Nucleation of Transitions in Liquid $^3$He–$^4$He Mixtures


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We present a complete set of data describing the nucleation both of superfluidity and phase separation at container walls in liquid $^3$He–$^4$He mixtures. The appearance of superfluidity and the growth of phase-separated films are measured locally at the walls. A theoretical interpretation is given, important results of which are that the phase separation and superfluid transitions become uncoupled when the transitions are localized near the walls and that quantum fluctuations most probably strongly affect the nature of the superfluid nucleation transition at low temperature. Further, comparison of our results with data for transitions in pure $^4$He films demonstrates that a universality principle governs the transitions in both systems.

1. INTRODUCTION

The role of dimensionality in determining the properties of ordering phenomena such as magnetism, superconductivity, and superfluidity is a subject of continued and current interest. Of particular concern is the question of whether or not coherent phenomena observed in three-dimensional configuration space persist in two-dimensional space.$^1$

Liquid helium affords the opportunity of studying extremely thin uniform films which can be regarded as two-dimensional systems, and in recent years a plethora of data$^2-7$ has been gathered on superfluid properties in restricted geometries. The essential features which have emerged from these experiments are: the existence of superfluidity in films as thin as 2.1 atomic layers$^3$; the depression of the temperature of superflow onset with decreasing film thickness $d$; the variations of superfluid density $\rho_s$ as a function of $d$, and the vanishing of superflow at finite $\rho_s$. 

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Various theoretical models have been proposed to describe the behavior of $^4$He films. Ginzburg and Pitaevskii and Mammadze\(^8\) use the concept of order parameter with a spatial dependence. Chester and Eytel\(^9\) introduce surface excitations similar to those observed in bulk $^4$He. Kosterlitz and Thouless\(^1\) and Penrose\(^10\) propose vortex models which explain the fact that superfluidity disappears for a finite value of the superfluid density; Dash\(^11\) suggests an entirely different approach whereby the onset of superfluidity occurs via the formation of localized superfluid droplets which, when sufficiently numerous, become interconnected in a percolation-type transition. In view of the great number of different theoretical explanations, it is clear that new experimental observations are needed. Mixtures of $^3$He--$^4$He have the advantage over $^4$He systems that a new parameter, the concentration, is available. The study of helium film mixture should then be quite useful. However, because concentration inhomogeneities which develop in bulk mixtures in the vicinity of walls lead to the nucleation of both superfluidity and phase separation near the walls, it is possible (and easier) to obtain a considerable amount of information concerning phase transitions in systems of reduced dimensionality by studying bulk systems. The latter approach is the one taken here.

In Section 2, we introduce a local continuum model\(^12\) which gives explicit results for the spatial variations in the pressure $P$ and concentration $x$ in the vicinity of the walls. Knowledge of the local values of $P$ and $x$, together with known experimental results for the bulk $\lambda$ line and phase separation curves,\(^13\) permits us to predict the occurrence of both $\lambda$ and phase separation transitions in the vicinity of the walls. In other words, we predict the appearance of superfluid films near the walls. At the boundaries separating the films from the bulk of the mixture, $x$ may be either continuous or discontinuous. In the latter case phase separation has taken place, the film being the $^4$He-rich phase. The film transitions, for fixed bulk concentrations $x_d$, occur at temperatures higher than the corresponding bulk transition temperatures $T_s(x_d)$. As $T$ is lowered toward $T_s(x_d)$, the film widths increase toward infinity, at which point the transition nucleations become complete.

In Section 3 the experimental apparatus capable of detecting both superfluid onset and phase separation near the walls is described in some detail.

In Section 4, the experimental results are first presented. These results do not agree with the simple local continuum theory of Section 2, a fact which is not surprising since the local theory does not account for any effects of reduced dimensionality. The local theory is corrected to account for such effects via a coherence length argument. Good agreement with experiment is obtained over most of the relevant range of $x_d$. Important conclusions drawn are: