PASCHEN-BACK EFFECT FOR THE MUONIUM ATOM

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The polarization of μ^+-mesons as a function of longitudinal magnetic field strength is measured between 0 and 3 kOe in single-crystal quartz and corundum. For quartz the experimental data are found to be in good agreement with the theory of muonium depolarization. The experimental value of the critical magnetic field strength for muonium in quartz equals, within the experimental errors, the value obtained in vacuum. The possibilities which the method affords for measuring the size of muonium in various media are considered.

1. INTRODUCTION

In the study of the processes of depolarization of μ^+ mesons in a medium, it is assumed that the main cause of the depolarization is the formation of the muonium atoms Mu, i.e., the μ^+e^- system, as the intermediate or final product of the interaction of the μ^+ mesons with the medium[1-3]. In the case of total longitudinal polarization of the μ^+-meson beam, the appearance of muonium in the states J = 1, m = 1 (parallel spins of the meson and the electron) and J = 0; 1, m = 0 (antiparallel spins), is equally probable. Both states can be observed experimentally by determining the character of variation of the experimentally-observed polarization of the μ^+ mesons in external magnetic fields. The atoms in the state (1, 1), which conserve the initial polarization of the μ^+ mesons in a magnetic field that is longitudinal relative to the direction of the particle spin (or in the absence of the field), precess in a transverse field with a frequency determined by the system of spins and magnetic moments of the muonium[4]. In atoms with m = 0 in weak magnetic fields, the μ^+ mesons become depolarized within times $\sim 10^{-10}$ sec, as a result of $(1, 0) \rightleftarrows (0, 0)$ transitions between the levels of the hyperfine structure. The "critical" field intensity H_0, which is numerically equal to the magnitude of the field produced by the μ^+ meson at a distance of the radius of the first Bohr orbit of muonium (H_0 = 1585 Oe in vacuum[2]), separates arbitrarily the region of weak fields from the region of the Paschen-Back effect, namely fields in which the connection between the magnetic moments of the μ^+ meson and the electron is violated. With increasing intensity of the longitudinal magnetic field $H_{\parallel}$ (here and henceforth the indices $\parallel$ and $\perp$ pertain, respectively, to the longitudinal and transverse directions of the fields) there occurs a "restoration" of the polarization $P_{\parallel}$ of the μ^+ mesons that enter in the muonium with m = 0[3],

$$P_{\parallel}=\frac{1}{2}+\frac{1}{2}\frac{x^2}{1+x^2},\quad x=\frac{H_{\parallel}}{H_0}. \tag{1}$$

Relation (1), which implies that all the μ^+ mesons produced muonium, contains one unknown quantity H_0 and can be used both for its experimental determination and to verify the validity of the muonium mechanism of depolarization. Since the value of the critical field intensity is connected with the radius r_0 and with the frequency of the hyperfine splitting ω_0 of the ground state of the muonium[2]:

$$2(\mu_e-\mu_\mu)H_0=\hbar\omega_0\approx\frac{32}{3}\frac{\mu_e\mu_\mu}{r_0^3},$$

where μ_e and μ_μ are the magnetic moments of the electron and of the μ^+ meson, measurement of the residual polarization of the μ^+ mesons as a function of the intensity of the longitudinal magnetic field would make it possible to determine the main characteristics of the muonium atom in those substances for which relation (1) is satisfied.

Experimental investigations of the $P_{\parallel}(H)$ dependence, carried out in different condensed media[5,6], have shown, however, that for many compounds (photoemulsion, polystyrene), the restoration of the polarization in longitudinal fields does not correspond to Eq. (1). The accumulation of experimental materials[7] and further development of the theory of muonium depolarization[8] have revealed that the time during which the μ^+ meson of the muonium retains the initial spin orientation depends on the chemical reactivity of the surrounding medium (the probability of formation of diamagnetic molecules that contain muonium), and also on the possibility of electron exchange in which the spin direction of the muonium electron then reverse ($m = 1 \rightleftarrows m = 0$ transitions). The former process is characterized by a time τ elapsed from the instant of formation of the muonium to its entry into the chemical reaction, and prevents further "muonium" depolarization, whereas the latter, at certain values of the exchange frequency ν, can lead to a total loss of the initial polarization of the μ^+ mesons.

A detailed analysis of the behavior of the functions $P(\omega_0, \tau, \nu, x)$ expected in longitudinal and transverse magnetic fields is contained in[9,10]. A comparison of theory with experiment in the general case, i.e., at arbitrary relations between ω_0, τ, and ν, is a very complicated matter and requires the performance of large numbers of experiments. Therefore a verification of the validity of the theory is desirable, primarily, for those substances in which chemical or exchange interactions of muonium are negligibly small. For example, in[7] chemical reactions of muonium—the analog of atomic hydrogen—were investigated under the assumption that there are no exchanges $\nu \ll \omega_0$, which is valid for the employed diamagnetic compounds with a high level of the energy of triplet excitation of the molecules.

The purpose of the present paper is to compare the experimental data obtained in strong longitudinal magnetic fields ($H_{\|} \gtrsim H_0$) with relation (1), under conditions when there are no noticeable chemical and exchange interactions between the muonium and the surrounding medium, and this absence is confirmed by the prolonged existence of the muonium in the polarized state (1, 1). The object of the investigation was quartz (SiO_2), in which we have previously observed muonium precession with a relaxation time on the order of a microsecond[4]. Using an example corundum (Al_2O_3), which is close in its chemical inertness to quartz, we consider also possible changes of the frequency of the hyperfine splitting of muonium for compounds in which the muonium precession in a weak transverse field was not observed experimentally.

2. EXPERIMENTAL DATA

The residual polarization of μ^+ mesons in single-crystal specimens of quartz and corundum in longitudinal magnetic fields of intensity up to 3 kOe was determined in the meson channel of the synchro-cyclotron of the Nuclear Problems Laboratory of the Joint Institute for Nuclear Research. The organization of the experiments and the operation of the electronic circuitry employed in the measurement were considered in detail in our earlier article[4,7,11]. In each individual experiment, by comparing the distributions of the times of the μe decays, one of which was obtained in a longitudinal magnetic field and the other in a transverse $H_\perp \approx 50$ Oe, we determined two values of the polarization: $P_\perp$, which is proportional to the amplitude of the meson precession, and $P_{\|}$, which corresponds to the summary polarization of the μ^+ mesons. The characteristics of a "typical" experiment are as follows: the number of stopped μ^+ mesons in the target is 1×10^6, the number of decays registered in one channel of width ~ 73 nsec near zero time (the instant of stopping of the μ^+ mesons) is $\sim 2 \times 10^3$, the random coincidence background is $\sim 100-200$ counts/channel, the total observation time is ~ 6.5 μsec, and the duration of exposure is 5–7 min. The muonium precession, which was not observed in the indicated conditions because of the small value of its period (~ 0.2 of a channel) was traced in a transverse field $H_\perp \approx 7.0$ Oe at a channel width ~ 10 nsec, and a total observation time ~ 0.7 μsec.

The iron-free coil for producing the longitudinal magnetic field had an inside diameter that exceeded slightly the dimensions of the targets. Therefore part of the registered decays corresponded to stoppings of μ^+ mesons in the brass walls of the coil. Since muonium is not produced in metal[12], the admixture of such decays increased the observed "mesic" fraction of the polarization, which does not depend on the intensity of the longitudinal magnetic field. A quantitative calculation of this admixture was based on measurements of the polarization $P_\perp$, performed with quartz, corundum, and naphthalene in the presence of a longitudinal coil and without the coil (for example, for naphthalene the experimental values of $P_\perp$ were respectively 0.211 ± 0.008 and 0.039 ± 0.017). Control experiments with graphite, in which the polarization of the μ^+ mesons, as in metals, is close to the maximum possible value[12],

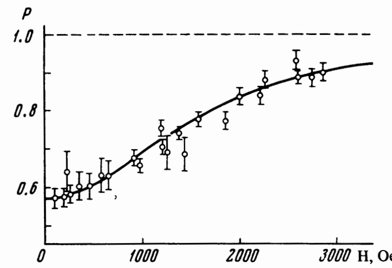

FIG. 1. Dependence of the polarization P of μ^+ mesons in quartz on the intensity of the longitudinal magnetic field H (in Oe). The solid curve is drawn in accordance with the expression (3) at $H_0 = 636$ Oe and A = 0.433.

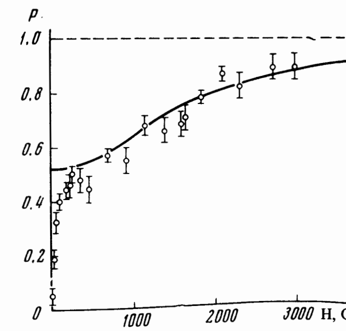

FIG. 2. Dependence of the polarization of μ^+ mesons in corundum on the intensity of the longitudinal field. $H_0 = 1650$ Oe, A = 0.478.

have shown that the yield of the decay positrons from the target remains constant ($\Delta P_{\|} \lesssim 0.01$) in the entire range of the intensities of the investigated longitudinal fields. The errors in the determination of the intensity of the longitudinal field are connected mainly with its inhomogeneity and do not exceed $\sim 10^{-2}$.

The values of the polarization $P_{\|}$ measured, with allowance for the contributions of the μ^+ mesons stopped in the walls of the coil, as functions of the intensity of the longitudinal field, are shown in Figs. 1 and 2 for quartz and corundum. The errors $\Delta P_{\|}$ include the error of interpolation necessary for quartz in fields with $H_{\|} < 200$ Oe, in which a time dependence of the polarization is observed[11], as well as random fluctuations of the efficiency of registration of the decays. An estimate of the magnitude of these fluctuations was based on the results of multiple repetitions of the same experiment in the field $H_\perp \approx 50$ Oe. The value of $P_{\|}$ for H = 0 in quartz is given with the use of results of the measurements of the amplitude of the muonium precession, $P_{\|} = P_\perp + P'_\perp$, where $P'_\perp$ is the polarization proportional to the amplitude of the muonium precession. Introduction of other corrections and absolute normalization of the results are considered in[4,7,11].

3. DISCUSSION OF RESULTS

In a target made of crystalline acoustic quartz it is possible to observe, under identical conditions, both muonium and meson precessions[4,13]. The former is due to the muonium atoms in the state (1, 1), and the latter is probably connected with the free μ^+ mesons, since the formation of diamagnetic molecules that contain muonium is not likely in this case and is possible only as a result of "prompt" processes that occur in the epithermal region. Since the amplitude of the meson precession in quartz remains constant during the entire observation time, the presence of some depolarizing factors for this part of the μ^+ mesons, such as the formation of muonium on the impurities and dislocations in the crystal lattice, is excluded. Therefore the polarization corresponding in these experiments to the value of $P_\perp$ remains unchanged also in longitudinal fields.

In the presence of a contribution of muonic polarization $P_\perp$ relation (1) goes over into

$$P_{\|}=\frac{1+P_{\perp}}{2}+\frac{1-P_{\perp}}{2}\,\frac{x^2}{1+x^2}. \tag{2}$$

On the basis of the experimental data, it is possible to verify both the character of the increase of the polarization $P_{\|}$ with increasing intensity of the longitudinal field, and the correctness of the assumption concerning the absence of additional depolarization channels of μ^+ mesons in quartz. In the latter case, the sum of the mesic and of the doubled muonium polarizations, measured in a weak field, should be equal to the maximum possible value. In the notation of Eq. (2), this means that as $x \to 0$ we get $2P_{\|} - P_\perp = 1$.

The mathematical reduction of the aggregate of the experimental points for quartz (Fig. 1) was carried out with a computer using least squares in accordance with the expression

$$P_{\|}=P_{\perp}+A\left(1+\frac{x^2}{1+x^2}\right) \tag{3}$$

and introducing an supplementary parameter A, which has the same physical meaning as the polarization of muonium in a transverse magnetic field. The results of the reduction are listed in the table. The table gives the experimental value of the polarization in a field $H_\perp \approx 50$ Oe, averaged over all the experiments and obtained with allowance for the contribution of the μ^+ mesons stopped in the coil walls, the values of A and H_0 satisfying Eq. (3) in the best manner, and the corresponding values of χ^2 (the number of degrees of freedom are indicated in the parentheses).

On the basis of the data of the table it can be concluded that the depolarization of μ^+ mesons in quartz is due to the muonium mechanism of depolarization. The character of variation of the polarization in a longitudinal magnetic field is in good agreement with the requirements of the theory, and it follows from the results of the calculation that the dimensions of the muonium atom, placed in the crystal lattice of quartz, are close to those for vacuum. The latter statement coincides with the conclusions of Gurevich et al.[13], who measured the frequency of the "beats" of the amplitude of muonium precession in transverse magnetic fields.

In Fig. 2 and in the second line of the table are given the experimental data and the calculated values of the parameters A and H_0 for corundum single crystals (the admixture of Cr^{3+} ions is less than 10^{-2}%). The physical difference between these two compounds (SiO_2 and Al_2O_3) lies in the large magnetic moment of the Al^{27} nuclei

Substance	$P_\perp$	A	H_0, Oe	χ^2	$2P_{\|} - P_\perp$, $x \to 0$
SiO_2	0.137±0.010	0.433±0.005	1636± 78	21.3 (23)	1.003±0.015
Al_2O_3	0.038±0.017	0.478±0.011	1650±120	14.2 (10)	0.994±0.027

(+3.64 n.m.), whereas in quartz the admixture of the silicon isotope Si^{29} (−0.56 n.m.) is about 4.7%. Therefore, if the "slow" depolarization[11] of muonium in quartz is due to interaction of its magnetic moment with the magnetic moments of the crystal-lattice nuclei, the expected lifetime of the polarized muonium in Al_2O_3 in the absence of an external magnetic field should be much smaller than 10^{-6} sec. Experiments in a transverse field $H_\perp \approx 7.0$ Oe have shown that precession with muonium frequency in corundum is missing at observation times exceeding 0.05 μsec. It is seen from Fig. 2 that longitudinal magnetic fields with intensity on the order of 20—100 Oe lead to restoration of the polarization of the μ^+ mesons in this substance to a level $P_{\|} \approx 0.5$, in agreement with the assumption concerning the depolarization action of the local magnetic fields of the same magnitude. Unlike quartz, in which a weak longitudinal field eliminates the slow depolarization while retaining the initial level of the polarization, in Al_2O_3 the value of $P_{\|}$ that remains constant during the entire time of observation is larger.

A similar picture is observed in certain organic compounds containing multiple bonds between the carbon atoms (polystyrene, naphthalene[6,14]). In these substances, however, fast chemical reactions resulting in paramagnetic radicals containing muonium are impossible. This is confirmed both by numerous investigations using atomic hydrogen, and by the data of our paper[7], in which the muonium consumed in the formation of radical compounds is manifest in experiments with homogeneous binary mixtures, and the second compound does not contain double bonds. At the same time, the dependence of the polarization on the intensity of the longitudinal magnetic field, observed in corundum, can be attributed to the pure muonium mechanism of depolarization in the absence of chemical reactions between muonium and corundum, if the investigated sample contains slight impurities of chemically active substances or crystal-lattice dislocations.

It follows from the experimental data that the intensity of the local magnetic fields in Al_2O_3 is of the order of 20—50 Oe. The average time of "depolarization" of the muonium in the field $H_\perp \approx 20$ Oe, corresponding to a spin rotation by 1 rad, is approximately 10^{-8} sec, which does not make it possible to observe muonium precession in weak transverse fields at observation times longer than 0.05 μsec. The number of collisions of the muonium in a solid substance can be assumed to be $\sim 10^{13}$ sec^{-1}. Then, assuming that as a result of the small dimensions the muonium atoms migrate freely through the lattice, the presence of impurities and dislocations at the 10^{-5} level admits, in principle, of the existence of channels for stabilizing the muonium. The experimental material confirms the possibility of such an explanation. The curve in Fig. 2 and the data of the second line of the table are given as results of the reduction of the values of the polarization $P_{\|}$ obtained in longitudinal fields with intensity $H_{\|} > 500$ Oe, in which the influence of random magnetic fields on the muonium with m = 1 is negligibly small. Just as for quartz, the relation $2P_{\|} - P_\perp = 1$ as $x \to 0$ is satisfied for Al_2O_3, and the value of the critical field intensity H_0 is close to the vacuum value.

4. CONCLUSION

The considered experimental material demonstrates the possibility of using strong ($H_{||} \gtrsim H_0$) longitudinal magnetic fields for the determination of the critical field intensity H_0 and of quantities directly connected with it, namely the frequency of the hyperfine splitting and the radius of the muonium, in different media. The measurements of ω_0 were performed also by methods of radio spectroscopy in gaseous argon[1] and in experiments aimed at observing harmonic oscillations of the amplitude of muonium precession in quartz[13]. The dependence of the μ^+-meson polarization on the longitudinal magnetic field was investigated, besides in quartz (and corundum), also in a large number of substances[5,6,15], in which, however, the mechanism of interaction of the μ^+ mesons with the surrounding medium cannot be regarded as finally established. Therefore, if precession with muonium frequency in a transverse magnetic field is not observed, then a certain caution must be exercised in the interpretation of the results of similar experiments.

In the absence of exchange interactions between muonium and a substance ($\nu < 10^7$ sec^{-1}, which makes it possible to extrapolate the experimental data to zero time), many processes preventing identification of the muonium precession in times longer than 10^{-7} sec still do not influence the single-parameter P(H) dependence expected in longitudinal magnetic fields in accordance with expressions (1) and (2), accurate to the easily-calculated contribution of the mesic component of the polarization. Such processes include, first, chemical reactions of muonium, the characteristic time of which lies in the interval $\omega_0^{-1} \ll \tau \lesssim 10^{-7}$ sec. The left part of this inequality excludes the "stabilization" of the muonium atoms with m = 0, the presence of which requires the use of more general formulas[9,10], and the right side depends on the experimental possibilities of observing the rapidly attenuating muonium precession[4].

If, second, the cause of depolarization of the muonium in transverse fields is the presence in the substance of randomly oriented magnetic moments, then even in weak longitudinal fields (on the order of tenths or hundredths of an Oe) the polarization of muonium with m = 1 is completely restored[8,11]. Under the indicated conditions, the method of restoring the polarization of the μ^+ mesons by a strong longitudinal magnetic field makes it possible to determine the dimensions of the muonium in those substances for which the use of other methods is difficult.

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