Neutron Radiography of Helium II

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Abstract

We have used a neutron radiography technique to investigate the spatial distribution of ^{3}He atoms in very dilute liquid ^{3}He-^{4}He mixtures at temperatures below the superfluid transition temperature. By imposing heat currents and monitoring the subsequent redistribution of ^{3}He within the sample volume we obtain a direct measurement of the relevant mass diffusion coefficient. Data from these experiments provides a striking demonstration of the manner in which the distribution of impurity atoms within the liquid can be influenced by the presence of a free surface.

Key words: superfluidity; diffusion; ^{3}He-^{4}He mixtures; neutron radiography; Helium Vapour Compression (HEVAC) Effect

The idea of using neutron radiography techniques to study the distribution of ^{3}He atoms in dilute liquid ^{3}He-^{4}He mixtures was described by Golub and Lamoreaux [1]. We have implemented a practical realization of their proposal as part of an effort to mount a new search for the electric dipole moment of the neutron [2]. In this report we present a preliminary analysis of neutron radiography data acquired using the Los Alamos Neutron Science Center (LANSCE) pulsed spallation source. Further theoretical and technical aspects of the experiment described herein can be found in our recent report of a measurement of the mass diffusion coefficient D for ^{3}He in liquid ^{4}He below 1 K [3].

Our experimental volume comprises a 100 cm^3 right circular cylinder with an inner radius of 2.57 cm (see Fig. 1). It is attached to the mixing chamber of a dilution refrigerator and aligned such that its axis is horizontal. The refrigerator-cell assembly is mounted to a translation table equipped with linear resistive displacement transducers. This arrangement provides for accurate positioning of the cell in the plane orthogonal to a well-collimated horizontal neutron beam.

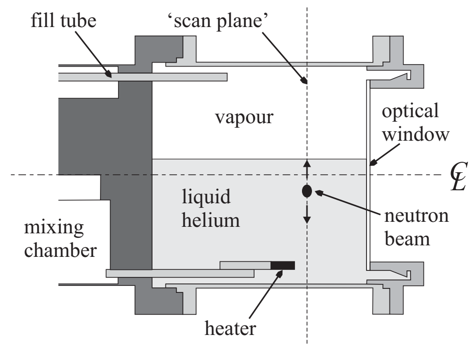

Fig. 1. The experimental cell is shown in a partially-filled state. The neutron beam has a FWHM of order 3 mm and is directed normal to the view shown here.

The cell can be filled to an arbitrary depth with liquid ^{3}He-^{4}He solutions by condensing a gas of the appropriate mixture through a fill-tube that penetrates the mixing chamber wall. Scintillation light, generated as products of the reaction $n+{}^3\mathrm{He} \rightarrow p+{}^3\mathrm{H}+784$ keV

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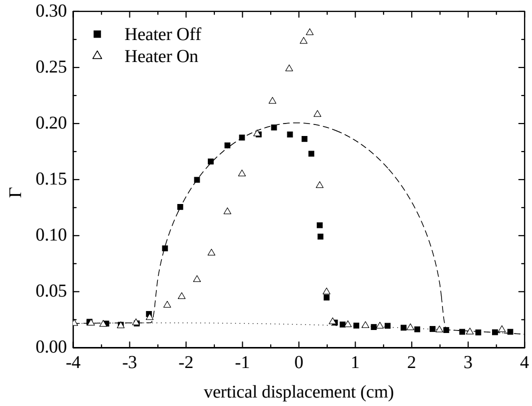

Fig. 2. The normalized PMT count rate Γ provides a measure of the volume integrated ^{3}He density along the beam trajectory. During the acquisition of these data the cell was approximately half-full of liquid with a nominal ^{3}He fraction $X_0 \sim 3 \times 10^{-4}$ and a temperature $T = 0.87$ K. The dotted line represents an estimate of the background while the dashed line indicates the count rate one expects in a completely full cell. The positioning of the beam relative to the cell is indicated in Fig. 1.

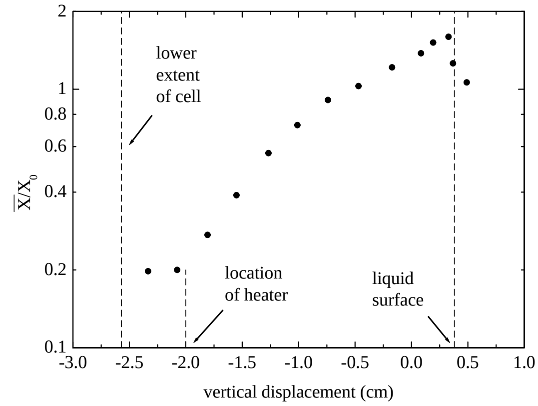

Fig. 3. The ratio of the two (net) PMT count rate measurements ('Heater On'/'Heater Off') shown in Fig. 2 is interpreted as a measure of the mean ^{3}He concentration $\overline{X}$ along the beam trajectory when a 6 mW heat current is imposed on the liquid relative to the nominal equilibrium concentration X_0.

are brought to rest in the liquid ^{4}He, is detected using a photomultiplier tube (PMT) mounted to the end of the cell. We also make use of a ^{6}Li-glass detector placed downstream of the apparatus to monitor the neutron flux transmitted through the cell. Both detectors are gated relative to the spallation source so as to select prompt events triggered by 5.7 to 10.4 meV neutrons.

In Fig. 2 we show two examples of measurements of the PMT count rate as a function of the vertical displacement of the neutron beam from the axis of the cell. These data are reported in terms of a dimensionless quantity Γ, defined as the PMT count rate normalized to the incident neutron flux. The first example (square symbols) corresponds to a situation in which the ^{3}He distribution is nominally uniform. After subtracting a background (dotted line), the PMT count rate is largely determined by the geometric path length of the beam through the liquid. Deviations from this behaviour near the liquid surface reflect systematic effects rather than non-uniformities in the ^{3}He density.

The second example (triangular symbols) corresponds to a situation in which an electrical current is passed through a resistive heater located near the bottom of the cell. A significant redistribution of the ^{3}He is evident. This behaviour is to be expected as the ^{3}He is entrained in the flow of the normal component of the fluid. However, one naively expects the ^{3}He to accumulate near the mixing chamber of the refrigerator, which must ultimately act as the heat sink. Instead, the data in Fig. 2 clearly indicate that the ^{3}He is driven primarily toward the liquid surface. A complementary presentation of these data is obtained by normalizing the net PMT count rate attributed to n-^{3}He-induced scintillation events measured with the heater 'on' to the rate measured with the heater 'off' (see Fig. 3).

Quantitatively, the steady-state distribution of ^{3}He in the liquid should satisfy the diffusion equation $\nabla \ln X = \mathbf{v}_\mathrm{n}/D$, where $\mathbf{v}_\mathrm{n}$ is the velocity of the normal component of the fluid. Gradients in the concentration X thus provide a measure of $\mathbf{v}_\mathrm{n}$, or equivalently, the heat flux $\mathbf{q} = \rho s T \mathbf{v}_\mathrm{n}$ transported by the fluid [3,4]; here ρ and s represent the density and entropy of the liquid. Clearly, the data shown in Fig. 3 indicate a significant heat flux directed towards the surface. Further examination of the distribution of ^{3}He in the cell reinforces the assertion that a large fraction of the total heat current is transported through the vapour phase. This is consistent with the extraordinarily large effective thermal conductances that can be associated with helium vapour refluxing effects [5]. It also allows us to determine $\mathbf{q}$ and hence to use the data shown in Fig. 3 to obtain an absolute measurement of the ^{3}He mass diffusion coefficient $D \sim 1$ cm^2/s at 0.87 K, in agreement with our previous report [3]. Full details of this work and its implications will be published elsewhere.

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References

[1] R. Golub and S.K. Lamoreaux, Phys. Rep. **237** (1994) 1.

[2] P.D. Barnes *et al.*, LANSCE Activity Report (2001) 110 and Los Alamos Unclassified Report 02-2331 (2002).

[3] S.K. Lamoreaux *et al.*, Europhys. Lett. **58** (2002) 718.

[4] F. London, *Superfluids, Vol* **II** (Wiley and Sons, N.Y.) 1954.

[5] M.E. Hayden *et al.*, Physica B **194-196** (1994) 677 and P.J. Nacher *et al.*, J. Low Temp. Phys. **97** (1994) 417.