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Habilitation thesis of Dr David Schmoranzer – opponent's review

Based on 10 publications in leading peer-reviewed journals, the habilitation thesis of Dr David Schmoranzer is an important contribution to the ongoing research in the fields of superfluidity and cryogenic fluid dynamics. Perhaps the most important and impressive contribution of Dr Schmoranzer is to the area of quantum turbulence in superfluid ^{4}He and ^{3}He-B, especially to the study of fundamental aspects of measurement techniques in quantum turbulence.

One of the traditional techniques widely used for experimental study of quantum turbulence in superfluid ^{4}He and ^{3}He-B makes use of oscillating probes (such as resonators, superconducting vibrating wires, piezoelectric tuning forks, or micro- and nanomechanical probes). Prague superfluidity group, to which Dr Schmoranzer belongs, has a long and distinguished record of developing such techniques. However, so far the properties of interactions between quantum turbulence and oscillating probes have not been fully understood and some (often nontrivial) questions remained unanswered. Another promising experimental technique is specific to quantum turbulence in ^{3}He-B in the zero-temperature limit. This technique makes use of the so-called Andreev reflection of thermal quasiparticle excitations from quantized vortices. The ultimate aim of this technique, currently being developed by Lancaster University in the UK and Aalto University in Helsinki, is the creation of the quantized vortex imaging device. The development of such a device (a so-called "thermal excitation camera") requires a detailed and elaborate study of interactions between configurations of quantized vortices and quasiparticle excitations. Although a significant body of work has been produced in the last decade, many aspects of interactions between vortex configurations and thermal excitations still require further experimental study.

Reported in **Chapter 2** of his dissertation, one of the most original and important contributions of Dr Schmoranzer to the study of quantum turbulence is the derivation and experimental confirmation of the new Universal relation which shows that the drag force exerted on the oscillating object in high Stokes number flows scales with a single non-dimensional parameter appropriately called by the authors a Donnelly number after one of the pioneers of quantum turbulence research. The other, equally important and somewhat unexpected finding resulted from the study of transition, in the zero-temperature ^{4}He, to quantum turbulence generated by oscillations of the quartz tuning fork: David Schmoranzer and his co-authors found three critical velocities of oscillating flows, explained their origins and investigated in detail physical mechanisms associated with each of them. These findings contribute significantly to the current understanding of dissipation in pure quantum turbulence.

In the text of Section 2.1 I found two insignificant omissions which do not affect the overall very high quality of work: 1) Having correctly said that at any finite temperature, and depending on the type of flow, turbulence may develop independently in either component of ^{4}He, the author should have added that the mutual friction may make the situation somewhat more complicated. 2) Page 7 of the thesis: the situation where the superfluid component is turbulent while the normal component is laminar is also observed in ^{4}He counterflow (the so-called T1 regime, see e.g J. T. Tough, Superfluid turbulence, in *Progress in Low Temperature Physics*, Vol. 8, Chapter 3 (North-Holland, Amsterdam, 1982), pp. 133-219). Theoretical studies of the T1 regime include Melotte & Barenghi, Phys. Rev. B **80**, 4181 (1998), Galantucci et al., Phys. Rev. B **95**, 014509 (2007).

The other aspect of dissipation in quantum turbulence, that of the acoustic emission produced by oscillating objects in ^{4}He, did not receive, until now, an attention it deserves. Dr Schmoranzer and his co-authors addressed this problem (this time for a wide range of superfluid ^{4}He temperatures) experimentally (making use of tuning

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forks as oscillating probes) and theoretically. Their experimental study and the developed three theoretical models led to a significantly better understanding of underlying physical mechanisms as well as to recommendations on suppressing acoustic damping in ^{4}He experiments. Building on these results, Dr Schmoranzer and his colleagues studied the crossover from the hydrodynamic to acoustic drag in both normal and superfluid ^{4}He. The main contribution of David Schmoranzer to this project was modelling of the acoustic emission to describe the series of tuning forks, and the development of the full mechanical model of the fork's tine. The most fundamental result of the latter, dynamical model is the effective mass of the tine. Compared to earlier, static approach this is a significant improvement as the static models yield incorrect results for high resonant modes.

Finally, Dr Schmoranzer contributed to the study of Andreev scattering of thermal quasiparticle excitations by a cluster of rectilinear vortices in ^{3}He-B at temperatures below 1 mK. While many features of Andreev reflection are, by now, well understood, the aim of this work was to investigate effects associated with the presence of many vortices. Such a study is of particular importance for the development of the so-called "thermal excitation camera" which is the novel, non-invasive technique of probing quantized vorticity in the zero-temperature limit. On page 12 of the thesis, having said that the thermal excitation camera was developed at Lancaster University, the author cites Refs. [56, 57]. While addressing the combined numerical/experimental study of visualization of quantum turbulence in ^{3}He-B, these citations do not directly describe the thermal excitation camera. A more appropriate citation would be of the paper by Ahlstrom et al., J. Low Temp. Phys. **175**, 725 (2014) which directly addresses the development of such a device.

Apart from numerous projects related to quantum turbulence the Prague group is also well known for its research activity in the area of cryogenic fluid dynamics, thermal convection of the Rayleigh-Bénard type in particular. This involves the study of thermal convection in both the normal and the superfluid phase of ^{4}He. An advantage of ^{4}He for the studies of convective flows is in the large values of the Rayleigh number achievable even in a small experimental cell.

As described in **Chapter 3** of the thesis, in their experimental study of heat transfer and condensation in the Rayleigh-Bénard-type convection of the two-phase helium at temperatures above the λ-point, Dr Schmoranzer and his co-authors found a regime in which the heat propagates in the direction of the temperature gradient (that is, from a colder plate to a colder plate in the Rayleigh-Bénard cell). This counterintuitive result might seem to contradict the laws of thermodynamics, but having analyzed physical mechanisms (one of the most important being the nucleate boiling at the bottom plate) in detail, David Schmoranzer and his colleagues found the fully self-consistent explanation to this phenomenon in perfect agreement with the laws of thermodynamics. The important contribution of Dr Schmoranzer to this study is the explanation of the temperature inversion and the development of the mathematical model. The experiment was then repeated for the superfluid phase of ^{4}He. As expected, in this case no temperature inversion was found. David Schmoranzer contributed to this project by investigation of the thermal counterflow, the latter leading to the equilibration of temperature throughout the experimental cell, and of the suppressiion of nucleate boiling. I found interesting the author's suggestion that the results of this project may have applications beyond the low temperature physics.

Finally, **Chapter 4** of the thesis describes Dr Schmoranzer's contribution to the technical development, at the Institut Néel in Grenoble, of the ultralow temperature (sub-millikelvin) refrigeration technique. David Schmoranzer performed numerical simulations of the continuous nuclear demagnetization refrigerator and developed a thermodynamic model for its nuclear refrigerant, $PrNi_5$; measured vibrational levels of the cryogen-free dilution refrigerator; together with his colleagues at the Institut Néel investigated experimentally and analyzed the mechanisms of thermal decoupling of silicon oscillators in cryogen-free dilution refrigerators. The research and technical developments reported in Chapter 4 of the thesis are of importance for the whole area of low temperature physics, including fluid dynamics of liquid helium and quantum turbulence which are the main areas of candidate's interests and activity.

In summary, while Dr Schmoranzer's work in the area of quantum turbulence mostly concerns fundamental aspects of measurements, his findings also reveal some fundamental properties of quantum turbulence itself. His study of thermal convection in the two-phase cryogenic helium resulted in unexpected and deeply nontrivial findings which will be of substantial interest not only to experts of cryogenic fluid dynamics, but also to a wider community of physicists and engineers interested in convection flows and their applications. Dr Schmoranzer's contribution to the technical development of ultralow temperature refrigerators will be of significant importance to the whole community of low temperature physicists.

Dr Schmoranzer is a prolific author well known within the quantum turbulence, low temperature physics, and fluid dynamics communities. He has 32 publications, listed by Scopus, in leading peer review journals, many of high impact factor (in particular, PNAS – Proceedings of the National Academy of Sciences of the USA, IF=9.58; Physical Review B, IF=3.736; Physical Review E, IF=2.353). He has 470 citations from Scopus (self-citations are excluded).

The breadth of Dr Schmoranzer's international links and collaborations is truly impressive. He spent long and productive periods abroad working with world leading groups in the area of quantum turbulence and wider field of low temperature physics (Institut Néel, Grenoble, France; Lancaster University, UK; Aalto University, Helsinky, Finland). As a result of his long periods of work with leading groups abroad (e.g. 1.5 years in Grenoble as well as elsewhere), Dr Schmoranzer was able to bring from abroad new techniques and ideas and implement them within Charles University.

Teaching activities of Dr Schmoranzer include the delivery of lecture courses on Fluid Dynamics and Programming, supervision of student laboratories, and supervision of Bachelor and Master level student projects at Charles University.

The thesis is logically structured and well presented. In my view, the reviewed work complies with the requirements of Charles University for theses aimed at the habilitation procedure.

Opponent's questions for the habilitation procedure

1. New experimental techniques making use of e.g. micro- and nanomechanical probes, excimer molecules, thermal excitation camera, etc., are currently being developed. What outstanding problems of quantum turbulence can be addressed by these new techniques?

2. Plans for the further development of the thermal excitation camera involve the replacement of tuning forks by multiplexed nanomechanical beam array. What possible improvement in resolution can be expected compared with the currently used device consisting of the 5x5 array of tuning forks?

Conclusion

The habilitation thesis entitled "Cryogenic Fluid Dynamics and Quantum Turbulence" by Dr David Schmoranzer fulfills the requirements expected of a habilitation thesis in the field of physics. In my opinion, Dr Schmoranzer certainly deserves a position of Docent at Charles University (with his research record, Dr Schmoranzer would certainly deserve a similar rank, e.g. of a Reader, at Newcastle University).

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