Temperature and concentration gradients in superfluid steady-state ^{3}He-^{4}He solutions

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Abstract

The temperature and concentration gradients ∇T and ∇x are measured in a superfluid ^{3}He-^{4}He mixture with a concentration 9.8% of ^{3}He in the temperature range 50-500mK. The gradients are produced by a steady thermal flow $\dot{Q}$ and registered by two thermometers and two capacitance - concentration gauges are placed at 1cm interval. The dependencies of ∇T and ∇x on $\dot{Q}$ and temperature are investigated at different $\dot{Q}$. The onset of the convection is observed where the dependencies ∇T ($\dot{Q}$) and $\nabla x(\dot{Q})$ deviated from the linear region. It is shown that the relationship between the steady values of ∇T and ∇x in the superfluid solutions is in agreement with a theoretical model derived from the temperature and concentration dependencies of the osmotic pressure.

Key words: superfluid ^{3}He-^{4}He solutions, temperature gradient, concentration gradient, osmotic pressure

1. Introduction

One of the features of superfluid ^{3}He-^{4}He solutions distinguishing them from pure HeII is the possibility of inducing simultaneously temperature and concentration gradients under a constant pressure P in the liquid. This was first observed by Khalatnikov [1] who formulated the expression for the flow of impurities:

$$i = -\rho D \left(\nabla c + \frac{\nabla T}{T} k_T + \frac{\nabla P}{P} k_P \right) \qquad (1)$$

where ρ is the density of the liquid, D is the diffusion coefficient, k_T the thermal diffusion coefficient, k_P the barodiffusion coefficient, c is the mass concentration of ^{3}He in the solution. Under the steady-state condition, when $\nabla P = 0$, the nonlinear effects are negligible and there is no mass flow, Eq. (1) can give the correlation between the temperature and concentration gradients. Different conditions for the steady states in superfluid ^{3}He-^{4}He solutions were studied theoretically in [2,3] taking into account the interactions between quasi-particles. At quite low temperatures, when the roton and phonon effects are negligible, the correlation between the temperature and concentration gradients in the solution is only determined by the pressure of the impurity excitations [3].

$$\frac{\nabla x}{\nabla T} = -\frac{(\partial \Pi / \partial T)_{x,P}}{(\partial \Pi / \partial x)_{T,P}} \qquad (2)$$

Here x is the molar ^{3}He concentration in the solution which is related to the mass concentration as $x = 4c/(3{+}c)$, Π is the osmotic pressure. Earlier the correlation of ∇x and ∇T in the ^{3}He-^{4}He solutions was investigated only at high temperatures in high-concentration solutions [4].

The goal of this work is to investigate experimentally the stationary gradients of temperature and concentration in the ^{3}He-^{4}He solutions whose thermodynamic and kinetic properties are determined by impuritons (^{3}He quasiparticles). The measurements were performed in a wide range of temperatures and heat flows, which permitted us to estimate the effect of phase separation in the solution and possible convection.

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2. Correlation between steady-state temperature and concentration gradients in solution. Comparison with theory

To measure the temperature distribution over the cell height, two thermometers and two capacitive concentration sensors were used. They were fixed in the middle of the cell at a fixed spacing (10 mm). Using the concentration sensors, we could find the changes solution concentration from changes in the dielectric constant (see [5]). The stationary temperature ΔT and concentration Δx gradients were measured at different temperatures and heat flow powers $\dot{Q}$. Two types of experiments were performed. A:- The temperature dependences of ΔT and Δx were measured at a constant power of the heat flow from the lower heater and the temperature of the liquid in the cell changed due to the variation of the temperature in the mixing chamber. B:- The temperature of the mixing chamber was constant, and the temperature dependence of ΔT and Δx was registered during variations of the heater power Q. The Δx and ΔT values obtained in experiments A and B were used to estimate the correlation between ∇x and ∇T. ∇x was calculated taking into account that the size of the concentration sensor (both are 0.5 cm high) is comparable with their spacing. Besides, we also considered the fact that the heat flow inside the sensor was different from that between the sensors since the cross-section area of the sensor was smaller than that of the cell. It was also assumed that the concentration gradient was constant along the cell axis. ∇T was calculated assuming that the sizes of the resistance thermometers were much smaller than the spacing between them. The heat released by the resistance thermometers and the concentration sensors in the process of measurement was negligible. The error in $\nabla x/\nabla T$ was mainly determined by the inaccuracy in the measurement of ∇x and reduced as higher power was applied. Besides, the concentration of the solution between gauges varied with the type of experiment (A or B). The average temperature dependence of $\nabla x/\nabla T$ is shown in Fig. 1.

The pressure of the ^{3}He particles in the ^{3}He-^{4}He solution is the osmotic pressure. For comparison of experimental and theoretical data, Fig. 1 includes two curves calculated by Eq.(2)based on the osmotic pressure for the 9.8% ^{3}He (upper curve) and the 6.5% ^{3}He (lower curve) solutions. The corresponding derivatives obtained from the osmotic pressure data in [6] and calculated in [7] are in good agreement at the temperatures studied. It is seen in the figure that the experimental results agree well within the measurement accuracy, with the calculation based on the osmotic pressure. Below the temperature of separation (T_c= 235 mK for $x = 9.8\%$ ^{3}He), the concentration of the solution is dependent on the temperature. The concentration dependence of $\nabla x/\nabla T$ should be taken into account. The calculation allowing for the concentration dependence is shown by the dash curve. At these temperatures the experimental results tend to be higher than the theoretical ones. The deviation may be due to convection - caused variations of ∇x and ∇T along the cell. The onset of the convective current may in turn be aided by the free boundary between the two separated phases of the solution.

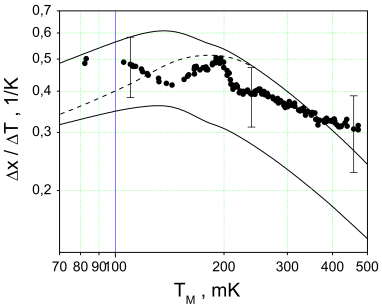

Fig. 1. Temperature dependence of $\nabla x/\nabla T$. ● - experimental results, — theoretical data for 9,8% and 6,5% 3He solutions (see the text), - - - calculated $\nabla x/\nabla T$ at the separation line

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