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STEADY AND DECAYING QUANTUM TURBULENCE GENERATED IN He II FLOW CHANNEL BY COUNTERFLOW AND PURE SUPERFLOW[1]

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We report experimental investigations of He II turbulence and its decay. Turbulent state was generated by counterflow and pure superflow in channels of circular and square crossection. The steady-state turbulence is generated by applying power to the heater placed either in the dead end of the channel or immersed in He II in a volume adjacent to one of the silver-sintered superleaks having an outlet above the helium bath level. When this power is switched off, quantum turbulence displays a complex decay. We discuss the steady state data and forms of the observed decays in terms of available models and compare with quantum turbulence generated by towing a grid of bars through a stationary sample of He II.

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1 Introduction

Below T_λ liquid helium becomes superfluid and is referred to as He II – a quantum fluid that exhibits extraordinary flow properties. In a limit of low flow velocities, they can be largely understood within a phenomenological two fluid model, where He II is described as a liquid consisting of two interpenetrating fluids of independent velocity fields - the inviscid superfluid of density ϱ_s, and the normal fluid of density ϱ_n and dynamic viscosity η; the total density $\varrho = \varrho_s + \varrho_n$. The superfluid has neither viscosity nor entropy and the entire heat content of He II is carried by the normal component. This simplified picture is reflected by the Landau two fluid equations of motion. One important outcome of these equations is the prediction of second sound – a wave described by temperature fluctuations rather than density fluctuations, as it is the case of ordinary sound, also referred to as first sound. The two fluid equations also explain the existence of a peculiar flow of He II called counterflow [1]. Under influence of applied heat the superfluid moves towards the heat source where becomes converted into the normal fluid and flows against the approaching superfluid in such a way that the total density of helium II stays unchanged.

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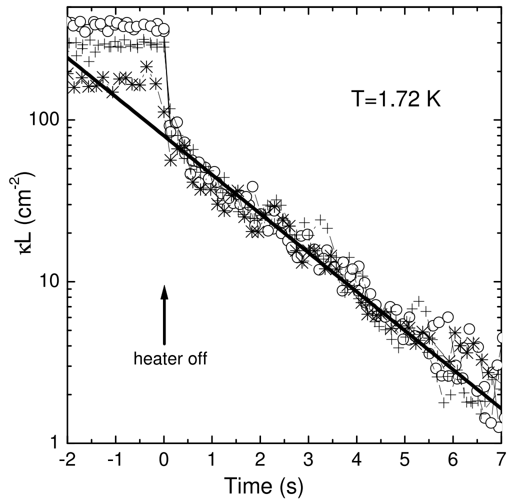

Fig. 1. Steady state and decaying vortex line density (assuming that the vortex tangle is random) generated by pure superflow measured in the middle of the channel of 6×6 mm^2 crossection. The steady state heat inputs 0.484 W (o), 0.388 W (+) and 0.295 W ($*$) applied to the heater placed above the upper superleak are switched off at $t = 0$. The solid line is a plot of the exponential function $\kappa L = 80 \times e^{-t/t_0}$ with $t_0 = 1.8$ s.

In He II any of these two fluids (or both) may become turbulent. The turbulence in He II can be generated either (i) classically, e.g., by a towed grid or between counterrotating discs or (ii) in a counterflow channel by applying a heat pulse to its closed end. Historically, He II turbulence research started with the pioneering counterflow experiments of W.F. Vinen [2], who recognized the quantum nature of it leading to an existence of a tangle of quantized vortex lines in the superfluid. Counterflow turbulence as well as its subsequent decay has been a subject of investigation by many authors (see reviews [1, 3] and references therein). However, superfluid turbulence was usually viewed as a tangle of quantized vortex lines and its possible relationship to conventional turbulence had not been given much thought.

More recently, however, a turbulent flow in He II has been generated in a manner similar to that in studies of classical turbulence (coflow turbulence). Maurer and Tabeling [4] produced turbulence in a flow of liquid helium confined between counterrotating discs and obtained the energy spectral density with an inertial range of the classical Kolmogorov form. A purely classical phenomenological spectral model [5, 6] was shown to describe most of the decaying He II turbulence in a channel of finite size.

Perhaps surprisingly, classical decay features were experimentally found not only for decaying grid turbulence [6], but also for the late decay of counterflow turbulence [8, 9]. Although the character of the decay does not appreciably change with temperature while the normal fluid to superfluid density ratio varies by a factor of ten or so, the role of the normal fluid (e.g., its profile in counterflow) remains largely unknown. In order to shed more light on this issue we designed and utilized a new experimental apparatus described in detail in a separate article presented at this Conference. Although the He II turbulence is, similarly as in counterflow turbulence, generated by the heat-induced flow, here both ends of the channel are covered by sintered silver superleaks mounted via In o-rings. Therefore there is no net normal fluid flow through it and turbulence is generated due to a pure superflow. To probe the flow we detect the vortex line density, L, utilizing the sensitive method of second sound attenuation based on gold–plated nuclepore membranes [6, 8, 9].

2 Steady-state heat–induced turbulence

The main functional character of the vortex line density versus the heat input, $\dot{Q}$, (or counterflow velocity, v_{CF}) in counterflow turbulence in a wide channel has already been establihed in the original Vinen experiments [2]: $\sqrt{L} \propto \dot{Q} \propto v_{CF}$. We have confirmed this in all our counterflow channels at a range of temperatures 1.4 K $< T < 2$ K [9].

With our new setup the turbulence is generated due to a pure counterflow through the channel. We have so far measured this dependence in detail at only one temperature $T = 1.72$ K and obtained $L \propto \dot{Q} \propto (v_{SF} - v_0)$, where v_{SF} is the superfluid flow velocity through the channel and v_0 is about 5 cm/s. Note that three steady levels of L are included in Fig. 1. Although this unexpected result awaits confirmation for a wider temperature region, it contradicts many earlier results obtained in thermal counterflow and strongly suggests that the nature of He II turbulence generated by superflow differs from that generated by the thermal counterflow.

3 Decaying heat-induced turbulence

Our results on decaying counterflow turbulence have been discussed in detail in [8, 9]. Here we present the preliminary data obtained in the same channel of 6×6 mm^2 crossection, but with both ends covered by superleaks. Fig. 1 displays the initial steady state levels and the decaying vortex line density calculated according to [2] and assuming that the vortex tangle is random [9].

When the heat of order 0.5 W is applied for typically 10-15 s the originally high second sound amplitude stabilizes to a steady state reproducible value (the last two seconds of this state is included in Fig. 1). At the instant marked as $t = 0$, the heat is switched off. After the initial fast decay, irrespectively of the steady state starting value of the vortex line density L, the subsequent decay can be described as exponential, of the form $\kappa L \propto$ exp $(-t/t_0)$ with the characteristic decay time $t_0 \approx 2$ s, where κ is the quantum of circulation. We have not yet investigated how this decay depends on temperature. This particular set of the preliminary decay data has been observed at experimental conditions when the bath temperature was controlled to T=1.72 K.

4 Discussion

The observed exponential decay is distinctly different from the decay of He II turbulence generated in thermal counterflow, where the decay of L over most of the time can be characterized by power law with exponent -3/2 [8, 9]. An exponential decay of L in He II turbulence was previously observed, but only as a very late low vortex line density stage. It was a part of a complex decay of the grid generated turbulence, consisting of four distinctly different regimes [6]. In a later paper [7] it was shown that the exponential decay is consistent with the spectral energy density of the form $\Phi(k) = C\varepsilon\kappa^{-1}k^{-3}$, if the energy containing length scale is assumed to be saturated by the size of the channel. Here C is the Kolmogorov constant and ε denotes the energy decay rate. Beyond the quantum scale $\ell_q = 2\pi(\varepsilon/\kappa)^{-1/4}$, the normal and superfluid eddies cannot be matched, due to quantized circulation in the superfluid. It seems plausible therefore that the exponential decay (Fig. 1) suggests that normal and superfluid eddies do not match even for larger length scales and much higher values of L.

Our new data on steady state and decaying He II turbulence, though preliminary, provide important evidence that the nature of quantum turbulence in He II above 1 K most likely depends on the way it is generated. If generated classically, using a grid of bars towed through a stationary sample or between counterrotating discs, on length scales exceeding the quantum length it closely resembles classical turbulence in viscous fluids. In that case He II can be described, at least approximately, as a single–component fluid possessing an effective temperature dependent kinematic viscosity.

The steady counterflow turbulence generated by applying a heat pulse to a dead end of a channel displays two distinctly different turbulent states, marked as T I and T II by Tough *et al.* (see [1] and references therein). These experimentally discovered turbulent states T I and T II are consistent with the possibility of the existence of the flow phase diagram for helium superfluids [10] recently predicted by Volovik *et al.* [11, 12]. Indeed, the quantum turbulence generated in He II by a pure superflow displays distinctly different behaviour - the vortex line density in the steady state differs from that in thermal counterflow and the decay is exponential. This is not consistent with the Kolmogorov form of the energy spectrum in superfluid and large turbulent eddies that ought to couple the normal and superfluid velocity fields seem absent. There is a clear call for further effort, both experimental and theoretical, in order to better understand the underlying physics of quantum turbulence in He II.

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