Anomalous Magnetic-Field Dependence of Positive Ion Mobility in Normal Liquid ^{3}He

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The positive ion mobility in normal liquid ^{3}He has been measured as a function of external magnetic field up to 15 T at temperatures down to 3 mK. At 3.2 mK, the field dependence is found to exhibit a pressure-dependent broad peak followed by a large decrease at pressures above 20 bars. On the other hand, at 20 mK, a monotonic decrease with increasing the magnetic field has been observed in the same pressure region. Possible origins for these anomalous behaviors are discussed.

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The ion in liquid ^{3}He is a powerful tool not only for studying elemental excitations but also for understanding the behavior of heavy charged particles in neutral Fermi liquid. In liquid ^{3}He there are two stable ions with a different sign of charge. The positive ion, called a "*snowball,*" is a cluster of ^{3}He atoms which are attracted to the core ($^3He_2^+$) by its large local electric field. Existence of the localized ^{3}He spins on the ion surface makes the positive ion a sort of magnetic impurity which is intentionally produced in the very pure Fermi liquid. The radius R^+ is in the order of 10 Å, which grows with an applied liquid pressure according to the following form [1,2]:

$$p_m(H,T) - P_{\text{liq}} = \frac{\alpha n e^2}{2\varepsilon^2 R^{+4}} - \frac{\nu_s}{\nu_l - \nu_s}\frac{2s}{R^+}. \qquad (1)$$

Here, p_m and P_{liq} are the melting pressure of the bulk ^{3}He and the liquid pressure, and ν_l, ν_s are the molar volumes of liquid and solid ^{3}He under melting pressure. ε, α, and s are the dielectric constant, the electrostatic polarizability of liquid, and the surface tension, respectively. The first term on the right-hand side in Eq. (1) is the electrostatic polarization force, and the second term denotes the surface pressure. On the other hand, the negative ion, called an "*electron bubble,*" is a hollow cavity in which a single electron is trapped from the Pauli principle. The radius R^- is in the order of 20 Å, which shrinks with raising the applied liquid pressure.

At low temperatures below 100 mK, the ion interacts with the Landau quasiparticles; hence the situation resembles the impurity scattering of the conduction electron in metal. However, in liquid ^{3}He, the ionic recoil is fairly important because of the absence of lattice. Many theorists have developed a self-consistent theory [3–5] which includes inelastic scattering among the ion and the quasiparticles. One such analytical formula, given by Prokof'ev, is as follows:

$$\mu = \frac{\mathrm{e}}{p_F^2 g}\left(1 + \frac{20C_4}{\pi g}\log\frac{\gamma\Gamma}{2\pi k_B T}\right). \qquad (2)$$

Here, $g = p_F^2\sigma/3\pi^2$ and $\Gamma = np_F\sigma/M$ are coupling constants, $\gamma = 1.5690\ldots$, C_4 is a constant related to a cross section σ, n is a number density of quasiparticles, and M is the mass of the snowball. It successfully explains the observed logarithmic temperature dependence of the positive ion mobility in normal liquid ^{3}He below 100 mK [6]. On the contrary, Èdel'shteĭn has proposed to take into account the *Kondo*-like exchange spin scattering of ^{3}He quasiparticles with the localized nuclear spins on the snowball surface [7]. If so, the exchange scattering is supposed to be suppressed by a high magnetic field ($\mu_N H \gg k_B T$; μ_N is the nuclear magneton of ^{3}He). However, the positive ion mobility measurement in such high magnetic fields is very limited, except for our preliminary one [8]. In this paper, we represent the first extensive study at various pressure and temperatures under higher magnetic fields up to 15 T.

The sample cell, housing a sharp metal tip as an ion source, and several grids, is installed inside a 15 T uniform magnetic field which is in parallel with the ion velocity. The radial field component over the entire drift space is less than 0.05% of the longitudinal one, so that the effect on the mobility is negligibly small. The liquid sample is thermally connected to the Cu nuclear demagnetization stage through a Pt-Ag sintered powder heat exchanger (150 m^2 surface area) and a massive silver thermal link with a high RRR of 3000. The temperature was determined by MCT (the ^{3}He melting curve thermometer) located in the low-field region. The temperature difference between the sample and the thermometer is negligible in the present temperature region. The details are given in Ref. [9]. The drift velocity was measured with a standard gated time-of-flight technique [10]. A typical signal at the collector is shown in the inset of Fig. 1. The mobility is determined from a linear region in the velocity v vs the electric field E relation as shown in Fig. 1. The error due to the fitting procedure is typically less than 1%, and a zero-field mobility [11] was not observed.

The temperature dependence of the snowball mobility at $P_{\text{liq}} = 28.6$ and 32.3 bars is given for various magnetic fields in Figs. 2 and 3. The temperature dependence above 25 mK is a well-known ^{4}He impurity effect [12] which corresponds to freezing of ^{4}He atoms in the core of the snowball. Although below 25 mK, ^{4}He atoms are adsorbed on the wall of the cell, especially on the vast

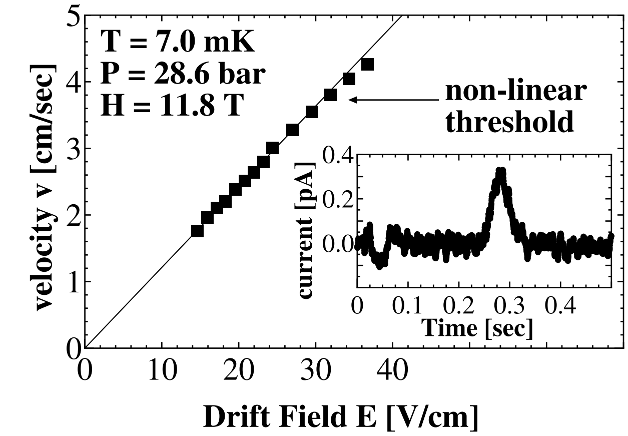

FIG. 1. Drift velocity v as a function of the electric field E. The inset shows a typical signal at the collector. The dip around 0.04 sec corresponds to the cross-talk noise arising from the high voltage gate pulse.

area of the heat exchanger, the different ion species were observed once in a while [13]. Nevertheless, the results for the fastest ion are found to agree with those obtained for the purified sample with ^{4}He impurity less than 10 ppm. Thus the observed dependence is for a completely pure ^{3}He system. At $T < 20$ mK, the logarithmic temperature dependence does exist even at high magnetic fields up to 14.8 T. If we fit the temperature dependence to the following formula with two parameters $\alpha(H)$ and $A(H)$,

$$\mu(H,T) = \alpha(H) + A(H)\log(1/T). \qquad (3)$$

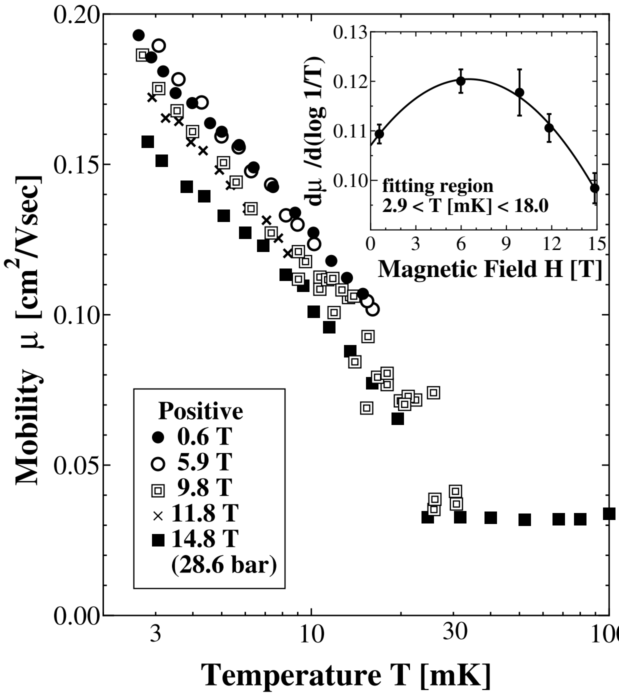

FIG. 2. Positive ion mobility as a function of temperature at 28.6 bars for various magnetic fields. The inset shows the field dependence of the coefficient $A(H)$.

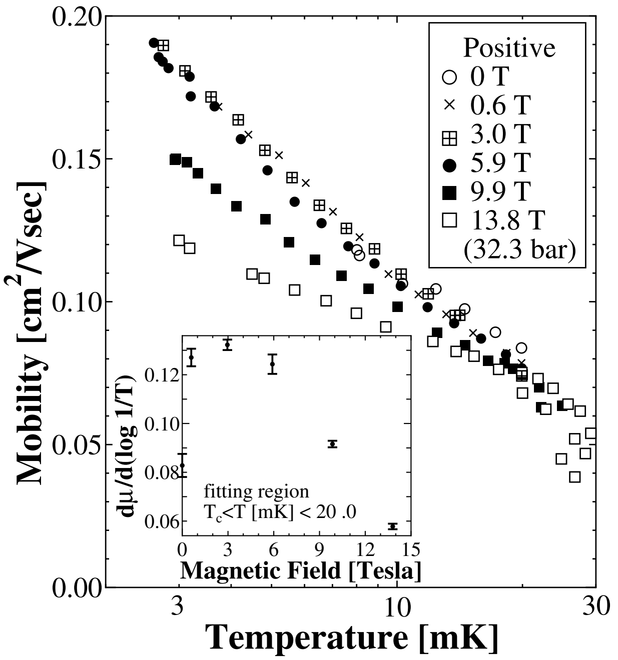

FIG. 3. Positive ion mobility as a function of temperature at 32.3 bars for various magnetic fields. The inset shows the field dependence of the coefficient $A(H)$.

The coefficient $A(H)$ exhibits a broad peak at the field near 7 T for 28.6 bars and 3 T for 32.3 bars, as shown in each inset. This fact indicates that there exists an exchange magnetic scattering as was pointed out by Èdel'shteĭn, but it is not a main cause of the logarithmic temperature dependence.

To get a more accurate magnetic-field effect, the mobility was measured at constant temperatures by changing the magnetic field step by step. Figure 4 gives a normalized field dependence at 28.6 bars under various temperatures. At $T = 20$ mK, the mobility slightly

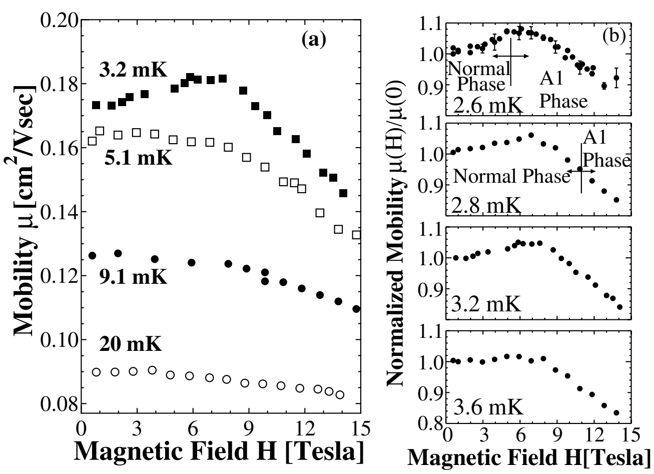

FIG. 4. Magnetic-field dependence of the positive ion mobility at 28.6 bars for various temperatures. Vertical axis is normalized at 0.6 T. (a) For wider temperature range; (b) for temperature around superfluid transition.

decreases with the applied magnetic field. By decreasing temperature, it shows a larger decrease in the higher-field region of $H > 7$ T with a *flat* in the low-field side. Finally at $T \leq 3.2$ mK, the field dependence starts to have a broad peak followed by a large decrease, although it is not so clear if there exists a *critical temperature* for the appearance of the peak.

How does the liquid pressure affect the observed field dependence at 3.2 mK? The results are shown in Fig. 5 in addition to those at 20 mK at several pressures. At low pressure of 3 bars, the mobility hardly or very weakly depends on the field at both 20 and 3.2 mK. However, at higher pressures above 15 bars, it exhibits a gradual decrease even at 20 mK. At 3.2 mK, there appears a small broad peak above 20 bars, and it is followed by a large decrease above 25 bars. The field H_P corresponding to the peak depends on the applied liquid pressure $P_{\rm liq}$ in the following form:

$$H_P = 28.26 - 0.7597 P_{\rm liq} . \quad (4)$$

In the lower field region than the peak, there exists a *flat* whose width depends on the pressure. A small dip is also observed at around 10 T at $P_{\rm liq} = 18.6$ bar.

To confirm that the above phenomenon is inherent to the positive ion, the negative ion mobility was measured at 29.3 bars where the ion diameter is more or less the same as that of the positive ion at 28.6 bars. As shown in Fig. 6, no magnetic-field dependence is observed at both 3.2 and 20 mK. Thus the above-mentioned field dependence is peculiar to the positive ion, and hence is probably due to the magnetic interaction between the localized spins on the ion surface and the ^{3}He quasiparticles.

What is a mechanism of the anomalous magnetic-field dependence of the positive ion mobility? First of all, it is difficult to explain the behavior based on the bulk liquid ^{3}He properties in a magnetic field. For example, the variation of the Fermi momentum is negligible even at 15 T because of Fermi degeneracy. Although the large Zeeman splitting of the Fermi sphere compared with the thermal energy may cause a forbidden spin flip scattering of the ^{3}He quasiparticles, the effect does not seem to be serious, judging from no anomalous field dependence at low pressures. The other possible origin could be the localized spins (solid ^{3}He) on the snowball, which are supposed to be on the melting curve, and the magnetic properties change drastically with the magnetic field at mK temperatures. However, it is not obvious that the produced snowball is in thermal equilibrium with liquid. A similar discussion has been made by Yu [14] *et al.* for the spin transport in a rapid Pomeranchuk cooling process under high magnetic fields, where the spin relaxation is determined by the spin diffusion from solid to the sample cell wall. In the present case, each ion has only a few layers of atoms (totally 100 atoms or so), much smaller numbers than in the Pomeranchuk case, and the localized spins on the snowball can be easily polarized even at 15 T.

Now we estimate the magnetization of snowball based on the experimental results for the ^{3}He melting pressure at high magnetic fields down to 1 mK [15]. An increase of the magnetization in the bulk solid ^{3}He causes the depression of p_m under magnetic fields, leading to an increase of the ion diameter (R^+) according to Eq. (1). Hence a classical cross section, $\sigma_H = \pi R^{+2}$, is a simple increasing function with the magnetic field. For simplicity, let us neglect the surface tension for a while, $s = 0$, where R^+ is most seriously affected by the magnetic field. At constant temperature, Eq. (2) is also simplified as follows:

$$\mu(H) \propto \frac{1}{\sigma_H}\left(1 + \frac{k_1}{\sigma_H}\log\frac{k_2\sigma_H}{T}\right)_T \sim \frac{1}{\sigma_H}\left(1 + \frac{\zeta_H}{\sigma_H}\right). \quad (5)$$

Here, k_1, k_2 are nearly constant. The logarithmic term in the bracket and therefore ζ_H is assumed constant because of a small change of σ_H over the entire field region. The calculation gives $\mu(H)/\mu(0) \sim 0.93$ at 28.6 bar, 3.2 mK,

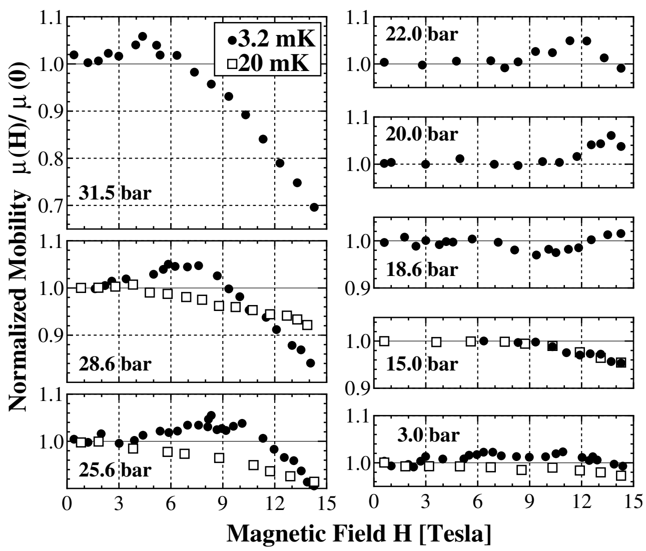

FIG. 5. Magnetic-field dependence of the positive ion mobility at 3.2 mK under various pressures. Each vertical axis is normalized at 0.6 T.

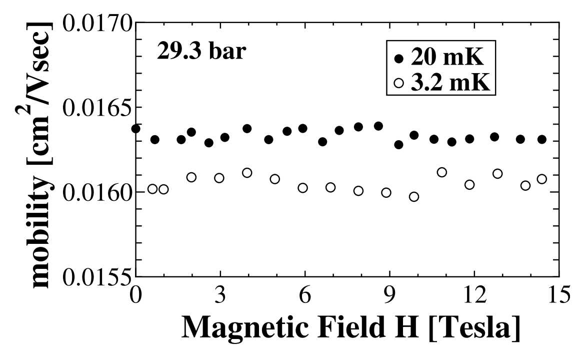

FIG. 6. Magnetic-field dependence of the negative ion mobility for $P = 29.3$ bars at $T = 3.2$ and 20 mK.

and 15 T, which is too small to explain the observed effect. The nonzero constant surface tension makes the discrepancy worse. A complicated field dependence of the surface tension may reproduce the observed field dependence of the mobility, although there is no theoretical discussion.

Anyway, a simple depression of the melting pressure, which reflects a bulk solid ^{3}He magnetization on the melting curve, is not large enough to explain the observed field dependence. However, there should be various competing ferro and antiferromagnetic multiple-spin-exchange interactions J_{MSE} among the localized spins on the snowball, just as in the bulk or two-dimensional solid ^{3}He [16]. Moreover, to explain a pressure effect on the field dependence of the mobility, it is essential to take account of the quasiparticle mediated interaction J_{med}, so-called RKKY-type one,

$$J_{\mathrm{med}} \propto -\frac{J_0^2}{\epsilon_F}\left[\frac{X\cos X - \sin X}{X^4}\right], \tag{6}$$

$$X = 2k_F r\,, \tag{7}$$

where k_F, ϵ_F, J_0, and r are the Fermi momentum, the Fermi energy, the interaction between the localized spin and the quasiparticle, and a distance between two localized spins, respectively. k_F, ϵ_F, and J_0 are pressure dependent. Hence, the snowball magnetization should depend on liquid pressure through $J_{\mathrm{med}}(r; P_{\mathrm{liq}})$, but its estimation is very difficult at present because of no clear knowledge of the surface structure. Nevertheless, it is obvious that magnetization grows as the magnetic field increases. Existence of a large snowball magnetization should suppress a spin-flip exchange scattering of the quasiparticles as mentioned in the beginning, causing the increase of the mobility, μ_{inc}. At the same time, it induces a RKKY type local spin oscillation of quasiparticles in the vicinity of the snowball. Consequently, the snowball forms a complex of a polarized solid and quasiparticles (“spin polaron”), leading the enhancement of the scattering cross section and then the decrease of mobility, μ_{dec}. A delicate competition between these two terms, μ_{inc} and μ_{dec}, seems to cause a complicated field dependence of the mobility. Unfortunately, there is no theoretical and quantitative calculation at present, so we just try to speculate qualitatively how the snowball magnetization should be to explain the obtained results. Judging from a rather abrupt increase in the field dependence of the mobility, the snowball might have a unique canted antiferromagnetic ordered phase (CNAF) in the high magnetic field, similar to a peculiar one of bcc solid ^{3}He under the high magnetic field [15]. The transition field from a para to a large magnetization phase could be sensitive to the liquid pressure through J_{med}. Moreover, the large decrease of the field dependence of the mobility at high pressures reminds us of a spin fluctuation effect, which is a specific character of the liquid ^{3}He. It should enhance the spin polarization in the vicinity of the snowball, as was pointed out for the conduction electron in dilute magnetic alloys [17] and for a two-dimensional solid ^{3}He system [18,19]. The observed results are too complicated for us to clarify the whole mechanism. Further systematic measurements should be made over the wide range of parameters, and a new theoretical treatment is eagerly desired to understand the scattering of the snowball under high magnetic fields.

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