Edge Magnetoplasma-like Resonance in Two-Dimensional Electrons on the Surface of ^{3}He-^{4}He Liquid Mixtures

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Surface state electrons on liquid helium are a very unique two-dimensional system. The electrons have much lower densities and much higher mobility than those which have been obtained in semiconductor interfaces. The system is non-degenerate due to its low areal density, and undergoes the phase transition to the Wigner crystal. In the crystal state, the electrons are inevitably accompanied by periodic surface deformation. Such a state is referred to as the coupled plasmon-ripplon state, and this determines the unique in-plane dynamics of the Wigner crystal.

There are two stable isotopes in helium, namely ^{4}He and ^{3}He. The properties of liquid ^{4}He are quite different from those of ^{3}He due to quantum effects. At temperatures 10 mK < T < 1 K, liquid ^{4}He is a viscosity-free superfluid, whereas liquid ^{3}He shows very large viscosity proportional to T^{-2}. The surface tension, which also reflects dynamic properties of liquid surface, is 2.4 times smaller for liquid ^{3}He than for ^{4}He. One may therefore expect strong effects of the difference in surface properties of the two liquid isotopes, on the electron dynamics.

The transport properties of the surface electrons have been studied both on liquid ^{4}He and on ^{3}He. The Wigner crystal both on ^{4}He and ^{3}He shows a strongly nonlinear transport under a perpendicular magnetic field [1] [2]. However, on liquid ^{3}He, the nonlinearity is observed even in the absence of magnetic field [3]. Furthermore, the magnetoconductivity σ_{xx} is *anomalous* on liquid ^{4}He, i.e. $\sigma_{xx} \propto B^{-1}$, while on ^{3}He it obeys the classical Drude law, $\sigma_{xx} \propto B^{-2}$ [2](B : magnetic field). These interesting differences suggest that the underlying liquid plays a crucial role on the transport properties of the surface electrons.

^{3}He-^{4}He liquid mixtures offer us an intriguing "third" cryogenic surface for electrons. At the ^{3}He concentration n_3 < 6.4 %, there exist ^{3}He bound states on the surface, and the "surface ^{3}He" forms a two-dimensional Fermi fluid below 200 mK [4] . With increasing the ^{3}He concentration from 0 to 6.4 %, the surface tension decreases monotonically, as more ^{3}He atoms accumulate at the surface. At n_3 > 6.4 %, the mixture undergoes the two phase separation, and the nearly pure ^{3}He phase forms the free surface due to gravity. In this sense, the mixture surfaces may "link" together the properties of both pure liquid ^{4}He and ^{3}He surfaces. Studying the electrons on the mixture surface will shed light on the role of underlying liquid on the dynamical properties of the surface electrons.

In the present work, we have tried to measure the conductivity of the surface electrons on mixtures for various ^{3}He concentrations. However, as is shown below, we have observed quite unexpected *resonance* phenomena in the electrons on the mixture surfaces.

We have employed the standard capacitive method for the conductivity measurement, with a Corbino ring electrode (outer diameter 30 mm). The helium level is set 1.0 mm above the electrode. A small ac-voltage is applied to the inner electrode and the induced current in the outer electrode is monitored as a voltage on a capacitor connected in series. In the measurement reported here, we have swepted the frequency from 1 kHz to 300 kHz under a constant magnetic field perpendicular to the electron sheet. The concentration of ^{3}He is ranged from 0 % (natural ^{4}He) to 21.0 %, and the electron system is cooled down to 30 mK.

We have not been able to measure the conductivity of the surface electrons, because of unexpected resonance phenomena. We have observed the resonances only in a perpendicular magnetic field. Figure 1 shows the behavior of the resonances. The resonances are observed only when the ^{3}He concentration is from 0.055 % to 6.49 % .

The most intriguing property is the magnetic-field dependence of the resonance. In Fig. 2, we plot the resonance frequency f_c as a function of the field B. We have found that the resonance frequency is *inversely proportional* to B.

Under a constant magnetic field, f_c increases in proportion to the surface electron density. On the other hand, f_c is quite independent of the ^{3}He concentration when the electron density is constant. Furthermore, f_c is constant from 30 mK to 500 mK, whereas the peak amplitude (linewidth) starts to decrease (increase) at about 300 mK with increasing temperature. Above 500mK, the resonances are so broadened that becoming undetectable.

The inverse proportionality of the resonance frequency to the magnetic field is quite similar to the characteristics of “edge magnetoplasmons (EMPs)” or “inter-edge magnetoplasmons (IEMPs)” observed in many two-dimensional electron systems [5]. However, the typical frequencies of the EMPs or IEMPs which have been observed in the electrons on liquid ^{4}He are much (2–3 orders of magnitude) higher than that we have observed. Since the EMPs are charge-density fluctuations that propagate along the edge due to the Hall effect, they can never be detected when the bottom electrode has circular geometry, as in the present setup.

The IEMPs propagate the boundary between two regions with different electron densities, and the IEMP frequency is proportional to the electron density difference between two regions, δn. If such two regions exist on our mixture surfaces, and the boundary of the two regions lie *across the gap* of the Corbino electrodes, the IEMPs can be detected. Assuming so, δn is estimated to be of the order of 10^5 cm^{-2} from the f_c data, although there is no other evidences that such an inhomogeneity exists constantly on the surface of the mixtures only when the ^{3}He concentration is below 6.49 %. Theoretical studies for the possible origin of the electron inhomogeneity are obviously needed.

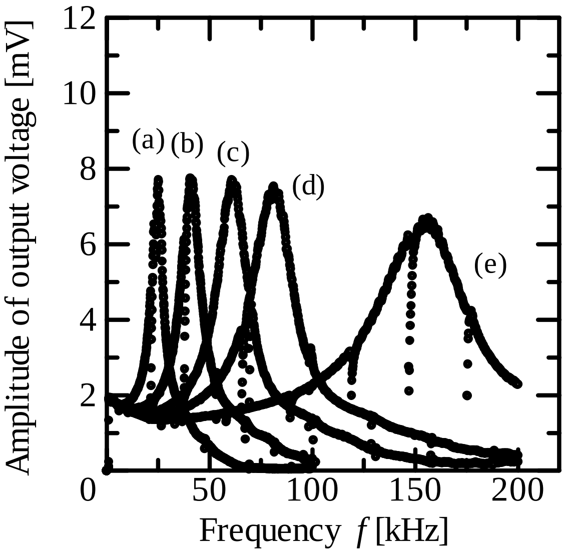

Fig.1. Amplitude of the output voltage as a function of frequency for the several magnetic fields B; (a) 730, (b) 438, (c) 292, (d) 219, (c) 109 G. The ^{3}He concentration n_3=0.68 %, areal electron density n_s=1.05×10^8 cm^{-2}. T=30 mK.

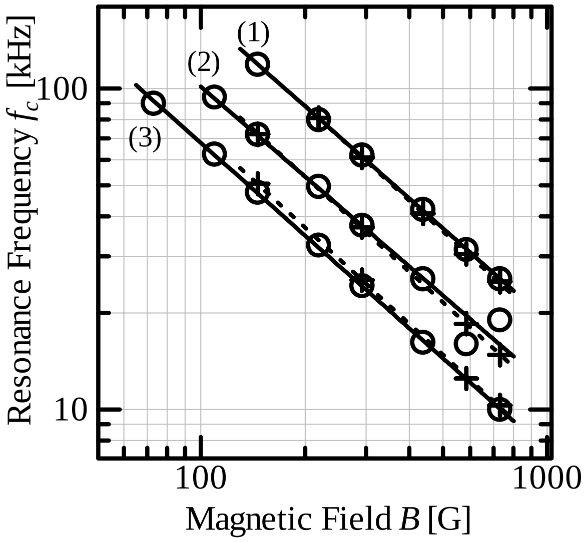

Fig.2. Resonance frequency f_c as a function of magnetic field B for ^{3}He concentrations n_3 = 0.68 % (○) and 6.48 % (+), and n_s= 1.05×10^8 (1), 0.53×10^8 (2) and 0.26×10^8 cm^{-2} (3), at T = 30 mK. The solid and dotted straight lines show the least-square fits to the data of n_3 = 0.68 %, and 6.48 %, respectively.

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[5] See for example, R. W. van der Heijden and P. K. H. Sommerfeld, in *Two-Dimensional Electron Systems*, edited by E. Y. Andrei, Kluwer Academic Publishing , Dordrecht, 157-174 (1997).