Anisotropy and Flow in $^3$He-A*

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Thermally driven counterflow in $^3$He-A is investigated, using techniques that exploit the anisotropy of the fluid. The results are discussed in terms of both uniform-texture and helical-texture hypotheses. Anisotropy of heat flow is observed for the first time and a limitation of the superfluid velocity is strongly suggested.

INTRODUCTION

Superfluid $^3$He-A is not a simple liquid. On the theoretical side it is characterized as being a BCS-superfluid-like state possessing two lightly coupled anisotropy axes. The variations of these axes in time and space give rise to a "textured" anisotropy which will influence and be influenced by currents and fields. On the experimental side, an unprecedented profusion of magnetic effects have been observed, and, although not as much has been done in the area, flow effects promise to be as complicated.

This paper presents the most direct measurements of thermally driven flow made to date. It is organized into a number of sections: (1) the two-fluid model; (2) effects influencing the orientation of the anisotropy axes in bulk; (3) a textural phase diagram; (4) experimental; (5) temperature measurement and heat leak; (6) comment on interpretation; (7) field ramping measurements: uniform texture hypothesis; (8) field turnoff measurements: uniform texture hypothesis; (9) anisotropy of heat transport: uniform texture hypothesis; (10) results: helical texture theory.

1. THE TWO-FLUID MODEL

Keeping in mind Henry Hall's\(^1\) dictum that it is best to be wary of an "excessive desire for analogies with $^4$He," we should learn what we can from that very extensively studied liquid.\(^2,3\)

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The two-fluid model, which has also been very successfully applied to superconductivity in metals, postulates the existence of two liquid components with strikingly different properties. The "superfluid" fraction, the density of which increases as the temperature is decreased, carries neither entropy nor viscosity, while the "normal" fraction has properties similar to those of the bulk liquid above the superfluid transition temperature. The densities of these two components are simply additive: $\rho_s + \rho_n = \rho$ ($\rho$ is the measureable bulk density), the proportions depending on temperature. The fluids obey separate Navier-Stokes equations and in the limit of small velocities their flows do not interact with each other.

An experiment that graphically displays these properties is that of heat conduction. The basic idea is that at the warm end of a column the density of the superfluid component is less than at the colder end, so superfluid flows down the concentration gradient and is converted into normal fluid which is flowing in the opposite direction carrying heat away from the source.

Quantitatively speaking, the equation of motion of the superfluid fraction is

$$\frac{Dv_s}{Dt} = -\frac{1}{\rho} \nabla P + S \nabla T$$

(1)

where $v_s$ is the velocity of the superfluid fraction, $P$ is the pressure, and $S$ is the entropy. In steady, uniform flow $Dv_s/Dt = 0$ and we obtain the fountain pressure equation

$$\nabla P = \rho S \nabla T$$

(2)

which has been verified in $^3$He by Shields and Goodkind. Normal fluid flows in response to the pressure difference, the equation for laminar flow between parallel plates with spacing $d$ being

$$\nabla P = -12\eta v_n/d^2$$

(3)

where $v_n$ is the velocity of the normal fraction and $\eta$ is its viscosity. In order to balance the flow of normal fluid the superfluid must move with velocity

$$v_s = -\rho_n v_n/\rho_s$$

(4)

Since only the normal fluid carries entropy, we must have (neglecting diffusive heat flow)

$$v_n = q/\rho ST$$

(5)

where $q$ is the heat flux. Combining the above equations, we find

$$\nabla T = -\frac{12\eta}{(\rho S)^2Td^2} q$$

(6)