

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

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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) ^4He when small quantities of ^3He are added to it. By measuring the first-arrival times of the evaporated atoms, we have determined that the ^3He - ^3He potential in this system is $V_{3S}/k_B = 0.23 \pm 0.02 \text{ K nm}^2$ (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 ^3He are added to bulk superfluid ^4He below $T \sim 100 \text{ mK}$ 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 ^3He n_{3S} is less than about half a monolayer, the ^3He chemical potential can be described [2] by

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

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

ing 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 ^3He atom beam was also collimated so that only

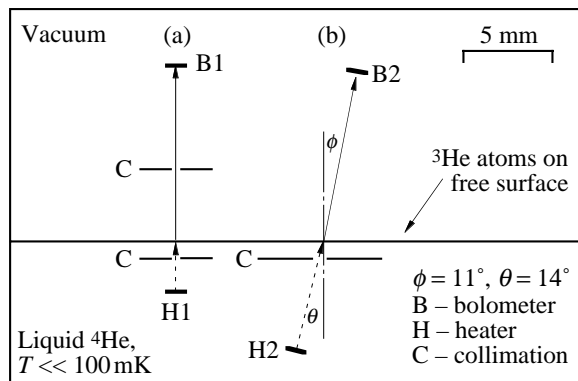


Fig. 1. Schematic diagram of the quantum evaporation experiment

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atoms with a nearly zero component of momentum parallel to the surface were detected. An incident phonon of energy E_p imparts kinetic energy to the ejected atom, which has bare mass m_3 , such that

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

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

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 $E_{3S}^{(1)}$ 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

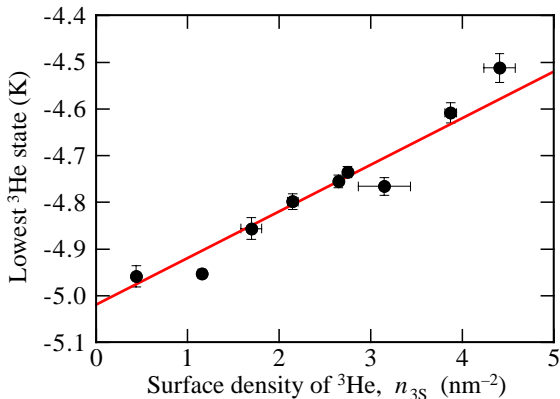


Fig. 2. Values of $E_{3S}^{(0)} + \frac{1}{2}V_{3S}n_{3S}$ deduced from measured first-arrival times for ^3He atoms evaporated by high-energy phonons as a function of surface density n_{3S} .

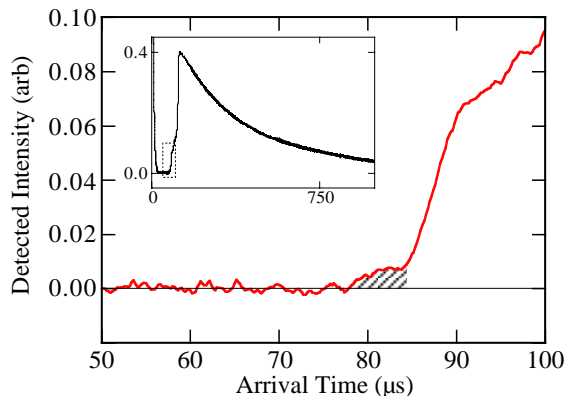


Fig. 3. ^3He atoms from the lowest surface-state start arriving at $85 \mu\text{s}$, the earlier component (shaded) is due to atoms from the excited surface state. The largest signal component (inset) is due to evaporated ^4He atoms.

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

Although this paper has discussed exclusively the states of ^3He above bulk ^4He , 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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