Quantized Vortex Dynamics and Superfluid Turbulence

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Report from the Organisers: CF Barenghi (Newcastle), RJ Donnelly (Oregon),
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The subject of the programme was primarily superfluid turbulence and its explanation in terms of quantum vortex dynamics. As such it attracted researchers working in a number of fields: the superfluidity of helium-4 and of helium-3, superconductivity, equations of motion, quantized vortex dynamics and simulations of the dynamics, applications of the NLSE (Nonlinear Schrodinger Equation) to problems in helium-4 such as reconnection, and NLSE as a model of the Bose-Einstein Condensate (BEC) under various conditions. We were encouraged to find that perhaps 25 of the attendees could be classified as 'young' compared to some of us who have been active for many years. Many professions were represented too: low temperature experimentalists and theorists, applied mathematicians and even one cryogenic engineer who undertook to let us know what is needed on the applied side. All of this worked to make a very exciting three weeks, and we trust that collaborations begun here will acknowledge the crucial role of the Institute in carrying all this out.
A number of exciting new developments were reported and they are listed below, in no particular order. Others would undoubtedly make a different list, for much new material was presented. At the same time many unsolved problems were identified, and progress towards their solution will have been greatly accelerated by discussions at the Institute.

1. Recognition that vortex reconnections are important for
• the dynamics of the quantum vortex tangle; and
• the emission of excitations (phonons and protons) from reconnecting vortices.

The emission of phonons has been observed in simulations (Tsubota, Adams) and may be relevant to dissipation of kinetic energy at very low temperature (still need to quantify it). Phonon emission may also come from Kelvin waves. The emission of excitations may be detected experimentally, ideally in a way that measures the excitation energy.

2. Helium II offers a huge dynamical range that challenges classical turbulence models and tests fundamental turbulence theories (Oregon swept grid, convection in helium gas).

3. The NLSE is an approximate model for helium II, but realistic for a trapped BEC. Current work with NLSE is focused on
• numerics: 3-D work is now possible in complex situations such as turbulence (Nore) and vortex-ion interaction;
• analysis: vortex nucleation, studied mathematically using bifurcation theory; and
• graphics: advanced 3-D time dependent visualisation.

4. Experiments on trapped BECs now address vortex systems. All issues studied in the past in helium II and some new ones, from nucleation to interaction to dissipation to perhaps turbulence (experiments at ENS), are now available in new BEC systems which have the advantage of more controlled experimental conditions (boundaries, etc.) and the great sophistication of atomic physics. In this context the NLSE is a realistic model. An entirely new area of quantized vortex dynamics is available now for investigation.

5. Helium II turbulence at low temperatures T: Svistunov and Vinen's conjectures of the importance of Kelvin waves have been demonstrated by Kivotides (evidence of a turbulent cascade which scales like k-1). Classically this is a new interesting type of cascade. The role of small vortex rings in the decay of helium II turbulence at low temperatures needs to be clarified.

6. New tools for self-consistent calculation of flows in the normal and superfluid components, taking account of the mutual friction from vortices which couple them, are now available to study helium II turbulence at T > 1 K (Kivotides, Idowu).

7. Partly owing to the previous point, more attention is being paid to the normal fluid which has been a mystery in the past (due to lack of direct flow visualisation.) Now Particle Imaging Velocimetry (PIV) is being implemented in a cryostat designed by Vinen at Yale. Extension of PIV to helium II is an exciting possibility but presents many challenges.

8. The NLSE is being made more realistic for helium II.
- The nonlocal model discussed by Roberts includes rotons.
- Adams couples NLSE to hard sphere gas to model the normal fluid (ballistic).
- Griffin now has NLSE with hydrodynamic limit of normal fluid.

9. There is new interest in the relationship between the topology (broken by reconnections, hence release of energy) and the geometry of structure, which cannot be changed arbitrarily as done traditionally by topologists but changes according to the dynamics (Biot-Savart law, NLSE or Navier-Stokes).

10. Experiments suggest that for dense vortex line tangles the two fluids tend to move with the same velocity on length scales large compared to the vortex line spacing (that is, there are no signs of a temperature dependence, which characterises the Landau two-fluid model). Some theoretical justification for this idea exists (Vinen), but more rigorous arguments are required.

11. Helium II with vortices as a turbulent fluid: new derivations of the HVBK equations were given for the macroscopic hydrodynamic description of superfluid helium turbulence with quantum vortices (Holm). These derivations cast light on the energetics of these flows and the parallels of their mathematical structure with that of turbulence models for normal fluid - including 'eddy viscosity'. New applications of the HVBK equations in numerical simulations highlight the non-classical behaviour of their solutions in Couette flow.

12. Classical turbulence experts (Tsinober and others) provided a valuable comparison between the physics of Navier-Stokes and helium II turbulence. Many physical concepts and mathematical tools from classical turbulence are still underutilized in superfluid turbulence research. Two specific suggestions made were that higher order statistics be measured in superfluid turbulence, and that the characterisation of even the random vortex tangle by a single length scale may be inadequate, when one considers the vorticity amplification processes of Eulerian fluid mechanics.

13. Experiments being performed on the nucleation of individual vortices in helium-4 down to millikelvin temperatures suggest both thermally-assisted and quantum tunnelling nucleation mechanisms (Packard, Avenel & Varoquax).

14. Numerical simulations of vortex nucleation by spherical objects (ions) have been made in the NLSE framework by Berloff, Adams and co-workers. The calculated critical velocities take into account the structure of the relevant very small vortex configurations. But they relate to those at which the energy barrier (see the previous point) disappears, and they are therefore too high; calculations that identify the height and width of the barrier need to be carried out. The evolution of existing vortices has been simulated in 3-D using the NLSE by Brachet, Nore and their colleagues.

15. Koplik has discussed vortex reconnections in the framework of the NLSE, giving valuable insight into the way this process might proceed.

16. Sonin and Thouless discussed the forces that act on a moving quantized vortex; earlier controversies are now being resolved.

17. The experimental study of quantum turbulence in superfluid helium-3 is now appearing as a realistic possibility (Fisher), and it could contribute in an important way to our understanding of such turbulence.

18. Similarities between the behaviour of vortices in a Kosterlitz-Thouless transition and in two-dimensional turbulence were explored (Williams).

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