Muonium in liquid helium isotopes

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The asymmetry of the muonium spin precession in liquid-helium isotopes and in a solution with a small amount of ^{3}He (0.2%) has been measured in a weak transverse magnetic field (0.4 G). The measurements were carried out in the temperature interval 0.5–2.5 K. There are essentially no muons in the free state at temperatures below 0.7 K in pure superfluid ^{4}He or in the solution. The muons instead form muonium atoms, Mu, with electrons.

Although the physics of the formation of the muonium atom dates back a long way, we are far from having an adequate description of the process, particularly in the case of condensed matter. There are basically two models for the formation of muonium: the hot-atom model[1] and the track model.[2,3] However, it is difficult to find any *a priori* estimates of the relative number of muonium atoms, Mu, which form on the basis of these models. This is true even for media with a weak interaction, such as liquid helium, hydrogen, and neon, not to mention complex structures. It has been suggested[4] that the probability for the formation of muonium is small in liquid helium, since the binding energy of muonium is smaller than the ionization potential of the helium atom; the respective figures are 13.5 and 25 eV. The observation[5] of a free spin precession of muonium in superfluid ^{4}He at $T=0.52$ K has refuted that suggestion. In most cases, one observes Mu with a short formation time in experiments. The visible changes in the formation of muonium (in the asymmetry) occur primarily in the course of phase transitions, e.g., solidification. So far there has been little study of other conditions which affect the physics of the process. According to the track model,[3] the rate of muonium formation is proportional to the mobility of the charges. From this standpoint, superfluid helium presents us with a unique opportunity for studying the formation of muonium, since the mobility of charges increases by five orders of magnitude as the temperature is lowered from 2.17 to 0.5 K in this case.

In the present letter we are reporting a study of the kinetics of muonium formation in liquid-helium isotopes and in a solution of these isotopes in the temperature interval 0.5–2.5 K. The experiments were carried out in the surface-muon channel of the Paul Scherrer Institute in Switzerland, with the help of apparatus which has been described elsewhere.[5] The only new feature of the present experiments was that the window of the sample chamber was cemented with gold-plated Kapton (1000 Å). The metal-plated surface of the Kapton faced the liquid helium and made electrical contact

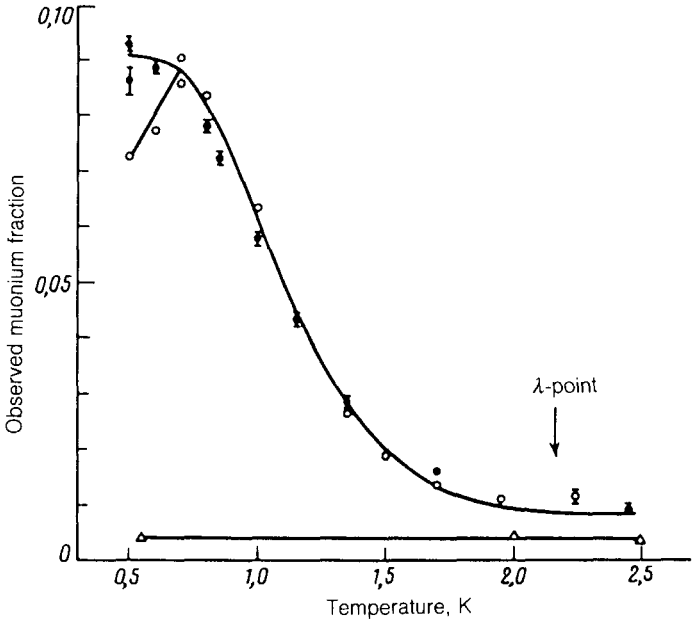

FIG. 1. Temperature dependence of the observed asymmetry of the muon precession in liquid-helium isotopes. Open circles—Pure ^{4}He; filled circles—^{4}He+0.2%^{3}He; triangles—pure ^{3}He. The statistical errors not indicated are smaller than the size of the symbol itself.

with the copper wall of the chamber. Since charges in this new chamber were not captured by the dielectric Kapton of the window, a residual electric field affecting the formation of muonium was eliminated.

Figure 1 shows the temperature dependence of the muonium asymmetry in pure ^{4}He and ^{3}He and also in the solution ^{4}He+0.2%^{3}He. These measurements were carried out in a weak transverse field $H=0.4$ G. Actually, the field makes it possible to detect Mu atoms which form over times shorter than $\tau \leqslant 10^{-7}$ s. As τ (or the field) is increased, the amplitude of the precession signal falls off because the phase matching of the spins is degraded. As a result, slowly forming Mu atoms are not observed in the precession.[5] At high temperatures, A_{Mu} is small both in the pure liquids and in the solution. At low temperatures, in contrast, the functional dependence $A_{\mathrm{Mu}}(T)$ is quite different in the different cases. The mobility of the charges in ^{3}He depends weakly on the temperature,[6] and (as expected) the asymmetry of the muonium in this case is independent of the temperature, within the measurement errors. The onset of superfluidity causes a dramatic change in the production of muonium. In pure ^{4}He and in the dilute solution, A_{Mu} increases with decreasing temperature. At $T \simeq 0.7$ K, a maximum forms in ^{4}He; thereafter, the asymmetry falls off by 15%. In an earlier experiment,[5] the value of A_{Mu} at $T=0.5$ K was slightly smaller, because of the residual electric field of trapped charges. In the solution at intermediate temperatures, the Mu

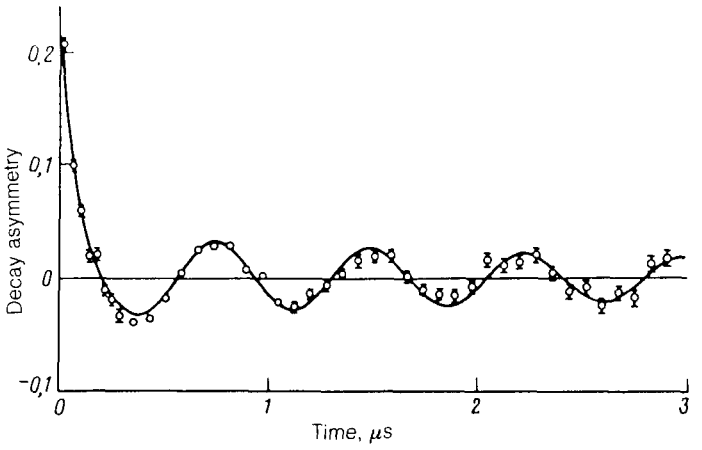

FIG. 2. Precession of the muonium spin in the solution ^{4}He+0.2%^{3}He for $H=100$ G, $T=0.5$ K, $A_\mu=3.6\pm0.2$, and $\lambda_\mu=0.21\pm0.04$ μs^{-1}. The first part of the histogram corresponds to the formation of muonium with a time scale of 60 ns.

asymmetry is smaller than in ^{4}He, and the maximum (if it exists at all) is shifted to a lower temperature.

The initial muonium asymmetry for the given geometry of the target and the scintillators is 0.21. Since half the asymmetry disappears upon the formation of muonium,[4] it is easy to see that the muonium asymmetry at a low temperature (0.7 K for ^{4}He and 0.5 K for the solution) is close to the maximum possible value (0.105). An experiment in a strong field showed that the muonium component is indeed small. Figure 2 shows a histogram of the muonium precession in a 100-G field. We see that the signal amplitude does not exceed $A_\mu\simeq0.036\pm0.002$. The slight decay of the precession ($\lambda\simeq0.2$ μs^{-1}) is due to the slowly forming muonium fraction. A large fraction of the muonium atoms (90%) form over times shorter than 10^{-7} s at low temperatures. A magnetic field much weaker than 0.4 G is required for observing the slowly forming part.

Several factors make it difficult to offer a quantitative description of the observed behavior. No information is available on the relative radial and angular distributions of the electron–muon pairs at the end of the track. Recent experiments have shown that this distribution is anisotropic. The topic which has received the least study in the field of muonium formation is the kinetics of the charged particles in strong electric fields and over short time intervals. The suppression of muon relaxation by an electric field near T_λ (Ref. 7) and the lowering of the muonium asymmetry in a field at $T=0.52$ K (Ref. 5) indicate that the electrons and muons in liquid helium move apart after the last ionization, in a narrow interval of distances from $r_0=(2\text{–}3)\times10^{-5}$ cm to $r_1=1\times10^{-4}$ cm. This movement corresponds to fields $E=10\text{–}1000$ V/cm, for which the kinetics of charges has been studied relatively well.[8] Using this circumstance, one

can find a qualitative understanding of the physics of muonium formation in liquid helium isotopes within the framework of a viscous motion.

Muonium forms in helium in three steps. (1) An excited Mu* atom formed as a result of the last charge exchange[1] collides with helium and breaks up into an electron and a muon. The particles moving apart have an energy insufficient to ionize the helium (this is true at least of the muon). As a result of elastic collisions, the e^- and the μ^+ undergo a decrease in energy, and at the low-energy level the electrons form "bubbles,"[9] while the muons form polarization "snowballs" with a large effective mass.[10] (2) The Coulomb attraction then causes the particles to move toward each other. (3) The muonium formation process terminates with the recombination of a bubble and a snowball.

The mobility of charges in normal ^{4}He, in the solution, and in ^{3}He is relatively low; the process in which the particles close on each other is the longest process. The time scale for the viscous closing of charges on each other in a Coulomb field is $t=r^3/(3be)$. At $T=2.5$ K, the relative mobility of the charge is[8] $b=b_+ + b_- \simeq 0.08$ cm^2/(V·s), and only the nearest electron–muon pairs (with $r<r_0$) move together over a time $t \simeq 10^{-7}$ s. In this case, an insignificant number of muonium atoms form over the formation time of the precessing part of the spectrum, τ, so the amplitude of the muonium precession is small. As the temperature is lowered (and as the mobility increases exponentially), A_{Mu} increases. When the mobility has risen three orders of magnitude, all the pairs which are furthest apart, with distances r_1, manage to close on each other over the time τ, and the muonium precession amplitude reaches its largest value. This occurs at $T_m=0.5$ K for the solution and at $T_m=0.85$ K for pure ^{4}He.

The mobility of charges in the solution is limited by impurity scattering; below 0.6 K, it remains essentially constant.[8] In pure ^{4}He, the charge mobility increases to 0.5 K. The apparent reason for the maximum on the plot of $A_{\mathrm{Mu}}(T)$ for pure helium is a slowing of Mu formation under conditions of an anomalously high charge mobility. If the formation of the polarization sheath around the muon (with a mass of $M \simeq 40$–50 He atoms) occurs at rates above the critical Landau velocity v_L, the effective time scale for the scattering of charges by the gas of excitations (and the velocity relaxation times $\tau_{\mathrm{rel}} \simeq b \cdot M/e$) becomes large at low temperatures. At 0.6 K, for example, we have $b > 10^3$ cm^2/(V·s), and the velocity relaxation time is $\tau_{\mathrm{rel}} > 2 \times 10^{-7}$ s. This result means that if a muon snowball has a velocity on the order of v_L, and if its kinetic energy, $Mv_L^2/2$, is larger than its potential energy e^2/r (the latter condition holds at $r > 5 \times 10^{-5}$ cm), the velocity relaxation occurs over distances $r \simeq v_L \cdot \tau_{\mathrm{rel}} \simeq 10^{-3}$ cm $> r_1$. This process is equivalent to a smearing of the effective distribution of muons. It increases the average closing time, and this increase in turn causes a decrease in the muonium precession amplitude. The formation of superfluid rings (if it occurs) might also explain the difference between the $A_{\mathrm{Mu}}(T)$ behavior in pure ^{4}He and that in the solution at low temperatures. One should also bear in mind that the time scale of recombination proper, associated with the fusing of a muon snowball and an electron, may be significant at very low temperatures, but this time is difficult to estimate.

In summary, in superfluid liquid helium and in dilute solutions thereof the number of muonium atoms which form increases with decreasing temperature. Below 0.7 K, essentially all the muons are bound with electrons because of the fast kinetics. This

result shows convincingly that the muon relaxation which has been observed previously[11] in helium is due to the formation of muonium. We do not rule out the possibility that similar effects may influence muon relaxation in other cryogenic substances, e.g., hydrogen.[12] This point should be kept in mind in analyzing diffusion processes on the basis of muon relaxation. If the muon fraction and the muonium fraction are comparable, then not only nuclear magnetic dipole–dipole interactions but also fast[2] and slow processes of muonium formation will affect the depolarization.

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