Relative evaporation probabilities of ^{3}He and ^{4}He from the surface of superfluid ^{4}He

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Abstract

We report a preliminary experiment which demonstrates that ^{3}He atoms in Andreev states are evaporated by high-energy ($E/k_{\mathrm{B}} \approx 10.2\,\mathrm{K}$) phonons in a quantum evaporation process similar to that which occurs in pure ^{4}He. Under conditions of low ^{3}He coverage, high-energy phonons appear to evaporate ^{3}He and ^{4}He atoms with equal probability. However, we have not managed to detect *any* ^{3}He atoms that have been evaporated by rotons, and conclude that the probability of a roton evaporating a ^{3}He atom is less than 2% of the probability that it evaporates a ^{4}He atom.

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

When small quantities of ^{3}He are added to bulk superfluid ^{4}He below $T{\sim}100\,\mathrm{mK}$ the atoms occupy so-called Andreev states [1] and form a degenerate two-dimensional fermion system. It has previously been reported that ^{3}He can be evaporated by phonons [2] in a quantum evaporation [3] process. This report briefly describes an experiment to compare the evaporation probabilities for ^{3}He and ^{4}He atoms by positive group-velocity rotons and high-energy phonons.

An electrically heated $1\,\mathrm{mm}^2$ thin-film heater in bulk superfluid ^{4}He was used to generate excitations which travelled ballistically (path length 6.3 mm at $\theta = 14°$ to the vertical) to the free surface (Fig. 1). Evaporated atoms were detected with a constant-temperature superconducting bolometer[4] at angle ϕ to the vertical and at radius 5.8 mm from the point of intersection of the liquid surface with the centre of the excitation beam.

The high-energy phonons that participate in evaporation have a narrow energy-distribution

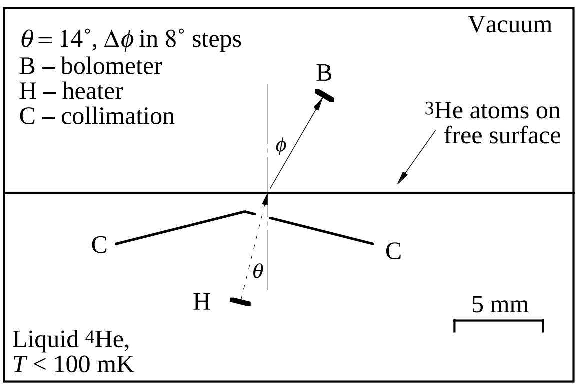

Fig. 1. Schematic diagram of the experiment. The bolometer angle ϕ is adjusted with a stepper-motor.

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which peaks at $E/k_B = 10.2\,\mathrm{K}$ and cuts off below 10 K [5]. These phonons are generated about a millimeter in front of the heater by a complicated up-scattering mechanism [6]. The ^{3}He atoms are less tightly-bound to the liquid surface than the ^{4}He and therefore have a shorter time of flight to the bolometer [2]. The signals were recorded as a function of angle and surface concentration of ^{3}He. The signal shapes are complicated because the ^{3}He affects the bolometer responsivity and time-constant, but a simplified analysis is possible by considering only energy-conserving processes involving the dominant 10.2 K phonons, and the relative probabilities of phonon–atom evaporation processes can be inferred as follows.

With an isotopically pure ^{4}He surface, the measured time τ_4 of the peak in the phonon-^{4}He evaporation signal at $\phi = 11°$ (the kinematic angle of evaporation for 10.2 K phonons) is used to establish the arrival time of these phonons at the surface (Fig. 2). Next, the arrival time $\tau_3(\phi)$ of a ^{3}He atom evaporated by a 10.2 K phonon as a function of evaporation angle ϕ is calculated (inset to Fig. 2). The ^{3}He atoms have a two-dimensional Fermi distribution of momentum. Those nearest the Fermi energy have the earliest arrival times and trvel along paths at the extremes of the angular-distribution of allowed evaporation directions. At a given bolometer position ϕ, the amplitude of the bolometer signal $S(\phi, t)$ at time $t = \tau_3(\phi)$ is – ignoring minor errors due to imperfect collimation – entirely due to ^{3}He atoms which have been evaporated by 10.2 K phonons. By integrating the measurements of $S(\phi, \tau_3(\phi))$ and $S(\phi, \tau_4)$ over the solid angle, the relative numbers of ^{3}He and ^{4}He atoms evaporated by 10.2 K phonons can be estimated. We conclude that when ^{3}He coverage is below 0.5 monolayers ($3.3\,\mathrm{nm}^{-2}$) a phonon will evaporate an atom of either isotope with equal probability (Fig. 3).

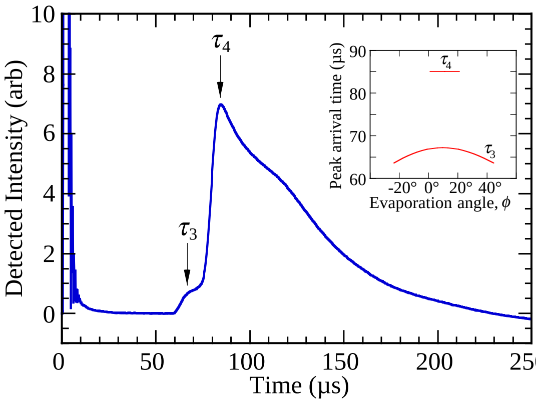

Fig. 2. A phonon–atom evaporation signal taken at $\phi = 7°$ and $n_{3S} = 1.1\,\mathrm{nm}^{-2}$. The inset shows predicted arrival times associated with evaporation by a 10.2 K phonon.

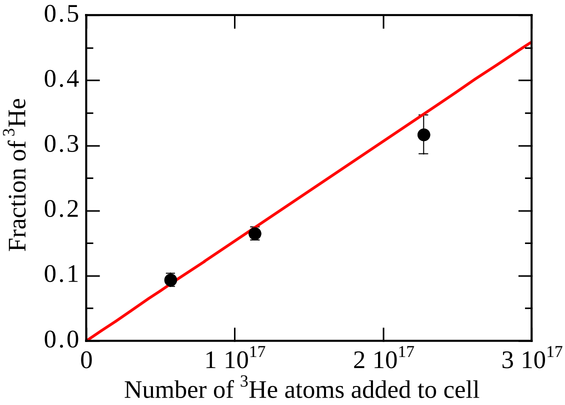

Fig. 3. Measured fraction of total evaporation signal due to ^{3}He atoms (points) compared with calculated coverage of surface by ^{3}He (line).

In the light of this result we were surprised to find no evidence, despite a careful search, that positive group-velocity rotons can quantum evaporate ^{3}He atoms. We believe that the probability that a roton evaporates a ^{3}He atom is less than our detector noise limit, *i.e.* 2% of its probability of evaporating a ^{4}He atom.

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