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The Wave-Vector Dependence of Quantum Evaporation from Superfluid ^{4}He

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Absolute measurements of the probability of quantum evaporation of atoms by rotons from the surface of superfluid ^{4}He are still problematic. However, it is possible to obtain information about the wave-vector dependence of the evaporation process by using a refined simulation[14] to interpret the experiments of Brown and Wyatt[12]. Two theories (Guilleumas et al.[9] and Sobnack et al.[10]) are compared with these experiments by incorporating their predictions for the quantum evaporation probability into a numerical simulation. Both theories over-estimate the probability of phonon-atom evaporation. For roton (R^+–atom) evaporation, compared with a simulation that assumes all kinetically allowed events are equally probable, the theory of Guilleumas et al. does not significantly improve the agreement with experiment, and the theory of Sobnack et al. increases the discrepancy.

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1. INTRODUCTION

The mechanism known as *quantum evaporation*, in which a single atom is ejected from the free surface of superfluid ^{4}He by the annihilation of a single phonon or roton in the liquid, was suggested thirty years ago[1]. Some while afterwards[2,3] experiments confirmed that the process conserved both the excitation energy and its wave-vector component parallel to the surface. However, the measurement and the calculation of evaporation probabilities are still problematic. A bolometer in the liquid can measure the flux of high-energy phonons, and it is found that they have a probability of ~ 0.1 of evaporating atoms[4], but the flux of rotons generated by a thin-film heater has defied direct measurement; they do not seem to be detected by bolometers. Attempts to deduce the absolute (R^+–atom) roton

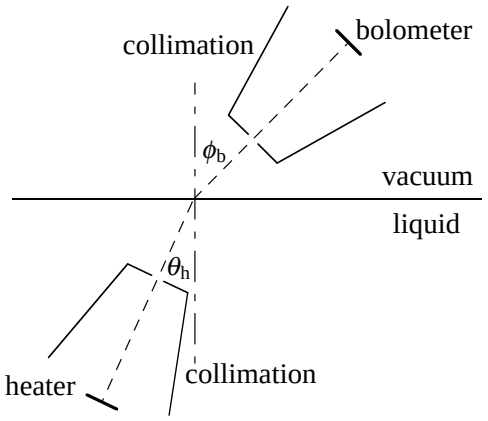

Fig. 1. Schematic diagram of a quantum evaporation experiment. The dashed line shows the path of the excitations.

evaporation probabilities by indirect means[5-7] seem to suggest a value, typically ~ 0.3, that increases with wave-vector.

The theoretical treatment of the quantum evaporation problem is also notoriously difficult. An ideal theory would be microscopic, self-consistent and reproduce the behaviour of the surface density profile as well as the bulk and surface excitations. At the time of writing, Campbell *et al.*[8] come closest to this ideal but their results, so far, are for $\theta_h = 0°$ and a rather thin helium film so their probabilities cannot be compared directly with experiment. Two other groups[9-11], using theories that describe simplified models, have recently calculated the probability $p(q,\theta_h)$ that an atom is evaporated at angle ϕ_b by an excitation of wave-vector magnitude q incident at angle θ_h to the surface (figure 1). This paper compares these two theories with published measurements[12,13] by incorporating their predictions for $p(q,\theta_h)$ into a recently developed high-precision simulation[14] of the experiments.

2. THEORETICAL MODELS

Guilleumas *et al.*[9] calculated evaporation probabilities using linearised time-dependent density-functional theory with the phenomenological 'Orsay-Trento' density functional. They found $p(q,\theta_h)$ to be independent of θ_h, and $p(q,\theta_h) \sim 0.5$ for phonons of energy $E/k_B \sim 10\,\mathrm{K}$. For R^+ rotons their $p(q,\theta_h)$ increases smoothly from zero near the roton minimum at $E/k_B \sim 8.7\,\mathrm{K}$, to nearly unity for rotons above $E/k_B \sim 12.5\,\mathrm{K}$ (figure 2).

Sobnack *et al.*[10,11] used a real-space Baeliaev formalism to derive equations of motion for the excitations that are valid in bulk helium, through the surface and into the vacuum. They found that $p(q,\theta_h)$ varies significantly with θ_h and that the most probable processes minimise the difference between the normal component of the incoming and outgoing particle wave-vectors, *i.e.* phonon-atom processes which

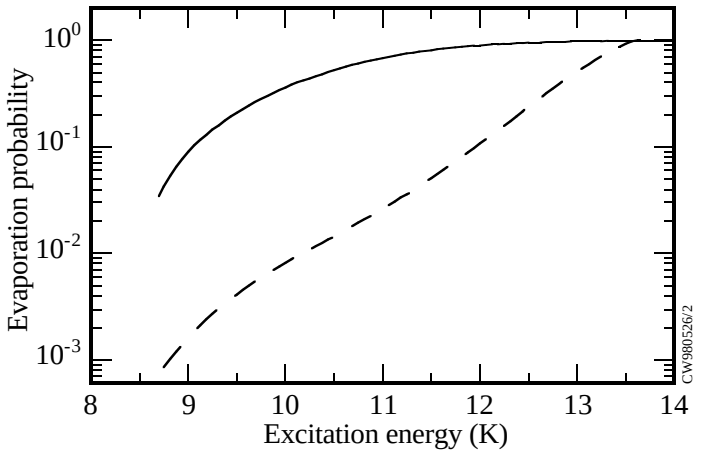

Fig. 2. Theoretical R^+ roton-atom evaporation probabilities. Guilleumas *et al.* (solid) and Sobnack *et al.* ($\theta_h = 14°$ dashed).

had a calculated probability of ~ 0.8 for phonons with $E/k_B \sim 10$ K. The form of figure 2 is also expected on these grounds – the difference in wave-vector that must be absorbed by the bulk liquid or surface reduces with increasing roton energy so the probability rises. In this paper the excitation energies arising from the Bruekner and Sawada pseudo potential used by Sobnack *et al.* have been rescaled by $\sim 4\%$ so that their roton-minimum matches the experimental value.

3. PHONON EVAPORATION EXPERIMENTS

The phonons used in quantum evaporation experiments are generated by electrically pulsing a thin-film gold heater. This generates a narrow beam of high-energy phonons with an approximately Gaussian distribution of energies[15], width $\Delta E/k_B \sim 0.3$ K, centred on $E/k_B = 10.2$ K. This narrow distribution of phonons that cause evaporation, and the small range of out-going atom angles, mean that the wave-vector dependencies predicted by the theories cannot be resolved by existing experiments. There has been one experimental estimate[4] of the absolute phonon-atom evaporation probability and this gave a value of ~ 0.1, significantly smaller than either of the theoretical calculations.

4. ROTON EVAPORATION EXPERIMENTS

Although for high-energy phonons created by thin-film heaters the generated spectrum is now known, there have been no successful attempts to measure it for rotons. The experiments are simulated by assuming that the number density *n(q)* of positive group-velocity rotons generated with wave-vector magnitude *q* is

$$n(q)\,\mathrm{d}q \propto \frac{q^{\lambda}\,\mathrm{d}q}{\exp\left(E(q)/T_{\mathrm{eff}}\right)-1} \quad \text{where} \quad \lambda = 2\,. \tag{1}$$

The shape of this distribution is dominated by the value of the parameter T_{eff} and is insensitive to the value of the density-of-states parameter for values $1 \le \lambda \le 3$. The value of T_{eff} is selected to fit the time-of-flight measurements; it increases with heater power and lies between 1.0 K and 1.5 K. It can be seen (*e.g.* figure 3) that, for the present purposes, the simulation is not sensitive to the precise value of T_{eff}. Figure 3 compares the roton evaporation measurements with a refined version[14] of the simulation used by Brown and Wyatt[12,13] to interpret their experiments which assumed $p(q,\theta_{\mathrm{h}}) = 1$. The refinements correct systematic errors that were previously unquantifiable and that affected the surface height, bolometer position and phonon spectrum. The main features of figure 3 arise from the collimation geometry and the kinematics of quantum evaporation, but most significant for this paper is the fact that atoms detected at large values of ϕ_{b} originate from rotons with relatively low energies. The measured values lie progressively below the simulation as ϕ_{b} increases above 40°, indicating that $p(q,\theta_{\mathrm{h}})$ increases with increasing q, in qualitative agreement with both theories.

Figures 4 and 5 show how including the calculated wave-vector dependencies affects the comparision between simulation and experiment. In the case of Sobnack

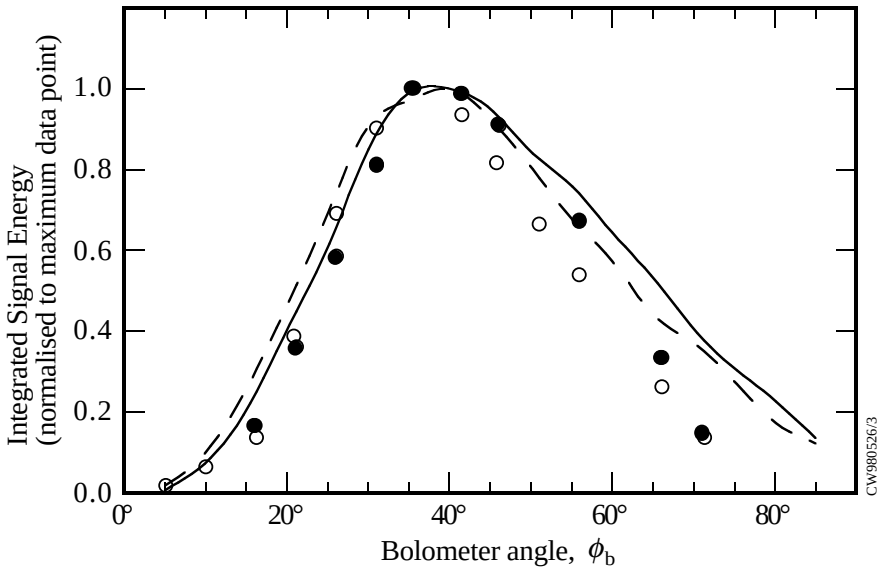

Fig. 3. The angular dependence of the R^+–atom signal energy when $\theta_{\mathrm{h}} = 14°$, integrated up to 160 μs after the heater input pulse. The experiments used two different heater powers, –24 dB (open circles) and –27 dB (full circles). The curves are simulations using $p(q,\phi_{\mathrm{h}}) = 1$ and injected-roton spectra at two characteristic temperatures, $T_{\mathrm{eff}} = 1.0$ K (unbroken) and $T_{\mathrm{eff}} = 1.5$ K (dashes).

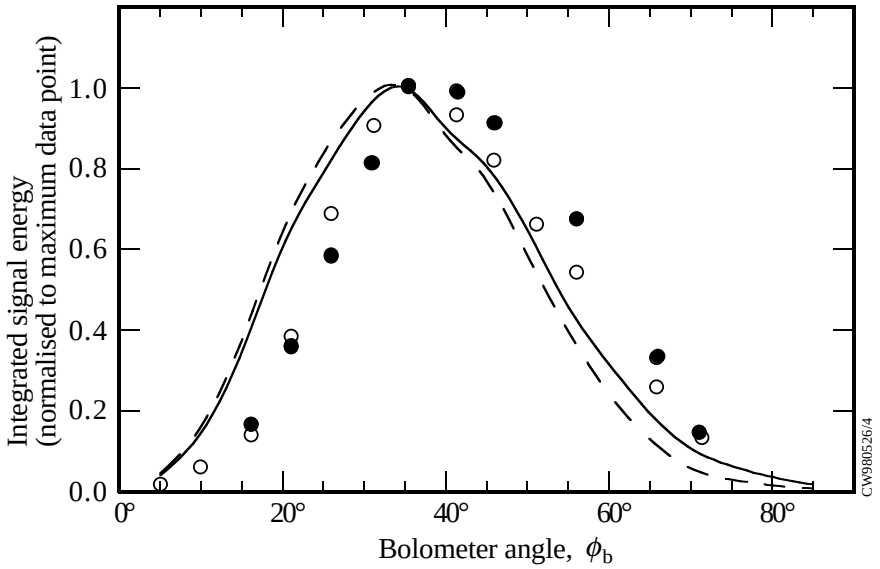

Fig. 4. As figure 3 but the simulation includes the wave-vector evaporation probabilities calculated by Sobnack *et al.* for incident angle ϕ_h.

et al. the shift in the angular distribution of evaporated atoms is large enough (~ 8°) to lie outside any plausible systematic error in the experiments or simulation. The Guilleumas *et al.* values for $p(q,\phi_h)$ seem to over-attenuate the low wave-vector rotons and it is fair to say that the fit is neither better, nor worse, than using a simulation that simply assumes $p(q,\phi_h)=1$.

5. CONCLUSIONS

Both theories considered in this paper over-estimate the phonon-atom evaporation probability suggesting that the neglected processes (*e.g.* ripplons and phonon-decay) may not be insignificant after all. Neither theory is entirely satisfactory in all respects: the roton-atom evaporation probabilities obtained by Guilleumas *et al.* is closer to the experiments but sacrifices locality in the surface region[10,16]; the microscopic theory of Sobnack *et al.* predicts probabilities that do not agree satisfactorily with experiment. Clearly more work, both to develop the theories and to improve the precision of the experiments, is urgently required.

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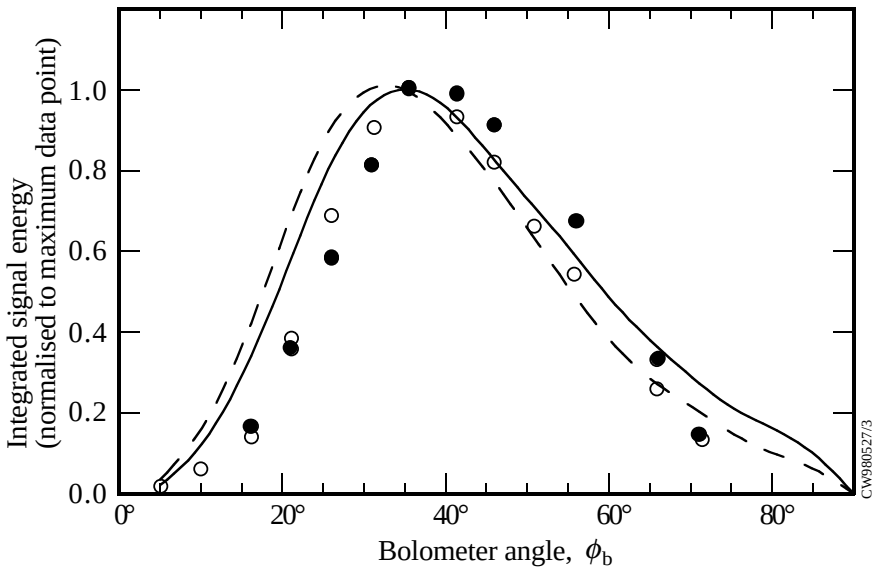

Fig. 5. As figure 3 but the simulation includes the energy-dependent evaporation probabilities calculated by Guilleumas *et al.*

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