Transmission of helium atoms through a helium-II slab

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Abstract

We describe a measurement of the transmission probability of ^{4}He atoms through a freely suspended slab of superfluid ^{4}He at low temperatures. This geometry was treated in a recent theoretical calculation [2]. In our experiment the slab is realised by using an array of parallel cylindrical holes of diameter 50 μm in a glass disc of thickness 200 μm. By controlling the chemical potential, the holes can be made to fill or empty with liquid, and the surface curvature varied. We have measured the transmission of atom beams, generated by a thin-film heater and detected with a sensitive bolometer, through this structure.

Key words: superfluidity; quantum-evaporation; quantum-condensation; Bose condensate

In essence, we have suspended a slab of superfluid ^{4}He with two accessible free surfaces in a vacuum. A beam of helium atoms is directed downwards at the upper surface of this slab and an attenuated beam is detected emerging from the free surface on the opposite side below (Fig. 1). The atoms condense onto the upper surface, create rotons that travel across the slab and quantum evaporate [1] atoms into the half-space on the other side.

Measurements of the ratio of the atoms detected with the slab present, and absent, yield direct information about the probabilities of quantum evaporation and condensation. These probabilities have hitherto been difficult to quantify for rotons; existing detectors cannot determine the flux of rotons because their responsivity to rotons is very low. By measuring ratios of atom fluxes we avoid such difficulties and obtain the product of the condensation probability $P_{\mathrm{a}+}$ and the evaporation probability $P_{+\mathrm{a}}$. This can be directly compared with the theory of Campbell *et al.*[2].

Quantum evaporation by phonons [3] and rotons [1] is well-established. When a phonon, or roton, reaches the free surface, an atom can be evaporated in a one-to-one process that conserves energy and the parallel

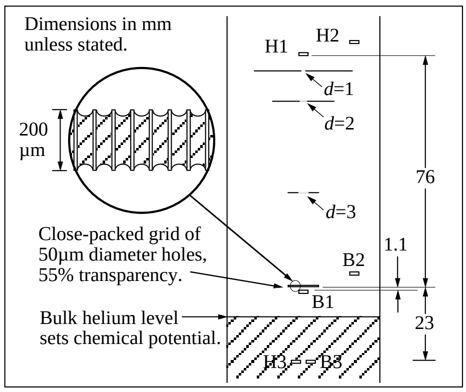

Fig. 1. Principal features of the experiment.

component of momentum. The probability of evaporation by rotons does not depend very strongly on the angle of incidence or energy [4,5]. R$^-$ rotons have two orders of magnitude lower probability of evaporating an atom than R$^+$ rotons [6]. There is indirect evidence that the evaporation probability for R$^+$ rotons is $\sim 1/3$ [7,8] and a rough estimate of the evaporation probability for phonons of energy ~ 10 K, is $P_{\mathrm{pa}} \sim 0.1$ [9].

Less is known about quantum condensation because it is difficult to detect rotons other than by quantum evaporation. However, it is clear that R$^+$ rotons are far

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more likely to be created than phonons in one-to-one processes [10–12], and that condensing atoms have a high probability of creating multiple ripplons [10].

Theoretical studies of quantum evaporation have predicted probabilities for the one-to-one processes [13]. Only Campbell *et al.* [2] include ripplons. For a slab geometry, they find that the atom transmission probability is typically $P_{\rm aa} \sim 0.1$ over much of the roton energy range.

We create the 'slab' of helium-II by exploiting the capillary action of a thin glass-plate (Fig. 1) penetrated by a close-packed array of cylindrical holes[14]. The holes fill with liquid when the bulk surface is $h \sim 20\,$mm below the plate. The minimum usable value of h in this experiment is 2.3 mm under which conditions the 'slab' surface has a maximum deviation of 6.7° from horizontal at the edge of a hole. The atom beam is created by pulsing ($\sim 2\,$mW, 1–5 μs) a thin-film heater (H1, 1 mm^2). The evaporated atoms pass through three collimator plates and arrive at the grid as a narrow and parallel beam. Atoms are detected 1.1 mm below the grid by a superconducting zinc film bolometer (B1, 1 mm^2) operated in a constant temperature mode. The cell is maintained at 60 mK, low enough for the vapour pressure to be considered zero, and the atom beam travels ballistically.

The atom signal through the empty holes is first measured with the liquid level $h = 28\,$mm below the grid (Fig. 2). The measurement is then repeated as the level is raised in small steps by adding isotopically pure ^{4}He to the cell. As expected, the signal increased as h decreased. The condensing atoms create, *inter alia,* R$^+$ rotons which are the excitations that carry the signal down through the slab. The kinematics governing the process mean that not all created rotons necessarily reach the second surface, and not all that do can quantum evaporate an atom.

Filling the holes has two obvious effects (Fig. 2). Firstly, the peak signal is reduced by a factor of roughly 18 at $h = 2.3\,$mm. Secondly, the energy distribution is changed. A detailed interpretation of this spectrum (which is complicated by the transient response of the bolometer) will be given elsewhere but one important feature is visible: there is an abrupt change in the low energy gradient at $E_{\rm atom} \sim 1.5\,$K. This is the lowest energy at which it is possible to create rotons and its presence, along with a ray-tracing analysis of the signals as a function of h support our conclusion that the transmission is mediated by R$^+$ rotons.

To summarise, we have prepared a thermodynamically stable slab of helium with two accessible surfaces [15]. We have measured the transmission of atoms through this structure as a function of surface curvature and extrapolated to the limit of a flat surface. Our preliminary analysis is that the product of evaporation and condensation probabilities is $P_{\rm a+}P_{\rm +a} \sim 0.14$ for an incident atom energy $E_{\rm atom} \sim 5$K. This is comparable with the theoretical prediction [2]. This low value suggests that the creation of ripplons plays a dominant role in condensation, which makes the fact that an atom can quantum evaporate without ripplon creation quite remarkable.

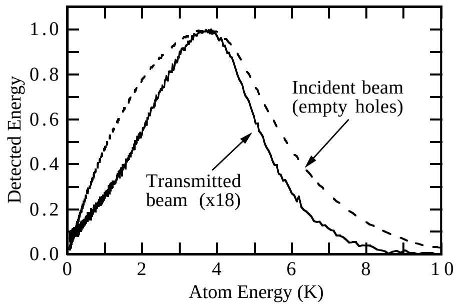

Fig. 2. Normalised energy-spectrum of the detected signal.

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