Anomalous Quasiparticle Reflection from the Surface of a ^{3}He-^{4}He Dilute Solution

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A free surface of a dilute ^{3}He-^{4}He liquid mixture is a unique system where two Fermi liquids with distinct dimensions coexist: a three-dimensional (3D) ^{3}He Fermi liquid in the bulk and a two-dimensional (2D) ^{3}He Fermi liquid at the surface. To investigate a novel effect generated by the interaction between the two Fermi liquids, the mobility of a Wigner crystal of electrons formed on the free surface of the mixture is studied. An anomalous enhancement of the mobility, compared with the case where the 3D and 2D systems do not interact with each other, is observed. The enhancement is explained by the nontrivial reflection of 3D quasiparticles from the surface covered with the 2D ^{3}He system.

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Dimensionality is one of the defining characteristics that govern physical properties of systems. Although a lot of experimental and theoretical investigations have clarified static and dynamic properties of quantum many-body problems, the studies so far have been mostly limited to the cases with a well-defined single dimension. Mixed-dimensional systems, in which two quantum many-body systems with distinct dimensions coexist, are expected to exhibit nontrivial dynamics that never occur in either subsystem by itself. Such systems are found in various fields, for example, electrons in noble metals [1] and unconventional materials [2,3] (electrons inside and on the surface) and ultracold atoms [4–6], but in many cases, the two subsystems are not well understood or well distinguished.

The free surface of a dilute ^{3}He-^{4}He mixture [7] is unique in this regard, since well-characterized two-dimensional (2D) and three-dimensional (3D) fermionic systems of identical particles, i.e., ^{3}He, coexist [8,9]. When a ^{3}He quasiparticle (QP) in the 3D system approaches the 2D ^{3}He layer formed at the free surface and interacts with it, the interaction is expected to affect the reflection process and surface dynamics. In this Letter, we demonstrate that the novel QP reflection from the surface manifests itself as an anomalous enhancement of the mobility of a Wigner crystal (WC) of electrons trapped on the surface of the mixture.

We consider the mixture with a free surface. The 3D ^{3}He system is formed in the bulk; ^{3}He atoms, which are soluble in liquid ^{4}He at concentrations of ^{3}He x_3 up to ~6.7% [10], behave as a dilute 3D Fermi liquid in the background superfluid ^{4}He [7]. At the surface, ^{3}He atoms are bound to the surface to form a dense 2D layer [Fig. 1(a)] [11,12], showing the 2D Fermi liquid behavior [8,9]. With increasing x_3, the thickness of the 2D ^{3}He layer increases in the range of several atomic layers except at $x_3 \sim 0$ and ~6.7% [Fig. 1(b)] [8,9,13], while the mean atomic distance is comparable to that of bulk pure ^{3}He and is almost unchanged with x_3. Therefore, the Fermi temperature T_F^{2D} is high (~2 K) without significant variation with x_3 [Fig. 1(c)]. This is in contrast to the low Fermi temperature of the 3D ^{3}He T_F^{3D} (< 0.4 K) owing to the lower density in the mixture. Just as the 2D and 3D ^{3}He systems have been investigated as the prototypical Landau Fermi liquid in each dimension [7–9] owing to their cleanliness, the mixed-dimensional system presented in this work will serve as an ideal model system to study the interplay between the two subsystems.

Electrons on a free surface of liquid helium [27,28] are often used as a sensitive microscopic probe for investigating fundamental properties of elementary excitations in quantum fluids. The electrons undergo a transition to a WC at a certain low temperature, where the crystallization generates a commensurate deformation of the helium surface called a dimple lattice (DL) [Fig. 1(a)] [27,28]. The emergence of the DL strengthens the coupling of the WC to the liquid, making the transport of the WC sensitive to properties of elementary excitations in the liquid [29–32]. This feature has been utilized to reveal, particularly, the specular nature of QP reflection from the surface in normal and superfluid ^{3}He [30–32]. In this study, we similarly measure the mobility of a WC over the ^{3}He-^{4}He liquid mixture down to ~10 mK over a wide range of x_3 (up to 6.1%) to investigate the nature of QP dynamics near the surface. (So far, there has been an experimental study of WC mobility only at $x_3 = 0.5\%$ [33].)

The mobility is measured with the Sommer-Tanner technique [34] in the Corbino geometry at a vertical magnetic field B of 380–1100 G. The Corbino disk consists of two concentric electrodes 18.0 and 11.9 mm in diameter and is attached to the ceiling of the sample cell. A bottom circular electrode, which is located 3.0 mm below the Corbino disk, is used to provide a vertical pressing electric field $E_\perp$. The free surface is set at a midway between the

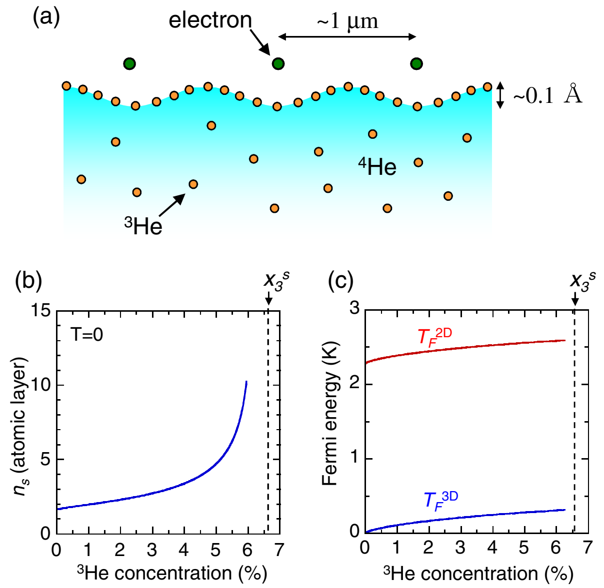

FIG. 1. (a) ^{3}He-^{4}He mixture and WC formed on a free surface. A 2D ^{3}He layer is formed at the free surface of the mixture as a result of the larger zero-point motion of ^{3}He than that of ^{4}He [11,12]. Electrons are trapped about 10 nm above the surface. At low temperatures, the electrons form a WC dressed with a DL. The lattice constant of the WC is $a = 0.93\ \mu$m for our electron density of $n_e \sim 1.35 \times 10^{12}$ m^{-2}, while the depth of the DL is only $\delta \sim 0.1$ Å. (b) Areal density of the 2D ^{3}He layer n_s (in the unit of atomic layers with monolayer density 6.4×10^{18} m^{-2}) as a function of x_3 at $T = 0$. This graph is based on the analysis by Guo *et al.* of their surface tension data [8] (see Supplemental Material for details [14]). The surface is covered by a monolayer of ^{3}He even at a very small x_3 (~200 ppb). n_s diverges approaching the saturation concentration ($x_3^s = 6.7\%$). (c) T_F^{2D} and T_F^{3D} as a function of x_3 (see Supplemental Material [14]).

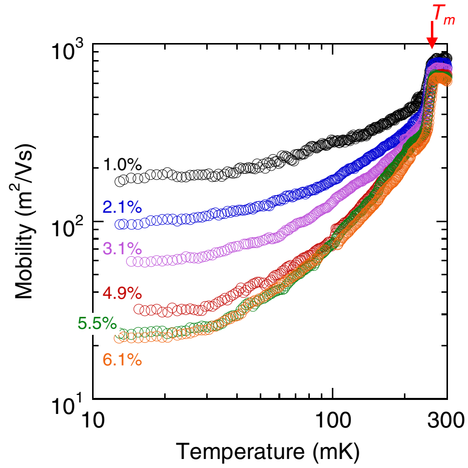

FIG. 2. Mobility of the WC as a function of T for different ^{3}He concentrations. T_m indicates the transition temperature to the WC phase.

Corbino disk and the bottom electrode, and electrons are deposited on it. The longitudinal conductivity σ_{xx} is measured by applying an ac voltage V_{ac} of frequency $f =$ 214 kHz to the inner electrode of the Corbino disk and recording the induced current I_{out} on the outer electrode. A small V_{ac} ($= 1$ mV$_{\mathrm{rms}}$) is used to avoid nonlinear effects. The mobility μ is deduced from the Drude relation $\sigma_{xx} = en_e\mu/[1 + (\mu B)^2]$, where n_e is the electron density. The mobility at each x_3 is measured at a certain value of n_e and $E_\perp$ in the range of $n_e = (1.33\text{–}1.40) \times 10^{12}$ m^{-2} and $E_\perp = (2.02\text{–}2.08) \times 10^4$ V/m. We use a rather high $E_\perp$ to avoid the WC from decoupling from the DL easily by the ac drive. The magnitudes of the mobility are calibrated by multiplying by a factor of about unity (0.94–1.14) so that the mobility agrees with the theoretical mobility of highly correlated electrons in the ripplon scattering regime [28] above T_m (see Supplemental Material [14]). The mixture is cooled to ~10 mK with a heat exchanger made of packed silver powder. The atomic concentration of ^{3}He x_3 is determined from the amounts of ^{3}He and ^{4}He introduced into the cell. We also monitor x_3 via the dielectric constant of the mixture using a parallel plate capacitor immersed in the liquid.

Figure 2 shows the mobility μ as a function of temperature T at different x_3. With decreasing T, μ exhibits a sudden drop at the transition temperature to the WC, $T_m \sim 260$ mK, due to the formation of a DL, followed by a further reduction at lower T. In the WC phase, two features are found: The mobility at each x_3 asymptotically approaches a constant value below several tens of mK, and μ is significantly suppressed when x_3 is increased.

Right below T_m, μ is limited by the viscosity of the bulk mixture η. In this regime, μ is determined by the viscous drag force acting on the DL moving together with the WC [28,32,35]. We evaluate the theoretical mobility at our measurement frequency (214 kHz) using experimentally known values of viscosity η [36–38], density ρ [39], and surface tension α of the mixture [8] (for the derivation of the theoretical mobility at a finite frequency, see Supplemental Material [14]; in the theoretical mobility, the contribution of the electron scattering by thermally excited ripplons, which is not negligible at a high mobility, is also included). As shown in Fig. 3, the theoretical mobility is in excellent agreement with the experimental data at high x_3 and high T (except for $x_3 = 1.0\%$, where the mean-free path of bulk QPs is larger than the period of the DL) without any adjustable parameters. This agreement suggests that there is no contribution from the 2D ^{3}He layer in the viscous regime.

The experimental mobility deviates from the viscosity-limited one and approaches a temperature-independent value at low temperatures. These observations suggest a crossover from the viscous regime to the ballistic regime with decreasing T as the mean-free path l_q of a ^{3}He QP in the bulk mixture becomes longer than the lattice constant of the WC, which is about 1 μm (in the Fermi liquid, l_q increases with decreasing T as $l_q \propto T^{-2}$). The mobility is

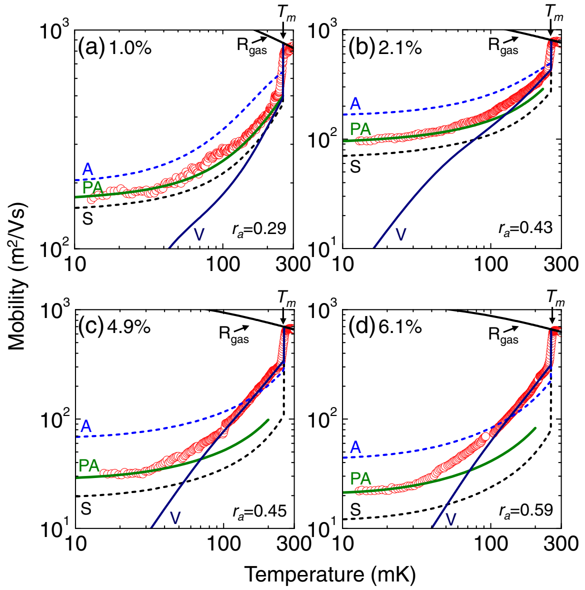

FIG. 3. Experimental mobility of the WC compared with the theoretical calculations. The experimental data are the same as those shown in Fig. 2. Theoretical mobilities limited by the viscosity (V), specular reflection (S), accommodation process (A), partial accommodation process (PA), and ripplon scattering in the electron gas regime (R_{gas}) are shown for $n_e = 1.35 \times 10^{12}$ m^{-2} and $E_\perp = 2.05 \times 10^4$ V/m. (a) $x_3 = 1.0\%$, (b) 2.1%, (c) 4.9%, and (d) 6.1%. An error in the theoretical curves associated with the deviation of n_e and $E_\perp$ used in the calculation from the actual values is estimated to be 3% at most. At $x_3 = 1.0\%$, the system is in the ballistic regime at temperatures just below T_m because of the long mean-free path, and therefore the viscous regime is not observed.

then limited by friction caused by bulk QP reflection from the moving DL. In the case of *pure* ^{3}He, a ^{3}He QP is demonstrated to be reflected specularly [30–32]. For the mixture, a similar process is shown in Fig. 4(a); however, it is not trivial how a ^{3}He QP is reflected from a surface element dS in the presence of the 2D ^{3}He layer.

As a reflection law, specular and diffusive reflections have been conventionally considered. For the specular reflection of a ^{3}He QP, the incident and reflection angles are equal [Fig. 4(a)]. In this case, there is no momentum transfer in the tangential direction to the surface element dS. For the conventional diffusive reflection [Fig. 4(b)], which generally occurs at a solid surface with microscopic irregularities, reflected ^{3}He QPs are in thermal equilibrium with the moving surface, and therefore their momentum distribution is significantly different from that of bulk QPs, resulting in a large average momentum exchange in the direction of motion. Drag forces dF_D acting on a surface element dS thus differ by orders of magnitude for the two cases:

$$dF_D \sim n_3 p_F V_0 (\delta/a)^2 dS \quad (1)$$

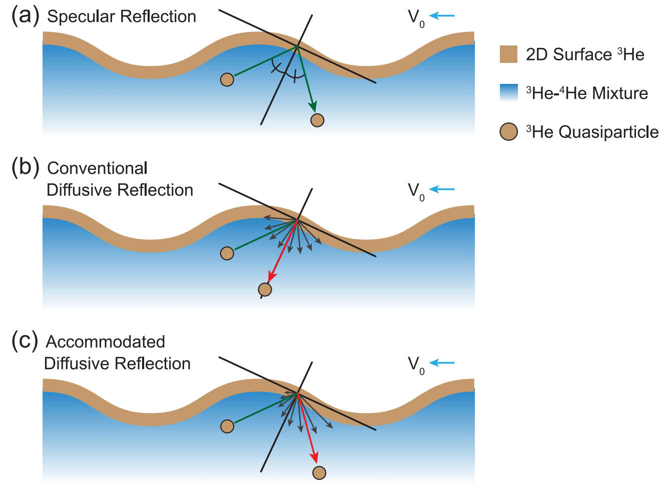

FIG. 4. Schematic pictures of microscopic reflection processes of a ^{3}He QP at the surface, seen in the reference frame moving horizontally together with the DL. (a) Specular reflection. The ^{3}He QP is reflected with an angle equal to the incident angle. (b) Conventional diffusive reflection. Small arrows indicate the probability of QP reflection in a given direction. Red arrow indicates the averaged direction of reflection. After reflection, ^{3}He QPs are in thermal equilibrium with the moving surface. (c) Accommodated diffusive reflection. Reflected QPs are in thermal equilibrium with the 2D ^{3}He layer which is not moving horizontally with the DL. The drag force in this process is by a factor less than that of specular reflection (see the text).

for the specular reflection and

$$dF_D \sim n_3 p_F V_0 dS \quad (2)$$

for the conventional diffusive reflection [40], where V_0 is the horizontal velocity of the surface profile, n_3 and p_F are the number density and the Fermi momentum of ^{3}He in the mixture, respectively, $\delta \sim 0.1$ Å is the depth of the DL, and a ($= 0.93$ μm) is the lattice constant of the WC. These suggest that (i) for specular reflection, dF_D is by $(\delta/a)^2$ ($\sim 10^{-10}$) smaller than the case of conventional diffusive reflection and (ii) when $\delta \to 0$, $dF_D \to 0$ for specular reflection, while dF_D is independent of the dimple depth for conventional diffusive reflection, which means that it is not applicable for the description of the drag force of the DL [40].

As shown in Fig. 3, the theoretical mobility of the specular reflection model evaluated at our measurement frequency (black dashed line) is in qualitative agreement with the experimental mobility (see Supplemental Material for the derivation of the mobility at a nonzero frequency [14]). However, the experimental mobility is still higher than that given by this model (as noted above, the conventional diffusive reflection results in even much lower WC mobility). This noteworthy result means that conventional specular and diffusive reflection laws cannot explain observed mobility data of the long mean-free-path regime.

As an unusual QP reflection model, Monarkha and Kono proposed a process involving the accommodation of an incoming ^{3}He QP with the surface layer of ^{3}He atoms [40], which is shown schematically in Fig. 4(c). Note that Fig. 4 is drawn for an observer moving horizontally with the DL. The key features of this process are (i) the momentum distribution of reflected QPs is described by the Fermi function $f_0(\varepsilon_{\beta,p})$ in the reference frame bound to the element dS' of the 2D ^{3}He layer (here $\varepsilon_{\beta,p}$ is the energy of a QP with a momentum $\mathbf{p}$ and spin β)—i.e., reflected QPs are in thermal equilibrium with the ^{3}He layer—and (ii) the 2D ^{3}He layer does not move horizontally together with the DL but just oscillates vertically with the amplitude of δ (this is the reason for a prime symbol in dS'). Because of (i), this process represents diffusive reflection; when the DL is stationary, the momentum distribution of reflected QPs is the same as that of the conventional diffusive model. However, because of (ii), the momentum distribution of reflected QPs is described by the equilibrium function in the frame which is not moving horizontally with a surface relief. Therefore, in the reference frame fixed to the DL, as qualitatively drawn in Fig. 4(c), the momentum distribution function of reflected QPs

$$f_{\rm out}(\mathbf{p}) = f_0(\varepsilon_{\beta,p} + \mathbf{p}\mathbf{V}_0 + p_z \nabla\xi\mathbf{V}_0) \tag{3}$$

is close to the distribution function of incoming QPs $f_{\rm in}(\mathbf{p}) = f_0(\varepsilon_{\beta,p} + \mathbf{p}\mathbf{V}_0)$, where $\xi(\mathbf{r})$ describes the surface relief of the DL. Thus, this reflection process reduces the average in-plane momentum exchange at the surface significantly. Only a small drag force is caused by the last term in the argument of the distribution function in Eq. (3) associated with the oscillating vertical motion of the ^{3}He layer with a small velocity of $\nabla\xi\mathbf{V}_0 \simeq (\delta/a)V_0$. Obviously, for a flat surface ($\nabla\xi = 0$), the drag force $F_D = 0$.

Remarkably, such a simple modification of the diffusive reflection model leads to a giant increase in the WC mobility—the drag force acting on the moving DL becomes smaller by a factor of $(\delta/a)^2$ as compared to that given by conventional diffusive reflection. Detailed theoretical analysis predicts that the dc mobility is by a factor of 4 larger than that found for the case of specular reflection [40] and by a smaller factor at a finite frequency as shown with blue dashed lines in Fig. 3 (see Supplemental Material for the finite-frequency effect [14]). However, not all incoming QPs are reflected by this accommodated diffusive process; thus, we fit the data using the partial accommodation model (green solid lines in Fig. 3), where a fraction r_a among QPs are scattered by the accommodated diffusive process and the others are reflected specularly. In this case, the dimple drag force is defined as

$$F_D = \left(1 - \frac{3}{4} r_a\right) F_D^{\rm (spec)}, \tag{4}$$

where $F_D^{\rm (spec)}$ is the drag force for the specular reflection.

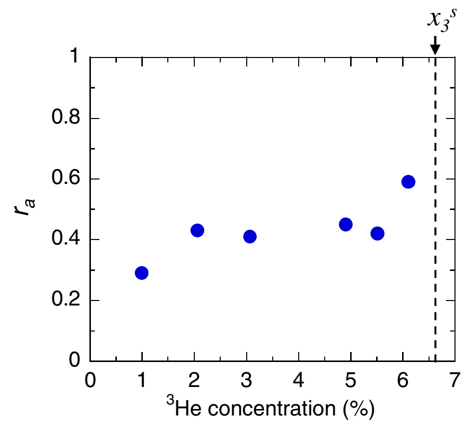

FIG. 5. Accommodation ratio r_a as a function of ^{3}He concentration.

As can be seen in Fig. 5, r_a increases with increasing x_3. This increase could be associated with a momentum mismatch between ^{3}He in the surface layer and ^{3}He in the bulk mixture caused by the large difference in the Fermi energies of the two systems: $T_F^{\rm 3D} < 0.4$ K, while $T_F^{\rm 2D} \sim 2$ K [Fig. 1(c)]. The mismatch suggests that the conservation of momentum and energy cannot be satisfied in the reflection process without involving other excitations such as surface waves, prohibiting the accommodation process. The momentum mismatch becomes less significant at higher x_3, making the accommodation process more favorable. Another possibility for the increase of r_a with x_3 is associated with the increase of the thickness of the ^{3}He layer according to Fig. 1(b).

Our work can be extended to lower temperatures where the 2D ^{3}He system is expected to undergo a superfluid transition, potentially to a topological superfluid state. The results obtained in this work indicate that the WC mobility could be useful for detecting the superfluid state of the surface layer, because the transition should affect microscopic details of the accommodation process.

In conclusion, we have demonstrated that the interplay of the 2D and 3D Fermi systems generates a new kind of QP reflection from an uneven surface relief moving along the interface, which reveals itself as an anomalous enhancement in the WC mobility on the surface of a ^{3}He-^{4}He mixture.

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