Acoustic resonator providing fixed points of temperature between 0.1 and 2 K

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Abstract. Below 2 K the speed of second sound in mixtures of liquid $^3$He and $^4$He first increases to a maximum of 30-40 m/s at about 1 K and then decreases again at lower temperatures to values below 15 m/s. The exact values depend on the concentration and pressure of the mixture. This can be exploited to provide fixed points in temperature by utilizing a resonator with appropriate dimensions and frequency to excite standing waves in the resonator cavity filled with helium mixture. We demonstrate that commercially mass produced quartz tuning forks can be used for this purpose. They are meant for frequency standards operating at 32 kHz. Their dimensions are typically of order 1 mm matching the wavelength of the second sound in helium mixtures at certain values of temperature. Due to the complicated geometry, we observe some 20 sharp acoustic resonances in the range 0.1...2 K having temperature resolution of order 1 µK. The quartz resonators are cheap, compact, simple to implement, easy to measure with great accuracy, and, above all, they are not sensitive to magnetic field, which is a great advantage compared to fixed point devices based on superconductivity transitions. The reproducibility of the resonance pattern upon thermal cycling remains to be verified.

1. Introduction

The official temperature scale ITS-90 defines absolute temperatures from 0.65 K to the highest values practically measurable by Planck radiation law. Temperatures from 0.65 to 3 K are defined by means of helium vapor pressure–temperature relations [1]. For many low temperature investigations these are still fairly high temperatures, so that a provisional temperature scale PLTS-2000 was developed to extend the low temperature scale from 1 K to 0.9 mK. PLTS-2000 uses the melting pressure of $^3$He to cover that range, providing also fixed points at superfluid A and A-B transitions, as well as at the magnetic Néel point of the solid [2].

Melting curve measurements require special equipment and are not always easy to implement in practice. Simpler and more practical secondary thermometers are available for the low temperature range, and to calibrate these against PLTS-2000, reference point devices with certain fixed temperatures have been developed. A fixed point device based on superconducting transitions of six elements in between 0.51 and 9.2 K (SRM 767 [3]) was engineered by NIST (former NBS) in 1972. Later, in 1979, a device with reference temperatures from 0.015 to 0.208 K (SRM 768 [4]) was developed. Another more recent superconducting reference device, labeled SRD1000, provides nine superconducting transitions in the range 15 mK to 1.2 K [5].
One problem with devices based on superconducting transitions is their sensitivity to magnetic field (\(-0.1 \text{ mK/µT} \, [6]\)) and to electromagnetic interference.

In this paper we describe a simple device that provides of the order of 20 sharp anomalies in the range 0.1 to 2 K to be used as calibration points for any other thermometers. It is based on the temperature dependence of the speed of second sound in helium mixtures. We have observed that ordinary quartz tuning forks couple strongly to second sound resonance modes, which are excited when the cell dimensions and the speed of sound meet the resonance condition. The exact resonance pattern is obviously not predictable for an individual device but we believe that it is reproducible as far as the measuring conditions can be restored. At very low temperatures, in the degenerate Fermi fluid, the dissipation due to the \(^3\)He component of the mixture increases as \(T^{-2}\), also providing means for thermometry.

2. Second sound in helium mixture

Helium mixture is described as a superfluid \(^4\)He background and a normal component, which can be thought of being a gas of elementary excitations, such as phonons, rotons, and \(^3\)He quasiparticles. Second sound is an excitation wave in this gas. As the second sound wave propagates, the total mass density of mixture remains nearly constant. At temperatures below 0.6 K and concentrations above 0.1 %, all excitations except \(^3\)He quasiparticles have ceased to exist, and the second sound is a \(^3\)He number density wave [7].

![Figure 1](image_url)

**Figure 1.** Speed of second sound for helium mixtures as a function of temperature at some pressures and concentrations [7]. The curve for about \(8\) % mixture below 1 K is taken from King and Fairbank [8], while that above 1 K was found from our measurements by looking for corresponding resonance peaks at low and high temperature sides. Pure \(^4\)He is included for comparison.

The speed of second sound depends on concentration, pressure, and temperature as illustrated in figure 1 [7]. There is a maximum at around 1.2 K, which means that any set of acoustic resonances can be observed twice: once when climbing up the curve at one side and then again, in reversed order, when continuing down at the other side.

3. Tuning fork measurements in helium mixtures

Quartz tuning forks are readily available from many manufacturers in variety of sizes. They are produced for frequency references in wrist watches and such, and are delivered in cylindrical capsules with two protruding electric contacts, see figure 2. An overview of quartz forks as sensors in helium liquids is given in reference [9].

We have tested two types of forks with capsule diameters of 3.0 mm (Fox Electronics NC38) and 1.5 mm (ECS-1X5X). The larger one was prepared for measurements by piercing two holes to the end of the capsule, leaving the fork itself untouched. The assembly was placed into a larger mixture cell attached to the mixing chamber of a dilution refrigerator. The second one was fitted directly to the bottom of the mixing chamber by soldering the capsule, with its top completely removed, to a CuNi capillary leading through the mixing chamber flange. The original electric
feedthrough was used to get sealed contacts to the device. A simple measuring scheme was devised resulting in very good vacuum Q-values ($>10^6$) [10]. The background signal was low and pretty much frequency independent, so that most of the time we could monitor the fork resonance on the basis of single point measurement tracking the changes in frequency [10].

Since the resonator frequency is about 32 kHz and the free dimensions inside the capsule are of the order of a millimeter, standing acoustic modes can be excited at sound velocities around 30 m/s. Sound modes were observed to couple to the resonator in mixture at the temperature range from 0.1 to 2 K (second sound) and in supercritical pure $^4$He (first sound).

When an acoustic mode is nearby the fork resonance frequency, the system becomes that of coupled oscillators, where there are actually two eigenmodes of oscillations with slightly different frequencies. This is nicely demonstrated in figure 3, where several acoustic modes pass by and always split the main resonance of the fork into two or even more repelling lines. It appears that the main resonance is first pulled to the side, it becomes smaller, while at the same time another line appears from the opposite side and takes the place of the main resonance. The measurement in figure 3 was performed in supercritical $^4$He, but the same rules apply for the second sound resonances in mixtures. Depending on whether the speed of sound is increasing or decreasing, the resonances are being pulled to the right or to the left. The minimum distance between the coupled resonances, when they are of equal amplitude, gives a measure for the strength of the coupling of the given sound mode with the quartz oscillator. It is seen to vary considerably from one resonance to another.

When the resonance is being tracked by our one point method, it appears that the resonance becomes very wide for a moment as it looses amplitude to the sound mode passing by, until the tracking algorithm jumps to the new position and recovers. Such behavior is illustrated in figure 4, where the widths of the tracked resonances as functions of temperature for both of the forks in helium mixtures are shown. Temperature was varied slowly with a rate roughly $15 \mu K/s$. The resonance peaks can be timed with 0.1 s precision, which converts to temperature resolution of the order of $1 \mu K$. 

![Figure 2](image1.png)

**Figure 2.** Photograph and a schematic drawing of a Fox Electronics NC38 tuning fork.

![Figure 3](image2.png)

**Figure 3.** Resonance spectra in $^4$He at 4.6 K temperature while some acoustic modes pass by. The recording shows a period of about 8 hours, while temperature increased by one millikelvin and pressure decreased from 2.6 to 2.1 bar. The panels at right show resonance curves at two different instances in time. The total area of the resonance peaks is about the same in both cases, but energy is distributed into several smaller or just one big resonance.
4. Discussion

We have shown that the second sound resonances in helium mixtures couple strongly to quartz tuning fork resonators and produce very sharp features, which may be used as fixed points in temperature for calibration purposes in the range 0.1 to 2 K. Quartz tuning fork resonators are simple to install and operate in a cryogenic system. Great advantage of the proposed principle is its insensitivity to magnetic field [11].

Our preliminary measurements were performed in an open setup, where careful control of concentration or pressure was not attempted. For these reasons, the reproducibility of the resonance pattern upon thermal cycling remains also unverified.

To construct and test a prototype reference device we plan to make a simple closed cell filled by appropriate helium mixture at some moderately high pressure at room temperature. A liquid phase at saturated vapor pressure and fixed concentration will appear as the cell is cooled down. It is also important to see, how much the resonance patterns vary, if identical forks are used in identical conditions.

In fact, it was somewhat surprising to find that the strength of the coupling of the two tested forks to the second sound modes was so similar overall, although their size was different by a factor of about two. It was expected that the smaller object would not be as efficient in emitting sound in helium as the larger one. Evidently, it is a demanding exercise to construct a valid model explaining the experimental observations.

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