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Quantum Turbulence Generated and Detected by a Vibrating Quartz Fork

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Abstract Flow due to a commercially available vibrating quartz fork is studied in gaseous helium, He I, He II and ^{3}He–B, over a wide range of temperatures and pressures. On increasing the driving force, the flow changes in character from laminar (characterized by a linear velocity versus drive dependence) to turbulent (characterized by a square root velocity versus drive dependence). In classical fluids, we characterize this transition by a critical Reynolds number, $Re_c = U_{\mathrm{cr}}\delta/\nu$, where U_{cr} is the critical velocity, ν stands for the kinematic viscosity, $\delta = \sqrt{2\nu/\omega}$ is the viscous penetration depth and ω is the angular frequency of oscillations. U_{cr} of order 10 cm/s observed in He II and 1 mm/s in ^{3}He–B agree with those found with other vibrating objects such as spheres, wires and grids, as well as with available numerical simulations of vortex motion in an applied ac flow.

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The vibrating quartz tuning forks (see Fig. 1) represent a new addition to the family of oscillating objects that have been used to probe the flow properties of both isotopes of cryogenic helium since the beginning of helium research. They are easy to use, robust, cheap and widely available. Commercially produced forks—frequency standards (≈32 kHz) for watches—are supplied in a cylindrical vacuum-tight metal

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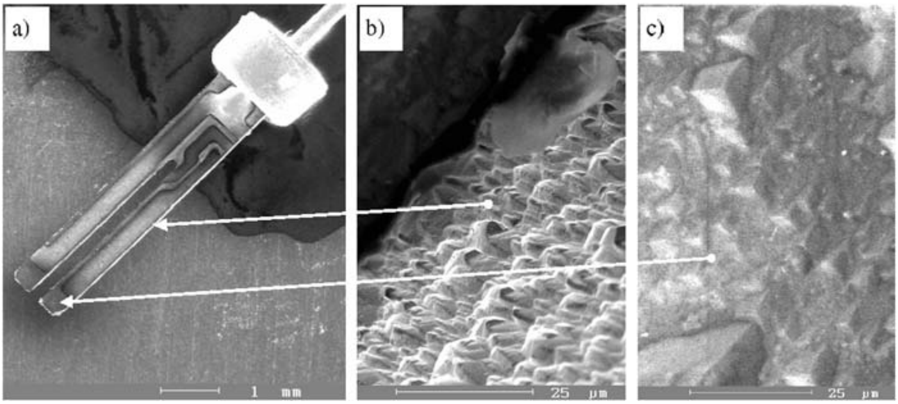

Fig. 1 The electron micrograph of the quartz tuning fork (**a**) and details of its side (**b**) and top (**c**) quartz surface

can that has to be entirely or partly removed for cryogenic applications; magnetically sensitive applications require replacing their magnetic leads by non-magnetic ones.

We have shown [1] that within a laminar regime, ignoring the vacuum linewidth (at low T typically only 0.05 Hz) the dependence of resonance frequency f_0 of the fork of density ρ_f and full width of the absorption curve at half height Δf depend on the fluid density ρ and viscosity η as

$$\left(\frac{f_{0\mathrm{vac}}}{f_0}\right)^2 = 1 + \frac{\rho}{\rho_\mathrm{f}}\left(\beta + \frac{BS}{V}\sqrt{\frac{\eta}{\pi\rho f_0}}\right);$$
$$\Delta f = \frac{CS}{2}\sqrt{\frac{\rho\eta f_0}{\pi}}\frac{(f_0/f_{0\mathrm{vac}})^2}{m_\mathrm{vac}}. \qquad (1)$$

Here $m_\mathrm{vac} = \rho_\mathrm{f} V$, where $V = TWL$ is a volume of one fork's leg of length L and rectangular cross-section TW, $S = 2(T + W)L$. These equations can be used to determine hydrodynamic fork parameters experimentally from measurements in fluids with known ρ and η. This approach assumes that once the fitting parameters B, β and C are known, the fork can be used for measurements of ρ and η for any other medium or as a pressure and/or temperature sensor if $\rho(p, T)$ and $\eta(p, T)$ are known. Unfortunately our measurements indicated that these parameters do vary from fork to fork and thus a calibration step is necessary. Moreover, we have now a convincing experimental evidence that, e.g., parameter β appreciably depends on the geometry of the surrounding container. For example, β repeatedly changes by about 10% in air at room temperature when the original metal cover of inner diameter 1.6 mm is on or off the vibrating fork. We believe that this effect is attributable to the existence of a steady secondary flow through the action of viscosity in the boundary layer, called "streaming" [2]. As far as we know, this effect was not taken into account for analysis of measurements recorded with other oscillating objects, most notably vibrating wires. It might become important in quantitative measurements of physical quantities spanning large ranges of values (such as the viscosity of ^{3}He Fermi liquid above T_c; $\nu \propto T^{-2}$), when the flow geometry of this large flow from the standpoint of suitably defined Reynolds number changes appreciably.

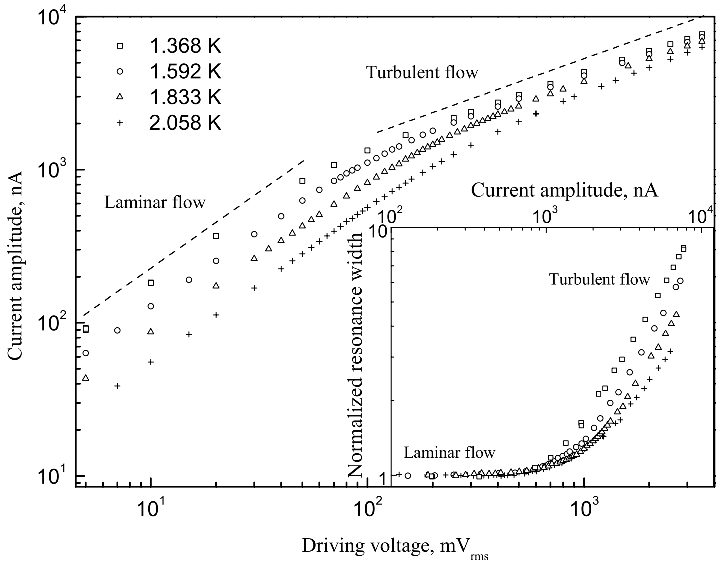

Fig. 2 Transition from laminar to turbulent flow of He II as detected by vibrating quartz fork at four different temperatures. At low drive level (in laminar regime) the measured current (proportional to velocity) is a linear function of the applied drive; around its critical value a crossover to a turbulent regime occurs, characterized by a quadratic driving force versus velocity dependence. The inset shows the normalized width of the resonance response; its increase indicates a transition to turbulent regime

The main result which we present here is our experimental observation of the transition from laminar to turbulent flow due to a vibrating fork. In fact, we do not observe the turbulent flow directly by, e.g., flow visualization, but we probe the flow via the resonant response of the fork itself. The main advantage is that the same fork can be used in a rich variety of classical and quantum fluids with widely and easily tuneable (by adjusting temperature and pressure in situ in the same pressure cell) and well-known [3–5] physical properties. With cryogenic working fluids, such as He I or He II, care must be taken in order to protect the extremely sensitive fork (typically $Q \approx 10^5$–10^6 in vacuum at low T) from gathering solid particles of air or other contaminants. We therefore start measurement cycles with liquid helium under high pressure in the cell, so that for any subsequent measurement the amount of fluid in the pressure cell is either kept constant or decreases. Sensitive measurements in the open helium bath are generally not recommended, due to insufficient purity of technical helium. An additional factor that has to be taken into account is (most likely heterogeneous) cavitation that often occurs when working at saturated vapour pressure and when the fork oscillates at a large amplitude. Its signature is an irregular shift of the resonant frequency to values between those of liquid and gaseous phase.

In a steady classical flow past a submerged object, transition to turbulence occurs at some critical value of the Reynolds number, defined as $Re_c = U_{\mathrm{cr}} L/\nu$, where U_{cr} is the critical velocity, ν stands for the kinematic viscosity, and L denotes a characteristic size of the object. We believe that in an oscillatory flow due to a vibrating fork a characteristic length scale is not the size of the object, but rather the viscous penetration depth $\delta = \sqrt{2\nu/\omega}$, where ω is the angular frequency of oscillations. Our

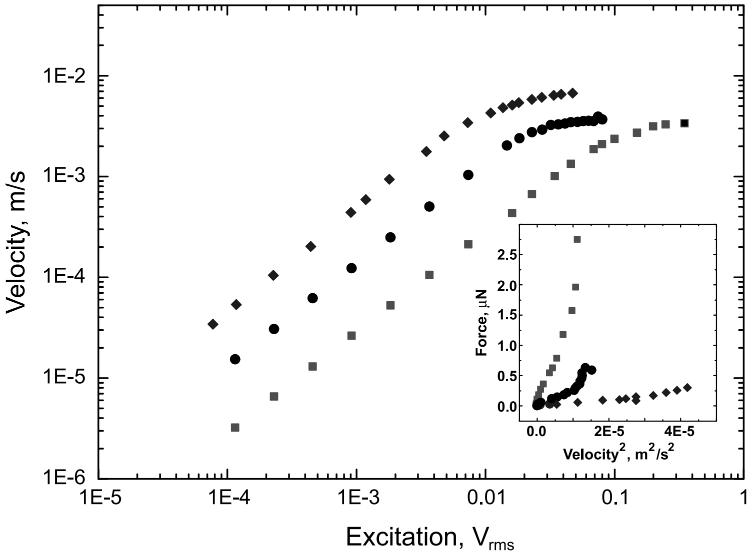

Fig. 3 Transition from laminar to turbulent flow of ^{3}He–B as detected by a vibrating quartz fork at $T = 360$ μK (♦), $T = 275$ μK (▲) and $T = 230$ μK (•). At low drive level the velocity is proportional to the applied driving force, while above the transition, in turbulent regime, for limited range of velocities there is a quadratic driving force versus velocity dependence, as emphasized in the inset

definition of $Re_c = U_{\mathrm{cr}}\delta/\nu$ suggests that under assumption that the transition to turbulence occurs at the same Re_c the critical velocity ought to scale as $\sqrt{\omega\nu}$. Our data in cryogenic helium gas and liquid He I at ambient and elevated pressures strongly support this scaling and, due to space restriction, will be published elsewhere [6]. Here we focus on the transition to turbulence in superfluid He II and ^{3}He–B, clearly marked by a change in the slope of the response versus drive dependence [7] (being linear in the laminar regime and of a square root type in the turbulent regime) as illustrated in Figs. 2 and 3.

Contrary to experiments with vibrating wires [8–11] or spheres [12], we observe neither irregularities nor any hysteretic phenomena in He II down to about 1.3 K or in ^{3}He–B. Although we have searched for the so called "virgin" response [13] after passing through T_λ, we have found no sign of it, possibly due to different surface roughness (see Fig. 1) or a much larger mass to surface ratio of the fork in comparison with typical vibrating wires or grids.

The experimentally observed values of U_{cr}, of order 10 cm/s in He II and 1 mm/s in ^{3}He–B, agree with those found with other vibrating objects such as spheres [12], wires [8–11] or grids [13, 14], as well as in numerical simulations of vortex motion in an applied ac flow [16]. Our preliminary He I and He II data suggest that $U_{\mathrm{cr}}(T)$ is continuous through T_λ, below which $U_{\mathrm{cr}}(T)$ decreases with decreasing temperature in a qualitative agreement with available data for oscillating grids and wires. Our data, covering both He I and He II, can be smoothly extended to $T \to 0$ limit, using the measurements of $U_{\mathrm{cr}}(T)$ by the oscillating grid [15]. This temperature dependence can be interpreted using the classical scaling (proved by us in He I and helium gas at ambient and elevated pressure), if a phenomenological T-dependent

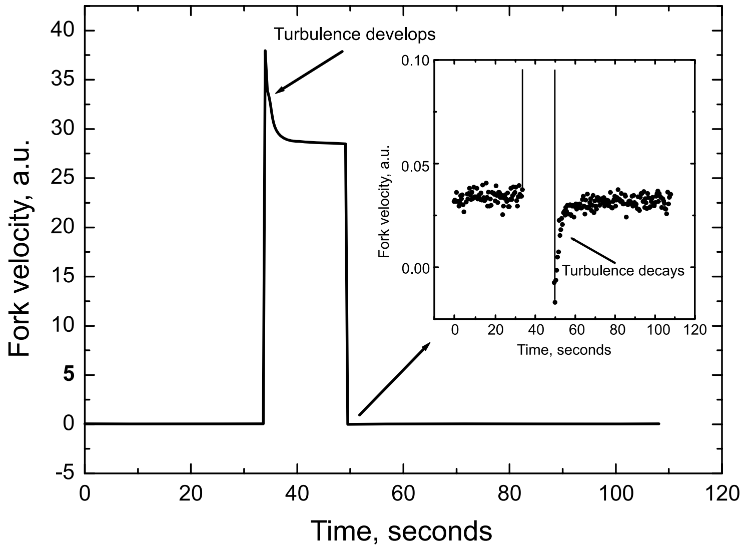

Fig. 4 Resonance response of the fork to step-like increase and decrease of the drive between laminar and turbulent levels. For details, see text

effective kinematic viscosity $\nu_{\rm eff}(T)$ is introduced, assuming that He II behaves as a (quasi)classical viscous fluid. Due to space limitations, these data and relevant discussion on $\nu_{\rm eff}(T)$ of He II deduced by various methods (such as from decaying grid and counterflow He II turbulence) will be published elsewhere.

Here we also present an experimental evidence (see Fig. 3) that the fork can generate and detect the quantum turbulence in ^{3}He–B as well, similarly to the vibrating wire [10, 11]. Firstly, there is a range of velocities where the drag force is proportional to the square of the velocity Secondly, an additional supporting argument is the time relaxation of the resonant response of the fork following a sudden change of the driving force from laminar to turbulent level and vice versa (see Fig. 4). The increase of the driving force leads to the creation of quantized vortices which gradually develop into turbulence. As the turbulence develops, the fork velocity decreases, due to mutual friction (see Fig. 4). When the driving force is switched back to its laminar level, the cloud of vortices decays and an opposite effect takes place.

In summary, we conclude that the vibrating quartz fork represents a valuable and easy to use tool to generate and/or detect classical turbulence in a variety of fluids, as well as quantum turbulence in helium superfluids.

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