Slip and the Effect of ^{4}He at the ^{3}He-Silicon Interface

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We present measurements of the slip of normal ^{3}He contained between a pair of highly polished silicon plates mounted on a torsional oscillator. The resulting effective viscosity of pure normal ^{3}He is not consistent with simple slip theory and shows characteristics previously observed only with a surface layer of ^{4}He present. We have also observed the onset of specularity induced by the addition of ^{4}He. This onset occurs after 2 monolayers of ^{4}He have been completed and can be associated with superfluidity of the ^{4}He.

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The boundary scattering condition for ^{3}He quasiparticles controls the behavior of the fluid in both the normal and superfluid states. In the normal phase, the degree of specularity determines the relative velocity or slip at the surface. In the superfluid phase, diffuse scattering (zero specularity) suppresses components of the order parameter [1,2].

No systematic studies have been performed which alter the surface scattering of ^{3}He. Recent experiments [2,3] have found that coating surfaces with 1 or 2 monolayers of ^{4}He reduces the order-parameter suppression in the superfluid phase, presumably due to the introduction of specularity. In earlier experiments in the normal phase [4,5], results for pure ^{3}He were consistent with diffuse scattering. The introduction of ^{4}He lowered the effective viscosity in a manner qualitatively consistent with specular scattering; however, the temperature dependence was inconsistent with theory. A mechanism suggested for the introduction of specularity by ^{4}He is the replacement of the magnetically ordered layer of ^{3}He with ^{4}He. Momentum transfer may also be impeded by the reduced probability of ^{3}He-wall interactions introduced by the barrier arising from the difference in the van der Waals potentials of ^{3}He and ^{4}He [6]. Alternatively, the superfluidity of the ^{4}He film may impede momentum transfer from the surface to the normal ^{3}He. The boundary scattering for ^{3}He thus remains an enigmatic property.

This paper describes a series of experiments on normal ^{3}He confined between walls mechanically polished to a local roughness of ~ 20 Å. These surfaces are much smoother and better characterized than those used in previous experiments and might be expected to exhibit specular scattering. We also carried out a survey of the changes induced by coating the surfaces with ^{4}He, concentrating on low ^{4}He coverages which have not been systematically explored in the past. These measurements reveal a rapid change in specularity with an onset at approximately 2 monolayers of ^{4}He.

Experimental arrangements which confine the fluid in a region with a small characteristic dimension are well suited for the investigation of slip for even a small fraction of specular scattering. Previous experiments on normal ^{3}He which investigated the effects of surface ^{4}He used large dimensions. Although specularity due to the addition of several layers of ^{4}He was observed in these experiments, the large dimensions precluded the observation of small slip at low ^{4}He coverages. Thus, these experiments were able to observe large specularities but not the onset of specularity itself. In our experiment, the ^{3}He was bounded by two parallel silicon plates separated by a nominal 50-μm glass washer and mounted on a torsional oscillator. The spacing (cell height) was measured to be 57.1 ± 2.5 μm after assembly. The oscillator was operated at constant amplitude at its resonant frequency of 1586 Hz and had a dissipation (Q^{-1}) when empty of 10^{-6} at 1 mK, which was subtracted from all the data. Temperatures were measured with a melting-curve thermometer [7] thermally anchored to the heat exchanger used to cool the liquid.

The oscillator dissipation depends on temperature through the dimensionless parameter $x = d/\delta$, where $\delta = \sqrt{2\eta/\rho\omega}$ is the viscous penetration depth and d is the cell height. Here, η is the viscosity, ρ the fluid density, and ω the angular frequency of oscillation. Provided that $x < 0.7$ (the well-locked limit), the dissipation is proportional to x^2 and consequently η^{-1}. For our cell's frequency and height, the well-locked limit is attained for $T < 12$ mK. In the Fermi-liquid regime, $\eta = \frac{1}{5} n p_F \lambda \propto T^{-2}$, where n is the number density, p_F is the Fermi momentum, and λ is the mean free path; thus Q^{-1} is expected to be linear in T^2 below about 12 mK. Finite-size effects in the Knudsen regime alter the temperature dependence below about 3 mK [8,9].

The boundary scattering properties can be characterized by a slip length ζ, the distance over which the fluid velocity extrapolates to that of the wall. The exact theory [10,11] predicts a value of $\zeta = 0.582\lambda(1+s)/(1-s)$, where s is the fraction of specular scattering. Slip manifests itself in the hydrodynamics as a diminished effective viscosity which may be written as

$$\begin{aligned}\eta_{\rm eff}^{-1} &= \eta^{-1}[1+6(\zeta/d)(1+s)/(1-s)] \\ &= (5/np_F d)[(d/\lambda)+6(\zeta/\lambda)(1+s)/(1-s)] \\ &= \eta^{-1} + \eta_{\rm slip}^{-1}\,.\end{aligned}$$

Since theory predicts that ζ is proportional to λ, slip has the effect of adding a temperature-independent viscous term in parallel to the bulk viscosity. It can readily be seen that small values of d enhance the slip contribution, which appears as the intercept on a plot of Q^{-1} vs T^2 [9,12,13].

Data for Q^{-1} vs T^2 are plotted in Fig. 1 for pure ^{3}He as well as for different coverages of ^{4}He (to be discussed later). The solid line is the calculated Q^{-1} for diffuse scattering ($s=0$), using $\eta T^2 = 2.50$ P mK^2 for the bulk viscosity. The measured Q^{-1} is not linear in T^2, but rather appears to vary as $T^{1.6}$ at low temperatures. At higher temperatures the dissipation approximates the expected T^2 dependence.

This anomalous temperature dependence is not an exprimental artifact. We cannot attribute it to either a thermal gradient or a choice of temperature scale. We also operated the cell with pure ^{4}He and observed no parasitic effects or spurious resonances. The Kelvin drag or χ factor, which measures the coupling of an ideal fluid to the oscillator, was found to be less than 1. Using infrared interferometry, no systematic variation was found in the parallelism of the silicon plates. Thus we have confidence that momentum transfer to the fluid occurs via shear motion rather than by displacement of the fluid, which could result in additional dissipation.

The effective viscosity calculated from the dissipation is displayed in Fig. 2. These data were calculated without using the well-locked-limit approximation and are thus valid to higher temperatures. The bulk viscosity and calculations from slip theory at several specularities between 0.0 and 0.95 are shown in the plot as solid lines. At higher temperatures slip affects $\eta_{\rm eff}$ less and the data approximate the bulk-fluid result.

Because of the anomalous temperature dependence, we can only offer qualitative interpretations about the results from pure ^{3}He in the presence of highly polished walls. The effective viscosity can be fitted by a temperature relation of the form $\eta_{\rm eff}^{-1} = A + BT^n$, where $n=1.6$. If we identify A, by analogy, as the slip intercept term, we find that $s=0$ for pure ^{3}He. We also note the similar temperature dependence of our pure-^{3}He effective viscosity and those measured in earlier experiments [4,5] on ^{3}He using rough surfaces coated with ^{4}He. We hypothesize that this behavior results from the locally smooth surfaces present in our experiment and induced by the smoothing effects of ^{4}He in the earlier experiments. An alternative explanation requires a specularity that decreases with lower temperatures, as can be seen from Fig. 2. This is contrary to what we expect, as will be discussed below.

Our silicon plates have a roughness (~ 20 Å) greater than the quasiparticle wavelength ($k_F^{-1} \sim 1.3$ Å). If the relevant wavelength is k_F^{-1}, then the scattering should be diffuse. On the other hand, if the relevant quasiparticle "size" is the thermal wavelength, $\Lambda = h/(2\pi m^* k_B T)^{1/2}$, which ranges from 180 to 60 Å between 1 and 10 mK, then specularity may be induced by these highly polished surfaces. However, if the particles sample surface imperfections on this length scale, then specularity should *increase* as the temperature is lowered, counter to the results inferred from Fig. 2. Thus, it is unclear if the data

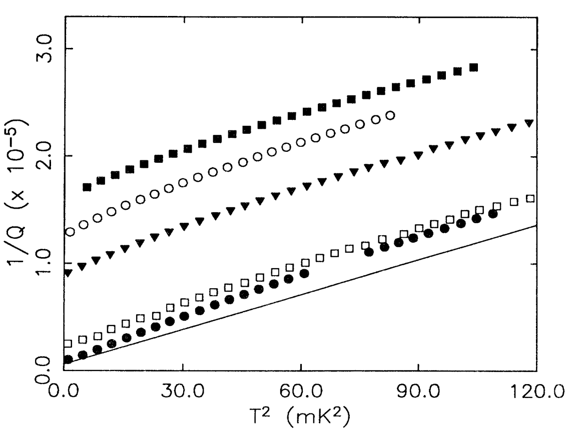

FIG. 1. The dissipation plotted as a function of T^2 for the various ^{4}He coverages (in μmole/m^2): ●, pure ^{3}He; □, 30.0; ▼, 39.2; ○, 57.7; and ■, 115.4. The data for the coverage of 20.8 μmole/m^2 are not plotted since they coincide with the pure-^{3}He data. The solid line corresponds to slip theory with diffuse scattering. Specular scattering should result in an increased intercept on this plot.

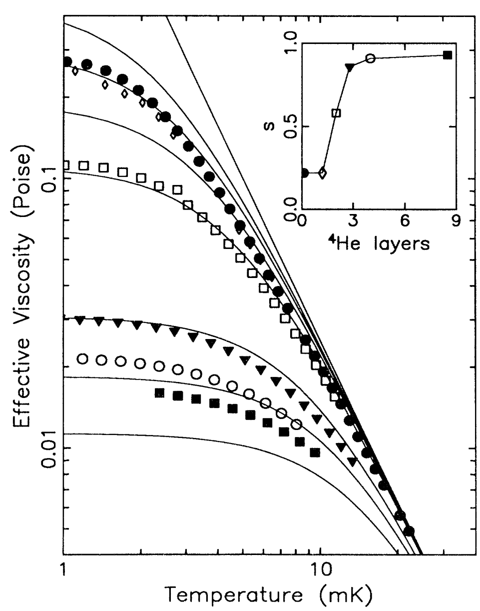

FIG. 2. The effective viscosity determined from the dissipation data. The symbols are identical to those shown in Fig. 1, with the exception of the diamonds which correspond to 20.8 μmole/m^2. The solid lines from top to bottom correspond to no slip, $s=0$ (diffuse scattering), 0.2, 0.4, 0.6, 0.87, 0.92, and 0.95. Note that the pure-^{3}He data approach the bulk result at high temperatures. Inset: The values of specularity inferred from this plot at a temperature of 3 mK, for the various ^{4}He coverages studied. The solid line is a guide to the eye.

support either hypothesis.

At this juncture it is appropriate to summarize the results of this and previous measurements of ^{3}He viscosity in the presence of ^{4}He. Recently, Ritchie, Saunders, and Brewer [4] used a torsion pendulum with an estimated surface roughness of 1 μm to measure the effective viscosity of ^{3}He. For a pure sample they found $\eta_{\rm eff}^{-1} \propto T^2$. Upon adding ^{4}He, the temperature exponent decreased to 1.8. The viscosity measured earlier by Betts, Brewer, and Lucking [5], using quartz polished to a roughness of ~ 500 Å, behaved similarly. In contrast, our surfaces are polished to a characteristic local roughness on the order of 20 Å. The resulting temperature dependence of the effective viscosity for *both* pure ^{3}He- and ^{4}He-coated surfaces is similar to that observed in these earlier experiments for ^{4}He-coated surfaces.

A recent theory [14] describing the effect of mesoscopically curved surfaces successfully fits the results of Ritchie, Saunders, and Brewer [4]. To make contact with this theory we have characterized the mesoscopic curvature of the polished silicon by making several profile scans. These reveal structure with height h at various length scales l. For $l \sim 50$ μm, $h \sim 20$ Å, for $l \sim 100$ μm, $h \sim 100$ Å, and for $l \sim 3000$ μm, $h \sim 600$ Å. The theory is only valid in the limit that l and h are large compared to the mean free path. Therefore we are unable to attribute our anomalous dissipation data to mesoscopic scale curvature; for the same reason, the theory cannot be applied to the earlier experiments using polished quartz [5].

We now examine the effect of adding ^{4}He. ^{4}He is more tightly bound to the surface because of its lower zero-point motion and displaces ^{3}He from the boundary. The solubility of ^{3}He into the boundary layer is not known; however, it is thought that the first few layers are nearly pure ^{4}He. To ensure a uniform coating of the surfaces, the ^{3}He was extracted from the cell by heating it to 10 K. The appropriate amount of ^{4}He (our cell incorporated a surface area of 26 m^2) was then admitted and allowed to anneal for several hours before cooling the cell and readmitting the ^{3}He. Care was taken to ensure thermal equilibrium between experiment and thermometer during subsequent measurements.

At the lowest ^{4}He coverage of 20.8 μmole/m^2 (corresponding to 1.2 monolayers), the Q^{-1} was nearly identical to that for pure ^{3}He. The effect of increasing ^{4}He was dramatic. At 30 μmole/m^2 (equivalent to about 2 monolayers) [2], the dissipation intercept increased. At still higher coverages the dissipation curves are displaced upwards by progressively larger amounts until ~ 8 monolayers are completed. Aside from the intercept, the overall temperature dependence of the different data sets shown in Fig. 1 is unchanged. In order to illustrate the onset and progressive increase of slip with ^{4}He coverage, we have calculated the specularity (assuming slip theory is valid) for each of the data sets at 3 mK, where Knudsen effects should be small. These values for s are plotted as a function of ^{4}He coverage in the inset of Fig. 2.

The fact that the curves for pure ^{3}He and for the lowest coverage of ^{4}He are identical provides evidence about the mechanism responsible for changes in scattering. At the lowest coverage, the localized magnetic layer of ^{3}He adjacent to the boundary has been completely replaced by nonmagnetic ^{4}He. Since there was no change in specularity, the magnetic state of the first layer must be unimportant. The specularity only increases when 2 monolayers of ^{4}He coat the surfaces, and continues to increase with coverage up to ~ 8 monolayers. At still higher coverages the effect saturates.

The onset of specularity observed in this experiment coincides with the Kosterlitz-Thouless transition measured by Freeman *et al.* [2], for ^{4}He films covered with bulk ^{3}He. Our data thus suggest that the ^{4}He superfluidity is responsible for the specularity observed in both this and the superfluid experiment. Naively, one would expect no momentum to be transferred between the fluid and the wall across a superfluid. Our results demonstrate that even with a superfluid layer present, a fraction of the ^{3}He quasiparticles exchange momentum with the surfaces. The simplest mechanism to explain the finite and progressive increase in specularity requires that only a fraction of the quasiparticles propagate ballistically through the ^{4}He. At extremely large coverages, finite solubility of the ^{3}He into the surface layer may limit the momentum decoupling and cause the effect to saturate. The model described by Hall [6] can qualitatively account for the progressive increase in specularity with ^{4}He thickness. It has also been proposed that momentum transfer occurs via vortex lines threading the ^{4}He layer [15]. Thicker films would support fewer vortices and decrease the total momentum transfer.

In conclusion, we have observed that the scattering of quasiparticles from our polished plates produces a lowered effective viscosity and an anomalous temperature dependence, similar to that observed by others using rougher surfaces covered by ^{4}He films. The results show that quasiparticle scattering from locally smooth surfaces is not adequately described by simple slip theory. In the future, we propose to explore the effects of roughening the same silicon surfaces to introduce microscopic and mesoscopic features. This may help to identify the origin of the anomalous temperature dependence of the effective viscosity as well as the characteristic roughness necessary to suppress it. Our experiment also unambiguously demonstrates the onset of specularity with ^{4}He coverage at a level similar to that necessary for superfluidity in the ^{4}He layer. We rule out the replacement of the localized magnetic layer as a mechanism to induce specular scattering from highly polished surfaces, and we cannot distinguish whether the characteristic size of the quasiparticles is the thermal wavelength or k_F^{-1}. Further, the observation of a progressive increase in specular scattering with increasing ^{4}He coverage provides clues about the mechanism for momentum transfer in this experiment. The progressive increase in slip may depend on the variation of ^{3}He solubility in ^{4}He with distance from the wall which results from the competing van der Waals potentials and decreases ^{3}He interactions with the wall. Our experiment has explored the complexity of the ^{3}He interactions at a polished surface. The results illustrate the role of an intervening superfluid layer as well as the incomplete understanding of momentum transfer across the dilute solution.

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