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# ASYMMETRY IN THE ANGULAR DISTRIBUTION OF ELECTRONS FROM $\mu$-e DECAY IN MAGNETIC FIELDS UP TO 35 000 OERSTED

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$\pi$-$\mu$-e decays were observed in nuclear emulsions placed in a magnetic field, the purpose of the experiment being to study the asymmetry in the angular distribution of electrons from $\mu$-e decays in a magnetic field. It was found that longitudinal magnetic fields up to 20 000 – 30 000 oe do not completely remove the depolarizing action of the medium (emulsion) on the $\mu$ meson.

## 1. INTRODUCTION

THE angular distribution of electrons from $\pi$-$\mu$-e decays is given by the formula

$$dN = (1 - a\cos\vartheta)\, d\Omega/4\pi. \tag{1}$$

The two-component neutrino theory, with V-A interaction, predicts that the asymmetry parameter a should have the value $1/3$. This prediction is difficult to check experimentally because the $\mu$ meson is depolarized upon stopping in condensed matter. The asymmetry parameter inferred from measurement of the angular distribution of the electrons is $a^* = Pa$, where P is the polarization of the $\mu$ meson after stopping in the absorber. The value of P depends on the medium and cannot be measured directly. Orear et al.[1] have considered the depolarization due to formation of muonium. The depolarization due to this process depends on the strength of the external magnetic field, directed along the spin of the muon:

$$a^* = a\,[1 - 0.5/(1 + x^2)], \tag{2}$$

In Eq. (2), $x = \mu H/\Delta E$, where $\Delta E \sim 1.8 \times 10^{-5}$ ev is the hyperfine splitting of muonium. Ferrell et al.[2] have carried out a more detailed analysis of the depolarization due to formation of muonium, taking into account multiple electron exchange. They found that a* depended on H through the relation

$$a^* = a\,[1 - 0.5/(1 + x^2 + \tau^{-2})]^n. \tag{3}$$

In Eq. (3), n is the number of electron exchange events, and $\tau$ is the mean lifetime of muonium in units of $\hbar/\Delta E = 3.58 \times 10^{-11}$ sec. For proper choice of the parameters n and $\tau$, formula (3) should be good up to fields of 10 000 oe. From (3) it follows that in sufficiently strong longitudinal magnetic fields there should be negligible depolarization of muons due to formation of muonium.

In the work being reported upon here we studied the asymmetry in the angular distribution of electrons from $\pi$-$\mu$-e decays in magnetic fields up to 35 000 oe. The dependence of a* on H was thus obtained for a wide range of magnetic field strengths. This check on formula (3) gives information on the mechanism by which muons are depolarized in matter, information which is necessary for a measurement of the asymmetry parameter a.

## 2. APPARATUS

Nuclear emulsions were placed in a magnetic field and irradiated with slow $\pi^+$ mesons which stopped in the emulsions. In scanning the developed emulsions, those events were selected in which the $\mu$ meson travelled in a direction making an angle $\beta$ of 0° to 30° or $\beta = 180° - 150°$ with the direction of the magnetic field. The direction of the magnetic field was marked on the emulsion by exposing the emulsion to x rays before taking it out of its holder. In scanning the emulsions, particular care was taken to avoid systematic errors due to different efficiencies for detecting different $\pi$-$\mu$-e decay events. Only those $\pi$-$\mu$ decays were considered in which the muon track ended no closer than $\Delta = 15\,\mu$ from the surface of the developed emulsion layer. Out of the 177 850 $\pi$-$\mu$ decays observed to satisfy the selection rules on $\beta$, only 66 had no visible electron from $\mu$-e decay. The angle $\alpha$ between the direction of emission of the electron and the magnetic field H was not found directly; only the projection of this angle on the plane of the emulsion was measured. The value of a* was found from the relation

$$a^*_{\text{exp}} = 2\,[N(\alpha > 90°) - N(\alpha < 90°)]/[N(\alpha > 90°) + N(\alpha < 90°)], \qquad (4)$$

where the angle $\alpha$ was taken in the sense from the direction of the muon spin to the direction of the field H. The value of $a^*_{\text{exp}}$ computed from (4) is a little low because the spin of the muon processes about the magnetic field. This effect can be corrected for by dividing by $\overline{\cos\beta}$

$$a^* = a_{\text{exp}}/\overline{\cos\beta}. \qquad (5)$$

where $\overline{\cos\beta}$ is the mean cosine of the angle between the direction of the field and the spin (or momentum) of the muon. The value of $\overline{\cos\beta}$ for those $\pi$-$\mu$ decays which were accepted was found experimentally.

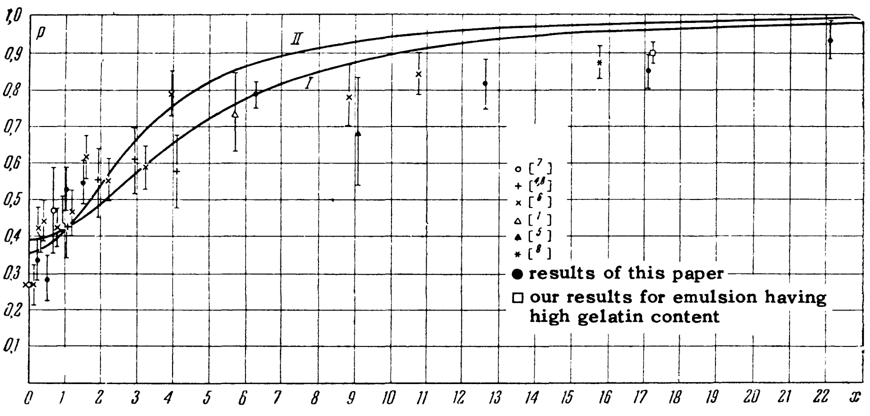
## 3. RESULTS AND DISCUSSION

A total of 177 850 $\pi$-$\mu$-e decay events satisfied the selection rules on $\beta$ and $\Delta$ described in Sec. 2. These were distributed among the various values of magnetic field strength as follows:

| **H, oe** | 405 | 805 | 1610 | 2370 | 10000 | 20000 | 27000 | 35000 |
|---|---|---|---|---|---|---|---|---|
| **Number of cases** | 9705 | 13430 | 11617 | 10005 | 30331 | 8851 | 17557 | 17715 |

**Table I.** Asymmetry parameter a* = Pa for various values of the longitudinal magnetic field strength H

| | H, oe | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|
| | 405 | 805 | 1610 | 2370 | 10 000 | 20 000 | 27 000 | 35 000 | 10 000—35 000 |
| $a^*(\uparrow)$ | 0,115 | 0.115 | 0.170 | 0.165 | 0.262 | 0.277 | 0,296 | 0,317 | 0,284 |
| $\delta a^*(\uparrow)$ | 0.030 | 0,027 | 0,023 | 0.030 | 0,017 | 0,032 | 0,023 | 0,023 | 0.011 |
| $a^*(\downarrow)$ | 0.114 | 0,077 | 0,185 | 0,202 | 0,264 | 0.266 | 0,273 | 0,309 | 0.277 |
| $\delta a^*(\downarrow)$ | 0.030 | 0.027 | 0.028 | 0.030 | 0,017 | 0.032 | 0.023 | 0.023 | 0.011 |
| $a^*$ | 0,114 | 0.096 | 0,178 | 0,184 | 0,263 | 0,272 | 0.284 | 0,313 | 0,281 |
| $\delta a^*$ | 0,021 | 0.020 | 0,020 | 0.020 | 0,012 | 0,023 | 0,016 | 0,016 | 0,008 |



**P(x) as a function of x, where P = 3a* and x = H/1580 (H in oersteds). The curves (I, II) are theoretical, while the points are experimental.**

For emulsions with high gelatin content there were 58 639 cases at H = 27 000 oe.

Among all the observed $\pi$-$\mu$-e decays we did not see one $\mu$-3e decay, or any other anomalous decay modes of the muon. There was one case in which the muon decayed into an electron, neutrino, antineutrino and virtual $\gamma$ ray, the latter being converted into an electron-positron pair[3] (Dalitz effect)

$$\mu^+ \to e^+ + \nu + \bar{\nu} + e^+ + e^-.$$

Table I shows the asymmetry coefficients calculated from (4) and corrected by (5). These results apply to emulsion with the normal amount of gelatin. The table also shows the values of a* obtained for muons going in the direction (↑) of the magnetic field ($\beta < 30°$) and for those going in the opposite direction (↓) ($\beta > 150°$). δa* is the standard error ($\delta a^* = 2/\sqrt{N}$).

The data in Table I are shown in the figure, together with data obtained by other authors.[1,2,4-8] The figure also shows data obtained with emulsions having high gelatin content.

The table below gives value for the coefficient a* obtained from emulsions having a high gelatin content and in a field H = 27 000 gauss. The gelatin content is measured by the ratio of gelatin volume to total volume, $V_g/(V_g + V_{AgBr})$, and is 0.51 for normal emulsions.

| | | | | | |
|---|---|---|---|---|---|
| $V_g/(V_g + V_{AgBr})$ | 0.51 | 0,61 | 0.71 | 0,76 | 0,61—0,76 |
| $a^*$ | 0.284 | 0,284 | 0.323 | 0.277 | 0.301 |
| $\delta a^*$ | 0,016 | 0,016 | 0.013 | 0.018 | 0,009 |

The values of a* obtained from the emulsions with high gelatin content agree with those obtained from emulsions with normal gelatin content:

$$a^*(\uparrow) = 0.297 \pm 0.013, \qquad a^*(\downarrow) = 0.305 \pm 0.013.$$

Table II shows the values of a* obtained by different observers. The scatter in the values obtained by different observers is within the statistical error.

Table II. Asymmetry parameters a* = Pa from data taken by different observers

| Observer | Normal emulsion H > 10000 oe | Emulsion with high gelatin content |
|---|---|---|
| 1 | 0,254 ± 0,018 | 0.312 ± 0,022 |
| 2 | 0.282 ± 0,016 | 0,347 ± 0,020 |
| 3 | 0.294 + 0.017 | 0,283 ± 0,023 |
| 4 | 0.284 + 0.017 | 0,283 ± 0.021 |
| 5 | — | 0,338 ± 0,028 |
| 6 | 0,258 ± 0.030 | 0,278 ± 0.023 |
| 7 | 0.355 + 0,034 | 0.246 ± 0,029 |
| | mean: | |
| | 0.281 ± 0,010 | 0,301 ± 0.009 |

Two conclusions can be drawn from the above data:

1. The value of a* for muons which have stopped in matter in a magnetic field of 20 000 — 30 000 oe is less than the maximum value a* = ⅓. This result is statistically meaningful.

2. The coefficient a* tends to increase as the field is increased from 10 000 to 35 000 oe, or when the emulsion is diluted. This conclusion is not as reliable, statistically, as is the first one. The $\chi^2$ test shows that with probability $W(\chi^2) = 0.3$ the observed dependence of a* on H in the region H = 10 000 to 35 000 oe is a statistical fluctuation.

As mentioned above, our data can be used to check the dependence of a* on H as calculated on the assumption that the depolarization is due to the formation of muonium. This comparison is made on the figure [cf. Eq. (3)]. The curves I and II correspond to parameters n and $\tau$ which have been chosen to give the best fit to the experimental data. The curves were drawn so as to minimize the quantity

$$M = \sum_i [(P_{i\,\text{calc}} - P_{i\,\text{exp}})/\delta P_{i\,\text{exp}}]^2.$$

Curve I was calculated using the experimental data for all values of x $(0 < x < 22.15)$. The values of n and $\tau$ for this curve are $n_I = 22$, $\tau_I = 0.31$. The probability that the data would lie along this curve P(x) by accident is $W_I(\chi^2) < 0.01$. Curve II was obtained by minimizing M only for x in the range 0 to 4.09. The corresponding values of n and $\tau$ are $n_{II} = 12$, $\tau_{II} = 0.44$. The probability that curve II agree with the data by accident is $W_{II}(\chi^2) = 0.03$. It appears that the curves P(x) do not describe the experimental data $P_{\text{exp}}(x)$ satisfactorily. The emulsion really consists of two components — gelatin and silver bromide; this can be roughly taken into account by replacing formula (3) by the relation

$$P = f + (1 - f)\,[1 - 0{,}5/(1 + \tau^{-2} + x^2)]^n. \qquad (3')$$

The assumption is made here that a certain fraction (f) of the muons stop in the gelatin and do not depolarize at all. The value of f is less than $P(x \to \infty)/P(x = 0) = 0.3$. Values of P(x) calculated from (3′), with f = 0.3, agree closely with values calculated from (3). Hence the discrepancy between the theoretical and experimental values of P(x) cannot be due to the inhomogeneity of the emulsion. The discrepancy is particularly marked for x > 10. For such values of magnetic field, the calculated values of P are practically equal to the maximum value (one), while the experimental values of P remain less than one. Hence we can finally conclude that if a = ⅓ (V-A interaction) than a comparison of theoretical values for P(x), as given by (3), with experimental ones implies that there is some mechanism for depolarization other than the formation of muonium, and that this mechanism is almost entirely responsible for the departure of $P_{\text{exp}}$ from one for values of x greater than 10.

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