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Experiments on a high quality grid oscillating in isotopically pure superfluid ^{4}He at very low temperatures

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Abstract We have investigated a copper-mesh grid oscillating at its fundamental (0,1) Bessel mode in isotopically pure superfluid ^{4}He for temperatures $10 < T < 1500\,\mathrm{mK}$ at a pressure of $P = 5$ bar. The high quality factor ($Q \sim 10^5$) of the oscillator allowed us to observe new features of its response to a periodic drive which, at the lowest T, was found to depend on the prehistory of the helium. The experiments have confirmed the existence of two critical velocities, believed to be associated quantized vortices. The observed phenomena are discussed.

Keywords quantum fluid · quantum turbulence · vibrating grid · Superfluid helium · Critical velocity

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1 Quantum Turbulence

The experimental investigation of vibrating structures in superfluid helium began in the early 1950s with experiments by Andronikashvili in which he used a torsional oscillator consisting of a pile of disks [1] to verify Landau's two-fluid model. Since then, the resonance properties of different vibrating structures, e.g. spheres, [2–4] wires, [5–10] and grids, [11–14] have been used to study the flow properties of liquid helium, and especially for the investigation of quantum turbulence, its formation, and its decay in time and space. Quartz tuning fork resonators [15–18] are the latest addition to this family of vibrating objects. All of these devices have been used as generators of quantum turbulence (QT) in superfluid helium. Until recently, most experiments were carried

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out above 1K where a significant amount of viscous normal fluid is present. Vibrating bodies are very sensitive to the viscosity of the surrounding liquid, and thus to the concentration of normal component. Even in the zero temperature limit, where the normal fluid density is virtually zero, it has been found through numerical simulation [19,20] and experiments [12,21–23] that the decay of turbulence is classical-like [24], an unexpected result that has attracted a lot of attention and interest.

Previous investigations of a grid-mesh resonator [25,26] have revealed a range of phenomena associated with the conversion of grid oscillatory energy to QT, e.g.: "virgin" and "regular behavior" (depending on the prehistory of the liquid); first and second critical velocities v_{c1} and v_{c2}; a shift of the resonant frequency for velocities between v_{c1} and v_{c2}; and "cleaning" of the grid by cycling through high and low drive amplitudes to yield reproducible results. The new measurements described below were undertaken to clarify the process(es) via which quantum turbulence is created.

2 Experiment

The experimental setup was similar to that described previously [25,26]. The experiment consists a high-voltage grid sandwiched between two plates to form a triple-capacitor of radius $R = 4.5\,\mathrm{cm}$ with $d = 1\,\mathrm{mm}$ spacing between grid and each of the plates. The only difference in geometry from the earlier investigations is the presence of 7 holes in the top electrode of $\sim 8\,\mathrm{mm}$ diameter. These were cut in order to allow QT to diffuse out into the space beyond the formation region, where it was hoped to detect it by use of quartz tuning forks (the results of the detection experiments will be published elsewhere).

A static voltage of $V_0 = 536\,\mathrm{V}$ (the same value as that used earlier [26]) was applied to the grid. A harmonic signal V_G on the bottom electrode provides the driving force

$$f_d = \varepsilon_0 \varepsilon_r \pi R^2 V_0 V_G / d^2,$$

on the grid, where ε_0 and ε_r are the absolute permittivity of the vacuum and dielectric constant of helium. This force excites the fundamental (0,1) Bessel mode. The induced current I in the top electrode, proportional to the grid velocity v, is ideally

$$I = (CV_0/d)v, \tag{1}$$

where C is the capacitance between the grid and the top electrode. Allowing for the Bessel function shape of the grid excursions and the empty areas of the holes, the response can be calculated as $4.5\times$ the measured response, and hence the effective maximum velocity of the grid should be $4.5\times$ the velocity calculated from Eq. (1). A current-to-voltage ($I - V$) convertor (with zero input impedance), used to detect the signal has the advantage that its input terminal is a virtual ground, so that the effect of cable capacitance is removed.

The stainless steel body was of volume $\sim 1.5\ell$. The measurements were made at different temperatures in the range $10 < T < 1500\,\mathrm{mK}$ at a pressure of $P = 5\,\mathrm{bar}$. The temperature was measured from a calibrated $\mathrm{RuO_2}$ thermometer on the mixing chamber of the ^{3}He-^{4}He dilution refrigerator. There was also a Ge thermometer immersed in the helium inside the cell.

3 Experimental results

The resonant frequency of the (0,1) mode at room temperature under vacuum was $f_{300} = 765$ Hz; and for the (0,2) mode it was $f_{300} = 1750$ Hz. The ratio of these value is very close to the value of 2.295 calculated for a thin membrane. The Q-factor of the grid was $Q \sim 100$ ($\Delta f = 7.2$ Hz). The resonant frequency increased to $\sim$ 926 Hz in superfluid helium at base temperature near 10 mK; the width of the resonance curve decreased to $\Delta f = 0.004 - 0.006$ Hz, corresponding to a quality factor of $Q \sim 2.5 \times 10^5$ Because this Q was at least an order of magnitude higher than in the previous work [25, 26] using a nickel grid, we were able to observe new and interesting features of QT and its generation at low temperatures.

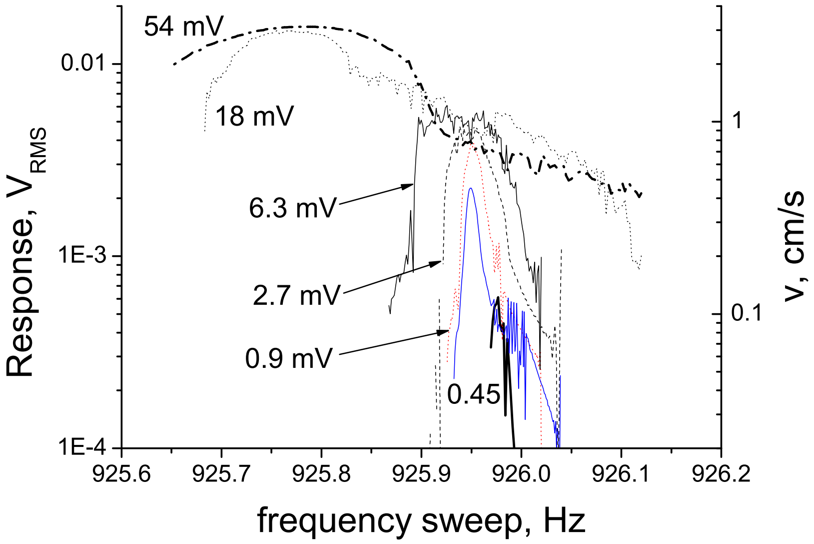

Fig. 1 Amplitude response (in V_{rms}) measured on the top electrode as a function of frequency, swept in the forward and backward direction for the drive amplitudes U_G indicated (in mV_{rms}) applied to the bottom electrode. The measurements was performed at base temperature $T \sim$ 10 mK and pressure 5 bar.

3.1 Low temperatures

The dependence of the grid response on the driving frequency has a Lorentzian-like shape only at the lowest drive amplitudes ($U_G < 1$ mV) as shown in Fig.1 – the low excitation region (LE). Here, the maximum amplitudes of the resonance curves were proportional to the drive amplitude, corresponding to a laminar flow regime. When the value of U_G exceeded a few mV_{RMS}, however, sudden jumps occurred in the signal amplitude. The lower-frequency sides of such curves always exhibited discontinuities –

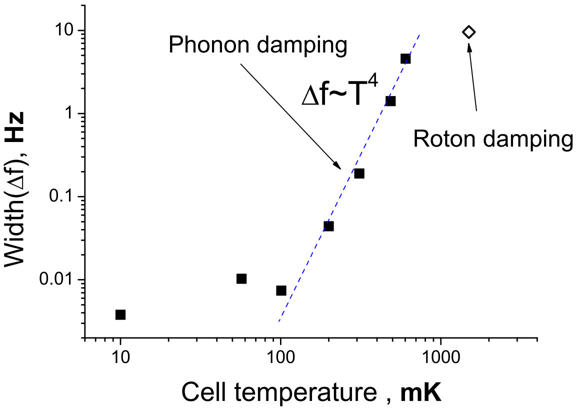

Fig. 2 The temperature dependence of width of resonance curves at low excitation of grid (in laminar regime). $P = 5\ bar$.

the medium excitation region (ME). Sweeping the frequency forwards and backwards many times under the same conditions produced similar results but with irregular shifts in frequency. The maximum of the response shifts towards lower frequencies as the drive level increases. For drives above 20 mV, smoother and more reproducible resonance curves were obtained. The maximum response of the grid is then a slower function of drive amplitude, corresponding to the turbulent regime where QT is being created and leaving the grid – high excitation region (HE). The resonance maximum in HE was ~ 0.2 Hz lower in frequency than in LE.

We did not observe the "cleaning" effect reported earlier [25,26]: driving the grid very hard, before measuring full frequency sweeps at lower amplitudes, did not eliminate hysteretic behavior or stabilise the resonance. If the sample was slowly cooled to base temperatures from above T_λ, it resulted in a slightly enlarged LE region and more distinct boundaries between LE-ME and ME-HE regions, as compared to measurements after an initially turbulent state,

3.2 Higher temperatures

In the laminar regime below 100 mK, the width $\varDelta f$ of the resonance was < 0.01 Hz independent of temperature, as shown in Fig. 2. Increase of the temperature above 100 mK led to a steep increase in dissipation, reducing the Q. In the range $100 < T < 700$ mK, $\varDelta f \propto T^4$ to a good approximation. The increase in width can be attributed to the scattering of thermal excitations, consisting mostly of phonons below 700 mK. It strongly reduces the sensitivity of the grid to the presence of vortices.

4 Discussion and conclusions

Our experiments have revealed a regime near 10 mK where measurements at intermediate drives yield results that are erratic, hysteretic, and history-dependent. Such effects

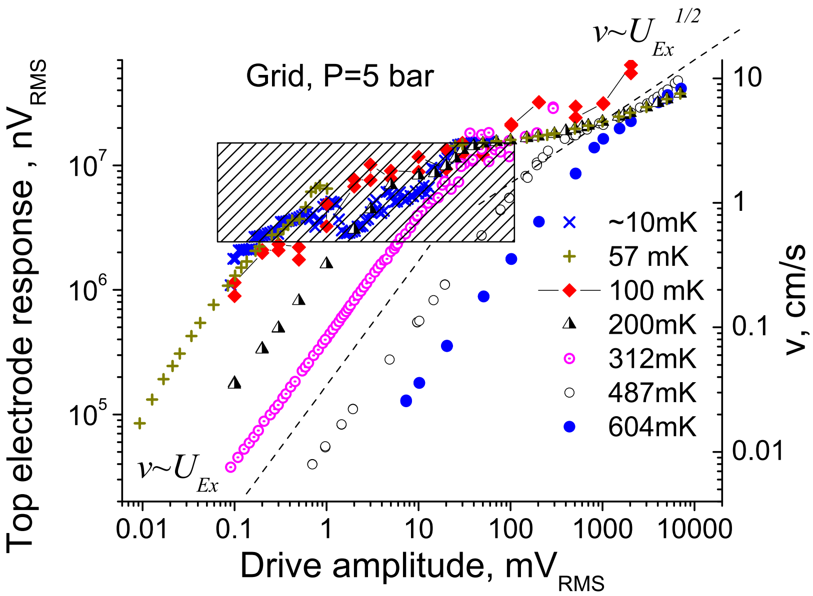

Fig. 3 Dependence of grid response from its excitations at different temperatures. Dashed lines - liner and square root dependencies, corresponding to laminar and turbulent grid motion, respectively. Shaded rectangle indicates the region of irregular behavior at frequency sweeping with velocities grid vibration between v_{c1} and v_{c2}.

can be accounted for, at least qualitatively, in terms of remanent vorticity [27]. Pinned vortices and the flow of superfluid around them will influence the effective mass of the grid, and hence its resonant frequency. The sudden jumps observed during frequency sweeps suggests the co-operative movement of many pinned vortices together. The history-dependence probably relates to the number and positions of the vortices. At higher temperatures, depinning will occur more easily, assisted by thermal fluctuations.

The results appear to confirm the existence of the two critical velocities identified earlier [13,25]. In addition to v_{c2} above which the response amplitude varies as the square root of the drive (Fig. 3), presumably corresponding to the production of QT, there is also a lower critical velocity. Fig. 1 shows that the resonant frequency remains unchanged within experimental error until $v_{c1} \sim 1\,\mathrm{cm\,s^{-1}}$ is attained, and then starts to move towards lower frequencies with further increase of velocity. The main difference from the earlier work is that the frequency shifts here are very much smaller, which is may be associated with the higher Q of the present grid. It is within the velocity range $v_{c1} < v < v_{c2}$ (the shaded rectangle in Fig. 3) that the erratic and hysteretic behaviour is mostly observed.

In an on-going experiment, we are studying the free decay of grid oscillations, and the results will be published elsewhere.

The three grids studied to date ([13,14] and the present work) have all exhibited differences in behaviour, but we can nonetheless conclude that: (i) at very low velocities, the damping is linear and due to phonons/rotons at higher temperatures and, presumably, to (linear) internal friction in the material of the grid at lower temperatures; (ii) at high velocities there is a square root behaviour, indicative the generation of turbulence in the helium; and (iii) at intermediate velocities the results vary in an irreproducible way from grid to grid, and over time for a given grid. In case (iii) we do not know for sure what is going on. We may speculate that it corresponds to conditions under which remanent vortices can depin, move, perhaps cross and reconnect, and then repin in different positions, but the lack of reproducibility makes it impossible to develop a detailed model.

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