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VIEWPOINT

Atoms to quanta—quantum evaporation and condensation

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Conceptually simple experiments are always appealing. A classic example is the photoelectric effect—being the first demonstration of *photons* and the foundation of particle–wave duality and quantum physics. Light waves carry quantized energy and momentum. The analogous quantization of sound waves in condensed matter into *phonons*, with quanta of energy and momentum, is straightforward. A very direct confirmation of this quantization comes from the *quantum evaporation* of helium atoms from the surface of superfluid helium by experimentally generated phonons, or other ballistic excitations (see figure 1) in the liquid, in a one-to-one process of energy and momentum transfer from quanta to individual atoms.

This beautiful idea was first proposed by Anderson in 1969 [1]. In 1978 Balibar *et al* [2] showed that evaporation of atoms by rotons in helium occurred, but they did not demonstrate the kinematics of the quantum process. This was done later by Adrian Wyatt and his group at Exeter University, UK in a remarkable series of experiments on the quantum evaporation of atoms from the superfluid ground state by elementary excitations in superfluid ^{4}He (both rotons and phonons). Mark Brown and Adrian Wyatt gave a full account in 1990 [3], followed by a new analysis by Charles Williams in 1998 [4].

A key feature of this phenomenon is that the quantum evaporated atoms come directly from the Bose–Einstein condensate (BEC) of the superfluid, in which the atoms have zero momentum. Hence they do not contribute to the momentum of the evaporated atoms. Although only some $10 \pm 1.5\%$ of the helium atoms are in the zero-momentum and coherent BEC [5] (this is less than 100% because of interactions between the helium atoms) they dominate in the evaporated atomic beam as detected, which has a very narrow angular distribution. This gives direct evidence for the presence of the condensate at the surface of the superfluid helium [6]. Atoms evaporated from the non-condensate fraction would produce a very diffuse atomic beam and have not yet been observed.

In this issue of *J. Phys.: Condens. Matter* [7], Mark Brown and Adrian Wyatt have now systematically explored the physics of the inverse effect of *quantum condensation*, first observed in 1977 [8]. An atom incident on the helium surface falls into the BEC and its kinetic energy and momentum, plus the binding energy, are transferred to a single quantum excitation. This simple idea reveals a wealth of experimental physics. A pulsed heater above the liquid produces a collimated beam of helium atoms, which impinge on the surface. The resultant excitations propagate through the superfluid at 80 mK and are detected by a superconducting Zn bolometer which measures the time-of-flight and the energy received. Three independent channels for energy transfer have been observed.

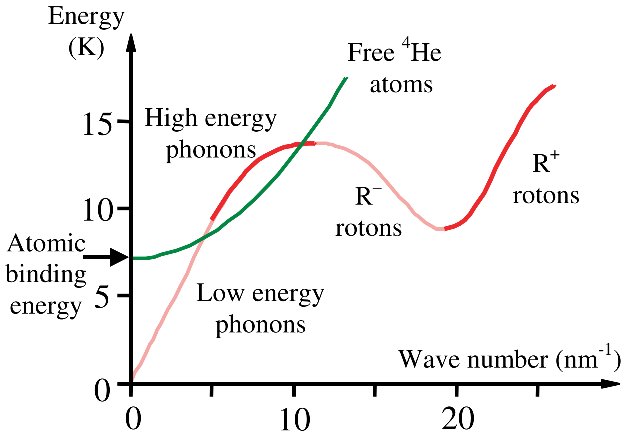

Figure 1. The dispersion curve of the excitations in superfluid helium shows the four types of excitations from the ground state: (a) low-energy phonons, (b) high-energy phonons, (c) R$^-$ rotons (with negative group velocity) and (d) R$^+$ rotons. High-energy phonons, with energy >10 K, are stable and can be created by the up-conversion of low-energy phonons. The parabolic line shows the energy of the free ^{4}He atoms in the vapour, starting from the atomic binding energy in the liquid at 7.16 K. Quantum evaporation and condensation conserve energy and the momentum parallel to the liquid surface.

(This figure is in colour only in the electronic version)

The first comes from the direct one-to-one quantum conversion from atoms to R$^+$ rotons. This is an exciting result in two ways: first Brown and Wyatt estimate that these rotons are created by atomic quantum condensation with a high probability of 44% (for a particular geometry). Secondly, R$^+$ rotons have not previously been unambiguously detected by a bolometer in the liquid itself (as opposed to indirect detection via the roton evaporation of atoms). They conclude that in earlier experiments with both heater and bolometer in the liquid the R$^+$ rotons were masked by the flux of low-energy phonons. It is also interesting that no signal can be attributed to the generation of R$^-$ rotons, in line with the low probability of evaporation from R$^-$ rotons [3].

The second channel comes from the one-to-one conversion of incident atoms, with kinetic energy >2.84 K, to stable, ballistic phonons, with high energies >10 K. This gives a narrow angular distribution of phonons and a small time dispersion. The signal disappears for temperatures above 150 mK, as the phonons are strongly scattered by thermal phonons. However, the conversion probability is estimated as less than 1%—very much smaller than the theoretical estimates [9].

In the third channel, the atoms excite multiple ripplons on the helium surface. These non-equilibrium excitations rapidly come into internal thermal equilibrium and then decay into low energy phonons in the bulk liquid. Over a typical transit time (50 μs) from source to bolometer, the phonon energy flux closely follows the incident atomic energy flux. This is the dominant channel for condensation, with a probability of 55%. However, as the atomic beam intensity increases, the high ripplon density corrugates the superfluid surface, which ‘spoils’ the translational symmetry and hence broadens the quantum condensation channels via high-energy phonons and rotons.

Brown and Wyatt present a coherent and convincing picture of the kinematics of atomic quantum condensation on helium and give new estimates of the probabilities for evaporation and condensation through the various channels, although not always in agreement with theoretical calculations [9]. They clearly show how it works!

So where next? There are some exciting possibilities and directions in which the understanding of quantum evaporation and condensation can play a crucial role and in which further work is required. The most ambitious experimentally is the helium-roton observation of neutrinos, or HERON, project [10] at Brown University, Providence, RI, USA, to create a solar neutrino detector using superfluid helium as a target. The concept is that an incoming neutrino, generated by p–p or Be^7 reactions in the Sun, scatters from an electron in the helium, producing a recoil electron which stops in the liquid within some 2 cm, producing ultraviolet (UV) radiation through scintillation from excited dimers as well as phonons and rotons. The excitations travel to the helium surface to eject atoms by quantum evaporation. Prototype experiments have measured both atomic and UV pulses from the same event on a time-resolved bolometer. This enables the position of the event to be determined, essential for background discrimination and energy reconstruction. A 5 m cube of helium would form the full detector. Design and development work is proceeding. However, absolute values of the evaporation and condensation probabilities and their energy dependences are still not known or understood at the precision needed for effective design. For instance, the high-frequency phonon channel should be much more significant than it appears experimentally.

A key experiment to elucidate the absolute probabilities has been the recent observation of the transmission of energy through a 190 μm thick suspended slab of superfluid helium [11]. An atom incident on the upper surface can condense into an R^+ roton, which travels through the liquid to evaporate an atom from the lower surface and is detected by a bolometer. The overall probability of the atom $\rightarrow$ R^+ roton $\rightarrow$ atom channel is surprisingly high at $15 \pm 1\%$.

It has also been suggested [12] that another channel for transmission through a suspended helium slab could be directly via the condensate itself, without any intermediate excitation. The slab of helium would then essentially be 'transparent' to ^{4}He atoms, with a transmission time of the order of a picosecond, from the uncertainty principle, which does not depend on the speed of sound (which travels only 0.24 nm in 10^{-12} s). The most striking theoretical prediction is that this time would be independent of the thickness of the slab, even for macroscopic dimensions (a slab of helium 1 m thick has been simulated!), though retardation effects should limit the effective speed to the speed of light. This would be spectacular indeed, but the hyperfast condensate channel would be difficult to distinguish experimentally from transmission via excitations for realistic slab geometries.

Another point of interest is the evaporation of ^{3}He atoms from the surface of ^{3}He–^{4}He [13]. Phonons evaporate both ^{3}He and ^{4}He atoms with equal probability but, surprisingly, the roton evaporation rate of ^{3}He atoms is less than 2% of the rate for ^{4}He atoms. This may even help to illuminate the long-standing problem of 'What is a roton?'.

Liquid helium is, of course, not the only BEC, and quantum evaporation is a hot topic in quantum atomic gases. In particular, recent experiments [14] have shown that condensed BEC gases can become unstable, with the rapid emission of bursts of atoms. The exact origin of this effect is under debate [15], but is probably due to time dependence in the wavefunctions or the scattering length of the trapped atoms, rather than via collective excitations. It has also been suggested that these instabilities could shed light on the inflationary epoch of the early universe and lead to laboratory cosmology. Further experiments and theories are sure to follow. Quantum evaporation and quantum condensation will remain fascinating phenomena.

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