Physics | Lancaster University

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Title: "Quantum fluid dynamics and quantum turbulence probed using micro- and nano-resonators"

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Thesis Report by Richard P. Haley, Professor of Low Temperature Physics and Deputy Dean of the Faculty of Science and Technology at Lancaster University.

This thesis contains novel research and comprises a body of work at PhD level, proving the author's abilities in creative scientific endeavour. The thesis and published papers contain new scientific results, their interpretation and importance in the field of low temperature physics and quantum fluids, as well as their wider significance and application to turbulent fluid flow in general, one of the last great unsolved science problems.

The thesis covers an impressive range of theoretical and experimental knowledge, sets the advances made in context and provides background and supplementary information in support of six selected papers, all published in prestigious international journals. The author has also collaborated scientifically with researchers looking at similar problems in other institutions in Finland, the UK and the US.

In the introductory "Theoretical background" chapter the author gives an overview of the relevant properties of the helium liquids and their superfluid phases and their description using the two-fluid model in the hydrodynamic and then ballistic regimes. There follows a section on turbulent flow, tracing its development through classical turbulence of normal fluid flow, through the dynamics of quantum vortices carrying circulatory flow in superfluids, to the mutual friction interactions between the normal and superfluid components. This accessible review demonstrates an in-depth understanding of the material.

An extensive section on the latest understanding of quantum turbulence, to which the author has now contributed, complements the selected publication A1, looking at the creation and subsequent decay of turbulence in various scenarios and experimental configurations. I agree with the author(s) that a unified description of the Vinen and Kolmogorov forms of quantum turbulence has been provided and the existence shown of a quantum length scale.

The author then moves to the experimental techniques used to detect and characterize quantum fluid flow, and gives more detail on the detection methods used here, second sound attenuation and mechanical probes. The latter comprises three complementary tools:

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vibrating wires which have been used in quantum fluids for many years; quartz tuning forks, a somewhat newer development; and micro- and nano-fabricated mechanical resonators, cutting edge probes that the author has developed and constructed. The important contributions of the author in developing and using these techniques is made clear.

Chapter 2 deals with the onset of quantum turbulence via flow instabilities in normal and superfluid components. Data is presented and discussed for vibrating wires and tuning forks, both commercial and custom-made, and for oscillator counterflow in a second sound cell, more fully described in paper A3. The chapter ends with a section on the interplay of normal and superfluid instabilities, drawing strands together which are explored in more detail in paper A2. New insight has been provided on the transition from laminar to turbulent oscillatory flow for a range of objects of different geometries and the crossover between normal versus superfluid instability.

In Chapter 3 the author describes the design, construction and operation superconducting wire loops as local probes of turbulence (also see A4). It is shown how the vibrating wire can detect the presence of quantum turbulence created by counterflow and give a measure of vortex line density. The analysis in terms of vorticity-induced boundary layer effects is compelling and handled well by the author.

Chapter 4 is concerned with the use of micro-scaled mechanical resonators and includes a section on the limiting issue of acoustic emission, with the author contributing to a collaborative work in superfluid helium-3 (see A5), and describes the author’s success in creating and characterizing MEMS vibrating wires (A6) which will be used in attempts to measure single quantized vortices. Finally, the author details their work in the Aalto laboratory with a breakthrough result demonstrating the trapping and measurement of single vortices with a NEMS device mounted on a rotating cryostat.

The activities described in this well-written thesis and accompanying papers represent a substantial amount of work carried out over several years at the cutting edge of low temperature physics and quantum fluids research. The author has performed many demanding experiments and gone to great lengths to understand them, disseminating their results in the thesis and in well-received published works. Careful consideration has been given to questions raised by this work, and that of others, and has opened new avenues for research. The author has added to the body of knowledge.

The quality of the author's physics is excellent, and this is reflected in the written work. I have no hesitation in recommending the award of a PhD.

Yours faithfully,

Richard P. Haley

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