Quantum Oscillations Ring Out Loud and Clear

It took a sophisticated instrument—the human ear—to alert Berkeley researchers that the quantum oscillations they sought were indeed coming from their container of superfluid helium-3. Their experiment is a dramatic demonstration of the AC Josephson effect in superfluids.

At the Symposium on Quantum Fluids and Solids in Paris this past July, Richard Packard of the University of California, Berkeley, entertained the audience by playing a brief recording: The sound on the tape began as a high-pitched whistle and slid down the frequency scale over a period of a few seconds. What people were hearing was the sound of a superfluid surging rapidly back and forth through the holes in a membrane[1] in response to a pressure difference applied across the membrane. This phenomenon is the superfluid analog of the AC Josephson effect for superconductors, according to which a supercurrent will oscillate across a thin tunnel junction under an applied voltage. (A French group had earlier reported evidence of this phenomenon.[2]) In addition to recording the sounds of the mass oscillations, Packard and Séamus Davis and their respective groups at Berkeley found that the measured frequencies agreed with those predicted by the Josephson equations.

In 1962, Brian Josephson predicted the remarkable macroscopic interference phenomena that bear his name, and the concepts were soon extended to superfluids as well as superconductors. As applied to superfluids, the Josephson effects comprise two equations that describe the behavior of two reservoirs separated by a weak link—that is by any barrier or restriction, such as a membrane with a hole in it, that allows a weak coupling between the macroscopic wavefunctions on either side. Even in the absence of a pressure drop across the weak link, a mass current can flow. That's the DC Josephson effect. The first of Josephson's equations states that the magnitude of the current density J will depend on the phase difference $\Delta\varphi$ between the superfluid wavefunctions on either side of the weak link:

$$J = J_c \sin(\Delta\varphi), \qquad (1)$$

with J_c the maximum current density.

If there is a pressure difference ΔP across the membrane, the phase difference $\Delta\varphi$ will change at a rate that depends on the applied pressure, as given by

$$\partial(\Delta\varphi)/\partial t = -m(\Delta P)/\rho\hbar, \qquad (2)$$

where ρ is the mass density and m is the mass of one ^{4}He atom or two ^{3}He atoms.

If the pressure difference is constant, the phase difference will grow linearly with time, and, according to the first equation, the current density will vary sinusoidally with a frequency $f = m\Delta P/\rho h$. The appearance of this alternating mass current is known as the AC Josephson effect.

The efforts to find the superfluid Josephson effects date back to the mid-1960s, when Philip W. Anderson (then at Bell Telephone Laboratories), who had helped to generalize Josephson's ideas and to demonstrate the Josephson effect experimentally, joined with Paul Richards in a search for the predicted oscillations. But neither they nor others were successful. As Anderson says now, "we were excessively hopeful."

The problem in those early days was that the technology required to do the experiment was not yet in hand. What was needed was a way to put a submicrometer-sized hole in a very thin membrane. The small hole is required because the mass oscillations are predicted to appear only when the hole size is on the order of or smaller than the so-called healing length—that is, the minimum distance within which there can be a significant variation in the superfluid wavefunction. For helium-4, that distance is on the order of 0.1 nm at very low temperatures; for superfluid helium-3, which was not even known until the early 1970s, the low temperature limit of the healing length is considerably longer—about 50 nm—but still requires a very small hole. Also needed was a means to detect extremely small mass currents.

Staircases and phase slips

Around the mid-1980s, researchers began to renew their quest to see Joseph-

ESSAY CONTEST:
Can You Write Physics Tomorrow?

May 1998 marks the 50th birthday of PHYSICS TODAY. You can join in the celebration by writing your own "Search and Discovery" story. But not about current research. Imagine that you are writing it in 2008 or 2023 or even 2048. Your essay should report on an exciting discovery, advance in physics (where physics is broadly defined) or a new technology.

A distinguished jury of physicists will select the winners in the final round of judging. The jury members will include Roger Blandford (California Institute of Technology), John Hopfield (Princeton University), Leo Kadanoff (University of Chicago), Daniel Kleppner (MIT), Burton Richter (Stanford Linear Accelerator Center) and Jerry Woodall (Purdue University). The winning stories will be published in PHYSICS TODAY, probably in the May 1998 issue.

Your entry should be at most 2000 words long and should not have been published previously. Be sure to specify the year of your "Search and Discovery" story. Include your complete mailing address, daytime phone number, and fax or e-mail address if available.

You may only submit one entry.

The decisions of the jury and PHYSICS TODAY are final.

The winners will be asked to sign the usual AIP transfer of copyright agreement.

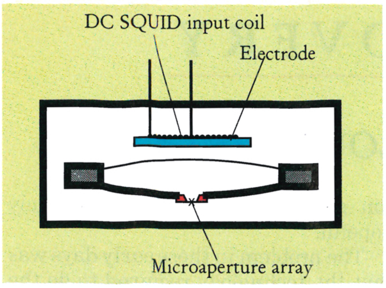
Entries must be received by 1 December 1997.

Entries will not be returned.

Employees of the American Institute of Physics and regular PHYSICS TODAY contributors are not eligible for this contest.

Entries should be sent to:

Search and Discovery Essay Contest
Physics Today
American Institute of Physics
One Physics Ellipse
College Park, MD 20740-3843



SUPERFLUID HELIUM-3 oscillated across a microaperture array (red) between the inner and outer cells sketched here when pressure was applied to the top membrane. The oscillating current is analogous to the AC supercurrent flowing across a Josephson tunnel junction under a constant applied voltage. The oscillations vibrate the top membrane, which is coated with a superconducting thin film; they are sensed by a SQUID magnetometer. (Adapted from ref. 1.)

son effects. Their efforts paid off with the results of Olivier Avenel of the Center for Nuclear Studies in Saclay, and Eric Varoquaux of the University of Paris—South in Orsay, France, who found staircase-like structures in the response of superfluid ^{3}He and ^{4}He that are reminiscent of the stepwise behavior seen in radiofrequency SQUIDs. From their observations of these steps in ^{3}He and their detailed fits to the staircase shapes at different temperatures, the Saclay–Orsay team inferred that superfluid ^{3}He was exhibiting both the AC and DC Josephson effects.[2]

For their experiments, Avenel and Varoquaux built a hydrodynamic resonator with inner and outer cells of superfluid. Within the top of the inner cell were two parallel openings: the weak link—a small slit measuring 0.3 μm wide and 5 μm long—and a much larger channel to provide a return path for the superfluid. The researchers drove the superfluid at a constant frequency through a soft membrane on the bottom of the inner cell and monitored the maximum amplitude at which the membrane vibrated. The peak amplitude moved in a stepwise fashion as the drive increased, having successive flat portions where it changed little and steep portions where the response changed abruptly.

The Saclay–Orsay team saw stepwise behavior in both ^{4}He and ^{3}He but with variations in shape that revealed the different underlying mechanisms. When the healing length is much smaller than the slit-width—as it is in ^{4}He and in ^{3}He at low enough temperatures—tunneling is not likely to be involved. In those cases, Avenel and Varoquaux attribute the observed steps to phase slips in the superfluid. Specifically, the quantum phase of the superfluid across the weak link changes by 2π whenever a vortex crosses the streamlines of flow through the orifice.[3] Avenel told us that the behavior reflects the basic periodicity of the current–phase relationship (see equation 1) but does not demonstrate any departure from linearity, which would be seen in an ideal Josephson junction.

When the temperature in ^{3}He is close enough to the superfluid transition temperature that the healing length is relatively large, the aperture acts more like the ideal tunnel junction that Josephson assumed. As Avenel and Varoquaux dropped the temperature in ^{3}He below the transition temperature, they saw the full range of behavior, from that which characterizes genuine tunneling to that which marks departures from such a weak link. Specifically, the steps in the staircase patterns are more rounded close to the transition temperature and become sharper at lower temperatures. Avenel and Varoquaux fit their data quantitatively with a model that allows for the departure of the weak link from an ideal tunnel junction.[4] From these fits, they concluded that they were seeing both the AC and DC Josephson effects in superfluid ^{3}He.

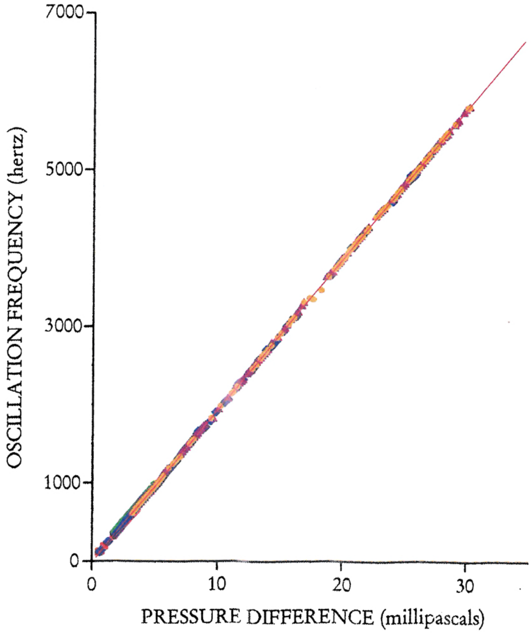
The new Berkeley experiment

The approach of the Berkeley group is a bit easier to understand. They measured the relation between the pressure difference and the oscillation frequency in superfluid ^{3}He and compared it to the frequency $f = m\Delta P/\rho h$ predicted by equation 2 in the case of a constant ΔP. Packard, Davis and their coworkers—Sergey V. Pereverzev, Alex Loshak and Scott Backhaus—used an experimental cell like the one diagrammed on this page, with an inner cell nested inside an outer cell, and both cells filled with superfluid. The inner cell was bounded on top by a soft membrane, which was used to both excite and sense the mass oscillations. Its bottom surface was a stiff membrane in which the weak link was embedded. In the Berkeley experiment, the weak link was a silicon nitride membrane with not just one hole but 4225 apertures, separated by about 3000 nm. Each aperture was 100 nm in diameter, comparable to the healing length of about 50 nm expected in the experiment.

An electrode above the soft membrane was used to apply a pressure difference between the fluid in the two cells. The subsequent vibrational motion of the fluid was detected by changes in the magnetic induction through the coils of a SQUID magnetometer as the membrane moved (the top surface of that membrane bore a thin coat of lead, which resisted the penetration of the magnetic field of the superconducting coils). This very sensitive detector is based on one developed for gravity-wave detection[5]; the Saclay–Orsay team used a similar detector.

With this apparatus, the Berkeley collaboration applied a stepwise increase in pressure and measured the position of the membrane as mass flowed through the weak link until the pressure was again equalized across

FREQUENCY of a superfluid oscillation varies linearly with the pressure difference across an array of micrometer-sized holes, with a slope consistent with the Josephson equations. Included in the plot are data taken at five different temperatures. (Adapted from ref. 1.)



the membrane. The membrane position at each moment was a measure of the pressure drop ΔP. At the same time, the vibrations of the membrane reflected the mass current oscillations. At first, Packard, Davis and company could not distinguish the oscillations from the background noise just by looking at the oscilloscope trace from their detector. But when they connected the output to audio headphones, their ears were able to sort out the signal. Davis says they were ecstatic when they first heard the tone. They hadn't expected that the sound would be so clear.

With the confidence that the desired signal was there, the Berkeley collaboration was then able to extract the graph of the frequency of the oscillations as a function of pressure, as shown in the figure on page 18. All the data from five temperatures fall on a nice straight line, whose slope is close to the expected value of $m/\rho h$.

Each of these frequencies was determined by averaging over very short time intervals because the pressure did not remain constant at one value for long; the researchers applied a pressure pulse and listened to the frequencies drop down the scale as the pressure decayed.

Although the published data do not determine the Josephson current–phase relationship embodied in equation 1, Packard, speaking at the Paris symposium, discussed more recent work in which the Berkeley team had made a direct measurement of this relationship.

An intriguing—and rewarding—aspect of their results is the demonstration that the separate flows through the thousands of apertures in the membrane apparently acted coherently: if they hadn't, the various oscillations would have cancelled one another out. The Berkeley researchers had gambled on their expectation that the array would act as a single coherent weak link, and that gamble paid off. It enabled them to effectively magnify the extremely faint signal one would hear through a single opening.

Barbara Goss Levi

References

1. S. V. Pereverzev, A. Loshak, S. Backhaus, J. C. Davis, R. E. Packard, Nature **388**, 449 (1997).
2. O. Avenel, E. Varoquaux, Jpn. J. Appl. Phys. **26**, Supplement 26-3, 1798 (1987); Phys. Rev. Lett. **60**, 416 (1988).
3. See, for example, P. W. Anderson, Rev. Mod. Phys. **38**, 298 (1966).
4. B. S. Deaver, J. M. Pierce, Phys. Lett. **38A**, 81 (1972).
5. H. J. Paik, J. Appl. Phys. **47**, 1168 (1976).

Exhaustive Searching Is Less Tiring with a Bit of Quantum Magic

The elementary particle of information used by modern digital computers is the bit—a register or memory element that can be in one of two distinct states, 0 or 1. But we live in a quantum world, and one can design computers in which each elementary unit of information is a quantum bit, or qubit, which can be in any superposition of two quantum states, $|0\rangle$ and $|1\rangle$. A quantum computer built with n such components could itself be in a superposition of 2^n distinct states, each splinter of the superposition performing its own computation in parallel with all the rest.

Quantum computers have been shown to provide a dramatic speedup over classical computers in solving problems by exhaustive searching. For example, the widely used 56-bit Data Encryption Standard could be cracked with a mere 200 million or so computations instead of about 35 quadrillion.

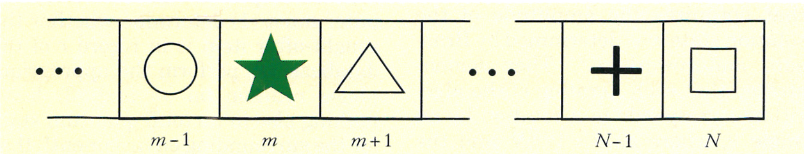
What computational magic could be performed on such a device? Three years ago, much interest in quantum computation was sparked when Peter Shor of AT&T Laboratories devised a quantum algorithm that could solve the factorization problem much faster than any known classical algorithm. Now, Lov K. Grover of Bell Laboratories, Lucent Technologies, has devised a fast quantum algorithm to search for an entry in an unordered database.[1] (See figure at right.)

"If quantum computers are being used a hundred years from now," said John Preskill of Caltech, "I would guess that they will be used to run Grover's algorithm or something like it." He calls Grover's algorithm "the simplest example of an interesting problem for which a quantum computer has a clear advantage (in principle) over a classical computer."

Furthermore, Preskill said, "the Grover algorithm, much more so than the Shor algorithm, can be adapted to many different computationally hard problems. In principle, the unsorted database search can be used to solve any NP problem—a problem for which the solution may be hard to find but is easy to verify. The database is all the trial solutions; we can invoke quantum parallelism to try them all at once and search for the one that works." If there is only one correct solution among N possibilities, an exhaustive search like this will typically take $N/2$ trials before the answer is found. By contrast, Grover's quantum algorithm almost certainly finds the correct answer in about $\sqrt{N}$ trials.

To get an idea of the significance of this, consider an example cited[2] by Gilles Brassard (University of Montreal): The widely used Data Encryption Standard relies on a 56-bit key. In "a classic scenario in secret intelligence," to crack the code one must try out keys from the $2^{56} = 7 \times 10^{16}$ possible keys. Classical methods will take, on average, about 3.5×10^{16} trials; Grover's algorithm will need only about 200 million. At a million trials per second, that's more than 1000 years versus less than 4 minutes.

The advantage of Grover's algorithm is known with certainty: The $N/2$ time needed on average by a classical algorithm cannot be improved by the discovery of some unexpectedly efficient algorithm. Furthermore, ear-



Searching an unordered database of N records for a unique item (represented by the green star in record m of the database) will take, classically, $N/2$ steps to have even a 50% probability of success. A quantum computer programmed with Grover's algorithm, however, achieves essentially 100% success in only $\pi\sqrt{N}/4$ steps, a dramatic speedup for large N. The algorithm can be used to achieve a comparable speedup in solving many other problems.