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Translated by P. F. Schmidt
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ENERGY DEPENDENCE OF $\mu^+ - e^+$ DECAY ASYMMETRY

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Submitted to JETP editor March 3, 1958

J. Exptl. Theoret. Phys. (U.S.S.R.) 35, 340-347 (August, 1958)

The energy dependence of the asymmetry of electrons originating in the decay of polarized μ mesons was studied with a set of scintillation counters biased against bremsstrahlung. The measurements were carried out for electron energies above 20 Mev. The observations are in a quantitative agreement (within a few percent) with the two-component neutrino theory. The experiments indicate that the degree of polarization of the μ meson beam is 0.81 ± 0.11.

INTRODUCTION

THE hypothesis of parity nonconservation in weak interactions[1] has led[2] to a special variant of the neutrino theory, called the two-component or longitudinal neutrino theory. The attractiveness of such a theory makes it desirable to conduct experiments to decide whether the theory is correct or not.

A study of the spectrum of electrons produced in the decay of polarized μ meson at various angles offers such an opportunity. It is, however, necessary to note that such an investigation can, in principle, only disprove the two-component neutrino theory, but cannot provide a final proof of its validity. In other words, a four-component neutrino theory can, for an appropriate choice of the coupling constants,[3] give a spectrum similar to that predicted by the two-component theory, namely

$$f(E,\theta) = 2E^2\{(3 - 2E) + \lambda(2E - 1)\cos\theta\}. \tag{1}$$

Here f(E, θ) denotes the electron energy-distribution function, θ is the angle between the electron momentum and the μ-meson spin, E is the ratio of the electron energy to the maximum energy possible, and λ is a parameter that depends on the coupling constants.

Parity nonconservation in $\pi - \mu - e$ decay was discovered in the classical experiments of Garwin, Lederman, and Weinrich[4] who showed, using electronic methods of particle detection, that μ-meson beams from an internal target of a synchrocyclotron are polarized to a large degree, and that the angular distribution of electrons in $\mu - e$ decay is of the form $1 + a\cos\theta$. It follows from the above that the two-component neutrino theory predicts a definite dependence of the factor a on the electron energy.

The energy dependence of the factor a found in reference 4 is weaker than that given by Eq. (1). The energy of the electrons was estimated in these experiments by determining the penetrating power of electrons passing through a graphite absorber. Taking it into account that the arrangement of counters in reference 4 was such that the bremsstrahlung radiation of the electrons could be re-

corded,[5] we undertook an experiment in which the detection probability of bremsstrahlung radiation has been markedly lowered by using an appropriate arrangement of counters. It will be shown below that the results of our measurements, in which (apart from strong suppression of the bremsstrahlung) good angular resolution was obtained, made it possible to verify Eq. (1) for electron energies above 20 Mev.

A second publication of the Columbia group[6] appeared after our experiment had been started. The observed energy dependence of electron asymmetry in $\mu - e$ decay reported is close to that predicted by Eq. (1). A qualitative agreement has also been obtained in recently-published experiments using emulsions[7] and a propane bubble chamber.[8] The degree of accuracy of these methods is, however, much lower than that obtained by means of electronic recording.

EXPERIMENTAL ARRANGEMENT

A beam of positive π mesons of ~ 80 Mev, produced on an internal synchrocyclotron target, was used in the experiments. The beam was analyzed and focused after passing through the scattered magnetic field of the accelerator. The beam was analyzed again by a magnetic field before reaching a concrete wall four meters thick, and, passing through a collimator, reached the hall where the experiments were conducted. The intensity of the beam was relatively low (100 mesons/cm^2-sec), and its good monoenergetic qualities permitted it to separate stopping μ mesons from stopping π mesons. It was therefore more convenient for experiments on μ mesons than other, more intense beams available in our laboratory.
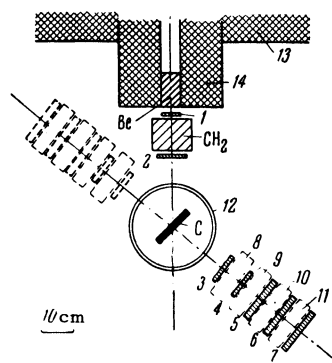

FIG. 1. Diagram of the experimental setup. Be) beryllium absorber, CH$_2$) polyethylene absorber 10 cm thick, C) graphite target, 1, 2, 3, 4, 5, 6, 7) scintillation counters, 8, 9, 10, 11) polyethylene absorbers, 12) magnetic shield, 13) shielding wall, 14) collimator.

The experimental setup is shown in Fig. 1. A beryllium absorber was placed directly in front of the monitoring counters 1 and 2. Its thickness was chosen such as to stop the π mesons in the graphite target. This was necessary for calibration purposes. An additional polyethylene (CH$_2$) absorber 10 cm thick was placed between counters 1 and 2 for asymmetry measurements, when the μ mesons had to be stopped in the graphite.

Two difficulties arise in measurements of the energy dependence of the asymmetry of $\mu - e$ decay electrons by the absorption method: (a) the spectrum of electrons traversing the absorber is distorted by effects of multiple scattering and bremsstrahlung, and (b) electrons with energy lower than that determined by the absorber thickness are detected thanks to the relatively penetrating bremsstrahlung radiation. Point (a) is discussed in the following section. As far as point (b) is concerned, in order to decrease the probability of registration of electrons through their bremsstrahlung radiation, a telescope consisting of a large number of scintillation counters was used for electron detection in our experimental arrangement. The minimum threshold of electron detection in the telescope (3, 4, 5, 6, and 7 in Fig. 1) was therefore relatively high and, including half the thickness of the graphite target, was equivalent to 9.7 g/cm^2 of polyethylene. The electron-detection threshold could be varied by means of polyethylene absorbers, placed between the counters.

The intensity of the vertical magnetic field used to rotate the μ-meson spin was made small in order to improve the angular definition of the recording system as compared with that of reference 4. It was constant throughout the experiment and amounted to 4.4 ± 0.1 oersteds over the total target volume.* A graphite target 2×14×14 cm was placed in the center of the magnetic shield formed by two iron cylinders placed one above the other with a gap of 11 cm. The shield excluded horizontal components of the magnetic field present in the hall, and ensured at the same time homogeneity of the vertical magnetic field established at the target.

The operation of the electronic apparatus (block diagram shown in Fig. 2) was as follows: a pulse from the monitor coincidence circuit (1, 2) passing through the anticoincidence circuit (1, 2)-3

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*The authors are obliged to D. P. Vasilevskaia for the measurements of the topography and of the value of magnetic field inside the magnetic shield.

operated a time discriminator, the channels of which (CF_1, CF_2, CF_3) were gated in turn by triggers T_1, T_2, and T_3. Duration of each gate was equal to $1\,\mu$sec. Pulses from the decay electrons detected in a five-fold coincidence were fed into the gated channels of the time discriminator and, in the case when these were open, were recorded by mechanical registers.

The rate of $\mu - e$ decay electrons detected in the geometry of Fig. 1 at the minimum threshold setting was 30/min. For the case when only the beryllium absorber remained in the beam, which corresponds to the stopping of π mesons, the rate of $\pi - \mu - e$ decay electrons amounted to 200/min.

The magnetic field applied rotated the angular distribution only by 21° in a microsecond, the μ-meson precession frequency being $f = geH/4\pi m_\mu c$. Two series of measurements were therefore carried out, each at two angles symmetric with respect to the collimator axis (and the target): (1) 52° and 180 + 52°, and (2) 128° and 180 + 128°. The target was placed at 45° to the beam (cf. Fig. 1 for the first case). Taking the rotation of μ-meson spin in constant magnetic field into account, measurements at these four angles (using three time-discrimination channels) made it possible to obtain the angular distribution of electrons with respect to the μ-meson spin between 0 and 360°. After corrections for angular definition and exponential decay within gate duration, these angles were 11, 32, 61, 88, 110, 170, 191, 212, 241, 268, 290, and 350°.

In essence, three pairs of points were in our disposition for determination of the factor a, symmetric with respect to the direction of the μ-meson spin (and shifted by about 21°) at 0° and 180°. Six additional points were available, symmetric in pairs about 90 and 270°. These points, which did not increase appreciably the accuracy of asymmetry determination, served as a check on the geometrical symmetry of the experiment. It follows that a possible difference in gate duration was of no consequence in determination of the factor a since the counting rate at various angles was measured using the same time channels.

A variable delay line (VDL, Fig. 2) made it possible to vary the time of gating from 0 to 5.0 μsec relative to the passage of the meson through the counters (1,2), which was used for determination of the chance coincidence rate. A delay equal to $0.4\,\mu$sec was used in the measurements. The background, due mainly to μ mesons stopping in the walls of the magnetic shield and producing de-
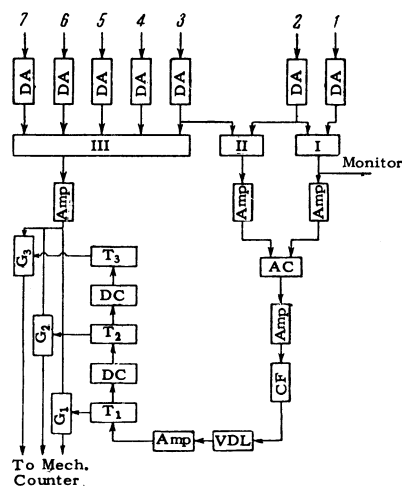

FIG. 2. Block-diagram of the electronic apparatus. DA) distributed amplifiers connected to photomultipliers 1, 2, 3, 4, 5, 6, 7; I, II, III) coincidence circuits ($r = 1.5 \times 10^{-8}$ sec.): AC) anticoincidence circuit (1, 2)-3; CF) cathode follower; VDL) variable delay line; DC) differentiating circuits for consecutive operation of trigger circuits. T_1, T_2, T_3; G_1, G_2, G_3) gated channels.

cay electrons, depended on the polyethylene absorber thickness practically in the same way as the rate of electrons from μ mesons decaying in the graphite, and amounted to $\sim 5 \sim 10\%$, depending on the number of gates and on the angle of observation.

INVESTIGATION OF THE ABSORPTION OF ELECTRONS EMITTED BY UNPOLARIZED μ MESONS

For the interpretation of the absorption curves of polarized μ-meson decay electrons discussed in the following section, it is necessary to know the probability $\varphi(E, R)$ that an electron of a given energy E is detected while traversing the polyethylene absorber of thickness R. In our case R denotes the total thickness of the absorber in the telescope accounting for the thickness of the scintillation counters themselves and of the graphite target.

The passage of electrons through matter is a relatively complicated phenomenon because of multiple scattering and bremsstrahlung. The basic laws of the interaction involving electron deceleration are well known, and the solution of the problem of the passage of electrons through matter is subject to mathematical difficulties only. In practice the problem can be solved experimentally, using a source of monokinetic electrons of different energies, and by the Monte Carlo method. We have made use of the results of Monte Carlo calculations of the probability that an electron traverses different thicknesses of polyethylene,

given by Lokanathan and Steinberger.[9]

In order to evaluate the validity of the method used we studied the absorption in polyethylene of electrons possessing a known spectrum, originating in the decay of unpolarized μ mesons. The experimental absorption curve was compared with the theoretical, calculated for the same spectrum according to reference 9.

It is well known that the spectrum of electrons from unpolarized μ mesons is completely described by the Michel parameter ρ. According to experimental data (cf., eg., reference 3), the value of that parameter is close to that predicted by the two-component neutrino theory and we used the value $\rho = 0.75$ in our calculations.*
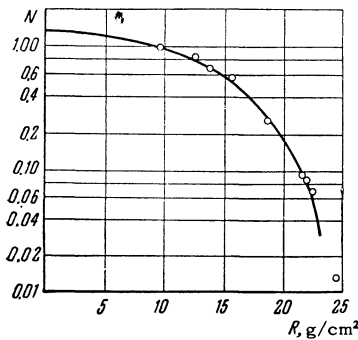

FIG. 3. Absorption curve of electrons from decay of unpolarized μ mesons. Solid curve – calculated dependence of electron intensity on the polyethylene absorber thickness R; o) experimental points. The counting rate of the telescope without additional absorbers (telescope recording threshold equal to 9.7 g/cm²) is taken as unity.

The solid curve in Fig. 3 represents the calculated dependence

$$N(R) = \int_0^1 E^2(3-2E)\varphi(E,R)dE.$$

The curve is normalized so that the counting rate of electrons recorded by the telescope (3, 4, 5, 6, 7) is unity when the telescope threshold is determined by the thickness of scintillation counters only.

In the experimental determination of the curve, no absorber was placed between the counters 1 and 2, and π mesons were stopped in the graphite target. For the detection of electrons the telescope was set at 232° to the direction of the meson beam, in the same geometry as used for the study of μ – e decay asymmetry. Polyethylene absorbers were placed between the counters. The experimental points are shown in Fig. 1.

It can be seen from the figure that the calculated curve fits well the experimental points. This

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*Radiative corrections[3] do not introduce any errors important to the problem on hand.

facts serves as the basis for the method of accounting for the distortion of electron spectrum in passage through polyethylene given in the following section. A marked discrepancy ($\sim$ 10%) between the calculated curve and the experimental points can be observed only when the total absorber thickness amounts to more than 21.7 g/cm² of polyethylene. The discrepancy increases with increasing absorber thickness. For an absorber 25.2 g/cm² thick, sufficient for ionization deceleration of 55-Mev electrons, the telescope records 0.4% of the number of electrons detected without additional absorbers. It can be concluded therefore, that the discrepancy is not due to theoretical calculations but to the finite probability of bremsstrahlung radiation detection by the telescope. The fact that this probability is small is due to the large number of counters used for electron detection.

ENERGY DEPENDENCE OF THE ASYMMETRY OF μ – e DECAY ELECTRONS

Experimental values of the asymmetry factor a, obtained using the least squares method from the angular distribution curves measured for different absorber thickness, are shown in Fig. 4. Statistical errors only are shown in the figure.

It has been shown that, for an absorber 21.7 g/cm² thick (maximum thickness used), about 10% of the counts recorded by the telescope detecting electrons from unpolarized μ mesons were due to the bremsstrahlung. This could cause a decrease of the degree of asymmetry observed using such an absorber. The upper limit of the correction accounting for that effect, is however, much less than the statistical error shown. Nevertheless, it is possible that in references 4 and 6, where the bremsstrahlung detection probability was much higher, this effect could cause a more considerable decrease of asymmetry.

The solid curve in Fig. 4 represents the expected dependence a(R) = Bα(R) of the asymmetry factor on the total absorber thickness in the telescope, calculated using the spectrum predicted by the two-component neutrino theory [Eq. (1)]. The value of the constant B (which serves as a scale in the drawing) will be discussed below. Bremsstrahlung and multiple scattering of electrons, as well as the angular definition of the telescope were accounted for. The solid curve represents the relation

$$\alpha(R) = \int_{\Delta\Omega} \int_0^1 E^2(2E-1)\varphi(E,R)\cos\theta dEd\Omega \Big/ \Delta\Omega \int_0^1 E^2(3-2E)\varphi(E,R)dE,$$

where the finite angular definition of the telescope was accounted for integrating over Ω. The degree

of accuracy of the function φ (E, R) — the proba-
bility that an electron with energy E will be re-
corded by the telescope for the absorber thickness
equal R — was discussed in the preceding section.

An idea about the good accuracy of the solid
curve in Fig. 4 can be obtained by comparing it
with the dashed curve

$$\alpha(E) = \int_E^1 E^2(2E-1)dE \Big/ \int_E^1 E^2(3-2E)dE$$

$$= (1 + E + E^2 + 3E^3) \Big/ 3(1 + E + E^2 - E^3),$$

calculated for the idealized case of the absence of
any instrumental distortions of the spectrum con-
nected with recording the electrons traversing the
absorber. It can be seen from Fig. 4 that the dis-
crepancy between the curves is relatively small,
in spite of the fact that the change of spectrum is
considerable. This can be explained by the fact
that the discrepancy reflects only the varying de-
gree of spectrum distortion at different angles.
That fact makes the method used perfectly suit-
able for the problem under consideration.

It can be seen that the curve calculated on
basis of the two-component neutrino theory is,
within a few percent, in agreement with experimen-
tal points in the investigated energy region above
20 Mev.

The constant B = 0.70 ± 0.02, obtained by com-
parison of experimental data with the calculated
curve, can be expressed as B = P (1 - W_C) λ,
where P is the degree of polarization of the μ -
meson beam used, W_C is the probability of de-
polarization of μ mesons in graphite, and λ =
$(g_V g_A + g_A^* g_V)/(|g_V|^2 + |g_A|^2)$ is the fundamen-
tal constant of $\mu - e$ decay in the two-component
neutrino theory [Eq. (1)]. The error given is sta-
tistical only. The constant B and its error are
based on the results of all four sets of measure-
ments with different absorbers and it has been
implicitly assumed that the fit between the theo-
retical curve and experimental points (Fig. 4) is
sufficiently good to confirm the validity of Eq. (1).
The integral value of the asymmetry factor a_0 for
the whole electron spectrum can be then automatic-
ally obtained extrapolating the solid curve to zero
absorber thickness. It has been found that a_0 =
B/3 = 0.233 ± 0.007. Naturally, this value refers
to the μ -meson beam used.

Analyzing the available data on the measure-
ments of the asymmetry of $\pi^+ - \mu^+ - e^+$ decay
electrons in emulsions and $\mu^+ - e^+$ decay elec-
trons in emulsions and graphite. Wilkinson came
to the conclusion that $(1 - W_C)\lambda$ = 0.87 ± 0.12.[10]
Comparing this result with the value of B =
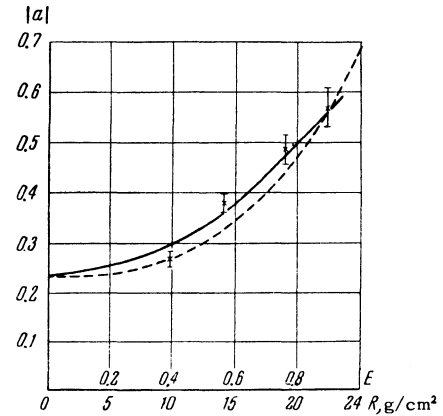P (1 - W_C)λ = 0.70 ± 0.02 obtained in the present

FIG. 4. Dependence of asymmetry coefficient a on elec-
tron energy. The solid curve a (R) calculated accounting for
the electron detecting efficiency of the experimental arrange-
ment (for total absorber thickness R), the dashed curve a(E)
calculated — assuming the absence of any spectrum distortion.
X) experimental values of a.

experiment it may be concluded that the μ -meson
beam used had a degree of polarization P = 0.81 ±
0.11, i.e., probably was not totally polarized.

A comparison of the asymmetry factors a_0 ob-
tained for graphite using different μ -meson beams
(though extracted from accelerators by analogous
methods)[6,11,12] shows that any differences in their
value cannot be regarded as essential. It follows
that the beams have a similar degree of polariza-
tion, independent of the energy of proton beam
producing π mesons on the internal synchrocy-
clotron target.

In conclusion, it should be mentioned that, so
far, there is no experimental evidence indicating
that λ is less than one, i.e., less than the value
required by the Feynmann — Gell-Mann theory.[13]

CONCLUSION

1. The energy dependence of the electron asym-
metry in $\mu^+ - e^+$ decay was measured using an
electronic method of recording which suppressed
strongly the bremsstrahlung recording probability.

2. The asymmetry dependence found for the
energy region studied, from 20 Mev to the limit
of the electron spectrum, is in quantitative agree-
ment (within a few percent) with the predictions
of the two-component neutrino theory.

3. Under the assumption that the dependence
remains valid for the non-investigated region of
spectrum < 20 Mev, the asymmetry factor a_0
was found for graphite for the total integral spec-
trum. The value obtained is a_0 = 0.233 ± 0.007.

4. It can be maintained that, most probably,
the μ -meson beam used was not totally polarized:
its degree of polarization was found to be equal
P = 0.81 ± 0.11.

5. μ-meson beams from internal synchrocyclotron targets have an approximately equal degree of polarization, irrespective to the energy of accelerated protons.

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EFFECT OF FINITE NUCLEAR SIZE ON THE RELATIVE INTERNAL CONVERSION COEFFICIENTS IN L SUBSHELLS*

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The relative conversion coefficients in L subshells have been measured for three pure M1 transitions: 46.5 kev in Bi^{210} and 115.1 and 238.6 kev in B^{212}. It is shown that in order to obtain agreement with experimental data the finite nuclear size must be taken into account in theoretical calculations of the L-conversion coefficients. The ratios $L_I : L_{II} : L_{III}$ for the M1 transition of 277.3 kev in Pb^{208} have also been measured.

1. INTRODUCTION

IN several experimental papers[1-6] it has been established that the K-conversion coefficients found experimentally for heavy nuclei for M1 transitions turned out to be appreciably lower than the theoretical coefficients calculated by Rose[7] for a point nucleus. This difference agrees approxi-

*This paper has been presented at the eighth annual conference on nuclear spectroscopy held by the Academy of Sciences U.S.S.R. in January 1958 in Leningrad.

mately with the correction ($\sim 30\%$) for finite nuclear size proposed by Sliv.[8] It has been shown both theoretically[9] and experimentally[1,4,10] that approximately the same correction should be applied also to the L_I-conversion coefficients. At the present time it may be considered as established that it is necessary to take into account the finite nuclear size in making theoretical calculations of internal conversion coefficients for the K and L_I shells in the case of M1 transitions.