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Oscillatory motion

Quantum whistling in superfluid helium-4

Fundamental considerations predict that macroscopic quantum systems such as superfluids and the electrons in superconductors will undergo oscillatory motion when forced through a small constriction. Here we induce these oscillations in superfluid helium-4 (^{4}He) by pushing it through an array of nanometre-sized apertures. The oscillations, which are detected as an audible whistling sound, obey the so-called Josephson frequency relation and occur coherently among all the apertures. The discovery of this property in ^{4}He at the relatively high temperature of 2 K (2,000 times higher than the temperature at which a related but different phenomenon occurs in ^{3}He) may pave the way for a new class of practical rotation sensors of unprecedented precision.

The Josephson effects in superconductors have received attention both as an aid to scientific understanding and for their technological importance[1]. Analogous effects, including Josephson oscillations, have been observed[2,3] in superfluid ^{3}He below 1 mK. However, detection of oscillations at the Josephson frequency in superfluid ^{4}He has remained elusive until now, despite almost four decades of attempts[4].

Superconductors and superfluids are both described by a macroscopic wave function that includes amplitude and phase, ϕ. A chemical-potential difference, $\Delta\mu = \mu_2 - \mu_1$, between two baths of superfluid separated by an aperture causes the phase difference, $\Delta\phi = \phi_2 - \phi_1$, to change in accordance with the Josephson–Anderson phase-evolution equation

$$\frac{d\Delta\phi}{dt} = \frac{-\Delta\mu}{\hbar}$$

where $\hbar$ is Planck's constant (h) divided by 2π and where $\Delta\mu/m_4 = \Delta P/\rho - S\Delta T$ (and m_4 is the mass of the ^{4}He atom, ΔP is the pressure difference, ρ is the mass density, S is the entropy per unit mass, and ΔT is the temperature difference). A non-zero $\Delta\phi$ results in a superfluid current, $I(\Delta\phi)$, through the aperture. If $I(\Delta\phi)$ is periodic for 2π, a constant $\Delta\mu$ causes current to oscillate through the aperture at the Josephson frequency $f_j = \Delta\mu/h$. The periodicity in $I(\Delta\phi)$ can occur if the aperture acts like an ideal weak link[3,5], in which case $I(\Delta\phi) \propto \sin(\Delta\phi)$, or by the generation of 2π phase slips[6], in which case $I(\Delta\phi)$ is expected to follow a sawtooth waveform.

The experimental set-up is shown in Fig. 1a (for methods, see supplementary information). We used an electrostatically driven diaphragm[2] to apply an initial pressure step between two baths of superfluid separated by an aperture array. The array consisted of 65×65 nominally 70-nm apertures spaced on a 3-μm square lattice in a 50-nm-thick silicon nitride membrane. After the pressure step, fluid flowed through the array and the chemical-potential difference relaxed to zero. When the output of a diaphragm position sensor, which monitored fluid flow, was connected to a set of headphones, we heard a clear whistling sound that passed from high to low frequency (audio recording in supplementary information).

By using Fourier transform methods, we extracted the frequency and amplitude of this whistle as a function of time throughout the transient. Immediately after the pressure step is applied, the temperatures on either side of the aperture array are equal and the entire $\Delta\mu$ is determined by the initial pressure head, ΔP_0. Figure 1b shows that the initial frequency is proportional to the initial chemical-potential difference. The slope of the line agrees, within the systematic error of our pressure calibration, with the Josephson frequency formula ($f_j = m_4 \Delta P_0/\rho h$).

Oscillations resulting from 2π phase slips are expected to have a velocity amplitude $\kappa/2l$, where $\kappa = h/m_4$ is the circulation quantum and l is an effective length for one aperture[7]. If, in addition, the oscillation in each of the N apertures occurs coherently, the amplitude of the diaphragm-displacement Fourier component at f_j is

$$X_0 = \alpha \frac{\rho_s N \kappa a}{4\pi f_j \rho A l}$$

where A is the area of the diaphragm, a is the area of a single aperture, and ρ_s is the superfluid density. The factor α would be $2/\pi$ for a sawtooth waveform, or unity for a sinusoid of the same peak amplitude. We find $\alpha \approx 0.6$, independent of temperature in the range where, if T_λ is the superfluid transition temperature, $T_\lambda - T$ is between 1.7 and 2.9 mK.

We conclude that the oscillation is a coherent phenomenon involving all the apertures in the array, and is possibly sawtooth in waveform. This coherence is remarkable, because earlier work using a single aperture showed that thermal fluctuations in the phase-slip nucleation process destroy time coherence in the rate of phase slippage, so that no Josephson oscillation exists[8]. However, it seems that thermal fluctuations are suppressed for an array — an observation that calls for further investigation[9].

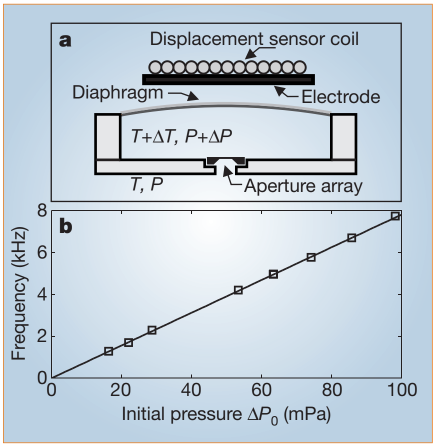

Figure 1 Quantum oscillations in ^{4}He. **a,** Experimental cell (see supplementary information for details). **b,** Whistle frequency plotted against the initial pressure, $\Delta P_0 = \rho\Delta\mu_0/m_4$. Temperature is in the range where, if T_λ is the superfluid transition temperature, $T_\lambda - T$ is 1.7–2.9 mK. A fit (solid line) to the data gives a slope of 78 Hz mPa^{-1}, with a systematic uncertainty of 20% arising from our pressure calibration. This agrees with the Josephson frequency relation $f_j = \Delta\mu/h$ value of 68.7 Hz mPa^{-1}. The oscillation is still present down to at least 150 mK below T_λ, where the healing length is much smaller than the aperture diameter and $I(\Delta\phi)$ is linear. The oscillation is presumably due to periodic 2π phase slips.

We have found that superfluid ^{4}He in an array of small apertures behaves quantum coherently, oscillating at the Josephson frequency. Because these oscillations appear in ^{4}He at a temperature 2,000 times higher than in superfluid ^{3}He, it may be possible to build sensitive rotation sensors using much simpler technology than previously believed[10–13]. This could find application in rotational seismology, geodesy and tests of general relativity.

E. Hoskinson, R. E. Packard,
Thomas M. Haard
Physics Department, University of California, Berkeley, California 94720, USA
e-mail: packard@socrates.berkeley.edu

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