Superfluid helium quantum interference devices: present status and future prospects

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Abstract.
The development of superfluid weak links has led both to the discovery of new physical phenomena and also to the development of superfluid helium quantum interference devices (SHeQUIDs). We describe the physics underlying the SHeQUID and present a brief overview of the current state of this promising technology.

Superfluid $^4\text{He}$ and $^3\text{He}$ are described by the Landau two fluid model [1] augmented by a macroscopic wavefunction $Ψ = \sqrt{ρ_s}e^{iφ}$, where $ρ_s$ is the superfluid density and $φ$ is the quantum mechanical phase. When two such reservoirs are coupled weakly, various fascinating phenomena emerge. The superfluid mass current $I$ across the weak link is observed to be proportional to the sine of the quantum phase difference across the junction [2, 3, 4]:

$$I = I_0\sin\Delta φ.$$  \hfill (1)

This is analogous to the superconducting dc-Josephson equation [5]. The quantum phase difference $Δφ$ evolves according to the Josephson-Anderson phase evolution equation [6]:

$$\frac{dΔφ}{dt} = -\frac{Δ\mu}{h}. \hfill (2)$$

For superfluid helium, the chemical potential difference $Δμ = m(ΔP/ρ - sΔT)$. Here $m$ is the mass of the superfluid’s constituent particles (i.e. $^4\text{He}$ atoms or two $^3\text{He}$ atoms), $ρ$ is the fluid density, $s$ is the entropy per unit mass, and $ΔP$ and $ΔT$ are the pressure and temperature differences respectively [7].

When a constant chemical potential difference is applied across the weak link, one observes mass currents oscillating [8, 9] at the Josephson frequency $f_J = Δμ/ℏ$. For superfluid $^4\text{He}$, depending on the proximity to the superfluid transition temperature $T_λ \sim 2.176K$, the oscillations are due either to a dc-Josephson type current-phase relation ($I \propto \sin Δφ$) or to a linear current-phase relation with $2π$ phase slips [4]. These phenomena can be exploited to construct novel interferometer devices.

The weak coupling is established by joining the two fluids through an array of apertures. Apertures are $\sim 50nm$ in size, and 5,000-10,000 such apertures are fabricated in $\sim 50nm$ thick SiN membranes using e-beam lithography. $^4\text{He}$ experiments are typically carried out at $T_λ - T \leq 15mK$ to take advantage of the growth of superfluid healing length near $T_λ$. 

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Consider now a loop of superfluid interrupted by two weak link junctions as depicted in Fig. 1. When a chemical potential difference $\Delta \mu$ is applied across the arrays, the current oscillates through each junction as $I_{c, 1} \sin \Delta \phi_1$ and $I_{c, 2} \sin \Delta \phi_2$. The wavefunction of the superfluid in the torus is single valued. This implies that, integrating around the closed loop of the fluid, 

$$\oint \nabla \phi \cdot dl = \Delta \phi_1 - \Delta \phi_2 + \Delta \phi_{ext} = 2\pi n,$$

where $\Delta \phi_{ext}$ is some external phase shift induced in the system. Then the overall amplitude of the total current can be written as

$$I = (I_{c, 1} + I_{c, 2}) \sqrt{\cos^2 \left( \frac{\Delta \phi_{ext}}{2} \right) + \gamma^2 \sin^2 \left( \frac{\Delta \phi_{ext}}{2} \right)},$$

(3)

where $\gamma = (I_{c, 1} - I_{c, 2})/(I_{c, 1} + I_{c, 2})$ characterizes the asymmetry between the two arrays. Thus the wavefunctions describing the neutral system interfere such that the total mass current oscillation amplitude modulates with varying external phase shifts. The device is a neutral version of a superconducting quantum interference device (dc-SQUID [10]).

Figure 1. Superfluid interferometer in double-path geometry. Two junctions (indicated by crosses) are placed in a superfluid torus as in the case of a dc-SQUID.

The first superfluid helium equivalent of a dc-SQUID, a device we refer to as a SHeQUID, was constructed using superfluid $^3$He-B, and its operation was demonstrated with interference through rotation-induced phase shifts [11]. When the device such as that depicted in figure 1 is placed in a rotating frame, the superfluid is forced into quasi solid body motion in a direction normal to the partition walls containing the weak links. If the interferometer is rotating with angular velocity $\vec{\Omega}$, the fluid in the connecting tubes moves with it and gives rise to a phase difference

$$\Delta \phi_{ext} = \frac{2m}{\hbar} \vec{\Omega} \cdot A.$$

(4)

Here $A$ is the loop area vector. This is the superfluid version of the optical Sagnac phase shift $\Delta \phi = (2\omega/c^2)\vec{\Omega} \cdot A$ [12], where now the effective photon mass $\hbar \omega/c^2$ is replaced by the mass of the superfluid atom. It follows from Eq. 4 that the overall oscillation amplitude from two junctions should modulate as a function of $\Delta \phi_{ext} \propto \vec{\Omega} \cdot A$, making the device a rotation sensor. Since the helium atomic mass is ten orders of magnitude greater than the photon effective mass, the rotation induced superfluid phase shift is enormous compared to that observed for light.

Soon after the discovery of Josephson (and phase slip) oscillations in superfluid $^4$He near 2K [9], a proof-of-principle $^4$He quantum interference device was constructed [13]. The more forgiving operating temperature of 2K (2000 times higher than the associated temperature of the $^3$He equivalent) has made the $^4$He device a more practical instrument. A $^4$He SHeQUID has since been utilized to probe some aspects of fundamental physics that have heretofore remained elusive [14, 15, 16], and various novel techniques that enhance the sensitivity and utility of the device have also emerged from those new phenomena [17, 18, 19, 20].
The overall device configuration has also seen some changes tailored to particular experimental applications. A large area $^4$He SHEQUID with a long multi-turn path in astatic geometry has been recently reported with an intrinsic rotational sensitivity of $1 \times 10^{-8}\text{rad/sec}/\sqrt{\text{Hz}}$ [21]. A circuit representation of such an apparatus is shown in Fig. 2. Turns of opposite helicity cancel global perturbations, while allowing differential measurements on external phase shifts. If combined with nonlinear amplification techniques that utilize homodyne mixing of Josephson oscillation with cell resonances [17, 19], this type of superfluid device has the potential to surpass the rotational sensitivity of the best-reported dual-atom interferometers [22].

Figure 2. Superfluid interferometer with multiple turns in astatic geometry. From [21].

Superfluid interferometry is not restricted to the conventional double-path geometry depicted in figures 1 and 2. One can place more than two aperture arrays in parallel, which narrows the interference pattern and increases the device sensitivity [23]. Recently, in an experiment to probe the superfluid phase coherence among the aperture array, a Fraunhofer-like interference pattern was observed from a single array of apertures with a uniform phase shift applied along the array [16]. See Fig 3. This raises a fascinating possibility for developing a superfluid sensor based on diffraction-like interference.

There have been several key developments with experimental components. What lies at the heart of the SHEQUID technology is the Josephson weak links. With the continuous advancement in lithography techniques and characterization tools, nanoscale aperture arrays necessary as weak link elements are becoming more easily accessible. Displacement transducers with $10^{-15}\text{m}/\sqrt{\text{Hz}}$ resolution (initially developed for gravity wave detection [24]) are also now well established using commercial SQUID systems and are utilized for Josephson mass current measurements. Thermometry with sub-nK resolution, originally developed for space-based fundamental physics experiments [25], can be readily employed in Josephson work for temperature stability near $T_\lambda$. The 2K environment is easily achievable, and a properly designed dewar system could maintain the required temperature for at least one year without periodic transfers of liquid helium. With these developments, one can envision field instruments based on SHEQUIDs operating for long periods of time with little human intervention or cryogenic expertise.

Although some analysis of the thermal noise limits of related devices has been performed [26], the corresponding limit for a SHEQUID is not yet known. Experiments have shown that the device sensitivity is currently not close to any fundamental limitations, and various techniques are available to further enhance the intrinsic sensitivity. Phase fluctuations ($\sim N^{-1/2}$ where $N \sim 10^{21}$ is the number of atoms in the device) may be the ultimate noise source but a practical limitation is normally the vibration and rotation coupling from the environment. This is an engineering challenge that needs to be met to exploit the full resolution of a SHEQUID. Many effective vibration isolation techniques exist, such as supporting the floors and experimental stages with an “inner-loop” active damping and/or employing multiple inverted pendulums [27].
Although these methods, designed to decouple the instrument from the environment, are useful for self-contained experiments, they are not ideal in applications such as seismology, where a good coupling to the environment is necessary. A cryostat design that emphasizes rigidity and positioning in underground low vibration laboratories [28] can go a long way to mitigate background signals. Furthermore, the astatic coil configuration such as that shown in figure 2 can help make the devices less susceptible to nuisance motion.

Josephson weak links between samples of macroscopic systems provide a unique tool with which to explore quantum mechanics and an opportunity for applications based on macroscopic quantum physics. One of the promising practical utilization of superfluid-based matter-wave interferometers remains to be rotation sensing which would find applications in geodesy, seismology, inertial navigation and potentially testing fundamental theories such as frame-dragging effects. Due to their unique ability to sense quantum phase shifts, SHeQUIDs may also become important tools for studies such as Berry’s phase investigations and gauge-field rotation of polarized Bose condensates [29, 30, 31]. Such work is currently in progress [32].

An asymmetric grating configuration constitutes an absolute gauge for quantum mechanical phase differences [33], and those devices could provide insights to equilibrium state and non-equilibrium dynamics of phase coherent quantum matter and may become useful for researchers investigating Kibble-Zurek scenarios of formation of topological defects [34, 35].

More details can be found in Ref [36]. For review on superfluid gyroscopes based on a single junction and a large parallel path, see Ref [37].

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