SLIP OF NORMAL ^{3}HE ON SMOOTH SURFACES

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Measurements of the slip length of normal ^{3}He confined by smooth silicon suggest that the boundary condition for ^{3}He scattering at surfaces is diffuse even for substrates which are smooth compared to the mean thermal wavelength of ^{3}He. Coating the surface with just two or three monolayers of ^{4}He greatly increases the specularity. In addition, the expected behavior of the bulk viscosity of ^{3}He appears to be modified by the reduced momentum transfer caused by the smooth surface and specular scattering condition.

1. INTRODUCTION

In classical hydrodynamics, one solves the Navier-Stokes equation for fluid flow with the boundary condition that the relative velocity of the fluid with respect to a surface go to zero. If the details of the scattering process at the surfaces are included, it is found that this velocity is not zero at a boundary; there is finite slip of the fluid. The amount of slip depends strongly on the type of scattering. If the surface scatters the liquid particles diffusively, there is significant momentum transfer between the solid and the liquid, and thus small slip. In the other extreme, if the scattering is specular, then little momentum is exchanged and the slip becomes very large.

The purpose of this experiment is to gain information on the scattering mechanism for normal ^{3}He particles at solid surfaces by measuring the slip at a surface of known characteristics. In particular, highly polished silicon with a roughness small compared to the mean thermal wavelength of ^{3}He particles was selected. We measured the microscopic roughness to be better than 50 Å. If the scattering process depends on geometrical roughness alone, then such smooth surfaces would be expected to scatter particles specularly.

2. THE EXPERIMENTAL APPARATUS

A flat cylindrical region for ^{3}He is produced by gluing together two flat silicon disks spaced by a thin glass washer of height 50μm. The height of the cell is made small to amplify the contribution of the fluid near the walls to the total dissipation of the oscillator. A small hole through the center of one disc acts as a fill line for the liquid. The oscillator is run at constant amplitude via capacitive electrodes; the drive voltage is thus directly proportional to the dissipation. The empty-cell dissipation is subtracted to yield the contribution from the fluid alone.

3. RESULTS

The coupling of the fluid to the solid cell controls the behavior of the oscillator. At low temperatures, the fluid is very viscous and its motion is well-locked to that of the cell. The moment of inertia (period) is large, while the dissipation is small. As temperature is increased, some fluid begins to unlock, so the period drops and the dissipation rises. At some point, the fluid is sufficiently decoupled from the cell and the dissipation falls while the period continues to decrease. The dissipation and period thus trace out a peaked curve.
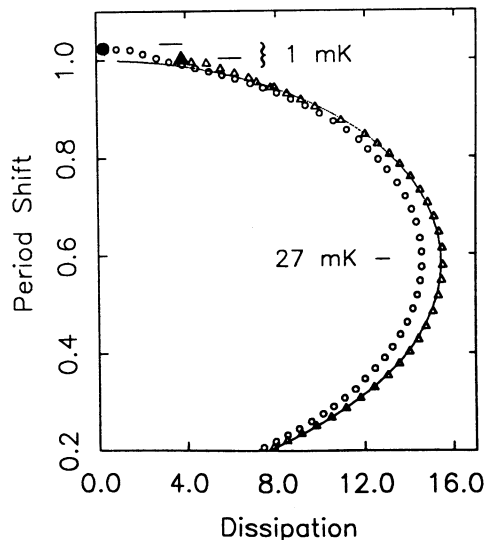

Figure 1

Period shift (relative to the full-cell period shift) versus dissipation (in arbitrary units). Note the dissipation offset between the two sets at low T.

In figure 1 we plot the dissipation versus period shift. Data were taken for three cases. First the cell was filled with pure ^{3}He. Next, a 50 μmole/m^2 layer of ^{4}He was admitted to coat the surfaces before the addition of the ^{3}He. In the third case, the ^{4}He coverage was increased to 75 μmole/m^2. The circles represent the pure ^{3}He and the triangles represent the data taken with surface ^{4}He added. The two ^{4}He-coated cases trace out very similar curves; for clarity, only the 50 μmole/m^2 data is shown here. The period endpoints were similar for all three cases. Thus, one theoretical curve applies to all the data sets. For the pure ^{3}He, the dissipation falls short of its expected value at the maximum, but for the cases with ^{4}He the data matches theory fairly well in this region. At low temperatures, the period overshoots theory for all data sets.

The presence of slip should not modify the hydrodynamic relation between dissipation and period shift. The temperature dependence of these variables is expected to change, however, when slip is present. In particular, theory predicts that, in the Poisieulle flow limit, slip simply adds a temperature-independent term to the inverse viscosity of the liquid; for normal ^{3}He, the viscosity is known to be proportional to $1/T^2$. Since the dissipation of a torsional oscillator is simply proportional to $1/\eta$ at low temperatures, the dissipation should be of the form:

$$D = D_s + D_b T^2,$$

where D_s is the extra dissipation caused by slip and $D_b T^2$ is the ordinary bulk dissipation. The size of this slip term is expected to increase with specularity according to the following relation:

$$D_s = D_o(1 + s)/(1 - s),$$

where s is the fraction of particles that are specularly reflected from the surface and D_o is the completely diffuse value for the slip term. Scaled to the arbitrary units of dissipation used for our setup, D_o is predicted to have a lower bound of about 0.20.

In none of three runs did the dissipation fit the form expected above. One can, however, produce a good fit by allowing the temperature exponent to vary. Figure 2 shows the dissipation as a function of temperature for the three cases.

$$D = 0.09 + .0786T^{1.70} \qquad \text{(pure }^3\text{He)}$$
$$D = 3.70 + .0885T^{1.65} \quad \text{(50 }\mu\text{mole/m}^2\ ^4\text{He)}$$
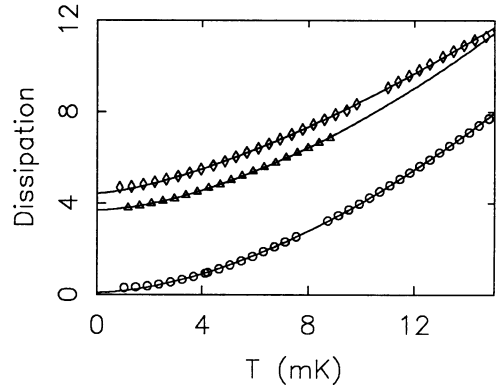$$D = 4.43 + 0.143T^{1.45} \quad \text{(75 }\mu\text{mole/m}^2\ ^4\text{He)}$$

Figure 2
Dissipation as a function of temperature for the three cases described. The solid lines represent the fits to the above power laws. The circles represent pure ^{3}He; the smaller ^{4}He coverage is shown by triangles, and the greater with diamonds.

It is clear from this graph that there is an offset term in the dissipation which increases dramatically upon the addition of ^{4}He, as if the surface were becoming more specular. However, the remaining dissipation does not seem to behave as expected for bulk ^{3}He, but instead fits a power law with an exponent somewhat less than the expected 2.0. This exponent also seems to depend on the amount of ^{4}He coverage on the surfaces. An alternative fit for the ^{3}He data which does conform to a bulk $1/T^2$ behavior for the viscosity would require an additional scattering length on the order of 100 μm, independent of temperature.

4. CONCLUSIONS

The addition of ^{4}He affects the slip and the bulk behavior of the liquid ^{3}He. It is possible that the momentum transfer occurs only because of surface imperfections or the non-zero amount of ^{3}He dissolved in the ^{4}He layers. This effect may be dominating the dissipation and thus leading to the unusual temperature dependence for apparent viscosity.

REFERENCES
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