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ASYMMETRY IN THE ANGULAR DISTRIBUTION OF $\mu^+ \to e^+$ DECAY ELECTRONS OBSERVED IN PHOTOGRAPHIC EMULSIONS

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Herewith are presented the results of measurements of the angular distribution of $\pi \to \mu \to e$ decay electrons observed in a photographic emulsion located either inside a magnetic screen or in a magnetic field $H \sim 1100$ G, longitudinal with respect to the μ-meson motion. The electron angular distributions were found to be describable by a relation of the form $1 + a \cos \theta$. The parameter a was found to be equal to $-(0.092 \pm 0.018)$ and $-(0.16 \pm 0.04)$ for the cases when the emulsion was inside the magnetic screen and the magnetic field respectively.

IN the fundamental work of Lee and Yang[1] and Landau,[2] it was shown that a possible method for testing parity nonconservation in weak interactions is to study the asymmetry in the angular distribution of the electrons emitted in the decay of polarized μ mesons. The two-component neutrino theory, developed by the same authors, leads to the conclusion that the μ meson formed in the $\pi \to \mu$ decay should be fully polarized in the direction of its motion. According to this theory, the electron angular distribution from the $\mu \to e$ decay is described by the relation

$$f(\theta) = 1 + (\lambda/3)\cos\theta, \tag{1}$$

where θ is the angle between the electron momentum and the μ-meson spin. The constant λ depends on the relative amount of vector and axial vector coupling in the β decay of the μ meson and can vary between -1 and $+1$.

The first experimental confirmation of parity nonconservation in the $\pi \to \mu \to e$ chain came from Garwin et al.[3] Thereafter a rather large number of papers appeared devoted to a more accurate determination of the constant λ, using photoemulsions, counters and bubble chambers. It was established in these experiments that in the $\mu^+ \to e^+$ decay the positrons are emitted predominantly backwards, i.e., $\lambda < 0$. It also follows from these experiments that the asymmetry in the angular distribution of electrons from $\mu \to e$ decay depends sensitively on the substance in which the μ meson decays. This indicates the existence of a partial depolarization of the μ mesons and consequently the electron angular distribution from the $\mu \to e$ decay may be written in the form

$$1 + a\cos\theta, \quad a = (\lambda/3)(1-\gamma), \tag{2}$$

where γ is the depolarization coefficient of the μ mesons. The experimentally obtained angular distributions of electrons from $\mu \to e$ decay agree qualitatively with formula (2) throughout the electron energy spectrum. However, more definite quantitative conclusions can be reached only by substantially increasing the statistical accuracy.

In this work we studied the angular distribution of $\mu^+ \to e^+$ decay electrons in emulsions. A 7×4×1 cm emulsion chamber consisting of 23 layers of NIKFI type R photoemulsion was irradiated with slow π^+ mesons from the synchrocyclotron of the Joint Institute for Nuclear Research. The chamber was placed inside a double magnetic screen to avoid precession of the μ-meson spin in the stray magnetic fields of the synchrocyclotron. The emulsion was developed by D. M. Samoilovich. The emulsion was scanned with MBI-2 microscopes at an amplification of 450 X, and the measurements were made at an amplification of 1350 X. In scanning, we selected those cases for which the μ meson from the $\pi \rightarrow \mu$ decay was entirely within one emulsion layer and stopped not nearer than $50\,\mu$ from the undeveloped surface of the emulsion layer. This method of selection assures the detection of every electron from a stopped μ meson with practically 100% efficiency. Thus, out of 4055 cases of $\pi \rightarrow \mu$ decays, only 11 cases were found where the decay electron was not seen. To determine the angle θ between the direction of μ-meson emission in the $\pi \rightarrow \mu$ decay and electron emission in the $\mu \rightarrow e$ decay, we measured the corresponding angle α in the emulsion plane as well as the inclination angles β_1 and β_2 of the μ meson and electron tracts relative to the emulsion plane. The angle θ is given in terms of α, β_1 and β_2 by

$$\cos\theta = (\tan\beta_1 \tan\beta_2 + \cos\alpha)\cos\beta_1\cos\beta_2. \tag{3}$$

In this work the angle θ was determined with the help of a special three-dimensional plotter. The error in θ measured in this way did not exceed $\pm 1°$. The total error in the determination of θ includes the errors in the measurement of the angles α and β as well as the error in determination of the photoemulsion settling. Estimates carried out indicate that the sum of these errors does not have a systematic character and does not exceed 3°. In order to find the angles β_1 and β_2 it is necessary to know with sufficient accuracy the emulsion settling after development. The settling d was determined by a comparison of the thickness of developed and undeveloped emulsion layers as well as from measurements of the track lengths of μ mesons from $\pi \rightarrow \mu$ decays parallel and perpendicular to the emulsion plane. To correct the settling coefficient for ambient temperature and humidity variations, the thickness of all emulsion layers was measured twice daily at marked points.

In addition to measuring the angular distribution of the $\mu \rightarrow e$ decay electrons for the case when the emulsion was placed inside a magnetic screen, we irradiated with slow π^+ mesons an emulsion chamber of the same dimensions, placed in a magnetic field of intensity $H \sim 1100$ G. In the latter case we selected those μ mesons emitted at an angle of no more than 30° with the magnetic field. The magnetic field here played the role of a magnetic screen in that it confined the stray magnetic fields of the synchrocyclotron and of the earth to one fixed direction. The decrease in μ-meson polarization, resulting from such a selection of $\pi \rightarrow \mu$ decays and due to the μ-meson spin precession around the magnetic field H, is not large and amounts to $\sim 7\%$.

Altogether we measured 8990 angles between the directions of electron and μ-meson emissions in the $\pi \rightarrow \mu \rightarrow e$ chain in the case when the emulsion was inside the magnetic screen, and 2005 angles in the case of $\pi \rightarrow \mu \rightarrow e$ decays in a magnetic field. The results of these measurements are given in Table I, which shows the number of events in a given interval of $\cos\theta$. The resulting angular distributions are also illustrated in Fig. 1.

It can be seen from Fig. 1 that the angular distributions obtained do not contradict the theoretical relation (2). The best value of a of formula (2) is obtained from the relation

$$a = 3r^2 \sum_{i=1}^{r} n_i \cos_i\theta \,/\, (r^2 - 1)\, N, \tag{4}$$

where N is the total number of cases studied, r the number of intervals, and $\cos_i\theta$ the average value of $\cos\theta$ in the i-th interval. The statistical error in the parameter a obtained in this way is given by

$$\delta a = \sqrt{3r^2 / N\,(r^2 - 1)}. \tag{4'}$$

TABLE I. Electron angular distribution in $\mu \rightarrow e$ decays in emulsions located inside a magnetic screen and in a magnetic field of intensity $H \approx 1100$ G (θ = angle between the directions of emission of the electron and μ meson).

cos θ	Magnetic screen	Magnetic field	cos θ	Magnetic screen	Magnetic field
1.0—0.8	834	181	0 — —0.2	910	188
0.8—0.6	893	187	—0.2— —0.4	928	197
0.6—0.4	836	167	—0.4— —0.6	914	216
0.4—0.2	867	202	—0.6— —0.8	938	229
0.2—0	839	196	—0.8— —1.0	1031	242

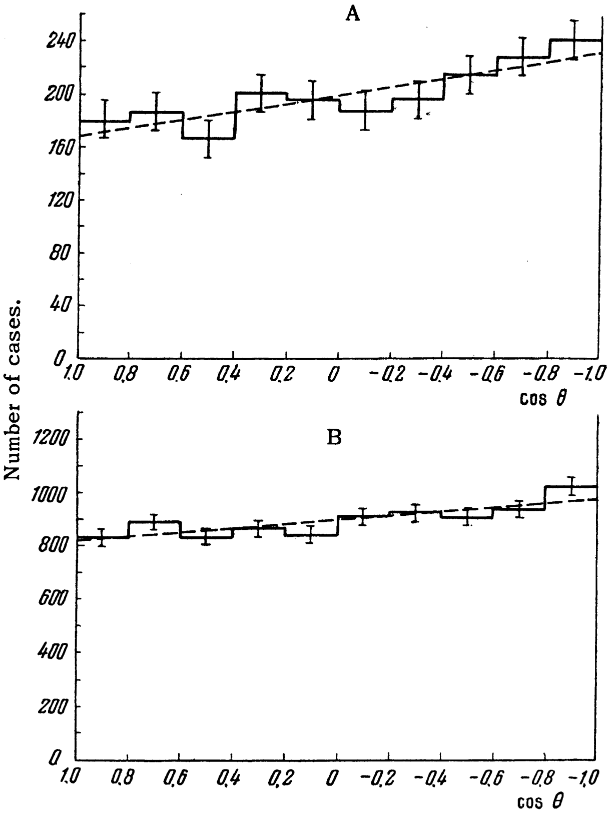

Fig. 1. Electron angular distribution in $\mu \rightarrow e$ decay: A – measurements in a magnetic field H ≈ 1100 G, a = –(0.16 ± 0.04); B – measurements inside a magnetic screen, a = –(0.092 ± 0.018).

The values of the quantity a calculated from these formulae for r = 10 were found to be:

1. For emulsion inside magnetic screen,* a = –(0.092 ± 0.018).

2. For emulsion in magnetic field, a = –(0.16 ± 0.04). It is seen that the magnetic field (H ≈ 1100 G) increases the asymmetry somewhat, i.e., decreases the depolarization of μ mesons in emulsion. However this effect is not definitely proven, in view of the small number of $\mu \rightarrow e$ decays found in the magnetic field. It would be interesting to measure the electron angular distribution from $\mu \rightarrow e$ decays in a magnetic field of higher intensity and with better statistics.

After completing this work we became acquainted with the work of Orear et al.[4] dealing with analogous measurements in a magnetic field H = 9,000 G. In a field of this intensity these authors obtained in emulsion a value a = –0.25, which coincides with the maximum value of a observed in any of the substances studied. Inserting H = 1100 G into the formula of Orear et al. for the polarization magnitude in an external magnetic field H

$$p = \frac{1}{2}\left(1 + \frac{1}{1 + (1600/H)^2}\right),$$

we obtain a = 0.13 – 0.16, in agreement with our measurements.

The value of a for the case of emulsion inside a magnetic screen is in agreement with measurements of other authors as summarized in Table II.

TABLE II. The parameter a of formula (2) for photoemulsion from the data of various authors.

$-a$	Number of cases	Method of observation	Reference
0.222±0.067	1028	In cosmic rays	[5]
0.08 ±0.05	1562	,,	[6]
0.03 ±0.04	2117	,,	[7]
0.00 ±0.07	700	,,	[8]
0.174±0.038	2000	Artificially produced π^+ beams	[9]
0.095±0.04	2003	,,	[10]
0.22 ±0.12	831	,,	[11]
0.149±0.033	2789	,,	[12]
0.11 ±0.08	580	,,	[13]

It is interesting to note that in the observations of $\pi \rightarrow \mu \rightarrow e$ decays in cosmic rays, the parameter a is found to be somewhat smaller than in the corresponding observations with accelerators.

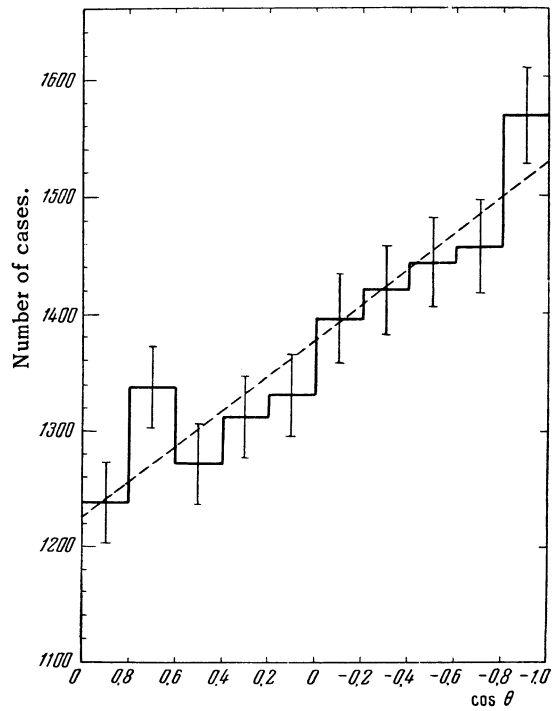

Fig. 2. Electron angular distribution using the combined data of this work and of Ref. 9 and 12; a = –(0.111 ± 0.015).

*For r = 2, the experiment inside the magnetic screen gives a = –(0.10 ± 0.021).

It is possible that this is to be explained by the absence of special screening in the former case.

The average value of a computed from the data of Table II and from the results of this work is

$$a = -(0.108 \pm 0.0094).$$

The angular distributions of $\mu \rightarrow e$-decay electrons are given in Refs. 9 and 12. Combining those with our data, yields the angular distribution shown in Fig. 2, which represents 13,770 cases of $\mu \rightarrow e$ decays. It can be seen from Fig. 2 that, within the experimental accuracy, the electron angular distribution is described by $1 + a \cos\theta$ with $a = -(0.111 \pm 0.015)$.

In conclusion, the authors express their gratitude to V. P. Dzhelepov, B. S. Neganov, and V. N. Mekhedov for help in emulsion irradiation, and to N. M. Polievktov-Nikoladze for assistance in the statistical analysis of the results.

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HYPERFRAGMENTS IN NUCLEAR EMULSIONS

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The properties and relative frequency of appearance of hyperfragments were investigated. Some effects produced by other types of unstable heavy particles are also mentioned.

THIS investigation was performed with two emulsion stacks which were exposed to cosmic rays in the atmosphere. One stack consisted of $600\,\mu$ Ilford G5 emulsions which were exposed at the time of the international expedition in the valley of the Po River, The second stack consisted of NIKFI R-type emulsions $400\,\mu$ thick, which were exposed in the Soviet Union. The scanning located all stars with prong numbers $N_h \geq 8-10$ or $n_s \geq 2-3$ as well as σ stars and all double stars regardless of the number of prongs.

The main procedure was area scanning with $10 \times 10 \times 1.5$ magnification. In a small number of instances all black prongs were continued until they emerged from the emulsion, and sometimes even up to their termination in other emulsions. But, as a rule, only those double stars were fixed, which were entirely in the field of view of the objective. Altogether there were found six τ mesons, one τ' meson, one Λ^0 particle, four K^- mesons, one Σ^- hyperon and ten hyperfragments, of which five decayed with emission of a π meson.