MEASUREMENT OF THE POLARIZATION OF NEGATIVE μ-MESONS IN CARBON, OXYGEN, MAGNESIUM, SULPHUR, ZINC, CADMIUM AND LEAD MESIC ATOMS

A. E. IGNATENKO, L. B. EGOROV, B. KHALUPA, and D. CHULTEM

Joint Institute for Nuclear Research

Submitted to JETP editor May 31, 1958

J. Exptl. Theoret. Phys. (U.S.S.R.) **35**, 1131-1134 (November, 1958)

Angular distributions of electrons from the decays of μ mesons in C, O, Mg, S, Zn, Cd, and Pb mesic atoms were measured using scintillation counters. The μ-meson polarization was determined from the results of these measurements. The polarization amounts to $(19 \pm 7)\%$ in Mg, Zn, Cd, and Pb mesic atoms, and to $(15 \pm 4)\%$ in C, O, and S mesic atoms. Depolarization of μ mesons in substances with zero nuclear spin is explained as due mainly to the spin-orbit interaction in the mesic atom formation process, and due in part to the action of the magnetic field of the atomic electron shell on the μ meson during its lifetime in the K orbit.

1. INTRODUCTION

It is known that in the process of slowing down, negative μ mesons first form mesic atoms and then undergo nuclear capture. The capture process may be described by the reaction $\mu^- + p \rightarrow n + \nu$. The study of the angular distribution of neutrons produced in the capture of μ^- mesons in liquid hydrogen provides a method for the determination of the form of the weak μ-meson-nucleon interaction.[1,2] However, experiments[3] on the polarization of μ^- mesons in liquid hydrogen indicate that this method is not useful, owing to the total depolarization of the μ^- mesons. A theoretical discussion of the capture of polarized μ^- mesons by light nuclei shows[2] that measurement of the angular distribution of neutrons with energies near the upper end of the spectrum may provide a means of determining the interaction form. The neutron angular distribution is given by the formula

$$W(\theta) = 1 + a\beta\gamma\cos\theta, \qquad (1)$$

where β is the asymmetry coefficient whose magnitude and sign depend on the interaction form, θ is the angle between the direction of emission of the neutron and the μ^- meson spin, a is a coefficient which depends on the degree of polarization of the μ^- meson in the mesic atom, and γ is a coefficient that depends on the depolarization of the neutrons inside the nucleus.

It follows from Eq. (1) that an experiment on the neutron angular distribution should be preceded by experiments on μ^--meson polarization in mesic atoms and on neutron depolarization in nuclear matter. The present work is devoted to the study of the μ^--meson polarization in various substances.

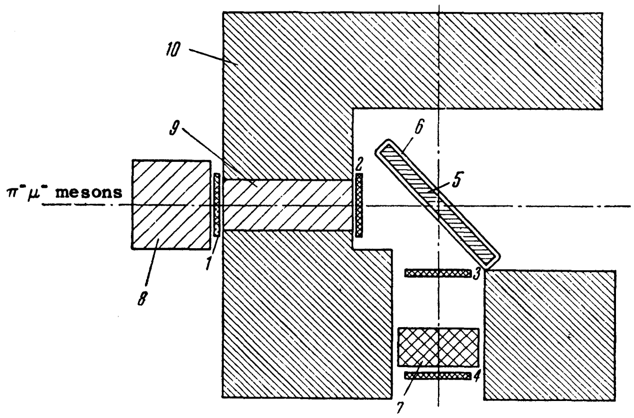
2. MAIN THEORETICAL ASSUMPTIONS

We start from the following assumptions about the depolarization mechanism of μ^--mesons which are being slowed down and stopped in matter. It follows from the work of Ford and Mullin[4] and Bincer[5] that in the slowing down of μ mesons no depolarization occurs prior to their capture into a mesic atom orbit. In the process of mesic atom formation depolarization is possible due to the fine structure, and due to the action of the magnetic fields of the atomic electron shell and the atomic nucleus. Depolarization due to the spin-orbit interaction will occur if the lifetime τ_{life} of the μ^- meson in a given $l \neq 0$ level is longer that the time τ_{flip} necessary for the μ-meson spin to flip under the action of the magnetic field created by the orbital motion. The lifetime τ_{life} can be calculated from the formula given by Fermi and Teller.[6] The time τ_{flip} can be estimated from the relation $\tau_{flip}\Delta E \sim h$ where ΔE is the separation of the fine structure levels in mesic atoms.[7] It turns out that τ_{life} is larger than τ_{flip} by several orders of magnitude. Depolarization due to the action of the magnetic fields of the electronic shell and of the nucleus will be negligible in the process of the meson reaching the K orbit. In fact, for this case one has $\tau_{life} < \tau'_{flip}$, where $\tau'_{flip} = h/\Delta E'$ ($\Delta E'$ is the separation of the hyperfine structure levels).

It can therefore be said that in the process of formation of mesic atoms depolarization proceeds mainly due to the fine and hyperfine structure interactions. After the μ^- meson reaches the K orbit, where it remains until its decay or nuclear capture, depolarization may be caused by the magnetic field of the electronic shell (I. M. Shmushkevich, private communication).

Depolarization due to the hyperfine structure can be avoided by employing materials with zero nuclear spin. Depolarization due to the field of the electronic shell cannot be avoided in this manner, since the mesic atom formation process is always accompanied by a rearrangement of the electronic shell of the capturing atom (owing to the change in the effective charge of the nucleus by one unit). Consequently, in the stopping of μ^- mesons in such materials the main sources of depolarization will apparently be the spin-orbit interaction and the interaction between the magnetic field of the electronic shell and that of the μ^- meson during its lifetime in the K orbit.

Starting from these assumptions, we measured the polarization of μ^- mesons in a number of substances, 85 to 95% of which were composed of atoms with zero nuclear spin, namely C, O, Mg, S, Zn, Cd, and Pb.



1, 2, 3, 4) scintillation counters; 5) target; 6) magnetizing coil; 7) paraffin filter; 8, 9) aluminum filters; 10) lead shield.

3. THE EXPERIMENT

The polarization of the μ^- mesons was studied by measuring the anisotropy in the angular distribution of the decay electrons. The experimental arrangement was the same as that used previously.[3] The π and μ mesons were slowed down by aluminum filters. The μ^- mesons, after traversing the filters, were stopped in a target made of the substance under investigation. The targets measured 15 × 15 cm and were 2 to 6 g/cm^2 thick. The angle between the target and the "axis" of the meson beam was 45°. The target was wrapped in a copper wire coil which served to create the magnetic field necessary to make the μ mesons precess. Our previously published work[3] gives a detailed description of the experimental conditions, the scintillation counters, and the electronic apparatus. In the present experiments the polyethylene filter between counters 3 and 4 was 4 to 8 g/cm^2 thick.

For carbon, oxygen, magnesium, and sulphur the asymetry coefficient a in the decay electron angular distribution $I(\theta) = 1 + a\cos\theta$ was determined from the dependence of the number of electrons observed on the intensity of the magnetic field H surrounding the target. For zinc, cadmium, and lead the quantity a was determined from the number of electrons obtained when the field value was H_{max} and H_{min}, corresponding to the maximum and minimum intensity of electrons in the precession curve calculated from the expression

$$I(H) = \int_{t_1}^{t_2} e^{-t/\tau}[1 + a\cos(2\pi f t + \theta_0)]\,dt,$$

taking into account the delay time t_1, the "gate" width $t_2 - t_1$, and the lifetime τ of μ^- mesons.[8,9]

The "gate" width was approximately equal to τ in the C, O, Mg, and S experiments and 2τ to 3τ in the Zn, Cd, and Pb experiments. The ratio $t_1/(t_2 - t_1)$ was approximately 0.3 in all experiments. In the carbon experiments, for example, the counting speed at H = 0 was 120 electrons per minute, while in the lead experiments it was about 8 electrons per minute. The background level amounted to 3 counts per minute and was independent of the field H. The background was taken as half the sum of the electron detector counts obtained without the target and magnetizing coil and the counts obtained with the coil but without the target.

As a result of the experiments, values of the asymmetry coefficient a were obtained for electrons which traversed more than $x = x_1 + \frac{1}{2}x_2 + x_3$ g/cm^2 (here x_1 is the thickness of the filter between counters 3 and 4, x_2 is the target thickness, and x_3 is the thickness of the scintillation counters in the electron detector). Then, using the data[10] on the energy dependence of the asymmetry in $\mu^+ - e^+$ decay, we obtained values for a_0, the asymmetry coefficient for the integrated spectrum, i.e., for $x = 0$. The values of a_0 are listed in the second column of the table.

The listed values of a_0 were corrected for the delay time, "gate" width, μ^--meson decay, and the solid angle of the electron detector. The indicated errors are standard statistical deviations.

Substance	$-a_0$	Polarization P, %
C	0.040±0.005	14±4
O(H_2)	0.043±0.005	15±4
Mg	0.058±0.008	20±5
S	0.042±0.006	15±4
Zn	0.056±0.011	19±7
Cd	0.055±0.012	19±7
Pb	0.054±0.013	19±7

4. DISCUSSION OF RESULTS

On the assumption of invariance under CP, the magnitude of the polarization P_- of μ^--mesons in mesic atoms can be obtained from the equality $a_0^-/P_- = a_0^+/P_+$, where a_0^- and a_0^+ are the asymmetry coefficients for the μ^-- and μ^+-mesons respectively and P_+ is the degree of polarization of μ^+-mesons before decay. Let us assume that the degree of polarization of μ^+-meson beams obtained from internal targets in synchrocyclotrons is independent of the energy of the accelerated protons.[10] If the μ^--meson beam we used is taken to have the same degree of polarization as the μ^+-meson beams, then P_- can be obtained from the inequality[11] $3a_0 \le P \le 4a_0$. Values of P obtained in this manner are listed in the third column of the table. Only errors in the quantity a_0 were taken into account in this calculation. As can be seen from the table the polarization amounts to $(19 \pm 7)\%$ in magnesium, zinc, cadmium, and lead mesic atoms, and $(15 \pm 4)\%$ in carbon, oxygen, and sulphur mesic atoms. From a comparison of the maximum polarizations observed for μ^- and μ^+ mesons we conclude that μ^- mesons are depolarized to a larger extent. The strong depolarization of μ^- mesons can be explained by the factors mentioned earlier.

The question arises whether it is possible to restore in some manner the polarization of μ mesons in mesic atoms. Clearly, there is no simple way to eliminate the depolarization due to the spin-orbit interaction. The depolarization due to the action of the electronic shell can, apparently, be eliminated. Placing the target in a longitudinal magnetic field of $\sim$ 10,000 Oe should result in a "partial restoration" of the polarization due to the decoupling of the electronic shell and the μ^- meson.

In conclusion, the authors consider it their duty to thank Prof. B. Pontecorvo for a number of valuable comments. The authors also take this opportunity to thank S. S. Gershtein, V. B. Beliaev, and B. N. Zakharev for discussion of the results and continued interest in this work.

[1] Shapiro, Dolinskii, and Blokhintsev, Dokl. Akad. Nauk SSSR **116**, 946 (1957), Soviet Phys. "Doklady" **2**, 475 (1957).

[2] B. L. Ioffe, J. Exptl. Theoret. Phys. (U.S.S.R.) **33**, 308 (1957), Soviet Phys. JETP **6**, 240 (1958).

[3] Ignatenko, Yegorov, Khalupa and Chultem, J. Exptl. Theoret. Phys. (U.S.S.R.) **35**, 894 (1958), Soviet Phys. JETP **8**, 621 (1959).

[4] G. W. Ford and C. J. Mullin, Phys. Rev. **108**, 477 (1957).

[5] A. M. Bincer, Phys. Rev. **107**, 1434 (1957).

[6] E. Fermi and E. Teller, Phys. Rev. **72**, 399 (1947).

[7] R. E. Marshak, Meson Physics, ch. 5, N. Y. 1952.

[8] Garwin, Lederman, and Weinrich, Phys. Rev. **105**, 1415 (1957).

[9] Sens, Swanson, Telegdi, and Yovanovitch, Phys. Rev. **107**, 1464 (1957).

[10] Mukhin, Ozerov, and Pontecorvo, J. Exptl. Theoret. Phys. (U.S.S.R.) **35**, 340 (1958), Soviet Phys. JETP **8**, 237 (1959).

[11] H. Öberall, Nuovo cimento **6**, 533 (1957).

Translated by A. M. Bincer
241