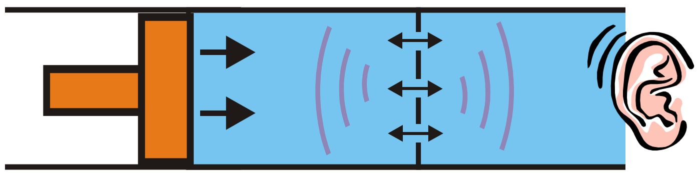
UNIVERSITY OF CALIFORNIA, BERKELEY

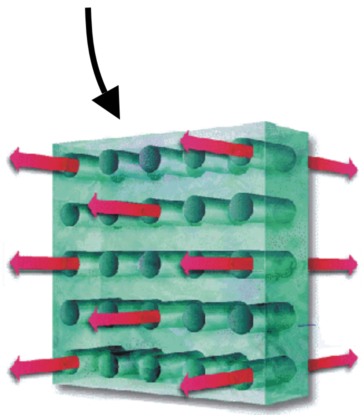
Discovery of Quantum Whistling in Superfluid ^{4}He

Richard Packard, DMR-0244882

Piston applies pressure

Superfluid "whistles" in aperture array

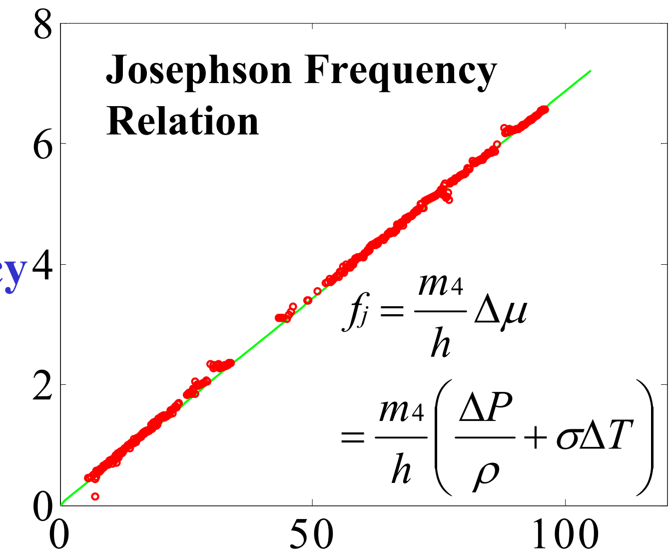




Aperture array: 4225 70nm diameter holes spaced 3μm apart

First observation of Josephson oscillations in ^{4}He!

Whistle Frequency f_j [kHz]



Chemical Potential ρΔμ [mPa]

m_4 = mass of ^{4}He atom

h = Plank's constant

$\Delta\mu$ = chemical potential

ΔP = Pressure

ΔT = Temperature

ρ = density

σ = entropy

Quantum Coherence: Each sound cycle is produced when the quantum phase of the superfluid across an aperture slips by 2π. Astonishingly, the signal from each aperture in the array adds coherently, magnifying the sound amplitude by 4225! This implies that thermal fluctuations are greatly reduced in an array compared to a single aperture.

Helium-4 is an amazing substance. Fill a balloon with it and the balloon floats. Breath it in and your voice squeaks. Cool it down to two degrees above absolute zero (–459 degrees Fahrenheit) and it undergoes a fascinating transition into a new form of matter called a superfluid. In the superfluid state, individual helium-4 atoms are no longer distinct particles. Instead they have all merged together into one big quantum wave function, which behaves in strange quantum mechanical ways.

The existence of the superfluid state of helium has been known for quite a while, but we are still discovering new things about its behavior. When superfluid helium is pushed through a microscopic hole, tiny vortices, like little tornadoes, are generated in the superfluid. What we have discovered is that these vortices are generated one after another, like clockwork, at a specific rate governed by something called the "Josephson Frequency Relation". The Josephson Frequency Relation is, amazingly, the same law that governs the behavior of superconducting Josephson Junctions, devices which form the basis of several important technological applications in superconducting electronics.

The clockwork generation of vortices produces a characteristic whistling sound – this effect was discovered by actually hearing this "quantum whistling" in a set of headphones. Furthermore, we discovered that if instead of a single microscopic hole you have an array of many holes, and you push the superfluid through this array, then when a vortex is generated in one hole, vortices are simultaneously, or "coherently" generated in all the the other holes. This quantum coherence means a large amplification of the signal is possible, bringing the practical application of this effect much closer to reality.

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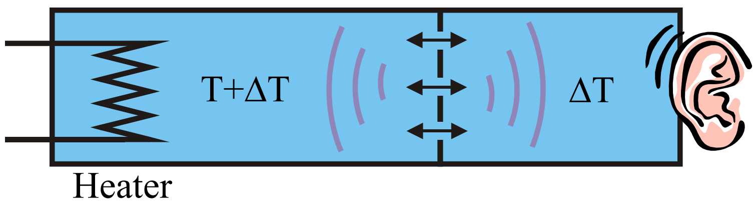
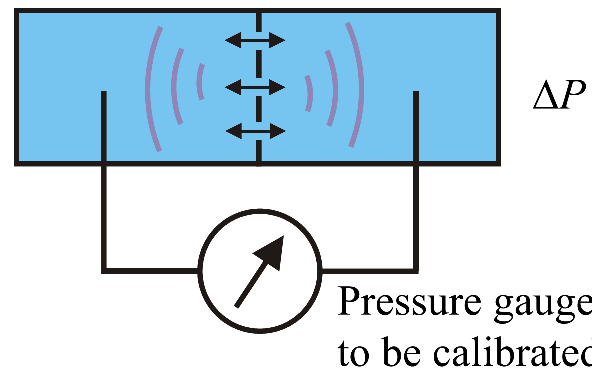
This is the first time a temperature difference ΔT has been shown to drive Josephson oscillations.



In analogy to the superconducting Josephson Junction voltage standard, a ^{4}He device could provide a practical pressure standard.



$$\Delta P = \rho \frac{h}{m_4} f_j$$

This discovery opens the way to the development of a practical superfluid gyroscope operating at 2K, a temperature 2000 times higher than previously demonstrated ^{3}He devices. Such a gyroscope could be useful for

- **Rotational Seismology**
- **Detection of underground nuclear explosions**
- **Corrections to the GPS navigation system**
- **Tests of General Relativity**

It turns out that quantum whistling in superfluid helium-4 can be driven not only by pushing the the superfluid through the array, but also by heating the superfluid on one side of it. This is the first time in any system that Josephson oscillations have been driven by a temperature difference. Not only is this an important scientific discovery in its own right, but it may prove to be the best way of operating a practical device.

Josephson oscillations in superconductors have already been put to use in many important technological applications. They are used to actually define the standard volt. In direct analogy, Josephson oscillations in superfluid helium could be used to define a practical pressure standard.

There are several other exciting possibilities for the practical application of the effect we have discovered. Already, a superfluid gyroscope has been demonstrated using superfluid helium-3. Such a device, using helium-4 instead, could be operated at a temperature 2000 times higher than the helium-3 device – this would be an enormous improvement in cost, complexity, and practicality. The superfluid gyroscope represents a new technology with the potential to revolutionize the field of rotational seismology. Rotational seismology is a new window into the structure of the Earth's crust. It could be used in a wide variety of applications such as the understanding and prediction of earthquakes, the detection of underground thermonuclear explosions, and improvement of the GPS navigation system.

The Josephson effect in superconductors lead to revolutionary technologies in superconducting electronics. The discovery of the quantum whistle in superfluid helium-4 paves the way toward the development of practical superfluid devices with potentially equal technological impact.