# Pressure and Temperature Dependence of Positive Ion Mobility in Superfluid $^3$He-$A_1$ and $A_2$

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**Abstract**

The positive ion mobility ($\mu$) in superfluid $^3$He has been measured as a function of temperature under high magnetic fields up to 15 T at several pressures. It exhbits a steep increase at both transition temperatures $T_{A_1}$ and $T_{A_2}$. The inversed mobility normalized at $T_{A_1}$ ( $=\mu(T_{A_1})/\mu(\mathrm{T})$ ) is found to follow a field independent universal curve as a function of $T/T_{A_1}$ in the $A_1$ phase and as a function of $T/T_c$ in the $A_2$ phase. Here $T_c$ is a zero field transition temperature. The observed behavior and the effect of the pressure is discussed in so called "a two-fluid model".

*Key words:* superfluid $^3$He; ion mobility

Ion mobility measurements are useful to get information not only on the motion of a heavy charged particle itself but also on the exctitation in the Fermi liquid [1]. A positive ion forms a so called "snowball" which is a cluster of $^3$He atoms. The mass is relatively smaller than that of the negative ion and the ion recoil is more important. Consequently the positive ion mobility in the normal phase is known to show a characteristic temperature dependence with $log(1/T)$ [2]. In superfluid phase the measurements have so far been made only in the low magnetic field region [2,3]. In this report we present temperature dependence of the mobility in the superfluid phase under various magnetic fields up to 15 Tesla.

The experimental setup is the same as that in our previous work [4,5]. The mobility is determined from a linear region in the velocity ($v$) vs. the driving electric field ($E$) relation. In the superfluid phase, the mobility rises rapidly and therefore $E$ should be so low that the ion velocity does not exceed the critical velocity. At temperatures below 1 mK, $E$ becomes comparable to a space charge electric field of the ion itself, and it is difficult to obtain a good accuracy in the present method because of a broadening of the ion current signal.

The temperature dependence of the positive ion mobility was measured at high pressures of $P = 20$, 28.8 and 32.3 bar for various magnetic fields. A typical result at 28.8 bar is given in Fig. 1(a). Contrary to a weak logarithmic increase in the normal phase, the mobility rises rapidly in the superfluid phase. Two transition temperatures ( $T_{A_1}$ and $T_{A_2}$ ) are clearly seen as an abrupt change of the slope in the obtained temperature dependence. The rapid rise of the mobility in the superfluid phase is attributable to the formation of the energy gap, which causes the reduction in the quasiparticle excitations as well as the modification of the transport cross section. To compare the obtained results with a theoretical calculation, it is convenient to use the inversed mobility which is shown in Fig. 1(b) at 28.8 bars under various magnetic fields.

The normalized inversed mobility in the $A_2$ phase does not depend on the applied magnetic field within an experimental accuracy, and is given by a universal function. In the $A_2$ phase, the normal fraction is independent of the magnetic field, and therefore this fact

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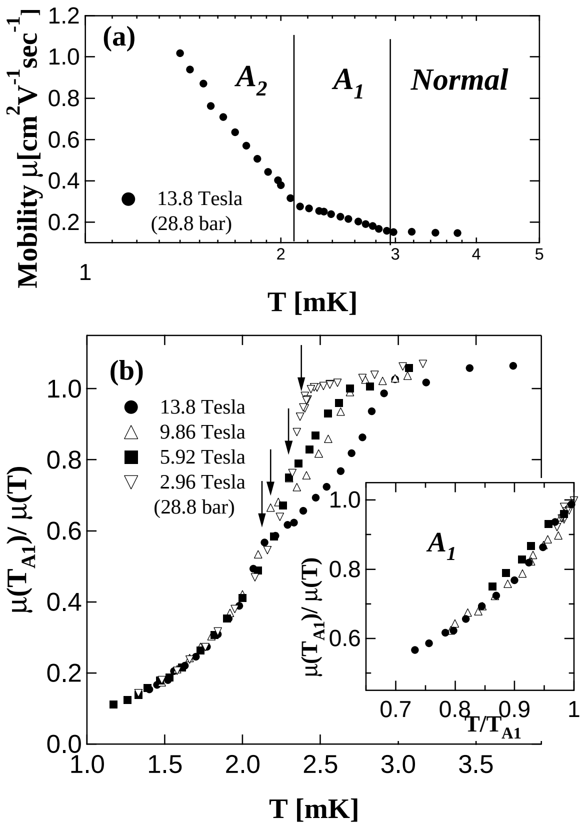


Fig. 1. (a) The positive ion mobility at 28.8 bar and 13.8 Tesla across the superfluid transition. (b) The normalized inversed mobility at 28.8 bar as a function of temperature. The arrows correspond to the transition temperature $T_{A_2}$ for each field. The inset is plotted as a function of $T/T_{A_1}$.

suggests that the transport cross section has the same magnetic field dependence in the temperature region across the superfluid transition. On the other hand, in the $A_1$ phase, the behavior is quite different, because the transition temperature ($T_{A_1}$) depends on the field. If the normalized inversed mobility is plotted as a function of $T/T_{A_1}$, the data for various magnetic fields lie on the universal curve approaching the value around 0.5 as shown in the inset of Fig. 1(b). This is explained by " a two-fluid model ". In the $A_1$ phase, only the up-spins ( the quantization axis is defined anti-parallel to the magnetic field ) condense into the superfluid phase and the down-spins still behave as a normal Fermi liquid. In this model, the normalized inversed mobility is given approximately as follows,

$$\frac{\mu(T_{A_1})}{\mu(T)} = \frac{1}{2}\frac{\mu(T_{A_1})}{\mu_\uparrow(T)} + \frac{1}{2}\frac{\mu(T_{A_1})}{\mu_\downarrow(T)} \sim \frac{1}{2}\frac{\mu(T_{A_1})}{\mu_\uparrow(T)} + 0.5. \quad (1)$$

Here $\mu_\uparrow(T)$ ($\mu_\downarrow(T)$) is the contribution from the up (down) spins. A small temperature dependence of the normal component $\mu_\downarrow(T)$ and the liquid $^3$He nuclear polarization are neglected.

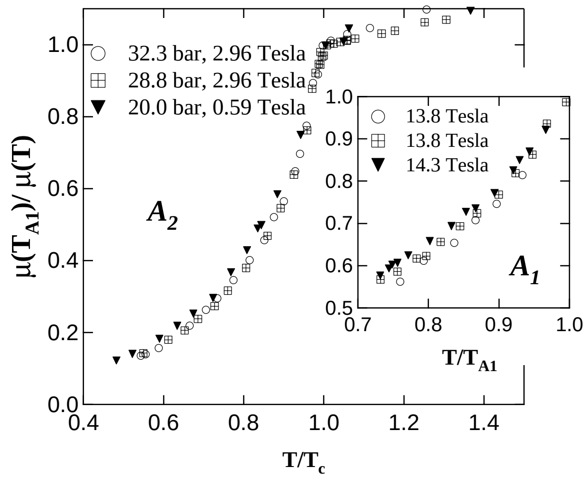


Fig. 2. The normalized inversed mobility at various pressures in the suprefluid $A_2$ phase is plotted as a function of $T/T_c$. The inset is plotted as a function of $T/T_{A_1}$ in the superfluid $A_1$ phase.

In order to see the effect of the pressure, the normalized inversed mobility is plotted in Fig. 2 for three pressures as a function of $T/T_c$ or $T/T_{A_1}$. In both the $A_1$ and $A_2$ phase the effect of the pressure seems to be small even if it exists. A similar result has already been obtained for the negative ion mobility in the superfluid A phase [6]. The strong coupling effect, which is expected for the liquid $^3$He at high pressures, is not dicisive on the ion mobility.

In summary, the normalized inversed mobility as a function of $T/T_{A_1}$ in the $A_1$ phase and as a function of $T/T_c$ in the $A_2$ phase hardly depends on the applied magnetic fields and the pressure of the liquid.

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