INVESTIGATION OF THE DEPOLARIZATION OF NEGATIVE MUONS IN LIQUID HYDROGEN

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

Joint Institute for Nuclear Research

Submitted to JETP editor May 5, 1958; resubmitted July 14, 1958

J. Exptl. Theoret. Phys. (U.S.S.R.) **35**, 894-898 (October, 1958)

The angular distribution of decay electrons from μ^- mesons was measured in liquid hydrogen with the aid of scintillation counters. The distribution was found to be isotropic within the limits of experimental error. The degree of polarization of μ^- mesons in mesic hydrogen was determined from the electron angular distribution to be less than 2.5%. The observed complete depolarization of μ^- mesons can evidently be explained essentially by the mechanism suggested by Zel'dovich and Gershtein, according to which the μ^- meson jumps from one proton to another simultaneously with a transition to the hyperfine-structure ground state. Due to this mechanism a transition between orthohydrogen and parahydrogen is possible. It is impossible to determine the form of the interaction between μ^- mesons and nucleons by measuring the angular distribution of neutrons from the $\mu^- + p \rightarrow n + \nu$ reaction in liquid hydrogen because of the complete depolarization of the μ^- mesons.

INVESTIGATION of the capture of polarized μ^- mesons in hydrogen makes it possible to obtain information on the nature of the weak interaction between muons and nucleons.[1-3] It is usually assumed that μ^- mesons are absorbed by protons in mesic hydrogen through the reaction $\mu^- + p \rightarrow n + \nu$. The angular distribution of neutrons from this reaction provides one method of determining the type of interaction. The neutron angular distribution is described by

$$w(\theta) = 1 + a\beta \cos\theta, \tag{1}$$

where β is the asymmetry parameter in the neutron angular distribution, the magnitude and sign of which depend on the type of interaction, θ is the angle between the neutron path and muon spin, and a is a parameter which takes into account the degree of polarization of μ^- mesons in mesic hydrogen.

It follows from Eq. (1) that the polarization of μ^- mesons in mesic hydrogen must be measured before the experimental determination of the neutron angular distribution. The present article is concerned with an experimental investigation of μ^--meson polarization in liquid hydrogen. The work was performed on the synchrocyclotron of the Joint Institute for Nuclear Research.

1. BASIC THEORETICAL CONCEPTS

We consider the possible depolarization mechanisms for μ^- mesons slowed down and stopped in liquid hydrogen. It was shown in references 4 and 5 that when muons are slowed down in matter to a velocity comparable with electron velocities in atoms, the muons are not depolarized. Depolarization evidently does not occur even while the velocity is subsequently being reduced to zero, i.e., until capture in mesic atomic orbits. When a mesic hydrogen atom is formed incomplete depolarization is possible as a result of the spin-orbit interaction.[6] The two hyperfine states of the mesic hydrogen atom are the singlet ground state ($F = 0$) and the first excited triplet state ($F = 1$). When $F = 0$ the meson "has forgotten" its initial spin direction (it is depolarized). In the state $F = 1$ the meson "remembers" its spin direction (it is not depolarized). It is easily seen that in an isolated mesic hydrogen atom the muon does not make a transition between levels of the hyperfine structure during its lifetime. Indeed, since the excited state is 0.2 ev above the ground state the probability of a radiative transition ($\tau_{rad} = 10^6$ sec) is many orders of magnitude smaller than the probability of meson decay ($\tau \sim 10^{-6}$ sec).[7] Let us now consider what happens to a mesic hydrogen atom which is formed in liquid hydrogen. The following processes are possible when such atoms are produced by the stopping of muons in liquid hydrogen:

(1) Muon capture by a deuteron present in the liquid hydrogen:

$$\mu^-H + D \rightarrow \mu^-D + H + 135 \text{ ev};$$

(2) Scattering:

$$\mu^-H + H \rightarrow \mu^-H + H, \quad \mu^-D + H \rightarrow \mu^-D + H;$$

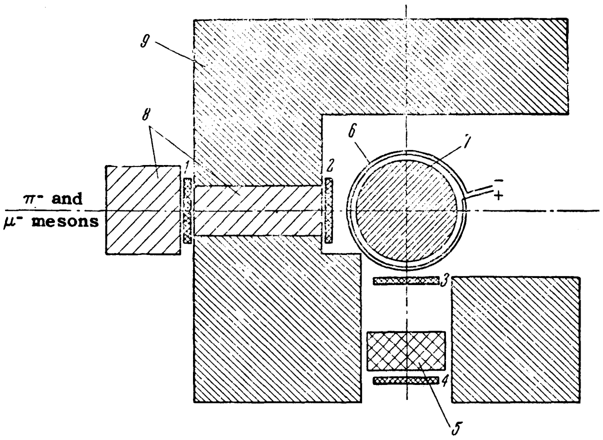
(3) Formation of mesic molecular ions:

$$\mu^- H + H \rightarrow \mu^- HH, \ \mu^- H + D \rightarrow \mu^- HD, \ \mu^- D + H \rightarrow \mu^- DH.$$

The probabilities of these processes have been considered theoretically in references 7 to 11. One interesting result of these studies is the fact that the cross section for process (2) is two orders of magnitude greater than the cross section for the other processes. Zel'dovich and Gershtein[7] have shown that, because of the neutrality of the mesic hydrogen atom, there exists in the scattering process a very effective mechanism of muon "jumps" from one proton to another with a simultaneous transition to the lower hyperfine level. Since the probability of these jumps ($\sim 10^9$ sec^{-1}) is three orders of magnitude greater than the probability of muon decay (0.5×10^6 sec^{-1}), all mesic hydrogen atoms are put into the ground state of the hyperfine structure within the muon lifetime. Complete depolarization of the μ^- mesons should result from these transitions.

2. EXPERIMENTAL PROCEDURE

The polarization of μ^- mesons stopping in liquid hydrogen was investigated by measuring the anisotropy of the angular distribution of the decay electrons.[6]



A negative pion beam of energy ~ 150 Mev and intensity $\sim 900\ \pi^-/\text{cm}^2$-sec was directed at the experimental setup (see the figure). Aluminum absorbers with a total thickness of 32 cm were used to slow down the muons and to clear the pions from the beam. A fraction of the muons passed through the absorbers and were stopped in the target, which consisted of liquid hydrogen in an ordinary glass Dewar vessel. The Dewar had an inside diameter of 15 cm and length of 30 cm. The target was surrounded by a copper wire coil which generated the magnetic field required for muon precession. Two scintillation counters 1 and 2 connected in coincidence registered the muons which struck the target. Electrons from muon decay in the target were registered by counters 3 and 4, which were also connected in coincidence. The resolving time of the coincidence circuits was 5×10^{-8} sec. Plastic (polystyrene + 2% p-terphenyl + 0.1 α NPO) scintillators of 100 mm diameter and 6 mm thickness were used. A 6 g/cm^2 paraffin absorber was placed between counters 3 and 4. The electronic circuit functioned as follows. A (1 + 2)-coincidence pulse was delayed for 0.5 μ sec and initiated a gate of 1.5 μ sec duration for (3 + 4)-coincidence pulses, which reached a scaler and were registered by a mechanical counter. At the same time (1 + 2)-coincidence pulses reached their own scaler, which served as a monitor. Thus the circuit registered electrons with a range greater than 8 g/cm^2 produced during the time interval from 0.5 to 2 μ sec after the stopping of muons in the hydrogen. The angular distribution of the electrons was investigated by measuring the number of electrons as a function of the magnetizing current in the coil. The range of the magnetic field containing the target was in accordance with calculations for the precession of a mesic hydrogen atom in the triplet state. In this state the magnetic moment of the mesic hydrogen atom is approximately equal to the magnetic moment of the muon and the angular momentum is given by $F = \frac{1}{2} + \frac{1}{2} = 1$. It is easily shown that the precession frequency of mesic hydrogen atoms in a magnetic field is one half as great as the precession frequency of free muons. A 20-cm lead shield entirely surrounded the target and counters for the purpose of reducing the background. The electron counting rate was usually 20 per minute. The background level was 4 counts per minute and was independent of the magnetic field. The "low" background was attained because the target Dewar, shield, and magnetizing coil consisted of materials with relatively large Z, in which the probability of μ^--meson decay is small. The experiment revealed no dependence of the electron counting rate on the magnetizing current. The asymmetry parameter a in the angular distribution of decay electrons, $I(\theta) = 1 + a \cos \theta$, was found to be -0.01 ± 0.01.

$R = 1.00 \pm 0.01$ was found for the ratio of the number of electrons at the maximum and minimum of the expected precession curve, for which the best statistical results are obtained.

a and R were corrected for the delay time, gate width, μ^--meson decay and solid angle of the electron detector. The indicated errors are the standard deviations.

3. INTERPRETATION OF RESULTS

The values of a and R show that the angular distribution of electrons was isotropic within the limits of experimental error. These results made it possible to determine the degree of polarization P of muons in mesic hydrogen through use of the energy dependence of electron asymmetry in μ^+-e^+ decay. We shall assume that μ^+-meson beams from internal synchrocyclotron targets have approximately the same degree of polarization independently of the proton energy.[12] By assuming that our μ^--meson beam had the same degree of polarization as a μ^+-meson beam we can determine P from the inequality $3a_0 \leq P \leq 4a_0$ in reference 13, where a_0 is the asymmetry parameter for the integrated spectrum. From this inequality we obtain $P = 2.9 \pm 2.9\%$. The results for R indicate that any remaining polarization of muons in hydrogen does not exceed 2.5%.

It was pointed out at the beginning of this article that, because of the fine and hyperfine structures, meson depolarization is incomplete when mesic hydrogen atoms are produced. Our experiments[14] show that in mesic atoms of C, O, Mg and S the polarization amounts to 16 ± 4%. When μ^--mesons stop in matter with zero nuclear spin the principal depolarization mechanisms will be the spin-orbit interaction and the interaction between the magnetic fields of the atomic electron shell and of the μ^- meson during its lifetime in the K orbit. In matter with non-zero nuclear spin there will be an additional depolarization mechanism due to the hyperfine interaction. This last mechanism reduces the polarization of μ^- mesons in such substances. As mesic-hydrogen atoms are formed in hydrogen, meson depolarization results mainly from the fine and hyperfine structure interactions. The electron shells cause no depolarization. For this reason the expected polarization of μ^- mesons would be much higher than 6% immediately after the formation of mesic hydrogen. The polarization which we observed experimentally was below 2.5%. In addition to the mechanisms already mentioned, μ^--meson depolarization can accompany the scattering of mesic hydrogen atoms in atomic magnetic fields. However, this will be insignificant because of the small number of collisions required for the muon to drop to the lower hyperfine state.[14,15] It appears that the observed complete depolarization results mainly from the mechanism suggested by Zel'dovich and Gershtein, whereby a muon "jumps" from one proton to another and simultaneously drops to the lower state of the hyperfine structure. This result is of fundamental importance since it shows that complete meson depolarization prevents determination of the nature of muon-nucleon interaction through measurement of the neutron angular distribution from the $\mu^- + p \rightarrow n + \nu$ reaction in liquid hydrogen.

The question arises whether muon depolarization can be prevented in some way. It is quite evident that we cannot prevent the depolarization that results from the fine and hyperfine structure. It might appear that we could prevent depolarization by the "jump" mechanism through the use of gaseous hydrogen, where the number of collisions between mesic hydrogen atoms and ordinary hydrogen atoms would be smaller, with a resulting smaller number of "jumps." But this is not a likely method of preserving the polarization, since the probability of the indicated transitions is so large that jumps occur after the first few collisions.[7]

As has been pointed out to us by V. B. Beliaev and B. N. Zakhar'ev, muon depolarization resulting from the jump mechanism and the hyperfine structure can be prevented only if we can completely polarize the (hydrogen) medium in the direction of polarization of the muon beam.

We have been considering collisions between mesic hydrogen atoms and ordinary hydrogen atoms. Let us now consider collisions between hydrogen molecules and mesic hydrogen atoms. We know that ordinary hydrogen consists of 75% orthohydrogen molecules (with parallel nuclear spins) and 25% parahydrogen molecules (with antiparallel spins). Since spontaneous transitions between ortho- and paramolecules are impossible the ratio 3:1 is preserved in liquid hydrogen. Only in the presence of certain catalysts (such as activated charcoal) can orthomolecules be transformed into paramolecules. It is easily seen that the jump mechanism can lead to such a transformation in the presence of mesic hydrogen atoms. Therefore if hydrogen is bombarded with a sufficiently intense muon beam the 3:1 ratio will become nearly 1:1.

In conclusion, the authors thank Academician Ia. B. Zel'dovich and S. S. Gershtein for making their work available to us before publication, and for a discussion of our results. The authors also wish to thank V. B. Beliaev and B. N. Zakhar'ev for numerous discussions and for their continued interest.

[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] Huang, Yang, and Lee, Phys. Rev. **108**, 1340 (1958).

[4] G. W. Ford and C. J. Mullin, Phys. Rev. **108**, 477 (1958).

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

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

[7] S. S. Gershtein, J. Exptl. Theoret. Phys. (U.S.S.R.) **34**, 463 (1958), Soviet Phys. JETP **7**, 318 (1958).

[8] Ia. B. Zel'dovich and A. D. Sakharov, J. Exptl. Theoret. Phys. (U.S.S.R.) **32**, 947 (1957), Soviet Phys. JETP **5**, 775 (1957).

[9] Ia. B. Zel'dovich, J. Exptl. Theoret. Phys. (U.S.S.R.) **33**, 310 (1957), Soviet Phys. JETP **6**, 242 (1958).

[10] J. D. Jackson, Phys. Rev. **106**, 330 (1957).

[11] Hayashi, Nakano, Nishida, Suekane, and Yamaguchi, Progr. Theoret. Phys. (Japan) **17**, 615 (1957).

[12] Mukhin, Ozerov, and Pontecorvo, J. Exptl. Theoret. Phys. (U.S.S.R.) **35**, 340 (1958).

[13] H. Uberall, Nuovo cimento **6**, 533 (1957).

[14] Ignatenko, Egorov, Khalupa, and Chultem, J. Exptl. Theoret. Phys. (U.S.S.R.) **35**, 1131 (1958), Soviet Phys. JETP **8** (in press).

[15] V. W. Hughes, Phys. Rev. **108**, 1106 (1958).

Translated by I. Emin
189