Pressure dependent attenuation peaks for quartz tuning forks in superfluid $^4$He at mK temperatures

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Abstract. Pure superfluid $^4$He at very low temperatures is thought to be free of mechanisms producing dissipation for slowly moving objects, and the superfluid merely contributes an effective mass to the motion without any anticipated dependence on temperature below 0.1 K. To our great surprise, we found that the smallest commercially available quartz tuning fork oscillators with tines shorter than 2 mm and resonance frequency 32 kHz experienced attenuation by as much as 100 times more than the internal dissipation of the oscillator at certain values of pressure at millikelvin temperatures in superfluid $^4$He. These features smeared out at temperatures above 20 mK, although practically no thermal excitations in $^4$He are yet present. Another fork somewhat larger showed indication of similar anomalies as well, but at greatly lesser scale.

1. Introduction
Superfluids are called so because they can flow without any dissipation as long as certain critical flow velocity is not exceeded. Similarly, slowly moving objects can travel through such fluids without friction, but only on the limit of zero temperature. At finite temperatures, moving bodies interact with thermal quasiparticle excitations, which exchange momentum with the moving body. At sufficiently low temperatures the quasiparticles become ballistic because of very long mean free paths, which simplifies the description of their effect. In $^4$He the low temperature excitations behave as phonons, whose contribution to the drag force vanishes in proportion to the fourth power in temperature, and below 100 mK it is negligible in most practical cases.

All sorts of oscillating bodies have traditionally been employed in studies of superfluids to indicate the temperature, for example, by measuring the resonance width of the mechanical oscillator put into the fluid. This becomes ineffective once the temperature is below about 1/10 of the superfluid transition temperature because of the reason outlined above, and then the instrument will only show its internal damping due to the nonideality of its making.

Probably the best sensors of this type in terms of low internal damping are the quartz tuning fork resonators, which have recently become popular for the superfluid research, see for example Refs. [1–5]. These devices are made from single crystal quartz and their Q-value at low temperatures in vacuum is often beyond $10^6$, translating to very good sensitive range. Quartz tuning forks are mass produced as reference oscillators for various devices, such as ordinary clocks. They are available in many sizes and packing, usually tuned to the frequency $2^{15}$ Hz = 32768 Hz at room temperature in vacuum, and their performance just improves as the temperature is reduced. The two tines of the fork are driven into antiphase motion by virtue of the piezoelectric effect on quartz, and their oscillation can be detected with great sensitivity due to the current induced by alternating stress on the constructing material.
The tip velocity of the fork tines at typical oscillation amplitudes here is less than 1 mm/s, so that we expected practically no dissipation due to superfluid \(^4\)He at millikelvin temperatures. Thus greater was our surprise, when we observed that the smallest quartz tuning forks could experience damping over 100 times larger than internal dissipation in certain ranges of pressure in such medium. This anomaly was very sensitive to pressure producing hundreds of attenuation peaks starting from the saturated vapor pressure up to the melting pressure of \(^4\)He. The explanation to such behavior remains to be found. Therefore, this paper merely describes our observations and calls for suggestions about its origins.

2. Experimental setting

A versatile experimental cell with instruments for measuring the pressure, density, and temperature of helium fluids and solids over wide ranges was used to study all flavors of helium, i.e. pure \(^3\)He, pure \(^4\)He, and also mixtures of these. There were two quartz tuning fork resonators of different sizes placed into the experimental volume. These were meant primarily as thermometers for superfluid \(^3\)He refrigerated deep below 1 mK. Work on \(^4\)He was initially thought only to serve as reference to experiments on \(^3\)He [6] and on helium mixtures [7].

The measurements on \(^4\)He were conducted after the investigations on helium mixtures, so that the cell had to be “cleaned” from traces of \(^3\)He first. For this purpose the system was warmed above the critical temperature of \(^3\)He and the cell was pumped empty. The cell was then refilled with pure \(^4\)He to 4 bar pressure and emptied again. Yet another partial filling cycle was performed, although the \(^3\)He/\(^4\)He ratio of the outcoming gas, as analyzed by a mass spectrometer, was observed not to differ from what we obtain using standard \(^4\)He from a gas bottle. It was concluded that the situation could not be improved any more and the remaining concentration probably did not differ from that of standard \(^4\)He from natural sources.

The two quartz tuning forks employed in these experiments were deliberately of quite different design. One of these was originally housed in a parallelepiped casing with inner dimensions \(0.5 \times 0.85 \times 2.75 \text{ mm}^3\). To be used in helium, the top plate of the casing was removed exposing the fork to the bulk experimental volume from one of its flat sides. A photograph of this device is shown in Fig. 1. The other fork was somewhat bigger and housed in a cylindrical metal casing. The top of the cylinder was filed open in order to bring the fork into contact with helium in the main volume. The dimensions of these two quartz resonators are listed in Table 1.

The resonance parameters — frequency, width, amplitude, phase, and background (practically constant) — were first determined by measuring full spectra. Fits to the expected

![Figure 1. Small fork used in this work. The dark background oval displays the size of the casing (0.85 \( \times \) 2.75 mm\(^2\)) of the fork. Table 1 shows the tine dimensions of this and another fork used.](image)

| Type          | Casing | Q-vac | T-length | T-width | T-thickness | T-spacing |
|---------------|--------|-------|----------|---------|-------------|-----------|
| ECS-.327-7-34B-TR | box    | \(10^6\) | 1.9      | 0.11    | 0.11        | 0.09      |
| ECS-.327-8-14X | cylinder | \(2 \cdot 10^6\) | 2.3      | 0.24    | 0.13        | 0.10      |
lineshape were excellent, the forks showed perfectly linear response, and the area under the resonance curve could be used to relate the resonance amplitude and width. Once this background information was available the forks could be driven in a single point tracking mode, which is described in detail in Ch. 3.3.1 of Ref. [8]. Resonances with rather high Q-values could then be monitored with fairly short time intervals, which were typically set at 1–10 s.

The residual resonance width of the two forks, including possible nonidealities due to the cables, electronics, etc., was about 30 mHz for the smaller and about 15 mHz for the larger one. The same value within few mHz was observed either in vacuum or in superfluid $^3$He or $^4$He deep below the superfluid transition temperature, that is, if the regions of the anomalous damping in superfluid $^4$He were avoided.

3. Results

Once the unexpected attenuation peaks of the small fork were discovered, we scanned the pressure-temperature landscape through selected paths, which can be observed in Fig. 2 displaying the changes in temperature and pressure as functions of real time together with the recorded resonance width of the smaller fork. It was not possible to cover the whole phase space systematically during the time available for this experiment, so that only selected slices through the entire area can be shown.

Figure 3 shows the resonance width of the smaller fork as function of pressure over a limited range at the temperature of 10 mK. The behavior is quite dramatic, as the quality factor of the

![Figure 2](image-url)  
**Figure 2.** Temperature and pressure of $^4$He and resonance width of the small fork as functions of time since the anomalous behavior was first encountered in the afternoon Sep. 3rd, 2013. The period of examining a narrow pressure region as the function of temperature is expanded on the pressure plot ($\times30$, light colored trace) and the corresponding scale is on the right.
fork changes as much as by a factor of 100 over rather narrow intervals of pressure. The pattern was reproducible as its outline remained the same over the entire span of this study, which took about 54 days and during which the temperature was cycled from over 100 mK to below 1 mK and the pressure was varied across the entire range from the saturated vapor pressure to the melting pressure of the solid phase. From time to time full resonance spectra were recorded in order to verify that the tracking algorithm functioned properly.

It is amazing that such strong coupling from the quartz resonator to superfluid $^4$He can happen, as the medium is supposedly at the zero temperature limit. Why does this coupling exist only at certain values of pressure producing very distinct attenuation peaks? Also the temperature dependence is quite peculiar, while features as sharp as in Fig. 3 were observed only below 20 mK or so. Above that the pattern became much more rounded and remained such until the quasiparticle contribution in $^4$He to the attenuation became appreciable causing general increase of width at any value of pressure.

A narrow interval in pressure including one of the most prominent attenuation peaks was examined more systematically as the function of temperature. The result is summarized in Fig. 4, where a 3D plot of the small fork’s width is displayed as functions of temperature and pressure. The same data are shown as a contour diagram in Fig. 5. As the temperature goes down the attenuation peak suddenly becomes very sharp and begins to push towards higher pressures. It has been questioned if superfluid $^4$He can be refrigerated to low millikelvin temperatures in the first place, while no thermal excitations are there any more to make any difference from absolute zero, but now there is a clear response to temperature even at this low range.

The bigger fork also showed clear indications of something similar influencing its resonance but the scale of effects was much smaller, obviously because of the larger mass involved in its motion. Typical changes in resonance width were only about a factor of two and they appeared as very sharp attenuation peaks as function of pressure, just as for the smaller fork.

4. Discussion
We can offer no proper explanation for the features just described. We can only speculate about the possible significance of traces of $^3$He present in the system or of the role of quantized vorticity around or pinned to the quartz tuning forks. Maybe the existence of both is essential, as the $^4$He vortices are known to capture $^3$He in their cores possibly playing some tricks there. We even contaminated our sample deliberately by about 10 ppm of $^3$He but this did not cause any significant change to the overall behavior. This happened at about 770 hours time in Fig. 2.

The observed pattern resembles a lot the results of our earlier studies on second sound coupled to quartz tuning forks in dilute helium mixtures [9–11]. We emphasize, however, that
second sound is not likely to cause the present anomalies, because the resonances should appear primarily while changing temperature, not pressure. It is unlikely that sufficient amounts of \(^3\)He impurities were present in order to produce pronounced second sound resonances. Support for this conclusion is also provided by the lack of such resonances, when the temperature was increased to the range of 1 K at the end of this experiment, during about 1240—1260 hours seen in Fig. 2. Only the emergence of thermal quasiparticle damping was observed.

Few cases of unexplained attenuation for quartz tuning forks in superfluid helium have been reported elsewhere [12–14]. In those cases the damping experienced by the forks varied with time in an uncontrolled manner under seemingly steady conditions. In that sense the characteristics of the earlier observations crucially differ from what we have described here. More studies using different types of tuning forks in variety of enclosures is obviously needed in order to gain better understanding of the mechanisms involved.

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