Quantum turbulence in He II induced by second sound shock pulses

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Abstract

Direct measurements are presented of quantum turbulence in He II induced by second sound shock (SSS) pulses in a wide channel. Through the use of a leaky capacitor model (LCM), a growth and decay characterization of the quantum turbulence is extracted from the measurements. Also taken is an explicit energy account of the quantum turbulence as well as of the SSS pulses that induced the turbulence. Tentative decay exponent results indicate that the induced quantum turbulence decays in a comparable way to that induced by a towed grid in a channel.

Key words: quantum turbulence; second sound shock; superfluid helium; fluid dynamics; thermal diffusion

Presented here are direct measurements of quantum turbulence development in He II induced by second sound shock (SSS) pulses in a wide channel. Although thermal pulses of this kind have been used in transient heat transfer research in He II for many years, direct measurements of the quantum turbulence they induce have not been previously exhibited. From such measurements, a more physical interpretation emerges of the development in He II of thermally induced quantum turbulence [1]. A growth and decay characterization of the quantum turbulence is acquired from the measurements. An explicit energy account is also acquired of the quantum turbulence as well as of the SSS pulses that induced the quantum turbulence. Tentative decay exponent results indicate that the induced quantum turbulence decays in a comparable way to that induced by a towed grid in a channel.

Excess attenuation versus time was measured with distance from a SSS pulse heater as a parameter, as shown in Fig. 1. Quantum turbulence, viewed as a tangle of quantum vortex lines, is characterized by a line density, the quantum vortex line length per unit volume of He II. The quantum vortex line density is proportional to the excess attenuation coefficient, as given by Eq. 1, where $\Lambda(\mathrm{t})$ is the quantum vortex line density, $\alpha'(\mathrm{t})$ is the excess attenuation coefficient, c_2 is the speed of second sound, κ is the quantum of circulation, ρ_n is the mass density of the normal component of the He II, and ρ is the total mass density of the He II.

$$\Lambda(\mathrm{t}) = \frac{3\,\mathrm{c}_2}{\kappa}\,\frac{\rho_\mathrm{n}}{\rho}\,\alpha'(\mathrm{t}) \qquad (1)$$

This is derived from related analysis elsewhere [2], under the assumptions that the quantum turbulence is isotropic, and the quantum vortex lines have hollow cores with surface tension.

Pulse power flux density was varied from 100 kW/m^2 to 600 kW/m^2 and pulse duration was varied from 50 μs to 1000 μs in He II at 1.70 K. The shock channel is 178 mm long, having a 19.1 mm x 12.7 mm interior cross-section, with the SSS pulse heater fastened to the bottom end. Transverse to the channel were five active pairs of ports, each port 12.7 mm in diameter, spaced 25.4 mm apart vertically. At the first and fifth port pairs were two SSS pulse thermometers. At the second, third, and fourth port pairs were three heater and thermometer pairs for the generation and detec-

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tion of second sound resonance (SSR) waves transverse to the channel, SSR waves being temperature resonance waves. The SSR waves, attenuated by the presence of quantum turbulence, provided continuous measurements of the quantum turbulence induced by SSS pulse propagation along the channel. Previous publications give details concerning experimental devices and techniques incorporated [3,4].

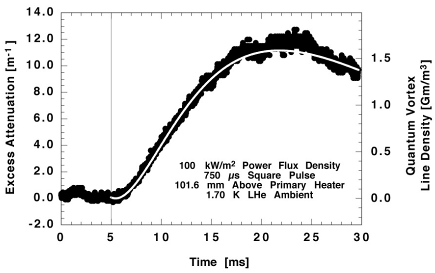

Fig. 1. An example plot of excess attenuation versus time at one position above the second sound shock (SSS) pulse heater, revealing the quantum turbulence development of the pulse. The vertical line marks the arrival time of the pulse. The white curve is a fit based on the leaky capacitor model (LCM) described in the text.

As a SSS pulse skims between each SSR pair, the excess attenuation versus time reveals that the induced quantum turbulence grows to a maximum, then decays within the volume of He II between the heater and thermometer pair, as shown in Fig. 1. An electrical analogy is suggested by the growth and decay of the electric field energy density of a leaky tank capacitor being supplied by a charged source capacitor through a series fill resistance. The tank capacitor leaks through a parallel drain resistance. The electric field energy of a capacitor is proportional to its potential squared. This is the leaky capacitor model (LCM) for the excess attenuation coefficient with respect to time. The source capacitor potential squared represents that fraction of the initial pulse energy injected into the shock channel but not transported as a SSS pulse. The tank capacitor potential squared represents the quantum turbulence energy. Since the electric field energy density of the leaky capacitor behaves in an analogous way to the quantum turbulence energy density, the fit to each excess attenuation versus time data set should approach an expression similar in form to that for the potential squared of the leaky capacitor, an expression such as Eq. 2.

$$\alpha'(\mathrm{t}) = \alpha_{\mathrm{p}} \left[\exp\left(-\frac{\mathrm{t}-\mathrm{t}_0}{\tau_{\mathrm{D}}} \right) - \exp\left(-\frac{\mathrm{t}-\mathrm{t}_0}{\tau_{\mathrm{G}}} \right) \right]^2 \qquad (2)$$

This is a four-parameter fit equation for the excess attenuation versus time, where α_{p} is a peak factor, t_0 is an onset time, and τ_{D} and τ_{G} are decay and growth time constants, respectively. These fits, such as the one shown in Fig. 1, were made to reduce the excess attenuation coefficient data. The purpose of the LCM is the extraction of characteristics, such as the peak excess attenuation and the peak time, from the data sets. Shown in Fig. 2 is peak excess attenuation versus initial pulse energy at two positions above the SSS pulse heater. The linear energy density in the caption follows from an estimating expression due to Feynman [2,5] for quantum vortex lines.

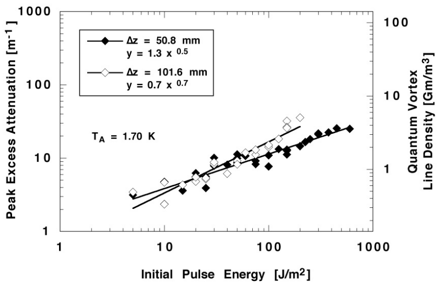

Fig. 2. A plot of peak excess attenuation versus initial pulse energy at two positions above the SSS pulse heater. The quantum vortex linear energy density is 1.68 pJ/m at the conditions of the plot.

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