Nonlinear transport of ions trapped below the free surface of superfluid ^{3}He - B

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Abstract

We have studied the driving-field dependent transport of ions trapped below the free surface of superfluid ^{3}He-B. For small driving-fields, the velocity of ions is a linear function of the field. At high electric fields, the velocity is observed to be a nonlinear function of the field. The onset velocity of the nonlinearity is consistent in magnitude with the Landau critical velocity. This implies that the nonlinear behavior is caused by the pair-breaking effect of the moving ions.

Key words: Superfluid ^{3}He; Free surface; Ions; Nonlinear transport

The presence of a boundary, such as the solid wall or the free surface, is expected to affect greatly the properties of superfluid ^{3}He near the boundary. Since the free surface of superfluid ^{3}He has no impurity and is smooth, it is an ideal boundary of the p-wave superfluid. At the free surface the order parameter is distorted due to the pair breaking. This effect may occur within a layer of some coherence length. For the p-wave pairing state and the specular reflection of the ^{3}He quasi-particle at the surface, the spatial variation of the order parameter becomes anisotropic[1]. Because of the lack of sensitive probes to study the surface properties, the suppression of the order parameter was not observed directly. The ions have proved to be useful probes of superfluid ^{3}He. Such ions can be trapped below the surface by a combination of an image potential and a uniform external electric field. The trapping depth z_0 is typically on the order of the coherence length. Therefore, the transport phenomena of ions trapped below the surface of superfluid ^{3}He may give information about the surface properties. In the experiment reported here we have studied the motion of ions trapped below the free surface of superfluid ^{3}He-B.

The apparatus and methods are the same as the one in the previous mobility measurement[2]. We have prepared the sample cell which contains sintered silver powder for good thermal contact. The free surface is located between two circular electrodes in the sample cell. The distance between the upper and lower electrodes is 3 mm and the liquid level is 1.7 mm. The upper electrode is a concentric copper electrode pair which is known as the Corbino disk. The ions are produced by applying high voltage to the sharp tungsten tips which are placed below the lower electrode and are trapped by applying a dc voltage to the lower electrode. Horizontal confinement of a circular sheet of ions is achieved using a suitable ring electrode.

In order to observe the response of ions trapped below the surface, we have employed a capacitive coupling method. Applying an electrostatic potential to the Corbino inner electrode, a charge distribution of ions becomes inhomogeneous. By releasing the potential, the motion of ions is induced so as to recover a uniform distribution and hence the current flows. In this case, the input voltage to the inner electrode is a *step* potential and the driving-field for the motion of ions becomes large as the step height increases. The response current in the radial direction flows into the outer elec-

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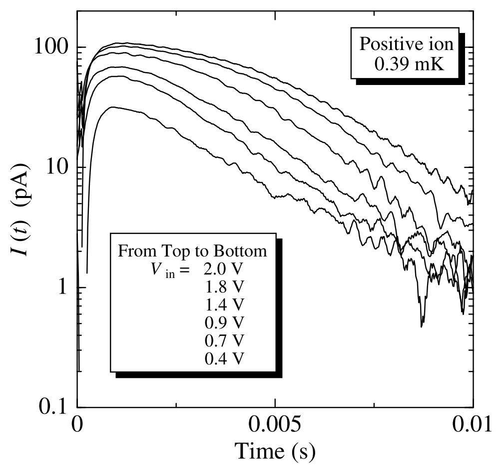

Fig. 1. The output current $I(t)$ induced by the motion of ions for various input step voltage at 0.39 mK.

trode via the capacitive coupling between the sheet of ions and the Corbino disk. The current signal is passed into a current preamplifier, the output of which is averaged over 32 sweeps by a digital storage oscilloscope. The observed current signal $I(t)$ decays exponentially with a time constant which is inversely proportional to the mobility of ions[2]. The cell is cooled down to 0.4 mK by copper nuclear demagnetization. In this experiment the data are taken at the ion density $n_0 = 7.7 \times 10^{11}\mathrm{m}^{-2}$ and the depth of ions $z_0 = 320$ Å.

In Fig. 1, we show $I(t)$ as a function of time for various input step voltage at 0.39 mK. At low step height, $I(t)$ decays exponentially from a peak. When the step height is large, $I(t)$ is truncated. At first, $I(t)$ decays gradually and after a certain time, depending on the step height, $I(t)$ starts to decay exponentially. The time constant of exponential decay for all step voltage are the same within an experimental error of about 15 %.

We estimate the maximum velocity of ions $v = I_{\mathrm{MAX}}/\pi r_{\mathrm{i}} n_0 e$, where I_{MAX} is the peak value of $I(t)$ and r_{i} is the radius of the Corbino inner electrode. Fig. 2 shows the maximum velocity of ions as a function of input voltage. For small driving-fields, the velocity of ions is a linear function of the field. At high electric fields, the velocity is observed to be a nonlinear function of the field. The onset velocity of the nonlinearity v_{c} is about 1.7 cm/s. The Landau critical velocity for pair-breaking v_{L} is given by Δ/p_{F}, where Δ is the superfluid energy gap and p_{F} is the Fermi momentum. At 0.39 mK, the critical velocity v_{L} is 2.6 cm/s. This critical velocity is consistent in magnitude with the onset velocity v_{c}. Therefore, the nonlinear behavior shown in Fig. 2 is caused by the pair-breaking effect of the moving ions. This nonlinear transport of ions have been observed in the superfluid phase of ^{3}He[3,4].

We can understand the behavior of $I(t)$ shown in

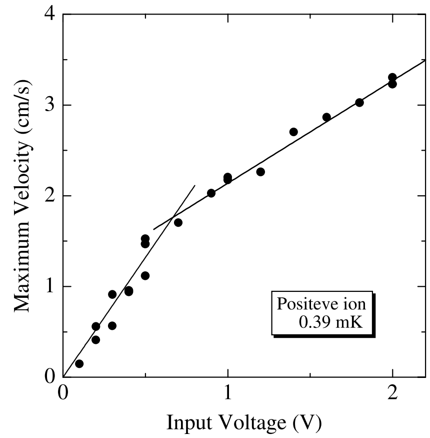

Fig. 2. The maximum velocity as a function of input voltage.

Fig. 1 as follows. When the velocity of ions exceeds the Landau critical velocity, the moving ion breaks the Cooper pairs. This effect causes extra resistance for the motion of ions and $I(t)$ decays gradually. After a certain time, the velocity of ions decreases below the critical velocity and the superfluidity around the ions recovers. Then $I(t)$ decays exponentially with the time constant determined by the mobility of ion in linear regime.

In conclusion, we have observed the transient response of ions trapped below the free surface of superfluid ^{3}He-B. In this experiment, the driving-field dependence of ionic velocity shows nonlinearity. The observed onset velocity v_{c} is smaller than the Landau critical velocity. This may imply the suppression of the energy gap near the free surface. If this is correct, we could study the spatial variation of the energy gap near the surface using the ions trapped below the surface. Experiments to observe the trapping depth dependence of the critical velocity of ions trapped below the free surface are currently in progress. Also reliable theories should exist so that both the mobility and the critical velocity of ions trapped below the surface can be used to make a direct mapping of the spatial variation of the energy gap.

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