WAVE TURBULENCE OF A ROTATING ARRAY OF QUANTIZED VORTICES IN THE $T \to 0$ TEMPERATURE LIMIT

Jere T. Mäkinen [1], Samuli Autti [1], Vladimir B. Eltsov [1], Petri J. Heikkinen [1], Jaakko Hosio [1], Matti Krusius [1], Victor S. L'vov [2], Paul M. Walmsley [3], Vladislav V. Zavjalov [1]

[1] *Low Temperature Laboratory, Department of Applied Physics, Aalto University, FI-00076 AALTO, Finland*

[2] *Department of Chemical Physics, Weizmann Institute of Science, Rehovot 76100, Israel*

[3] *School of Physics and Astronomy, University of Manchester, United Kingdom*

email: jere.makinen@aalto.fi

Abstract The dynamics of quantized vortices in the zero temperature limit $T \to 0$ is currently of great interest, particularly in the case of the Fermi superfluid ^{3}He-B. Here we study wave turbulence, generated by the librating motion of a rotating cylindrical container filled with ^{3}He-B, in the limit of vanishing viscous forces at temperatures $T \leq 0.2T_c$. The polarization of the quantized vortices with respect to the axis of rotation is measured using non-invasive NMR techniques. We observe a decrease of the polarization when the librating motion is started, and a two-stage relaxation process when the modulation of the rotation velocity is stopped. The first relaxation process is associated with the dissipation of large-scale flow stored in inertial waves and the solid body rotation of the vortex array. From the decay of these energy reservoirs we determine the rate of energy dissipation of large-scale flow. The later second process is related to the relaxation of Kelvin waves on individual vortices. This process is monitored by the recovery of the polarization. The existence of a Kelvin wave cascade at the lowest temperatures is currently a central open question. We supply some evidence for the cascade.

INTRODUCTION

Unlike vortices in viscous fluids, quantized vortices in superfluids are topological objects, and generally have exactly one quantum of circulation, while their core size is fixed. Quantum turbulence is usually regarded as a tangle of quantized vortices with multiple reconnection events between the vortices, or between the vortices and the container walls, with transfer of energy towards smaller length scales. The details of the transfer mechanism between the scales larger and smaller than the distance between neighboring vortices, and the role of reconnections, have been under heated discussion during the past years [1, 2, 3]. In this work we create a new type of quantum turbulence, wave turbulence, in which there are no reconnections but rather the energy is transferred towards smaller scales via nonlinear interactions between different wave modes.

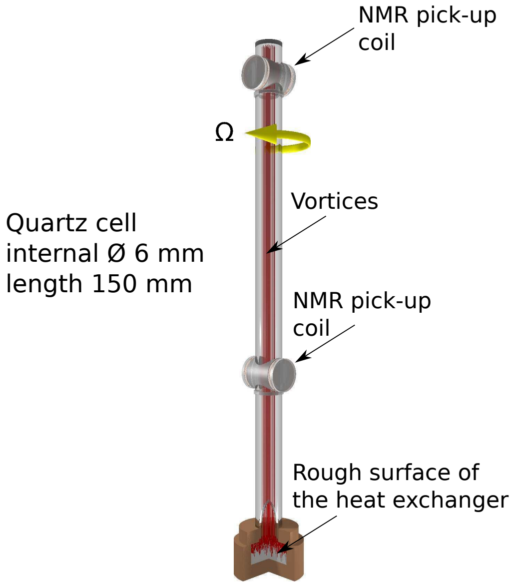

Figure 1: Sketch of the measurement setup.

EXPERIMENTAL SETUP AND METHODS

Our experimental setup includes a 150 mm long and 6 mm diameter quartz glass container, with smooth walls, two quartz tuning forks which are used as thermometers, and two NMR coils, one of which is close to the top and the other is close to the bottom of the container. The quartz container is closed from the top, and the bottom is connected to a rough sinter volume, which works as a heat exchanger. The container is filled with superfluid ^{3}He-B. The pressure of the superfluid has been varied between 0.5 bar and 29 bar in the measurements. First, the container is rotated around its axis with angular velocity $\Omega = \Omega_0$. Then, by driving the container using librating motion $\Omega(t) = \Omega_0 + \Delta\Omega \sin(2\pi t/p)$, we excite a new type of superfluid turbulence, which in this case is formed by waves in the rotating vortex cluster. Finally, after an hour of librating motion, we stop the modulation while changing the velocity to Ω_f, after which we observe the relaxation processes. A sketch of our measurement setup is shown in Fig. 1 and an example measurement with typical parameter values of the rotation drive is shown in Fig. 2. The average vortex polarization is probed through the textural parameter λ_{eff}, which probes the vortex polarization [4].

DISSIPATION OF ENERGY IN THE $T \to 0$ LIMIT

When the librating motion is stopped, we observe a two-stage relaxation process, during which the polarization of the vortices relaxes towards a fully polarized equilibrium state. We assume the equilibrium number of vortices at Ω_0 during the modulation and an equilibrium vortex state at Ω_f after the relaxation process. The first stage is related to the dissipation of the large-scale flow created by the librating motion of the cylinder and to the change of mean angular velocity at the end of librating motion. Towards low temperatures mutual friction damping of vortex motion decreases exponentially $\propto \exp(-\Delta/T)$ and dissipation at scales larger than the inter-vortex distance is slowed down. Instead the kinetic energy cascades to sub-inter-vortex scales via excitation of Kelvin waves on individual line vortices which preserves a low vortex polarization. The duration t_0 (Fig. 2) of this first stage of recovery is proportional to the energy initially stored in large-scale flow and inversely proportional to the rate of energy transfer. We calibrate the energy of the global flow by applying solid-body rotation and obtain the expected quadratic behavior $t_0 \propto (\Omega_0 - \Omega_f)^2$. From the coefficient in front of the quadratic term we extract the dissipation rate. It is temperature-independent below $\sim 0.2T_c$ as expected for a cascading process and the value of the rate is $(2-8) \times 10^{-18}$W/cm per vortex, depending on pressure. We also observe an increase of the energy stored in the inertial wave modes when the drive frequency coincides with one of the inertial wave resonances as shown in the inset of Fig. 2.

The second stage of relaxation involves the recovery of the vortex polarization, which we attribute to the decay of Kelvin waves on vortex lines. Our measurements show that at temperatures $0.15T_c \lesssim T \lesssim 0.19T_c$, the time scale of the second dissipation process, τ in Fig. 2, depends on the temperature as $\tau \propto \exp(\Delta/T)$, indicating that it is related to the damping of the Kelvin waves by mutual friction. However, at $T \lesssim 0.15T_c$, the behavior tends towards a plateau of constant dissipation, leading to a non-zero extrapolation of the dissipation at absolute zero temperature. This plateau might be caused by the existence of the Kelvin wave cascade, since the energy flow rate through the cascade is independent on the microscopic details of the dissipation mechanism. Dissipation mechanisms in Fermi-superfluids in the limit of vanishing frictional forces have been predicted [5, 6], but experimental proof is still missing. This research project made use of the Aalto University Low Temperature Laboratory infrastructure.

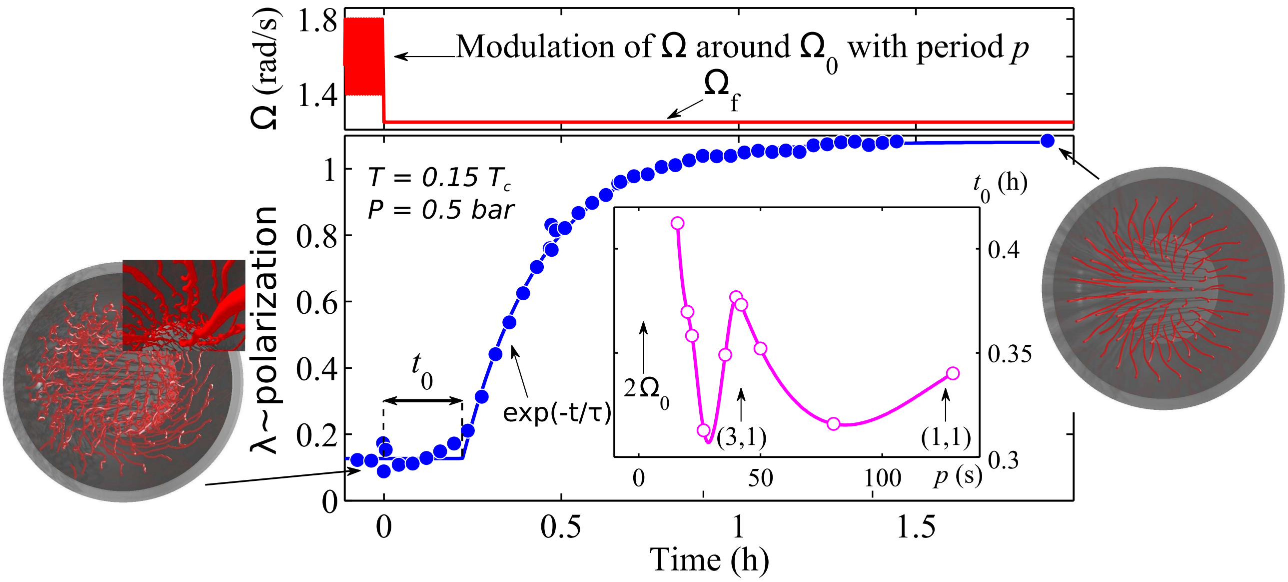

Figure 2: Example of a relaxation measurement: the parameter λ, from which the vortex polarization can be extracted, as a function of time after stopping the modulation of the angular velocity. **(Top)** Rotation drive as a function of time. **(Bottom)** The two-stage recovery of the vortex polarization. The configuration of line vortices in the rotating cylinder, as obtained from vortex filament calculations, is illustrated during the librating motion (left cross section of the cylinder) and after the relaxation process is completed (right). **(Inset)** Recovery time t_0 as a function of the period p of the rotation drive modulation. The resonance periods for the corresponding inertial wave modes (m, n), where m and n are the axial and radial wave numbers, respectively, are indicated with arrows.

References

[1] Evgeny Kozik and Boris Svistunov. *Phys. Rev. B*, 77:060502, Feb 2008.
[2] Victor S. L'vov, Sergei V. Nazarenko, and Oleksii Rudenko. *Phys. Rev. B*, 76:024520, Jul 2007.
[3] E. B. Sonin. *Phys. Rev. B*, 85:104516, Mar 2012.
[4] V. Eltsov, R. de Graaf, M. Krusius, and D. Zmeev. *Journal of Low Temperature Physics*, 162:212, Feb 2011.
[5] Mihail A. Silaev. *Phys. Rev. Lett.*, 108:045303, Jan 2012.
[6] W. Vinen. *Phys. Rev. B*, 64:134520, Sep 2001.