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To cite this version:
R. Scurlock, D. Utton. EXPERIMENTAL OBSERVATIONS ON THE BOUNDARY BETWEEN COEXISTING 4HeI AND 4HeII. Journal de Physique Colloques, 1978, 39 (C6), pp.C6-332-C6-333. 10.1051/jphyscol:19786147 . jpa-00217555

HAL Id: jpa-00217555
https://hal.archives-ouvertes.fr/jpa-00217555
Submitted on 1 Jan 1978

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EXPERIMENTAL OBSERVATIONS ON THE BOUNDARY BETWEEN COEXISTING $^3\text{He}\text{I}$ AND $^3\text{He}\text{II}$

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Résumé.- Les expériences simples avec un cryostat en rotation, démontrent l'existence d'une limite des phases entre HeI et HeII. Les "gradins" des températures remarquées, de 20-55 mK à travers la limite, sont expliqués au moyen du coefficient d'expansion négatif dans HeI auprès de la ligne $\lambda$.

Abstract.- Experimental studies have been made, in a rotating cryostat, of $^3\text{He}\text{I}$ in contact with $^3\text{He}\text{II}$ via a phase boundary between the two fluids. The observed temperature jumps of 20-55 mK across the boundary are explained in terms of the negative expansion coefficient for HeI close to the $\lambda$-line.

The 0.82 m diameter, 3000 rpm, rotating helium cryostat at Southampton provides a novel environment for studying the behaviour of both HeI and HeII. The centrifugal acceleration fields (up to 5000 g at the periphery) enable pressure differences up to 20 bars to be generated in a radial duct filled with liquid helium and extending from axis to periphery of the rotor. The change in thermodynamic state during radial flow under rotation is conveniently related to the fluid enthalpy by

$$\Delta H = \frac{1}{2} \omega^2 r^2 \text{ KJ kg}^{-1}$$

where $\omega$ is the rotation rate in radian.s$^{-1}$ and $r$ the distance from the rotation axis. Previous work has demonstrated that in HeI, the change in state during radial flow is closely isentropic whereas in HeII, it is isothermal as a result of the high effective thermal conductivity. There is no published data in the form of an $H$-$S$ diagram in the region of the $\lambda$-transition. However, by using the available data from a number of sources, we have generated a preliminary $H$-$S$ diagram for helium in this region (figure 1).

The thermodynamic state in the rotating frame can be accurately and directly controlled in terms of the speed of rotation, the radial distance and the axis temperature. Since these parameters are readily determined experimentally, a rotating cryostat enables precision studies of the thermophysical properties of helium to be carried out. In particular, with axial temperatures between 2.10 and 2.17 K, we have been able to set up an easily controlled situation with HeI in contact with HeII via a phase boundary between the two fluids. In practice, the boundary is moved in a radial direction by changing the rotation rate while the axial temperature is maintained constant. The coexistence of the phases at the boundary is a consequence of the inhomogeneity imposed by the pressure gradient.

The coexistence of HeI and HeII in the earth's gravitational field has been previously observed. The boundary region has an unexpected property, namely a significant positive step-like temperature difference $\Delta T$ between the HeI and HeII of several tens of millikelvins. Since this temperature jump was unexpected, a number of experiments have been carried out to verify its existence and to study its properties.
been carried out to gain a physical understanding of this phenomenon and to eliminate the possibilities of experimental artifacts.

$\Delta T$ is reproducible when the phase boundary is moved either inwards or outwards radially, and decreases as the axial temperature approaches the $\lambda$-temperature. $\Delta T$ also decreases with decreasing radius and appears to be related to the local pressure gradient $\frac{dp}{dz}$. In the presence of a large heat flux across the boundary applied via an electrical heater at the peripheral end of the radial duct, $\Delta T$ decreases non-linearly with increasing heat flux. For example, at $40 \text{ mW/cm}^2$, $\Delta T$ was 50% of its original value under the background heat flux of approximately $0.25 \text{ mW/cm}^2$, i.e., the temperature jump does not arise primarily from a Kapitza type thermal boundary resistance. $\Delta T$ does not depend on self-heating ($10^{-10} - 2 \times 10^{-8}$ watts) in the resistance thermometers or on differences in thermal resistance between the duct walls and HeI or HeII.

We believe that the temperature jump can be explained in terms of the unusual temperature dependence of the density of HeI just above the $\lambda$-line. It is not solely the result of an intrinsic property of HeI/HeII interface. The locus of the density maximum of HeI can be determined from the H-S diagram using Maxwells Equation

$$\frac{1}{\rho} \left( \frac{\partial \rho}{\partial T} \right)_P = -\rho \left( \frac{\partial V}{\partial T} \right)_P = \rho \left( \frac{\partial P}{\partial T} \right)_T$$

(2)

The locus of the point $\frac{\partial P}{\partial T} = 0$ describes the variation of the density maximum with pressure and is shown in figure 1.

In the presence of distributed heat flux through the wall of the radial duct containing a HeI/HeII interface at radius $r_1$, there will be an intermediate region $r_1 < r < r_0$ where heat transfer within the HeI cannot take place by convection in the normal sense until the temperature of the HeI in this region has increased to a value $T_0$ at which $\left( \frac{\partial P}{\partial T} \right)_T$ is zero. Above this temperature, the expansion coefficient is positive and convection can take place. The temperature jump across this intermediate region is determined by the intrinsic properties of the helium and to a first order of approximation is independent of the heat flux. Figure 2 shows that there is reasonable agreement between the predicted values of $T_0 - T_\lambda$ using equation 2 and the observed values of $\Delta T$. In this curious situation the heat transfer mechanism across the intermediate region is not clear and may include contributions from for example, conduction, oscillations or cellular fluid motion /7/ quantum mechanical tunnelling, phonon mismatching etc.

If the heat transfer is by conduction alone, then the thickness of the intermediate layer is approximately 0.2 mm (compared with our experimental resolution of 4 mm determined by the size of thermometer) when the background heat flux was measured to be about $10^{-3}$ W. The time taken to establish the intermediate layer depends on the heat flux, but in our experiment it was generally shorter than the time taken to observe the temperature jump by, for example, changing the speed of rotation.

References

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