Suppression of muon relaxation in liquid ^{4}He by an electric field

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As the external electric field is increased to 700 V/cm, the damping of the muon precession in liquid helium disappears.

A damping of the precession of the muon spin in liquid ^{4}He was observed in Ref. 1. According to the theory of spin relaxation with the diffusive motion of particles, the depolarization rate λ should decrease with increasing diffusion coefficient ($\lambda \sim D^{-1}$) because of an averaging of the local magnetic fields. In superfluid helium, the rate of muon relaxation increases with decreasing temperature, although the mobility of the charged particles, b, is known to increase.[2] The increase in the relaxation rate with increasing diffusion coefficient can be explained under the assumption that the depolarization results from a directed motion of a muon toward a depolarization center. The depolarization centers may be particles of the muon track: electrons, negatively charged helium ions, and ortho-helium atoms.

In this letter we report an attempt to determine which particles—charged or neutral—are responsible for the muon relaxation. An experiment was carried out in a low-background apparatus developed especially for the purpose, with cold scintillators.[3] In this apparatus the plastic scintillators are positioned inside the vacuum chamber of the cryostat and are cooled to ≈ 100 K. The systematic error in the measurement of the precession damping rate does not exceed 0.02 μs^{-1}. An electric field is produced by a row of plane wire grids inside the cryostate chamber. The grids are made of thin (0.1-mm) wire of nonmagnetic stainless steel. The distance between grids is 9 mm, and the distance between adjacent wires in the row is 2 mm. The total number of muon stoppings in the grids is 2%. Experiments on the effect of an electric field on the characteristics of the muon precession were carried out for temperatures of 4.2, 2.0, and 1.6 K. The polarization function was described by a single exponential function, $P(t) = \exp(-\lambda t)$.

As the electric field was strengthened, we observed a decrease in the depolarization rate. As E was varied from 0 to 6×10^3 V/cm in He-I, the depolarization rate fell from 0.066 μs^{-1} to 0.029 μs^{-1}. In superfluid helium, the suppression of the relaxation was seen much more vividly. At $T = 2$ K, for example, λ decreased from 0.128 μs^{-1} to 0.032 μs^{-1}, respectively. When the electric field was removed, λ increased to its previous value.

Figure 1 shows the depolarization rate versus the electric field for $T = 1.6$ K. Measurements were taken in two orientations of the electric field: parallel to ($E_{\parallel}$) and perpendicular to ($E_{\perp}$) the muon beam. The experimental results showed that λ does not depend on the field orientation. Over the field range 0–150 V/cm the depolarization rate remains essentially constant. As E is increased further, there is a sharp decrease in λ, and in fields above 700 V/cm the depolarization rate is at the resolution limit of the μSR apparatus. The observed temperature dependence and field depen-

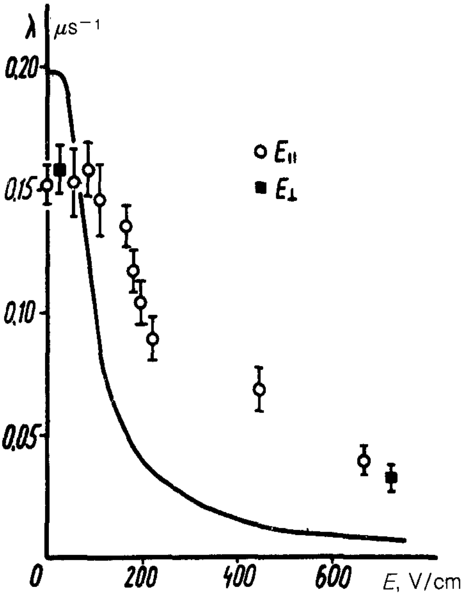

FIG. 1. Electric-field dependence of the muon relaxation rate in liquid ^{4}He at $T = 1.6$ K. The solid line was calculated from a model.

dence of the relaxation can be explained under the assumption that in the last stage of the stopping (thermalization) of a muon the electrons which are produced during the ionization of helium are close to the muon (with $\lesssim 10^{-4}$ cm). Coulomb forces cause an electron to approach the muon. As a result, there is a decrease in the asymmetry of the muon precesssion, either as a result of magnetic interactions or as a result of the formation of a muonium atom: Mu. An external electric field prevents the convergence of the particles and thereby suppresses the relaxation. The magnetic interaction $(\mu_B \cdot r^{-3})$ is important at distances $r_0 \lesssim 10^{-7}$ cm, while the formation of muonium occurs at even shorter range. In the experiments at $T > 1.5$ K, however, no precession at the muonium frequency was observed.[1] The Mu formation time is apparently random because of the spatial distribution of the electrons, and the spread in the initial phases of the muonium precession is greater than 2π.

We describe the muon precession by $A = P(t)\cos(\omega t + \varphi)$, where $P(t)$ is the polarization function. To calculate $P(t)$, we adopt the following model: At distance between the muon and the electron which are greater than $r_0 = 10^{-7}$ cm, the polarization of the muon is 1, while at distances smaller than r_0 the polarization vanishes. The time required for the particles to close from the distance r_0 ($t_0 = r_0^3/3be \leqslant 2.5 \times 10^{-9}$ s) is shorter than the time resolution of the μSR spectrometer, so it can be assumed that the loss of the polarization of the muon occurs at $r = 0$. At the time t, the relative number of depolarized muons is then $\int_0^{r(t)} W(\xi) d\xi$, and the polarization function is given by

$$P(t) = 1 - \int_0^{r(t)} W(\xi) d\xi \,, \tag{1}$$

where $W(\xi)$ is the spatial distribution of the electrons with respect to the muon, and $r(t)$ is the distance from which the particles close over the time t. As a very simple approximation of $W(\xi)$ we adopt a three-dimensional Gaussian function

$$W(\xi) = \frac{4\xi^2}{\Delta^3 \sqrt{\pi}} \exp(-(\xi/\Delta)^2) . \tag{2}$$

The closing of the muon and the electron is described by the equation for a mutual viscous motion:

$$\frac{d\mathbf{r}}{dt} = -b(T)e\frac{\mathbf{r}}{r^3} + b(T)\mathbf{E} \,, \tag{3}$$

where $\mathbf{r}$ is the radius vector connecting the particles, and $b(T)$ is the resultant mobility of the anions and cations. We have omitted a diffusion term from this equation since the distance from which the particles close over the lifetime of the muon is $r_\tau = (3be\tau)^{1/3} \leqslant 5 \times 10^{-5}$ cm and considerably smaller than the Onsager length, $r_c = e^2/kT \approx 10^{-3}$ cm. At $E = 0$, the experimental polarization function in He-I was approximated by the expression of Ref. 1, and the parameter Δ in distribution (2) was determined. It turned out to be $\Delta = 6.7 \times 10^{-5}$ cm. For this value of Δ we calculated the functional dependence $\lambda(T)$ in superfluid helium. This model gives a qualitatively correct description of the growth of λ with decreasing temperature, but the calculated values of λ are significantly higher than the experimental values at $T \leqslant 8$ K. For $E \neq 0$ we solved Eq. (3) by the Runge-Kutta method. We fitted an exponential function to the numerical values of $P(t)$. Figure 1 shows the behavior of λ as a function of the average electric field at $T = 1.6$ K found in this manner. The typical value found experimentally for the electric field at which λ decreases by half is twice the calculated value. A single-parameter distribution function (2) cannot eliminate the observed discrepancy. Apparently, the function $W(\xi)$ is quite different from Gaussian function (2). We of course cannot rule out the possibility that the kinetics of the closing of the particles slows down at short distances. The electron distribution function can be found from the experimental values of $dP(t)/dt$. The determination of the functional dependence $W(\xi)$ will be the subject of a separate paper.

In summary, the muon relaxation in liquid ^{4}He appears to be caused by the negative particles which are produced during the thermalization of a muon. This effect raises the possibility of observing muonium and using an electric field to extract cold (or thermal) muons from He-II at $T \lesssim 0.5$ K.

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