ to which these results correspond. In order to determine this probability, it is necessary to find the number of captures corresponding to the measured number of decays. Under the condition that the decay probability is the same for μ^- and μ^+ mesons, the number of captures $N_c = N_d(\tau_0/\tau - 1)$, where N_d is the number of decays, τ_0 is the lifetime of the μ^+ mesons, and τ is the lifetime of the meson in the given mesic atom. We shall furthermore assume that the captures in the Ag and Br crystals are distributed between the Ag and Br according to the Fermi-Teller law, i.e., proportional to Z. The number of captures corresponding to 207 decays of heavy nuclei is equal to

$$N_c = 207\left\{\frac{47}{82}\left(\frac{2200}{84} - 1\right) + \frac{35}{82}\left(\frac{2200}{100} - 1\right)\right\} = 4150.$$

Thus, for the ratio of the probability of the $\mu^- + X \rightarrow X + e^-$ process to the probability of the capture of a μ^- meson by heavy emulsion nuclei (AgBr, $Z \sim 40$), we find

$$\varkappa = w(\mu^- + X \rightarrow X^* + e^-)/w(\mu^- + X_z \rightarrow X_{z-1} + \nu) \lesssim 2.5 \cdot 10^{-4}.$$

6. PRINCIPAL RESULTS

The principal results obtained in the comparison of the electron and positron spectra in the μ-e decay are as follows:

1) The electron spectrum for the decays in mesic atoms of light emulsion nuclei is identical with the positron spectrum under our experimental conditions.

2) The electron spectrum for the decays in mesic atoms of Ag and Br indicates a considerable increase in the mean value of the inverse energy $\langle 1/\epsilon \rangle$.

Both these conclusions are in agreement with the predictions of the theory of the μ-e decay of a bound μ^- meson.

3) The relative probability of a neutrinoless electron decay of a μ^- meson estimated from our data is less than $\kappa \approx 2.5 \times 10^{-4}$. This value refers to the capture by Ag and Br emulsion nuclei. The probability of such a transition on the Cu nuclei was investigated in experiments [10-12] by other methods. In this experiment, the neutrinoless electron decay of a μ^- meson was also not observed, and the following upper limits were obtained for the value of κ: $\sim 10^{-3}$, [10] $(4^{+3}_{-2}) \times 10^{-6}$, [11] and 7×10^{-6}. [12]

4) The spectrum of Auger electrons produced in the capture of μ^- mesons by the heavy emulsion nuclei was measured.

5) It was shown that the number of Auger electrons with energy greater than ~ 25 kev in the capture of μ^- mesons by light nuclei amounts to more than a few tenth of a percent of the number of captures. These results confirm the theory of nonradiative transitions in mesic atoms. [9,13,14]

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