Study of the Muonium Stage of Depolarization of μ^+ Mesons in Potassium Chloride

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The residual polarization of μ^+ mesons in single crystals of potassium chloride (KCl) has been measured as a function of longitudinal magnetic field strength in the range 0–3 kG. It is shown that the experimental results are in agreement with the phenomenological theory of the muonium stage of μ^+-meson depolarization in matter in the presence of spin-exchange interactions of muonium with the medium. The measured value of critical magnetic field strength $H = 1540 \pm 60$G is identical to the vacuum value. The data obtained indicate that atomic muonium enters into a chemical bond and forms a diamagnetic compound. The relation between the rates of spin-exchange (ν) and chemical($1/\tau$) processes is expressed in the form of the product $\nu\tau = 1.81 \pm 0.10$. A number of processes which complicate investigation of the purely muonium stage of μ^+-meson depolarization in matter are discussed.

1. INTRODUCTION

THE phenomenological theory of μ^+-meson depolarization in matter, developed in Refs. 1–3, assumes as the main depolarizing mechanism the formation of atoms of muonium—a bound system of a μ^+ meson and an electron. The contact interaction[4] of the magnetic moments of the μ^+ meson and electron making up the muonium leads to a rapid loss of the initial polarization of that fraction of the μ^+ mesons which forms atoms in the para state. The frequency ω of transitions between levels with $m = 0$, $J = 0.1$, which determines the rate of the depolarization process, is related to the hyperfine splitting energy E of muonium and its radius r by the equations (see [5])

$$\hbar\omega = E \approx \frac{32}{3}\frac{\beta_e\beta_\mu}{r^3} = 2\beta_e H, \qquad (1)$$

where β_e and β_μ are the magnetic moments of the electron and the muon, and H is the critical strength of the magnetic field produced by the μ^+ meson at a distance equal to the radius of the first Bohr orbit of muonium. The vacuum values ω_0 and H_0 are respectively 2.804×10^{10} sec^{-1} and 1585 G.[5] In the triplet ortho state of muonium, the μ^+ mesons, in the absence of external effects, retain their polarization up to the time of the $\mu \to e$ decay. Spin-exchange interactions of the muonium electron with the medium lead, however, to the fact that the ortho and para states are mixed. If the rate of this process is rapid enough in comparison with the time of existence of free muonium atoms, the initial polarization of the μ^+ mesons can be lost completely. An external magnetic field directed longitudinally with respect to the particle spins prevents the depolarization, as the result of destruction of the coupling of the magnetic moments of the muon and electron in the para state.[6]

Quantitative inclusion of the factors enumerated above leads to the following expression (see [2]) for the residual polarization $P_\parallel$ (here and subsequently the indices $\parallel$ and $\perp$ indicate the direction (longitudinal or transverse) of the external magnetic field):

$$P_\parallel = 1 - \frac{(\omega\tau)^2(1+2\nu\tau)}{2[(\omega\tau)^2(1+\nu\tau+x^2)+(1+2\nu\tau)^2]}, \quad x = \frac{H_\parallel}{H}, \qquad (2)$$

where $H_\parallel$ is the external magnetic field intensity, H is the characteristic magnetic field of the hyperfine splitting of the muonium atom in the medium ($H \leq H_0$[2]), ν is the frequency of flipping of the electron spin in the muonium atom, and τ is the duration of the muonium stage of depolarization, which is determined by the chemical activity of muonium—a light isotope of atomic hydrogen.[7] In formation of diamagnetic molecules containing μ^+ mesons, the action of the depolarizing factors discussed above is cut short and further depolarization can occur only as the result of direct magnetic interaction of the μ^+ meson with the medium.

A particular case of Eq. (2) corresponding to an infinitely long existence (up to the $\mu \to e$ decay) of muonium ($\omega\tau \gg 1$, $\nu\tau \approx 0$) has been used by us[8] in analysis of experimental data; here we showed that in quartz (SiO_2) the experimental value of H agrees within experimental error with the vacuum value H_0, and the function $P_\parallel(H_\parallel)$ is satisfactorily described by the theory. It is of interest to compare the experimentally observed functions $P_\parallel(H_\parallel)$ with Eq. (2) in the more complicated case in which exchange and chemical interactions of muonium with matter prevent identification of its triplet state[9] in the time available for observation (of the order 10^{-8} sec or more).

Measurements of the residual polarization of μ^+ mesons as a function of intensity of the longitudinal magnetic field have been made previously for many materials (see, for example, Eisenstein et al.[10] and Buhler et al.[11]). However, for various reasons most of the data in the literature are, in our opinion, unsuitable for verification of the theory of the muonium stage of depolarization.

In the first place, the muonium stage does not always conclude with formation of diamagnetic molecules which include μ^+ mesons. As was shown by Firsov and Byakov[12] and confirmed experimentally by Babaev et al.,[7] the interaction of muonium with organic compounds containing multiple bonds between carbon atoms leads to formation of paramagnetic radicals (similar reactions of atomic hydrogen have been well investigated) in which the magnetic moment of the unpaired electron of the radical exerts a depolarizing effect on the μ^+ meson. Therefore the regeneration of μ^+-meson

polarization in longitudinal magnetic fields for such materials as polystyrene[11] and naphthalene[13] has a qualitatively different nature than for muonium atoms which form a diamagnetic chemical compound.

In the second place, some of the samples studied had inadequate homogeneity (nuclear photoemulsion, finely dispersed powders).[9]

In the third phase, it is well known that slow depolarization of μ^+ mesons is observed in a number of materials.[14] In determination of the polarization $P_{\parallel}$ by the forward-backward method[11] without analysis of the time distributions of $\mu \to e$ decays, this phenomenon contributes additional errors to the experimental results.

In the fourth place, a fraction of the μ^+ mesons can enter into the composition of diamagnetic molecules during the course of thermalization before thermal equilibrium of the muonium with the surrounding medium is reached.[8] According to estimates made by Nosov and Yakovleva,[1] muonium in condensed matter is thermalized appreciably faster than it is depolarized. The contribution of epithermal processes to the observed polarization $P_{\parallel}$ can be taken into account quantitatively only in analysis of measurements of the polarization $P_{\perp}$ over a wide range of transverse magnetic field intensities.[3]

In the present work we have chosen potassium chloride for comparison of theory and experiment. Single crystals of KCl of sufficient size can easily be obtained with a high degree of purity and uniformity. Preliminary experiments (see [15]) showed that for observation times greater than 50 nsec polarized μ^+ mesons are practically absent in a sample studied in a transverse magnetic field. This fact, on the one hand, indicates existence of intense exchange interactions of muonium, and on the other hand simplifies the formulation and performance of experiments as the result of the insignificant contribution of epithermal processes and the large range of expected variation of the polarization $P_{\parallel}$, which in the last analysis is equivalent to increasing the statistical accuracy of the results obtained.

2. EXPERIMENTAL RESULTS

Determination of the residual polarization of μ^+ mesons in single crystals of potassium chloride (KCl) was carried out in the meson beam of the synchrocyclotron at the Laboratory of Nuclear Problems, Joint Institute for Nuclear Research, by measurement of the asymmetry of $\mu \to e$ decays in the time range 0–6.5 μsec. The time distributions of these decays, obtained with a 100-channel analyzer with a channel width ~75 nsec in a transverse magnetic field $H_{\perp} \approx 50$ G, are modulated with the precession frequency of a free μ^+ meson; the modulation amplitude is proportional to the value of the polarization, designated $P_{\perp}$. Comparison of the results of experiments carried out alternately in a field $H_{\perp} \approx 50$ G and in longitudinal magnetic fields permitted also measurement of the polarization $P_{\parallel}$ as a function of field intensity in the range $0 < H_{\parallel} \lesssim 3$ kG. The equipment used for the measurements and the method of analyzing the experimental results have been discussed in detail in our earlier papers.[8,9,14] Most of the experiments were done with a target of diameter 10 cm and thickness 5.3 g/cm^2. The target temperature at the time of the experiments was 20–50°C. The following results were obtained.

1. The polarization in a transverse magnetic field of intensity $H_{\perp} \approx 50$ G was accurately measured and found to be $P_{\perp} = 0.084 \pm 0.005$. In the course of these measurements it was shown that if a slow depolarization of μ^+ mesons occurs in KCl, the corresponding relaxation time is greater than 15–20 μsec.

2. In a transverse magnetic field $H_{\perp} \approx 2.0$ G a polarization value $P_{\perp} = 0.099 \pm 0.014$ was obtained. Thus, the polarization $P_{\perp}$ in the transverse magnetic field strength range 2–50 G remains constant within experimental error. A similar result was obtained by Gurevich et al.[16] for NaCl in transverse fields $800\ \text{G} < H_{\perp} < 3500$ G.

3. Values of the polarization $P_{\parallel}$ were measured in the longitudinal magnetic field strength range 0–3 kG. The results are shown in Fig. 1. From the experimental values of $P_{\parallel}$ we subtracted the assumed contribution of epithermal processes—the polarization $P_{\perp} = 0.084 \pm 0.005$. The data were renormalized so that the maximum possible value $[P_{\parallel} - P_{\perp}]_{\max}$ was equal to unity. In the remainder of the article we will always use the renormalized polarization values, for convenience referring to them as before as $P_{\parallel}$. Over the entire range of longitudinal magnetic field strengths $0 < H_{\parallel} < 3$ kG, a decrease was observed in the regenerated part of the μ^+-meson polarization $P_{\parallel}$ with a relaxation time in the neighborhood of 5–7 μsec depending weakly on field strength. Therefore the polarization values plotted in Fig. 1 were obtained by extrapolation of the experimental data to zero time (the moment of stopping of the μ^+ mesons in the target). In this case the free muonium stage and the subsequent depolarization stage can be clearly distinguished. We observe a sharp increase in the polarization in the weak longitudinal field region $H_{\parallel} \lesssim 100$ G.

Several experiments in longitudinal magnetic fields of intensities up to 490 G were carried out with a single crystal of KCl with a minimal concentration of dislocations (average distance between dislocations 10–30 μ). In the field region $H_{\parallel} > 150$ G the experimental results are in good agreement with the data of Fig. 1. There is no time dependence of the polarization. In the weak longitudinal magnetic field region, a rapid increase in polarization is observed, similar to that shown in Fig. 1. However, in a KCl single crystal of high purity, this rise occurs in fields of intensity 5–20 G.

3. ANALYSIS AND DISCUSSION OF RESULTS

For a comparison of the experimental dependence $P_{\parallel}(H_{\parallel})$ with the theoretical expression (2) it is convenient to represent the latter in the form

$$\frac{P_{\parallel}}{1-P_{\parallel}} = aH_{\parallel}^2 + b, \quad a = \frac{2}{H^2(1+2\nu\tau)}, \quad b = \frac{1}{1+2\nu\tau} + 2\frac{1+2\nu\tau}{(\omega\tau)^2}. \tag{3}$$

In the coordinates $P_{\parallel}/(1-P_{\parallel})$ and $H_{\parallel}^2$ Eq. (3) is the equation of a straight line (Fig. 2). In analysis of the set of experimental data by the method of least squares, two

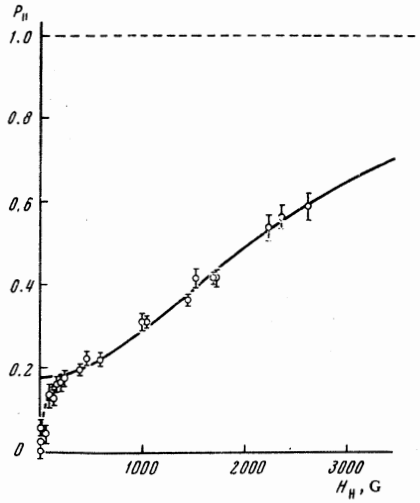

FIG. 1. u$^+$-meson polarization in single crystals of potassium chloride as a function of longitudinal magnetic field strength.

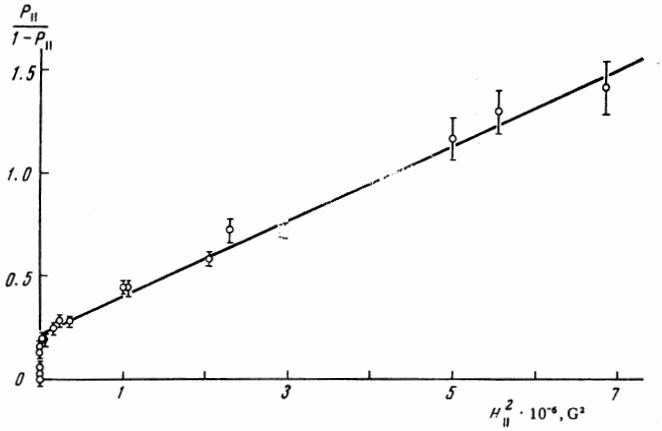

FIG. 2. The function $P_{\parallel}/(1-P_{\parallel}) = f(H_{\parallel}^2)$ in KCl.

parameters can be determined: a—the tangent of the slope angle of the straight line and b—the intercept of the straight line with the ordinate axis. As can be seen from the figure, the location of the experimental points is in good agreement with the requirements of the theory. In the region of weak longitudinal fields with intensity $H_{\parallel} \lesssim 100$ G, existence of an additional depolarizing mechanism for μ^+ mesons is evident. Let us consider the region of fields with $H_{\parallel} > 200$ G. The parameter values obtained in the calculation on the basis of 14 points are as follows: $a = (0.183 \pm 0.010) \times 10^{-6}$ G^{-2}; $b = 0.217 \pm 0.010$; the corresponding value of χ^2 is 11.4 (twelve degrees of freedom).

Determination of the three quantities completely characterizing the muonium stage of μ^+-meson depolarization in KCl: H, ν, and τ, from the two equations relating these quantities with the parameters a and b in the general case is impossible. Therefore we have made an analysis of the possible values of H, ν, and τ on the assumption that the last term in the coefficient b of Eq. (3) is known,

$$c = 2[(1 + 2\nu\tau) / (\omega\tau)^2].$$

Since all terms of Eq. (3) are necessarily positive, the range of possible variation of this term is $0 \leq c \leq b$. The case with $c = 0$ occurs when the rate with which muonium enters into a chemical reaction with the formation of a diamagnetic compound is small in comparison with the hyperfine interaction frequency ($\omega\tau \gg 1$). The μ^+-meson polarization remaining after completion of the muonium stage is associated with muonium atoms formed in the ortho state; the decrease of the polarization from a level $\frac{1}{2}$ (in coordinates $P_{\parallel}/(1 - P_{\parallel})$—from unity) is due to the existence of exchange interactions of the muonium. By setting $c = 0$ in Eq. (3), from the experimentally determined parameters a and b we can uniquely calculate the critical magnetic field intensity H, the frequency ω associated with it, the hyperfine splitting energy of the ground state of muonium, and the product $\nu\tau$ characterizing the ratio of the rates of exchange (ν) and chemical ($1/\tau$) interactions. Separate determination of the quantities ν and τ is impossible in this case. The value $H = 1540 \pm 60$ G determined in this way agrees within experimental error with the vacuum experiments: $H \approx H_0$; $\nu\tau = 1.81 \pm 0.10$.

For other values $c > 0$ the relation between the allowed values of H, ν, τ is clear from Fig. 3, in which we have shown error corridors for each of the quantities. Note that values $c > 0$ correspond to a decrease of the critical field strength for muonium atoms, i.e., to an increase in their size in comparison with the vacuum size. Although it cannot be stated a priori that a change in the size of muonium implanted in a KCl crystal lattice is impossible, inclusion in the analysis of data obtained in fields $H_{\parallel} < 200$ G permits the interval of allowed values of H and ω to be narrowed. One of the possible mechanisms of depolarization of μ^+ mesons in the region of weak longitudinal fields may be the presence in the KCl samples studied of local magnetic fields (LMF). The cause of the appearance of such fields may be, for example, the presence of impurities and dislocations in the KCl lattice. If we assume that the action of an external longitudinal magnetic field regenerating the polarization is important for $H_{\parallel} \geq H_{LMF}$, where H_{LMF} is the average intensity of LMF, then on the basis of the experimental data (Fig. 1) we can take for H_{LMF} a rough preliminary value ~ 50 G. The time of depolarization in this field corresponding to rotation of the muonium spins by 1 rad is ~ 2.5 nsec. We can see from Fig. 3 that if we take for the minimal duration of the muonium stage a value $\tau \geq 1$ nsec (appreciable depolarization in this time occurs in LMF with intensities of the order 100–150 G), then values of ω turn out to be possible in the left ($\omega \approx \omega_0$) and right ($\omega \ll \omega_0$) parts of the figure.

As we have already mentioned previously, in experiments with a KCl single crystal with a minimal concentration of dislocations, it was shown that an additional depolarizing mechanism is effective in longitudinal fields $H_{\parallel} \lesssim 10$–20 G. In this case evaluations similar to those made above lead to the conclusion that the most probable value of the hyperfine splitting frequency of muonium in a KCl crystal lattice is the vacuum value: $\omega = \omega_0$. The invariance of the product $\nu\tau$ for two samples of KCl with different concentrations of lattice dislocations can be explained specifically by the fact that

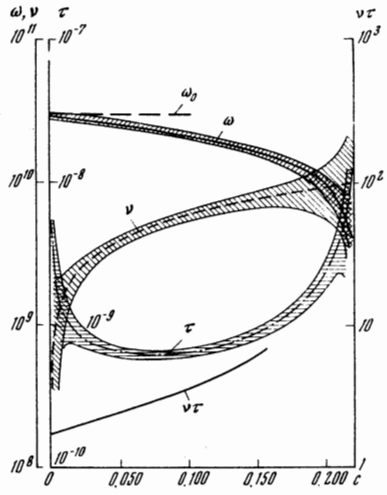

FIG. 3. Theoretical dependence of the parameters of Eq. (3) on the value of c.

both exchange and chemical interactions of muonium occur more intensely with an increase of the statistical density of uncompensated electron spins in the surrounding medium.

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