Transport property of surface state electrons on the rotating superfluid ^{4}He

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Abstract

A transport property of surface state electrons (SSE) on the rotating superfluid ^{4}He has been investigated in the angular velocity range $\Omega \leq 1.0$ rad/sec. A free surface is deformed by the periodic hollows at the quantized vortex lattice sites. We observed that it acts as one of the scattering factors in the liquid phase, and as the pinning center in the Wigner solid phase.

Key words: Surface state electrons, Superfluid, Vortex, Wigner solid

The most prominent phenomenon in surface state electron (SSE) system is a transition to the Wigner solid (WS). The localization of the electrons deforms the surface. The WS couple to the deformation, whose wave vectors equal the reciprocal lattice vectors of the WS to form the CPR state. Shirahama *et al.* investigated a nonlinear response of ac conductivity by applying the ac input voltage parallel to the surface[2]. It was interpreted as the transition between the CPR state and the collective sliding state in which the WS decouples from the surface, caused by the larger driving force. The dynamics of WS on the liquid surface has been offering an unique example for study of nonlinear phenomena. The superfluid ^{4}He in the rotating container has the array of the quantized vortices. The surface profile at the vortex sites is modified due to the velocity distribution and surface tension of the liquid. All the hollows induced by the vortices have a well-defined profile[4]: a depth 70Å is comparable to the expected distance of SSE from the surface. Especially the density of vortices is controllable by the rotation velocity. In this paper we report the transport property of SSE on the rotating superfluid ^{4}He and discuss the effects induced by the vortices.

The experiment was carried out in the angular velocity range $\Omega \leq 1.0$rad/sec and the temperature(T) range from 0.05K to 1.2K, by using a rotating ^{3}He-^{4}He dilution refrigerator mounted on a turntable. A cylindrical cell with radius R =25mm contains a concentric-ring electrode pair (the Corbino disk) which is submerged 1.7mm beneath the liquid surface. A static magnetic field (B) is applied perpendicular to the liquid surface. With applying a sinusoidal voltage V_{in} to the inner electrode with frequency 100kHz, the resulting current to the outer electrode is monitored with a biphase lock-in amplifier. In this experimental condition, the density of vortices are approximately $n_v \leq 2 \times 10^3$ cm^{-2}, which is quite lower than the electron density $n_e = 1.2 \times 10^8$cm^{-2}.

Figure 1 shows a T dependence of mobility μ in the range $\Omega \leq 1.0$rad/sec. The mobility on the rotating surface is the more reduced in the higher Ω. The nature of scattering on the static surface ($\Omega = 0$) has been understood experimentally and theoretically that the mobility is dominated mainly by the electron-helium gas scattering in the vapor phase above 0.7K and by the electron-ripplon scattering below 0.7K [3]. In the liq-

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uid phase above T_m, we observed that the ac Corbino conductivity σ_{xx} on the rotating surface is inversely proportional to B^2 when $\mu B \gg 1$. It suggests that the Drude's law is applicable to the SSE on the rotating surface, as well as on the static surface. In order to evaluate the scattering caused by rotation, we estimate the additional scattering rate τ_R^{-1} by $\tau^{-1}(\Omega) - \tau^{-1}(0)$. Here $\tau^{-1}(\Omega)$ is given by $e/m_e\mu(\Omega)$ and m_e is the electron mass. In the T-range from 0.4K to 0.9K, τ_R^{-1} is approximately T-independent, and increases as a function of $\sqrt{\Omega}$ which is inversely proportional to the distance between the vortices d_v. We can roughly estimate the mean-free-path of the SSE due to this scattering factor to be 10^{-4}m, by using the thermal velocity v_e in this T-range. It is comparable to the order of $d_v \approx 10^{-4}$m. These results indicate that the origin of the reduced mobility is the additional scattering at the surface hollows induced by the vortex lines.

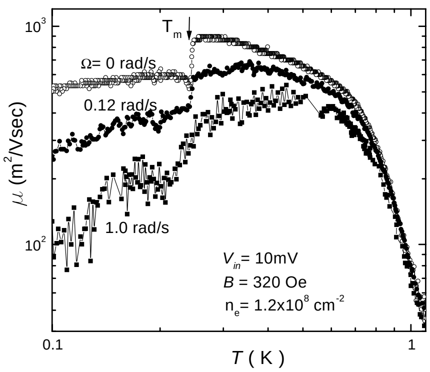

Fig. 1. Mobility of SSE on the rotating ^{4}He surface, together with the data on the static surface.

The abrupt drop of μ occurs at $T_m \approx$0.24K due to a transition to the WS. The observed T_m gives the critical plasma parameter Γ_c to be 140 which coincides with the values in the past works[1]. In the WS phase, the ac Corbino conductivity σ_{xx} strongly depends on the input voltage V_{in} as mentioned above. Figure 2 shows a V_{in} dependence of σ_{xx}^{-1} in Ω =0.15rad/s. Instead of the abrupt jump of σ_{xx}^{-1} with a hysteresis, the broad variation of σ_{xx}^{-1} without hysteresis was observed in the rotating state. Taking into consideration of the surface deformation by vortices, the threshold voltage should have the spatial distribution depending on the distance from the vortex cores. As indicated in the figure, we define the lowest threshold $V_{\rm th}^{\rm L}$ by the occurrence of transition from the CPR state and the highest threshold $V_{\rm th}^{\rm H}$ by the end of the transition. By sweeping T and V_{in}, we obtained the $V_{in} - T$ phase diagram of SSE on the rotating surface, as indicated in the inset of this figure. The intermediate phase between $V_{\rm th}^{\rm L}$ and $V_{\rm th}^{\rm H}$ corresponds to the coexistence of the two phases.

In the case of $\Omega = 0$, Shirahama *et al.* explained by the rigid potential model that the sliding occurs

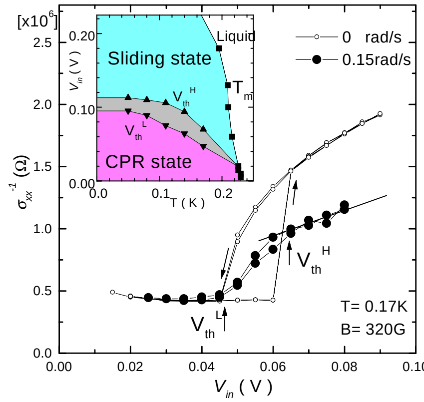

Fig. 2. V_{in}-dependence of σ_{xx}^{-1} in Ω $\approx$0.15rad/s at 170mK. Inset shows the $V_{in} - T$ phase diagram.

when a drag force $F_{\rm d}$ exceeds the restoring force $F_{\rm r}$ determined by the potential energy of the dimple[2]. On the rotating surface the saddle region between the vortices is approximately flat, so that the sliding may occur at the same threshold as in the static state. On the other hand, the WS in the hollows of vortices feels an additional force, which varies by the position in the hollow. It causes the broad transition between the CPR phase and the sliding phase. On the other hand, we can understand the transition from the sliding to the CPR phase as the nucleation of the CPR state around the pinning center.

In summary, we observed that the surface hollows by vortices act as one of the scattering factors in the liquid phase, and as the pinning center for the Wigner solid phase.

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