Quantised vortex line visualisation in superfluid helium using low temperature optics

James R.T. Seddon [a,1], Michael S. Thurlow [a], Matthew J. Lees [a], Peter G.J. Lucas [a]

[a] *Department of Physics and Astronomy, University of Manchester, Manchester, M13 9PL, UK.*

Abstract

An optical probe based on the technique of shadowgraphy is proposed that would enable visualisation of the surface depressions (dimples) above quantised vortex lines in a sample of rotating superfluid liquid helium. An analysis based on the dimple profile calculated by Sonin and Manninen shows that the technique is feasible from the known sensitivity of our shadowgraphy system used to visualise thermal convection rolls. Such a probe could be used to investigate vortex arrays in the presence of appreciable normal component, would provide information on the profile of the dimples, and could be adapted to visualise quantum turbulence.

Key words: helium; superfluid; visualisation; vortex

1. Introduction

Turbulence in superfluid liquid helium is expected [1,2] to involve both classical turbulence of the normal component and in the case of the superfluid component, turbulent motion of a tangle of quantised vortex lines. The existence of both kinds of turbulence is deduced indirectly from a variety of experiments [2,3]. However direct observation is not routine because no reliable technique exists analagous to the tracer methods (smoke, dye, etc.) used to make flow visible in classical fluids, although some progress [4] has been made in the use of $H_2 - D_2$ solid particles.

We propose here a new optical probe based on our successful implementation of the shadowgraph technique to make convection patterns visible in liquid helium [5]. As a first step we examine its use to make the uniform array of quantised vortex lines visible that are created when a container of superfluid helium is rotated at a constant angular velocity. Apart from the implication for visualising quantum turbulence, the dynamics and structure of such an array is interesting in its own right. Packard and coworkers [6] in particular developed a technique for taking images of positions of vortex lines where they end on the free surface of rotating HeII and obtained considerable information on the dynamics of the vortex array. However this technique requires that the temperature of the liquid helium sample must be below 0.6 K to reduce the vapour pressure sufficiently to avoid electron/vapour atom collisions in the image collecting process. The dynamics of vortex lines at higher temperatures where there is appreciable normal component present is of interest, both from the point of view of normal fluid/vortex line interactions [7] in quantum turbulence and also the interest [8] in the profile of the surface "dimple" near the $\lambda -$ transition and in the presence of ^{3}He.

2. Visualisation Probe

A direct optical probe of the array of dimples was proposed many years ago by Hall [9]. Here the regular lattice structure would weakly reflect light incident on the free surface of rotating HeII and provide diffraction images. However, this technique provides data av-

[1] Corresponding author. E-mail: james@grendel.ph.man.ac.uk

eraged over all the dimples whereas the technique of Packard and coworkers [6] permits the observation of individual vortex dimples.

The optical technique used by us [5] to visualise convective rolls in liquid helium relies on the tiny deviation of light caused by thermally induced refractive index variations. In this technique light enters the fluid layer normally, reflects off a lower mirror-finish plane boundary and reverses its path but with the roll pattern structure imprinted on the beam in the form of angular deviations. The reflected beam then falls on a cooled charge-coupled device (CCD) light sensitive surface and creates regions of higher or lower intensity depending on whether they are respectively converging or diverging. Various image enhancement techniques are used [5] to improve the image resolution. In effect the convection rolls act as cylindrical lenses with an effective focal length which can be hundreds of metres.

The principle of our adaptation of this technique for imaging vortex dimples on a free surface of rotating HeII is that the profile of the free surface is used to deviate the incident light beam by refraction at the vapour/liquid interface, but the boundary reflection and collection optics is similar to that used by us earlier [5]. Our optical alignment is shown in Figure 1 where we use the symbols of Sonin and Manninen [8] (whose analysis of the vortex dimple incorporates the earlier work of Hall [9] and Harvey and Fetter [10]). Their analysis shows that surface tension modifies the classical profile to a shallow depression of depth $Z_d \sim 0.006\mu$m with a much larger radius a proportional to the capillary length and which is of order 500 μm, with a very narrow vortex core of radius $\sim 10^{-4}\mu$m. The radius is of order 1000 times larger than the visible light of wavelength 0.63 μm that we use, so that geometric optics as used by Berry and Hajnal [11] should be an appropriate description.

We have obtained the dimple profile by numerical integration of Sonin and Manninen's equation (2), but we have not yet carried out a numerical investigation into the extent of the refraction of this profile. However a crude analysis obtained by assuming the depression is a cone of depth Z_d and radius a reveals a deviation angle of $\delta = (n-1)Z_d/a$, where $n = 1.0282$ is the refractive index of ^{4}He, yielding $\delta \sim 6 \times 10^{-7}$. We know from our convection experiments that our optical system can detect angular deviations of about this order without substantial image-enhancement, so that the technique ought to be feasible for detecting the dimples. In this application the dimples should provide a virtual image below the surface. The analysis [11] of the caustics produced by a similar surface deformation on water indicates a "halo" centred on the vortex location with a diameter providing information on the size of deformation.

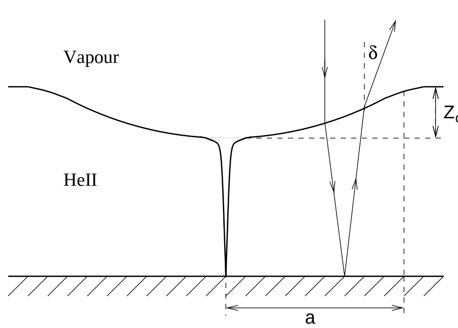

Fig. 1. Deviation of normally incident light by a vortex profile.

Numerical work is proceeding on a more precise calculation of the angular deviations produced by the calculated dimple profile, and experimental work is in progress on our rotating cryostat [12] to implement the proposed probe.

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