DEPOLARIZATION OF μ^+ MESONS IN NUCLEAR EMULSION

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Measurements were made of the asymmetry coefficient for π^+-μ^+-e^+ decay in ordinary and diluted NIKFI-R emulsion, and in the same emulsion placed in a strong magnetic field. An analysis of the data obtained and that known from the literature shows that the asymmetry coefficient in NIKFI-R emulsion ($a = -0.077 \pm 0.012$) is substantially less than that in Ilford G-5 emulsion ($a = -0.139 \pm 0.014$). A double dilution of the NIKFI-R emulsion with gelatin sharply increases the asymmetry coefficient ($a = -0.127 \pm 0.028$). The application of a magnetic field restores the polarization in the NIKFI-R emulsion, raising the asymmetry coefficient to a value $a = -0.28 \pm 0.02$ in a field of 17,000 gauss.

1. INTRODUCTION

THE obtaining of exact values for the asymmetry coefficient of a spatial distribution of protons in π^+-μ^+-e^+ decay in nuclear photoemulsions and bubble chambers is of substantial interest for the weak-interaction problem. According to the two-component theory of the neutrino the asymmetry coefficient depends in the following way on the ratio between the vector interaction constant g_V and of the axial vector constant g_A in μ decay:

$$a = \frac{1}{3}\frac{g_V^* g_A + g_A^* g_V}{|g_V|^2 + |g_A|^2}. \tag{1}$$

The magnitude of the asymmetry coefficient has been repeatedly measured in numerous experiments in which the μ^+ meson was stopped in various substances. However, the determination of the quantity a is complicated by the fact that experiments on the depolarization of μ^+ mesons give the quantity $a\xi$, where ξ is the average polarization. The "kinematic" depolarization and the depolarization in matter in the last stages of the retardation and after the stopping of the μ^+ meson exert a substantial influence on the experiment. The "kinematic" depolarization refers to the fact that not only the μ's incident in the collimator direction in the rest system but also the μ's which are moving in other directions after decay emerge from the collimator slit of the accelerator. The polarization losses arising from this cause are 5 – 25%. The depolarization in the last stages of the retardation and after the stopping is apparently connected mainly with the formation of muonium and more complex atomic systems and with the local magnetic fields in the stopping medium. It is reasonable to admit that such a depolarization is absent in metals and in graphite, where muonium is not formed. Therefore, to determine the "pure" asymmetry coefficient one can employ the type of setup described by Lederman et al.[1] and measure the ratio ρ of the asymmetry coefficient in photoemulsion (used as a target) and in graphite, which does not depend on the kinematic depolarization. If the μ mesons are created from π^+ mesons directly stopped in the emulsion, the kinematic depolarization is absent. Therefore, one can get the pure asymmetry coefficient by dividing the asymmetry coefficient a_{em} measured in the emulsion by the quantity ρ. Since ρ can be measured quite exactly, the error in determining a depends on the error in the asymmetry coefficients measured from emulsion or bubble chamber tracks.[2] The values of such measurements are not restricted to this use, however. Since the depolarization of mesons in a substance is closely connected with the existence of muonium atoms and with the effect on them of the internal magnetic fields, it is entirely possible that the study of the asymmetry in π-μ-e decay in various substances has importance for some questions in solid-state physics.

2. THE ASYMMETRY COEFFICIENT IN THE EMULSIONS NIKFI-R AND ILFORD G-5

To study the energy dependence of the asymmetry of decays in nuclear emulsions we had to investigate the integral asymmetry (averaged over the whole spectrum). For example, to be

TABLE I

Angles, in degrees	0—18	18—36	36—54	54—72	72—90	90—108	108—126	126—144	144—162	162—180
NIKFI-R	828	896	856	858	889	900	948	912	969	960
$(\text{NIKFI-R})_{\times 2}$	190	189	206	224	218	241	226	241	247	263

able to examine the asymmetry of a few hundred decay electrons in the initial region of the spectrum, we first chose 9101 π-μ-e decays in NIKFI-R emulsion which had been bombarded in the Joint Institute for Nuclear Research synchrotron under conditions of careful magnetic shielding ($H < 4 \times 10^{-2}$ gauss). These decays satisfied the following criteria: 1) the length of the electron track $l \geq 1$ mm; 2) the source of the π^+-μ-e decay was farther than $100\,\mu$ from the surface of the emulsion or the glass.

Such criteria correspond with great accuracy to the considerations of planar correlation given by the formula $(1 + a\cos\theta)\,d\theta$, where a is the asymmetry coefficient and θ is the angle in the plane of the emulsion between the original directions of the μ-meson and positron tracks. The angular distribution of the decays measured is given in Table I (line 2).

The coefficient a can be determined from this table either by the average value of $\cos\theta$, or by the forward-back difference:

$$a/2 = \overline{\cos\vartheta} = \sum n_i \cos\vartheta_i / \sum n_i, \tag{2}$$

$$a = (\pi/2)\left[\sum_{0-90^\circ} n_i - \sum_{90-180^\circ} n_i\right] \Big/ \sum n_i. \tag{3}$$

The geometry of our decays was not plane. It is easy to show that the correction coefficient k, which must be divided into the asymmetry coefficient a to take into account the deviation from plane geometry, is equal to

$$k = (\overline{\cos^2\alpha_e} / \overline{\cos\alpha_e})\ (\overline{\cos^2\alpha_\mu} / \overline{\cos\alpha_\mu}), \tag{4}$$

where the α are the angles of the inclination of the meson and electron tracks to the plane of the emulsion, and $\overline{\cos^2\alpha}$ and $\overline{\cos\alpha}$ are the average values of the second and first powers of the cosines of these angles. Knowing the distribution of the inclination angles for mesons and electrons, it is easy to carry out the corresponding correction. In our case it is close to 5%. According to formulas 1 and 2, after introducing correction 3 we get

$$a = -0.066 \pm 0.018,$$

where the statistical error is $\sqrt{3/N}$, $N = \Sigma n_i$.

Measurements of the asymmetry coefficient for NIKFI-R emulsion were also carried out by Gurevich et al.[4] who got $a = -0.092 \pm 0.018$ by analyzing 8990 decay.

In the recent work of Ivanov and Fesenko[5] the values $a = -0.065 \pm 0.041$ are given. These a values agree rather well, and combining them we get for the asymmetry coefficient in NIKFI-R emulsion

$$a = -0.077 \pm 0.012.$$

The average obtained can be compared with the asymmetry coefficient for Ilford G-5 emulsion in Table II, where all known values of a are given.

TABLE II. Asymmetry coefficient a in photoemulsion

Authors	Meson Source	Emulsions	a
Castagnoli[6]	Cosmic Rays*	Ilford G-5	0.20 ± 0.04
Fowler[7]	” ”	”	0.03 ± 0.040
Bøggild[8]	” ”	”	0.21 ± 0.04
Bhowmik[9]	” ”	”	0.081 ± 0.044
Babayan[10]	” ”	”	0.135 ± 0.040
Biswas[11]	Accelerator	”	0.095 ± 0.045
Davis[12]	”	”	0.190 ± 0.060
Friedman[13]	”	”	0.174 ± 0.045
Chadwick[14]	”	”	0.149 ± 0.033
Gurevich[4]	”	NIKFI-R	0.092 ± 0.018
Vaĭsenberg, this work	”	”	0.066 ± 0.018
Ivanov[5]		”	0.065 ± 0.041

*The data of Castagnoli et al. refer in part to cosmic rays and in part to accelerators. The exact distribution of the data on the basis of the information given in their papers is impossible to carry out, but this has little effect on the result of the following averaging (Table III).

It is very difficult to get a unique average from these values. Such a result, apparent "by inspection," is strengthened by the analyses of the table by the usual χ^2 criterion by the binomial expansion for 11 degrees of freedom: for an arbitrary value of a we get $\chi^2 = 25 - 30$, if we consider simultaneously the values of a in the Ilford G-5 and NIKFI-R emulsions. The comparison becomes entirely admissible ($\chi^2 \sim 12$) if it is restricted to the data observed separately for the Ilford G-5 emulsion. The average weighted values for the asymmetry coefficient for both emulsions are given in Table III.

Looked at in this way, it seems quite credible that μ^+ mesons experience a greater depolarization in NIKFI-R emulsion than in Ilford G-5: the ratio of the depolarization capacities of these two emulsions is close to $(0.139 \pm 0.014)/(0.077 \pm 0.012) = 1.81 \pm 0.33$. This result is difficult to understand, since the density and chemical composition of the two emulsions are almost identical.[15,16]

TABLE III. Average values of the asymmetry coefficient for NIKFI-R and Ilford G-5 emulsions

NIKFI-R	Ilford G-5		
	All data	Cosmic rays	Accelerators
—0.077±0.012	—0.139±0.014	—0.133±0.018	0.148±0.021

3. THE ASYMMETRY COEFFICIENT IN THE DILUTED NIKFI-R EMULSION

The first indication that increasing of the gelatin content of the emulsion leads to an increase in the asymmetry coefficient was given by Chadwick et al., who got for the doubly diluted Ilford G-5 $a_{\times 2} = -0.190 \pm 0.033$, which should be compared with the average value $a = -0.139 \pm 0.014$ (Table III) for ordinary Ilford G-5 emulsion.

In the third line of Table I we give the distribution we got for 2245 π^+-μ-e decays in NIKFI-R emulsion diluted by a double quantity of gelatin (the criterion of the previous choice). With the aid of Eq. (2) or (3) we get from this data $a\,(\text{NIKFI-R})_{\times 2} = -0.136 \pm 0.037$.

An analogous result is obtained in reference 5, where for 2300 π-μ-e decays an asymmetry coefficient for NIKFI-R emulsion with doubled gelatin content was determined to be $a\,(\text{NIKFI-R})_{\times 2} = -0.118 \pm 0.041$. Combining both results, we get

$$a\,(\text{NIKFI-R})_{\times 2} = -0.127 \pm 0.028.$$

Thus the increase in the asymmetry coefficient in doubly-diluted NIKFI-R emulsion, in comparison with ordinary emulsion, is

$$(0.127 \pm 0.028)/(0.077 + 0.012) = 1.65 \pm 0.40.$$

The experiments with diluted emulsions prove conclusively that gelatin is the component of the emulsion in which the polarization of the μ-mesons is conserved to a significant degree. This agrees with the experiments of Lederman et al.[17] which disclosed no significant asymmetry (complete depolarization) in AgBr. Therefore, the difference in the a values for NIKFI-R and Ilford G-5 emulsions, which have almost the same constituents, must indicate different properties of the gelatins: the NIKFI-R gelatin evidently produces depolarization twice as large as the Ilford G-5 emulsion, although the reason for this is not clear.

4. THE ASYMMETRY COEFFICIENT IN A MAGNETIC FIELD

The methods of destroying depolarization acquire a great significance, in connection with the small magnitude of the asymmetry constant of emulsions, for the solution of a series of experimental problems in meson physics. One of these methods is, as has been shown above, the increase in the gelatin content. Another method of removing the depolarization is, as is well known, a strong static magnetic field. Gurevich et al.[4] get an asymmetry coefficient $a = -0.16 \pm 0.04$ for an NIKFI-R emulsion placed in a field of 1000 gauss. Orear[18] and Barkus[19] showed that a magnetic field of about ten kilogauss restored the asymmetry coefficient in an emulsion to the maximum value $a = -(0.24 - 0.26)$, which is characteristic for metals or graphite. We carried out measurements for fields of 2500 and 17,000 gauss. (The measurement technique and method of exposure will be described later.) We obtained the following values of the asymmetry coefficient:

$$a\,(2500) = -0.186 \pm 0.020, \quad a\,(17\,000) = -0.28 \pm 0.02.$$

From these measurements it follows that even in the NIKFI-R emulsion, whose gelatin apparently depolarizes strongly, the magnetic field fully restores the polarization, taking it to the value, close to -0.33, which is required by the theory of the universal Fermi interaction of Feynman and Gell-Mann, in which $|g_V| = |g_A|$. Gurevich and his coworkers came to an analogous result on the basis of their measurements.[21]

5. DISCUSSION OF THE RESULTS

The question of the asymmetry coefficient in emulsion is connected with the distributions of stoppings of μ^+ mesons in gelatin and silver bromide.

$$a_{\text{em}} = a_{\text{gel}}\, d/(1 + d).$$

We shall begin with the asymmetry coefficient for Ilford G-5 emulsion, $a = -0.139 \pm 0.014$. Assuming that the gelatin in this emulsion has the maximum asymmetry coefficient $a = -0.33$, we get a lower bound for the magnitude of d. Thus we come to the result that the ratio of the number of stops in gelatin to those in AgBr must be $d \sim 3/4$ or more if the coefficient of asymmetry in gelatin is less than 0.33. This result appears rather unexpected if we consider that the size of d is determined by the ratio of the volumes of gelatin and AgBr, multiplied by the ratio of their stopping powers

$$d = (V_{\mathrm{gel}}/V_{\mathrm{AgBr}})\,(dE/dx)_{\mathrm{gel}}/(dE/dx)_{\mathrm{AgBr}}.$$

Actually, for the magnitude of d to be close to $3/4$ (or more), it is essential to suppose that the μ meson in the gelatin, which is five times lighter than silver bromide, has the same (or greater) ionization loss per micron of path as it has in AgBr. It is known that at the end of a charged particle path, when charge exchanges and elastic scatterings with the atoms as a whole begin to appear, the stopping power of light substances grows. This question is complicated, and unfortunately there are not enough data existing[21] to judge whether or not similar effects can insure the necessary increase in ionization losses in gelatin. It is entirely possible that the dimensions of the silver bromide crystals influence the distribution of stoppings in gelatin and AgBr. However, the existing data do say that the average size of the grains and their distribution in Ilford G-5 and NIKFI-R emulsions are about the same, so that the different dispersivities of the emulsions can hardly explain the difference in the asymmetry coefficients of Ilford G-5 and NIKFI-R.

A separate measurement of the asymmetry coefficients for gelatin and AgBr could give not only the distribution of stoppings by components but would also permit the investigation of the question of the stopping powers of light and heavy materials at low energies.

The measurements with and without magnetic field on NIKFI-R emulsion showed that, in spite of the strong depolarization in the gelatin of this emulsion, the magnetic field almost completely restores the full polarization of the emulsion. Therefore we can suppose that the mechanism corresponding to depolarization is unique, the same in gelatin as in silver bromide. The strong dependence on the magnetic field and the growth saturation gotten for fields of about ten kilogauss make quite credible the hypothesis that the depolarization mechanism is the formation of muonium. As is well known, muonium is formed with equal probabilities in two quantum states: with antiparallel (singlet) and parallel spins (triplet). The first of these states does not conserve the μ spin direction because of the hyperfine structure interaction. Such a depolarization is removed by a strong magnetic field, which breaks the bond between the meson and electron spins and sets both these spins to precessing around the direction of the H field (Paschen-Back effect). The restoring of polarization in this effect should be proportional to $x^2/(1+x^2)$, where x is the ratio of the applied field H to the field H_0 which is characteristic of the hyperfine structure interaction and which for muonium is $H_0 = 1580$ gauss.

Muonium with spins parallel has a resultant magnetic moment about that of the electron and will be depolarized by the action of even weak internal magnetic fields in the substance. If the applied homogeneous field significantly surpasses in strength the random internal fields, it sends parallel spin muonium into precession about it so that the polarization in the field direction will be conserved. From this it follows that if it is necessary to have fields on the order of several thousand gauss $(H > H_0)$ to restore the polarization of muonium with antiparallel spins, then fields on an order exceeding the internal fields are enough to conserve the polarization of triplet muonium. Therefore the curve of the asymmetry coefficient against the increase of the magnetic field may display two components with similar amplitudes: one, increasing with the field by the $x^2/(1+x^2)$ law, and the other whose growth is determined by a parameter characteristic of the strength of the internal fields. To examine such a picture it is important to make measurements with relatively weak fields, where the Paschen-Back effect plays no significant role, i.e., for fields < 500 gauss. This is one of the possible examples of how the study of the changes of the asymmetry coefficient with the field changes can give information on the internal magnetic fields of a substance.

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