Muon spin relaxation in solid ^3He

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Muon spin relaxation in solid ^3He exhibits a nonmonotonic temperature dependence. It is shown that this dependence is associated solely with the magnetic-dipole interaction. The observed line narrowing does not agree with the hopping mechanism of the motion of a positively charged particle within the scope of the well-known activation law. An anomalous increase of the relaxation rate under the action of an electric field was found at low temperatures.

The temperature dependences of the depolarization rate of muons (μ^+) in metals[1] and of the muonium atom ($Mu = \mu^+ e^-$) in alkali-halide compounds[2] are described by the theory of diffusion of a delocalized particle that interacts weakly with the lattice. The general theory is constructed under the assumption that the particle undergoes phonon-induced tunneling transitions between two equivalent lattice positions with close energy levels.[3] In quantum helium crystals, however, a positively charged particle (usually a matrix ion) deforms the lattice as a result of polarization-induced attraction, and the energy levels in neighboring cells are found to be strongly separated. This lowers the tunneling probability and leads to self-trapping of the particle, which forms a charged complex. The motion of charged particles in quantum crystals apparently occurs as a flow of vacancies, regarded as delocalized quasiparticles.[4] The number of vacancies in the high-temperature region (near the melting point) decreases according to an activation law, which is why the mobility of impurity particles decreases exponentially as the temperature decreases.[5,6] The diffusion parameters of charged and neutral particles in this region are very close, suggesting that the vacancy mechanism of the motion of impurities in solid helium is universal.[4]

It is known that the mass of a muon is 30 times smaller than that of $^3He^+$. Therefore the question of the self-trapping of a muon in an interstice remains open. After a time τ which the particle spends in an interstice the muon diffusion coefficient D and the magnetic-dipole relaxation rate λ of the muon spin are related to one another in a known manner.[1-3] It is of interest for this reason to study by the μ**SR** method the spin kinetics of a light, positively charged particle (muon) in solid helium. Muonium could be another interesting object in ^3He. If its formation probability is appreciable, this neutral particle is a unique probe for studying magnetic interactions. Our objective in the present paper work was to study muon relaxation in solid helium and to search for muonium.

The experiments under pressure were performed in a special bronze chamber with a thin (0.1 mm) titanium window isolated from the case. The window and the inner electrode served to produce an electric field in the sample. The ^{3}He (and ^{4}He for $T>2.2$ K) crystals were grown at a constant pressure (± 0.025 bar) and a temperature gradient of 0.05–0.1 K. Although the ^{4}He experiment is described first, ^{3}He was actually studied first. When the experiments are performed in this sequence, ^{3}He is not contaminated by the other isotope after the gas is replaced. The initial gas, obtained from Isotec Inc., contained $\simeq 0.05\%$ ^{4}He as an impurity.

We know that the amplitude of precession of muonium in ^{4}He is maximum at a temperature of[7] 0.8 K. The pressure dependence of the muonium amplitude was measured at this temperature in a transverse magnetic field $H_\perp = 0.7$ Oe. As the pressure increased, A_{Mu} decreased monotonically from 0.055 to 0.037 at the pressure $P=24.5$ bar, after which A_{Mu} dropped sharply and no muonium was recorded in the solid phase. The low probability of muonium formation in solid helium is explained by the fact that charge mobility decreases to $b \leqslant 10^{-5}$ cm^2/V·s. As a result, for characteristic muon–electron distances[8] $l \simeq 10^{-5}$ cm, the muonium formation time $\tau_{\mathrm{Mu}} \simeq l^3/3be \geqslant 10^{-4}$ s becomes much greater than the muon lifetime. The vanishing of the muonium fraction is accompanied by a complete recovery of the muon component, which precesses with virtually no damping $\lambda = 0.002(2)$ MHz. The low value of λ indicates that there are no magnetic interactions in solid ^{4}He (which is obvious), and that muons are not recorded in the structural materials of the chamber.

We note one other peculiarity of solid ^{4}He. In liquid helium (He-I) the muon depolarization arising as a result of the formation of muonium decreases or increases, depending on the direction of the weak electric field, and it is efficiently suppressed by a strong field.[8] In solid ^{4}He, however, the value of λ remains small in a field of 1.7 kV/cm, irrespective of the direction of the field. This very important circumstance indicates that there are no magnetic interactions between a muon and the track electrons. The importance of this fact will become clear below when we analyze muon relaxation in ^{3}He, which possesses a nuclear magnetic moment.

In solid ^{3}He the muon precession is damped in the entire temperature range from T_{melt} to 0.37 K and in magnetic fields of 15–500 G. The character of the damping is described better by a simple exponential function $P(t) \propto \exp(-\lambda t)$, characteristic of spin dynamics, than by a Gaussian function $P(t) \propto \exp(-\sigma^2 t^2)$ which corresponds to a static situation. Typical temperature dependences of the transverse relaxation rate λ in the field $H_\perp = 100$ Oe for two crystals with the molar volumes 21.3 cm^3/mole ($P_m = 71$ bar) and 22.6 cm^3/mole ($P_m = 53$ bar) are shown in Fig. 1. As the temperature decreases, λ decreases, passes through a minimum at $T \simeq 1$ K, and then increases rapidly. Figure 1 also shows the values of λ for a ^{4}He crystal with a volume of 20.5 cm^3/mole ($P_m = 33$ bar). The extremely small values of λ in ^{4}He show that in solid ^{3}He muon relaxation is due soley to the magnetic dipole-dipole interaction between the muon and the nuclei. Here we have a rare case in which both the chemical reactions and ancillary effects of the spin-exchange type are absent.

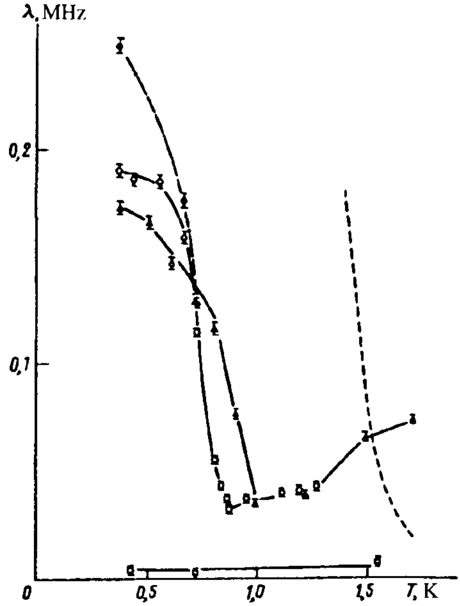

FIG. 1. Temperature dependences of the damping of muon precession in solid ^3He with different molar volumes (Δ—21.3 cm^3/mole, O—22.6 cm^3/mole) and ^4He (□—20.5 cm^3/mole). The filled circles ● represent the values of λ in an external electric field of 1.7 kV/cm and 22.6 cm^3/mole. The dashed curve on the right-hand side represents a calculation according to the activational motion of charge in solid ^3He.

In the experimental pressure range the ^3He atoms crystallize into a bcc lattice. The variance of the magnetic field at the interstices of the undisturbed lattice is $\sigma_0 = 0.35 - 0.4\ \mu s^{-1}$. It can be used as a lower limit of the relaxation rate of a stationary muon. The real value of σ is apparently higher because of the deformation of the crystal lattice by the polarization pressure. The observed relaxation rates (Fig. 1) are much lower than can be expected for a muon at rest. Ordinarily, this is due to the spin kinetics. As a result of the hopping of a spin from one position into another, the local magnetic fields are averaged (dynamic line narrowing) and the relaxation rate decreases, so that $\lambda = \sigma^2 \tau$, where τ is the characteristic time over which the spin configuration changes.

The structure of the environment around a muon and the character of the motion of the muon in helium are unknown. If it is assumed that the motion of a muon through the lattice is similar to that of a helium ion, then the muon motion is described by the well-known activation law of diffusion of positive charge. Using the expression for the diffusion coefficient $D = D_0 \exp(-\Delta/T)$ of cations in ^3He (Refs. 6 and 9) we shall estimate the characteristic displacement time $\tau = d^2/4D$ of a particle and the muon relaxation rate $\lambda = \sigma_0^2 \tau$. Setting $\sigma_0^2 \simeq 0.1 \times 10^{12}\ s^{-2}$, $D_0 = 2 \times 10^{-4}\ cm^2/s$, and $\Delta \simeq 18$ K for a molar volume of 21.3 cm^3/mole, it is easy to calculate the expected temperature dependence $\lambda(T)$. The result is represented by the dashed line in Fig. 1. The wide region of relatively small values of λ and the tendency for the relaxation rate at low temperatures to settle at a much lower value of σ_0 indicate that the observed behavior of $\lambda(T)$ is qualitatively

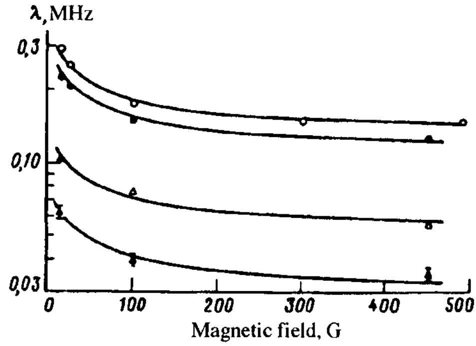

FIG. 2. Transverse relaxation rates as a function of the magnetic field for a crystal with a molar volume of 21.3 cm^3/mole at different temperatures: ○—0.37 K, ●—0.6 K, Δ—0.9 K, ▲—1 K.

different from the activation law for the diffusion of positive charge. In other words, the spin cofiguration around a muon changes over a time much shorter than the expected hopping time of a charged impurity particle.

Because of the quantum nature of ^{3}He crystals, the local magnetic field on μ^+ can change as a result of the spin exchange with the surrounding atoms.[10] At the same time, since the muon mass is small, for a muon the probability of tunneling is not small compared to He^+, and its kinetics can be described by the standard hopping mechanism.[3] For a spin diffusing through a rigid lattice, the magnetic-field dependence of the transverse relaxation rate has the form[11]

$$\lambda \simeq \sigma^2 \tau \left(1 + \frac{3}{2(1+\omega_i^2 \tau^2)} \right), \qquad (1)$$

which makes it possible to determine independently the value of τ and σ. According to Eq. (1), the half-width of the curve $\lambda(H)$ is determined by the condition $\omega_i \tau = 1$, where $\omega_i = \gamma_i H$ is the nuclear-precession frequency. The muon precession frequency is four times higher, and a feature similar to (1) lies in the range of weak fields. Figure 2 shows the magnetic-field dependences $\lambda(H_\perp)$ of a crystal with a volume 21.3 cm^3/mole for some temperatures in the range 0.4–1 K. The parallel (on a logarithmic scale) curves are drawn through points where the values of λ differ only by a scale factor. It is easy to see that the curves have virtually the same half-width ($\simeq 30-70$ G). As a result, we conclude that τ changes very little (by not more than a factor of 2) with temperature, and the tenfold changes in the relaxation rate are apparently due to the changes in σ — the average modulus of the local field on a muon.[1)] We note that $\tau^{-1} \simeq 1$ MHz, close to the characteristic exchange rate J of ^{3}He spins in a lattice.[10] This is easy to explain. Since the structure of the nearest-neighbor environment of μ^+ is determined by the polarization-induced attraction, near a muon $\tau = 2\pi/J$ is virtually independent of the temperature and the external pressure.

The temperature dependence $\sigma(T)$ does not fit into the now classical model[3] of free diffusion of a muon, since it assumes that σ = const. Another serious difficulty in applying this model to ^{3}He is associated with the observed effect of an electric field on

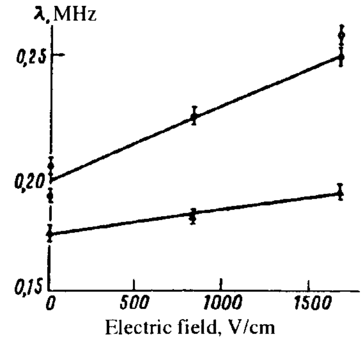

FIG. 3. Increase of the relaxation rate under the action of an electric field at $T=0.37$ K in two crystals: Δ—21.3 cm³/mole, ●—22.6 cm³/mole, ○—same but for a field directed in the opposite direction.

the spin relaxation. It was found that at low temperatures *an external electric field increases the muon relaxation rate.* Figure 3 shows the function $\lambda(E)$ at $T=0.37$ K for two crystals with the volumes 22.6 cm³/mole and 21.3 cm³/mole. For the filled circles **E** runs in the same direction as the momentum of the muons in the beam, and for the open circles the field is directed in the opposite direction. We see that within the limits of accuracy of the measurements the direction of the field **E** is not important. The effect of a field is much stronger in a crystal with a large molar volume. The reason for this is completely unclear. As the temperature increases, the influence of the field decreases, and above 1 K the changes in λ fall within the limits of the error. The dot-dashed line in Fig. 1 represents the values of λ in an electric field of 1.7 kV/cm. The increase in λ under the action of an electric field is apparently of a different nature than in liquid He-I (Ref. 8) and solid neon,[12] where the effect has the opposite sign and is caused by the interaction of a muon with the track electrons. Additional arguments in favor of a nonelectronic origin of the observed effect is that the effect is stronger at low temperatures, where the mobility of charges is lower, and the absence of relaxation in solid ^{4}He. It is clear that in the case of a diffusing muon, the external electric field can only accelerate its motion. This unequivocally excludes the hopping "dynamic narrowing" mechanism for the particle itself, since in this case λ decreases as the frequency of hops increases.

The temperature dependence of the local field could be associated with the redistribution of the ^{4}He concentration near a charged particle or with trapping of vacancies. Because of their attraction to a charge, vacancies can change the spin configuration near a muon and thus the relaxation parameters. Muon relaxation can be described qualitatively by assuming the existence of a vacancy band of width Δ_v. At high temperatures, the volume density of vacancies decreases exponentially $n \propto \Omega^{-1}\exp(-W/T)$, but the local density depends on the temperature only slightly if the vacancy trapping time of a charge is short $t \sim (4\pi D R_0 n)^{-1}$. Here R_0 is the trapping length. Vacancies decrease the local magnetic field, and $\sigma < \sigma_0$ but $\tau \neq 0$ because of the spin exchange of ^{3}He nuclei. When t exceeds the relaxation time in an unperturbed lattice $1/\sigma_0^2\tau$, however, the local density of the vacancies drops exponentially. This explains the sharp increase of the local field at a muon (and the increase of the relaxation rate) below 1 K. The value of σ continues to increase until the density of the vacancies becomes constant. A small, temperature-independent number of vacancies is produced by a muon in the process of thermalization. We note that an external electric field changes the character of the scattering of the vacancies. Upon application of an electric field such that $V = eaE > \Delta_v$, then a vacancy cannot penetrate into the region[13] $r < a\sqrt{V/\Delta_v}$. As a result, the density of vacancies which are associated with a muon decreases and σ increases.

Unfortunately, the vacancy model in its simplest form does not explain the large range of variation of σ^2 for a stationary muon. The point is that thirty of the closest ^{3}He nuclei make the main contribution to $\sigma^2 = \Sigma \mu_i^2 / r_i^6$. It is difficult to imagine that the vacancy concentration reaches several tens of percent in this local region.

An alternative explanation of the observed effects could be diffusion of ^{4}He impurity, whose content in the initial gas, as mentioned above, was about $\simeq 0.05\%$. The ^{3}He and ^{4}He atoms have the same polarizability, but because of its large mass and correspondingly lower amplitude of zero-point vibrations the ^{4}He atom occupies a smaller volume under otherwise the same conditions than the ^{3}He atom. For this reason, under the conditions of a strong pressure gradient, near μ^+ it is energetically advantageous for the nearest neighbors to be replaced by ^{4}He. If it is assumed that at high temperatures ($T < T_{\rm melt}$) the diffusion coefficient of ^{4}He in ^{3}He is the same as that of ^{3}He in a ^{4}He matrix (with the same molar volumes), i.e., $D > 10^{-8}$ cm^2/s (Ref. 14), then the equilibrium ^{4}He concentration in the region of the nearest coordination spheres may be of the order of one. As the temperature decreases, the vacancy-induced diffusion becomes ineffective, so that there is no longer enough time for redistribution of the ^{4}He atoms and the local magnetic field and correspondingly λ start to increase rapidly as the temperature decreases. We note that if ^{4}He diffuses via vacancies, then the electric field could be attributed to the effect it produces on the motion of the vacancies, which was described above.

In summary, the temperature dependence of the magnetic-dipole relaxation of the muon spin in solid ^{3}He does not agree with the established activation law of motion of charged particles. Other possible reasons for the characteristic features of the relaxation, for example, diffusion of ^{4}He impurity or trapping of vacancies by a muon, require additional investigation in connection with the observed increase in the relaxation rate under the action of an electric field.

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[1)] This assertion is valid if the condition $\sigma\tau \ll 1$ is satisfied. This condition is barely satisfied at the lowest temperature. More accurate formulas have shown, however, that this analysis gives the required accuracy.

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