Decay mechanisms of oscillating quartz tuning fork immersed in He II

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Abstract. The dissipative processes due to viscous friction and acoustic emission from vibrating tuning fork prongs, in the hydrodynamic and ballistic regimes at the scattering of thermal excitations, are investigated by measuring current - voltage characteristics of a quartz tuning fork immersed in He II. The vibrating tuning forks with resonant frequencies 32, 37, 77 and 97 kHz were used and measurements were carried out at saturated vapor pressure in temperature range 0.35 K - 1.5 K. It was found that at \( T > 1 \) K for the hydrodynamic flow regime in He II, the main dissipative process is the viscous friction, and acoustic dissipation mechanism is essential only at frequencies above 70 kHz. At \( T < 0.5 \) K, for the ballistic regime, the scattering mechanism of the dissipation due to scattering of thermal excitations by vibrating tuning fork prongs predominates only for low frequency (32 kHz) and acoustic dissipation mechanism dominates in almost the entire frequency range.

1. Introduction
In recent years, the new measurement technique of a vibrating quartz tuning fork is actively used for the studies of dynamic and kinetic properties of superfluids, such as the onset of turbulent flow [1], the measurements of coefficient of drag of a body vibrating in He II [2] and many others. The advantages of this technique are high sensitivity and easy to use. One of the features of this measurement technique is the possibility of the acoustic wave emission by a tuning fork. Part of the kinetic energy of the vibrating body passes into surrounding superfluid and as a result the acoustic wave is excited. The friction between superfluid and oscillating body is small and with decreasing temperature the friction reduces stronger. Therefore, under certain conditions, the energy expended in the creation of sound waves can be large, thus limiting the applicability of this technique for measuring weak dissipative processes. In spite of this, the tuning forks in original case were demonstrated to be an effective tool to measure the viscosity of He II down to \( T \sim 200 \) mK [3]. As it was shown in [4], tuning fork acoustic power is \( P_A \sim f^6 \), so with increasing frequency acoustic emission can be a principal factor that contributes to damping of tuning fork. In this paper we study the conditions for regime change of dissipative viscous friction by the mode of acoustic emission as a function of frequency at different temperatures.

2. Experimental Procedure
For the study of change of acoustic emission on the regime of viscous friction we used industrial quartz tuning forks with different resonant frequencies \( f = 32, 37, 77 \) and 97 kHz which were
in its original metal casing. In order to fill it with superfluid He II a hole was made by the size about 0.1×0.2 mm. The tuning forks with the heights resonance frequencies has slightly different dimensions. Tuning forks with the resonance frequency about 32 kHz was three types of dimensions. The dimensions smallest and largest forks more then tree times differ. Tuning forks were placed in a sealed cell and mounted on a plate of mixing chamber of dilution refrigerators. The measurements were carried out at pressures close to the saturated vapor pressures at four temperatures: 1.49 K, 1 K, 0.7 K, and 0.35 K. The amplitude-frequency characteristics of the tuning forks were measured at different driving voltages, and then the width of resonance was determined. The measurement procedure is described in detail in [2,3]. The measurements were carried out at linear mode tuning fork, which corresponds to the laminar flow regime of liquid near a vibrating tuning fork legs. Analysis of experimental data is also hampered by the fact that the temperature dependence of mechanisms of friction is different. So at high temperature the hydrodynamic regime of the scattering of thermal excitations dominates. At the same time at $T \leq 0.6$ K the scattering mechanism is ballistic because the mean free path of thermal excitations becomes larger than the characteristic size of the vibrating tuning fork. At such low temperatures the roton contribution to the scattering is negligible and the scattering is determined by the density and the mean free path of thermal phonons. In this mode, a hydrodynamic description of the friction of the surrounding liquid is not applicable. For both modes of scattering there are empirical expressions for calculating the dissipative losses [3]. As it was shown in [4] with decreasing the temperature the role of acoustic mechanism may be decisive even for the low-frequency tuning forks. Therefore, the calculation of friction is valid only for the tuning forks where the friction mechanism predominates. The calculations of friction for the corresponding temperatures are shown in Figs.1 and 2 by the dashed and dot-dashed curves. The curves 1 - 3 give in this Figures the hydrodynamic description, were the curve 4 describes the ballistic mode scattering of thermal excitations. As one can see the theoretical and experimental dependences agree with each other for low-frequency tuning forks. The estimate of dissipation due to friction in ballistic regime is consistent with earlier measurements given in [5, 6]. High-frequency data deviate from the calculated values in the entire temperature range investigated. This deviation is associated with change dissipation processes to the acoustic emission mechanism of energy of vibrating tuning fork legs. The characteristic acoustic losses [4] are shown by the solid line in Figs.1 and 2. This dependence is constructed with reference

![Figure 1.](image-url)
to high-frequency data. Position of the curve is almost an order of magnitude lower than the theoretical calculation and does not depend on temperature but depends on the size of used tuning forks. From the experimental data, we can conclude that, with decreasing temperature, the change of regime of friction by acoustic emission, as well as at high temperature [4], continues to shift to lower frequencies.

3. Discussion
In order to eliminate the size difference between the tuning forks, the primary experimental data can be normalized to the appropriate size of a tuning fork using the Eq.(3b) of Ref. 4:

\[ P_A = \frac{\rho \omega^6 T^2 W^2 (T + D)^2 L_{eff}^2}{40 \pi c^5 U^2} \]  

were \( \rho \) - \(^4\)He density; \( \omega \) - frequency; \( T, W, D \) and \( L_{eff}^2 \) - the thickness, width, distance between prongs and effective length of the prongs respectively; \( c \) - first sound velocity and \( U \) - velocity amplitude of the liquid flow. Emphasize the \( P_A/U^2 \sim \Delta f \). The result of normalization to fork dimensions for the temperature of 0.35 K is shown in Fig.3. The solid line is the consequence of the frequency dependence of the corresponding acoustic emission mechanism. As seen from Fig. 3, at temperature 0.35 K acoustic emission mechanism dominates for almost all tuning forks. Only for the tuning forks with low resonance frequency and of small sizes, marked with black circles (●), the mechanism of dissipation is determined by friction. Therefore, when such normalization was used the data greatly deviate from the solid line because the dissipation mechanism for small tuning forks is different from the acoustic emission.

4. Conclusion
Thus the experimental data show that the magnitude of the resonance linewidth are in good qualitative agreement with theoretical predictions for acoustic emission. In the experiment, the emission efficiency of acoustic waves by an oscillating tuning fork increases with increasing frequency and decreasing temperature was observed. Acoustic emission can be suppressed by the friction of He II on the oscillating prongs of a tuning fork. Changing regimes of friction by acoustic emission is determined by the ratio between the dissipation energy of oscillating...
prongs of the tuning fork due to friction and the flow of energy through the emission acoustic waves, in entire investigated temperature range. As the result, in order to determine weak dissipative processes at ultralow temperature one should apply the quarts tuning forks with smallest dimensions and lowest resonant frequencies.

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Figure 3. The width of the resonance, normalized to the characteristic dimensions of a tuning fork at $T = 0.35$ K. The solid line is the acoustic losses which have the frequency dependence $\sim f^6$. 