Quantum mechanics

Whistles from superfluid helium

Peter McClintock

On page 449 of this issue¹, Pereverzev *et al.* report mechanical oscillations spontaneously generated by two weakly coupled volumes of superfluid ^3He —providing a direct demonstration of its large-scale quantum behaviour.

At very low temperatures all materials tend to fall into highly ordered states. Most commonly, this order takes the form of perfect crystals, but there are exceptions. Most strikingly, the two isotopes of helium (^3He and ^4He) never solidify at all under their vapour pressures. Rather, they stay liquid to the lowest temperatures attainable, and are assumed to remain so right down to absolute zero.

This is baffling at first sight, because liquids are usually disordered, whereas the third law of thermodynamics says that, as the temperature tends to zero, the entropy of any system (that is, its disorder) should decrease towards a constant value that can be taken as zero. But ordering does also occur in the liquid heliums, albeit in momentum space rather than real (cartesian) space: they both undergo a form of Bose–Einstein condensation, in which the ^4He atoms (or pairs of ^3He atoms) all fall into the same quantum state, described by a macroscopic wavefunction that fills the entire volume of liquid.

By analogy with the microscopic worlds of atoms or electrons, conditions at any point in the liquid are determined by a wavefunction. Liquid motion is specified by the relative phases of the wavefunction at different points: if its phase is the same everywhere, the liquid is stationary; if in a particular direction the phase progressively advances, then the liquid is flowing in that direction. All of this makes good sense in relation to a single bath of liquid helium, or to the electron gas (also described by a macroscopic wavefunction) in a single piece of superconducting metal. But what happens when there are two separate baths, or two separate pieces of superconductor, and they are brought together?

Based on ideas introduced by Josephson², Anderson³ and Feynman⁴, one can expect a variety of counter-intuitive and very striking phenomena to occur when two separately phase-coherent systems of this kind are weakly coupled together. One of these, the a.c. Josephson effect, consists of an oscillatory flow of particles to and fro through the weak link coupling the two systems. It occurs when the chemical potential μ (an average energy per particle) differs on each side. In the case of weakly coupled superconductors, the effect can be detected through the electromagnetic radiation that is created by the

oscillatory current of negatively charged electrons. It is inherently much harder to demonstrate in liquid helium, partly because the oscillatory current is neutral and therefore creates no electromagnetic radiation, and partly because the weak link between the baths has to be made extraordinarily small.

Pereverzev *et al.*¹ have created their weak link by using modern silicon microfabrication techniques, enabling them to construct 100-nm-diameter apertures in a 50-nm-thick sliver of silicon nitride. The small diameter and length are crucial to success: unless they are both comparable with, or smaller than, the healing length ξ of the superfluid (the minimum length over which the wavefunction can vary significantly), the aperture cannot be expected to function as a weak link. Given that $\xi \sim 0.1$ nm for ^4He , and ~ 50 nm for ^3He , it is clear that the state-of-the-art Berkeley technology is just good enough to see Josephson effects in superfluid ^3He . Because oscillatory flow in such a tiny hole would be so slight as to be undetectable, they used 4,225 identical holes, hoping that this would amplify the effect.

The silicon chip with its tiny holes was placed in the pill-box-shaped cell sketched in Fig. 1b on page 449¹. A 'soft membrane' divides the cell into inner and outer chambers, and can be moved by changing the voltage on an electrode, thereby applying an electrostatic force. Its position can be detected by means of a d.c. SQUID (a superconducting quantum interference device, used here as a position transducer of extreme sensitivity). Following a change in the position of the soft membrane, two things happen. First, the tiny change of pressure of the helium in the inner reservoir, as compared with that in the outer one, will change their relative values of μ , leading to oscillatory flow through the apertures. According to the Josephson relation, its frequency should be 183.7 kHz Pa⁻¹ for ^3He . Second, superimposed on the oscillation, there will be a steady flow through the apertures that reduces the pressure difference, leading to a continuous decrease towards zero in the frequency of the oscillatory flow.

The experimenters found that the amplified output of the displacement transducer, passed to audio headphones, could be heard as a 'whistle' of steadily decreasing pitch—precisely what was expected. Remarkably, it was the discrimination and flexibility of the human ear that led to the initial discovery. Only later were the authors able to make quantitative measurements of the frequency as a function of pressure difference between

100 YEARS AGO

One is apt to forget how strong is the instinct to shout and sing, laugh and cry. It is especially noticeable in the savage and in the child. If these instincts are unduly repressed in the child, he is sure to suffer. Crying should certainly be restrained within limits, but there can be no doubt that it is primarily physiological, not only favouring the proper expansion of the lungs and accelerating the circulation, but deadening the effects of pain and relieving nervous tension (especially in woman). Rosbach thinks it not improbable that many evils which manifest themselves in later life, such as chlorosis, contracted chest and the phthisical habit, "may take their origin in the practice of mothers to stop their infants from screaming by soothing them to sleep in their arms or by stupefying rocking in the cradle." ... It is well known that children show a strong instinct to chatter and sing the first thing in the morning, and it should be allowed full vent as far as is practical. The shouting which young people indulge in during their play is quite remarkable and is manifestly physiological. The same tendency to shout is observed in young adults, especially among the poorer classes in holiday time. Though from the physiological point of view justifiable, and even beneficial, the noises they make are certainly not always pleasing, especially to the sensitive nerves of the cultured, amongst whom this instinct is consequently suppressed...

From *Nature* 29 July 1897.

50 YEARS AGO

In the course of cytological investigations for the establishment of the chromosome atlas of the endemic flora of Portugal, we found in *Luzula purpurea* Link – a rare annual species only known from Portugal, Madeira and the Canary Islands – the diploid number $2n=6$. Besides their low number, the chromosomes of this species seem to be provided with two centromeres, one placed at each end of the chromosome. No median, sub-median or sub-terminal constriction could be distinguished either in mitotic or meiotic metaphases. ... This appears to be the first time such chromosome behaviour has been found in plants, and we think it may be related to what Toledo Piza reported for the Brazilian scorpion *Tityus bayensis* Perty and for some Hemiptera. From *Nature* 2 August 1947.

the reservoirs. Gratifyingly, these fall on a straight line whose gradient agrees with the theoretical prediction based on the Josephson relations.

The way is now open for seeking other mechanical macroscopic quantum phenomena and applications of the Josephson relations in superfluid ^3He — the mechanical analogues of electrical effects in superconductors — and, perhaps, for developing

a pressure transducer of extraordinary sensitivity. □

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3. Anderson, P. W. in *Lectures on the Many-Body Problem* (ed. Caianello, E. R.) (Academic, New York, 1964).
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Cellular secretion

Now you see it, now you don't

W. J. Betz and J. K. Angelson

'Seeing is believing' is a reasonable guide for everyday experience. But when looking at the events that occur in living cells — events that must be observed through a light microscope — 'seeing is belying' may be a better aphorism. This is partly because photons (the fundamental unit of light) peek around edges, to diffract and blur an otherwise crisp image. Now, on pages 474 and 478 of this issue, Steyer *et al.*¹ and Ryan *et al.*² extend our ability to image individual secretory granules and vesicles in living cells, and they reveal new information about exocytosis and granule transport.

Because of optical diffraction, the smallest membrane-bound cellular organelles (such as synaptic vesicles) would appear larger than life, if they were visible at all. It's a bit like looking at a tennis ball through fogged glasses, and seeing instead a fuzzy football. In fact, it's much worse — imagine looking into a bucket of tennis balls, each one of which is transparent. This describes the biological challenge that has been elegantly addressed, and met, in these two very different papers. Ryan *et al.*² stained one (or a few) synaptic vesicles and illuminated the entire cluster (Fig. 1), whereas Steyer *et al.*¹ stained all secretory granules in chromaffin cells, but illuminated only a few (Fig. 2).

Until the early 1980s, about the only method that was suitable for studying secretion in individual living cells was the intracellular recording of synaptic signals. Then, three new techniques were developed which allowed secretion to be measured in isolated cells — a postsynaptic detector cell was no longer required. Patch-clamp capacitance³ detects exocytic and endocytic events by electrically measuring the surface area of a cell; amperometry⁴ detects secretions using a carbon electrode positioned near the cell; and optical microscopy is useful for tracking organelles labelled with fluorescent dyes, particularly dyes that are taken up in an activity-dependent fashion^{5–7}.

Staining a single synaptic vesicle is no trick, but imaging and identifying it is. A single electrical stimulus applied to a nerve terminal usually releases about one quantum

of transmitter⁸. This probably reflects exocytosis of one vesicle (from the many in the terminal), which is then endocytosed and recycled into the vesicle cluster. If the fluorescent dye FM1-43 is present in the bathing fluid during the endocytic step, the recycled vesicle becomes stained with a few hundred dye molecules⁹.

Imaging the stained vesicle is then the challenge. Ryan *et al.*² took pains to reduce background fluorescence, used a bright light for imaging (to reduce noise), and then took three pictures of hippocampal cultures in which synaptic contacts were abundant (Fig.

1). Image number one (see Fig. 1b on page 479) was obtained after giving one, or a few, electrical shocks in the presence of FM1-43, then washing thoroughly to get rid of any dye not taken up by endocytosis. This image gave a lot of really dim spots. Image number two (Fig. 1d on page 479) was acquired after exhaustive stimulation designed to release and wash away any FM1-43 that was taken up initially by recycling vesicles. Naturally, this image was even dimmer than the first. Image number three (Fig. 1g on page 479) was obtained after re-staining with FM1-43 using many electrical shocks to label all of the synaptic vesicles, so it was easy to identify the position of synaptic sites.

For the analysis, Ryan *et al.* worked backwards (see also ref. 10). They started with image number three to identify synaptic sites, then they analysed the data from images one and two at those positions. Their results indicated 'quantal' staining of synaptic sites — fluorescent spots stained after one or a few shocks showed mean brightnesses of about 0, 60, 120 or 180 photoelectrons at different synapses, probably reflecting the uptake of FM1-43 by 0, 1, 2 or 3 recycling vesicles, respectively. (Individual vesicles in the bright clusters could not be identified spatially because diffraction blurred them together.) Fluorescence at the fully stained

Figure 1 Stain a few vesicles, illuminate all. Ryan *et al.*² stained one, or a few, synaptic vesicles with the fluorescent dye FM1-43, by giving 1–3 electrical shocks to hippocampal neurons in culture. The brightness of different synaptic sites varied in a stepwise fashion, each step representing one stained vesicle.

Figure 2 Stain all granules, illuminate only a few. Steyer *et al.*¹ stained all secretory granules in a chromaffin cell with acridine orange, and then illuminated only those granules that lay close to the coverslip by using the evanescent wave from a reflected laser beam.