Monolayers of ^{3}He on the surface of bulk superfluid ^{4}He

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Abstract

We have used quantum evaporation to investigate the two-dimensional fermion system that forms at the free surface of (initially isotopically pure) ^{4}He when small quantities of ^{3}He are added to it. By measuring the first-arrival times of the evaporated atoms, we have determined that the ^{3}He–^{3}He potential in this system is $V_{3S}/k_B = 0.23 \pm 0.02\,\mathrm{K\,nm^2}$ (repulsive) and estimated a value of $m_{3S} = (1.53 \pm 0.02)m_3$ for the zero-coverage effective mass. We have also observed the predicted second layer-state which becomes occupied once the first layer-state density exceeds about 0.6 monolayers.

Keywords: Quantum evaporation; surface; liquid helium; 2-D fermion system

When small quantities of ^{3}He are added to bulk superfluid ^{4}He below $T \sim 100$ mK the atoms occupy so-called Andreev states [1] and form a degenerate two-dimensional fermion system. At low temperatures, and when the surface density of ^{3}He n_{3S} is less than about half a monolayer, the ^{3}He chemical potential can be described [2] by

$$\mu_3 = E_{3S}^{(0)} + \left(\frac{\pi\hbar^2}{m_{3S}} + \frac{V_{3S}}{2} \right) n_{3S} \qquad (1)$$

where $E_{3S}^{(0)}$ is the binding energy of a single ^{3}He atom (effective mass m_{3S}) to the ^{4}He surface. V_{3S} parameterises the ^{3}He–^{3}He interaction.

Values of m_{3S} and V_{3S} inferred from measurements of thermodynamic properties of the surface, such as surface tension, are strongly covariant (see [3] for example). However, we have been able to obtain independent values for these quantities using a new method based on quantum evaporation [4,5], as follows:

A tightly collimated beam of high-energy phonons [6] was directed at normal incidence to the free liquid surface (Fig. 1a). The evaporated ^{3}He atom beam was also collimated so that only

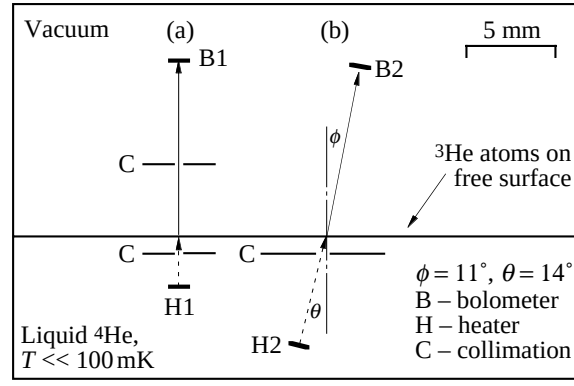

Fig. 1. Schematic diagram of the quantum evaporation experiment

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atoms with a nearly zero component of momentum parallel to the surface were detected. An incident phonon of energy $E_{\rm p}$ imparts kinetic energy to the ejected atom, which has bare mass m_3, such that

$$\frac{1}{2}m_3v^2 - E_{\rm p} = E_{\rm 3S}^{(0)} + \frac{1}{2}V_{\rm 3S}n_{\rm 3S}. \qquad (2)$$

The distribution of phonon energies arriving at the surface is unaffected by $n_{\rm 3S}$ at the coverages used, and the value of $E_{\rm 3S}^{(0)}/k_{\rm B} = -5.02 \pm 0.03\,{\rm K}$ [3] is constant. Therefore, the variation with $n_{\rm 3S}$ of arrival times of ^{3}He atoms at the bolometer is due simply to the term $\frac{1}{2}V_{\rm 3S}n_{\rm 3S}$ in Eqn 2. Our measured first-arrival times were consistent with Eqn 2 for coverages up to $n_{\rm 3S} = 4\,{\rm nm}^{-2}$ (Fig. 2) and we conclude that $V_{\rm 3S}/k_{\rm B} = (0.23 \pm 0.02)\,{\rm K\,nm}^2$. Knowledge of this value eliminates the uncertainty due to covariance (see above) in the value of $m_{\rm 3S}$ inferred from measurements [3,7] of surface-sound velocity and surface tension. Hence, the best estimate of $m_{\rm 3S}$ can refined from $(1.45 \pm 0.10)m_3$ to $m_{\rm 3S} = (1.53 \pm 0.02)m_3$.

We have also used a slight variant of the experiment (Fig. 1b) to search for evidence of a second 'excited' state predicted by Pavloff and Treiner [8]. Atoms in this state have a smaller binding energy $E_{\rm 3S}^{(1)}$ to the surface than those in the first surface state, and the signature of its occupation is therefore an additional faster component in the detected signal. This component appeared, albeit at a level

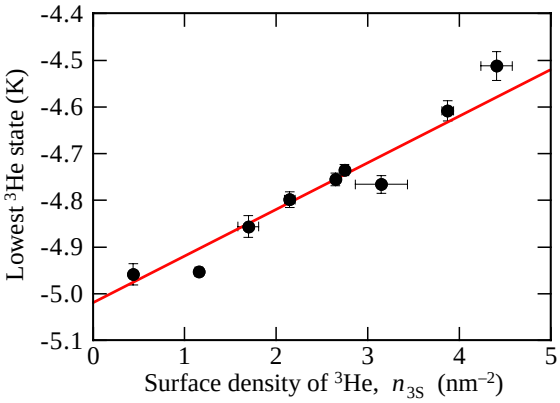

Fig. 2. Values of $E_{\rm 3S}^{(0)} + \frac{1}{2}V_{\rm 3S}n_{\rm 3S}$ deduced from measured first-arrival times for ^{3}He atoms evaporated by high-energy phonons as a function of surface density $n_{\rm 3S}$.

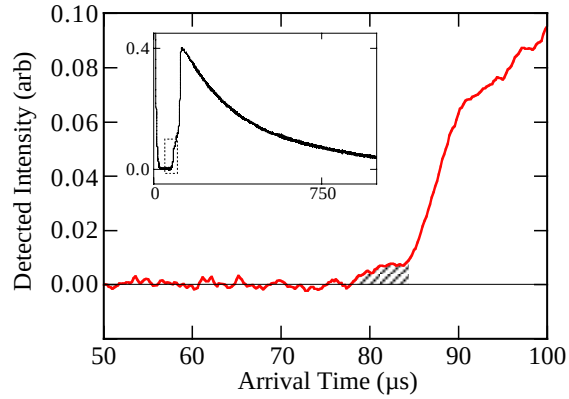

Fig. 3. ^{3}He atoms from the lowest surface-state start arriving at 85 μs, the earlier component (shaded) is due to atoms from the excited surface state. The largest signal component (inset) is due to evaporated ^{4}He atoms.

not greatly above the detector noise, on all signals taken below $T = 60\,{\rm mK}$ with surface coverages of, and above, about 0.6 monolayers, *i.e.* $n_{\rm 3S} = 4\,{\rm nm}^{-2}$ (Fig. 3). From our preliminary measurements of first-arrival times, we find that $E_{\rm 3S}^{(1)} = -3.4 \pm 0.4\,{\rm K}$, in agreement with the predictions [8].

Although this paper has discussed exclusively the states of ^{3}He above bulk ^{4}He, we note that thin film and layered systems have some comparable properties and have been investigated by other groups using NMR, third-sound and heat capacity measurements [9–11].

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