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Effect of ^{3}He impurities on the nucleation of phase slips in superfluid ^{4}He

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The critical value of the *dc* current of superfluid ^{4}He through a micro-aperture is found to decrease at low temperatures in the presence of ^{3}He impurities. We measure the dependence of the critical current on the pressure difference across the micro-aperture. In the temperature region where the ^{3}He affected decrease in the critical current is detected, we measure a large increase in critical current with pressure difference. The effect can be explained by the finite rate of arrival of ballistic ^{3}He atoms to a nucleation site. The critical velocity increases at high pressure difference when the rate of phase slippage becomes comparable to the flux of ^{3}He atoms.

1. INTRODUCTION

Experiments on the *ac* flow of superfluid ^{4}He through a micro-aperture, which is the inductive element of a low frequency Helmholtz resonator, show that the critical velocity occurs when phase slips are produced [1-3]. At temperatures above 200 mK these phase slips are mediated by thermal activation of quantized vortices over a hydrodynamic energy barrier[4,5]. At lower temperatures quantum nucleation dominates the phase slip production[6,7]. At these low temperatures ^{3}He impurities in the sample become concentrated in the micro-aperture and lower the energy barrier for the production of phase slips thus lowering the critical velocity[8].

When pressure driven flow through a micro-aperture is studied (where the rate of phase slippage is quite high) the individual phase slips cannot be distinguished. However, it is still possible to demonstrate that the critical velocity is limited by phase slippage and that this process is affected at low temperatures by the presence of ^{3}He impurities[6]. In this paper we report how the ^{3}He impurity effect can be measured by *dc* flow experiments. The measured critical velocity v_c depends linearly on the logarithm of the applied pressure difference P. This dependence is parametrized by a number α, which is proportional to $dv_c/d\ln(P)$ [9]. When the phase slip rate exceeds the arrival rate of ballistic ^{3}He atoms at the nucleation site the critical velocity increases back towards the level it achieves in the absence of ^{3}He.

2. EXPERIMENT

The experimental cell containing superfluid ^{4}He, is divided in two by a wall containing a flexible plastic diaphragm and a Si chip containing the

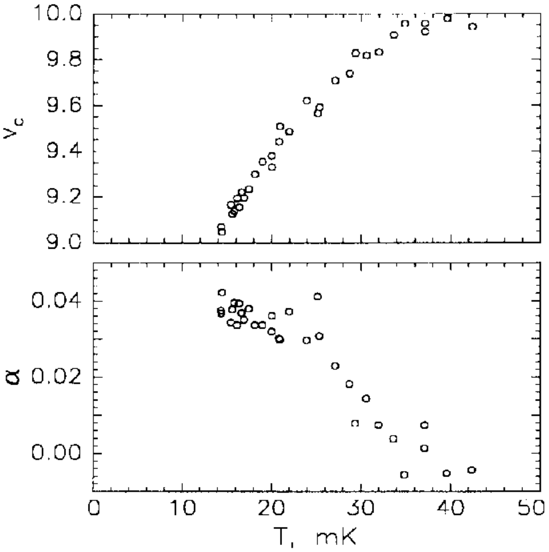

Fig. 1. The temperature dependence of the critical velocity and the parameter α in the temperature range, where the suppression of v_c, caused by ^{3}He impurity effect is important.

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micro-aperture. Mass current is driven through the aperture by the motion of a flexible plastic diaphragm, under the application of electrostatic forces, and is measured by an inductive position sensor with sensitivity $3\cdot10^{-13}\,\mathrm{m}/\sqrt{\mathrm{Hz}}$. The pressure difference across the aperture is calculated from the spring constant of the diaphragm and the measurement of its displacement. Pulsed NMR on two ^{195}Pt samples (one on each side of the diaphragm) provides thermometry. The micro-aperture is made by e-beam lithography in a 0.1 μm thick, free standing, silicon nitride window supported on a Si chip[10].

3. RESULTS

The *dc* critical velocity v_c is observed to rise linearly with falling temperatures in the thermal activation temperature range and to become almost independent of temperature below 200 mK [6]. At lower temperatures the *dc* v_c turns down (in the same fashion as the phase slip v_c) as shown in Fig. 1 (top). There is a sight difference between the v_c measured in the two flow directions[6].

Fig 1 (bottom) shows that α rises steadily with falling temperature. This is qualitatively consistent with an extension of Ref. 8 where the finite rate of arrival of ^{3}He atoms to the nucleation site is taken into consideration.

3. MODEL

A ^{3}He atom can be trapped on the vortex core, reducing the energy required for its creation. If several ^{3}He atoms are trapped by the vortex the barrier is further decreased. In a new model proposed by Varoquaux *et al* [8], a Bernoulli pressure drop produced by superflow, serves as an energy well, which concentrates ^{3}He near the nucleation site at low temperatures. This causes a decrease of the critical velocity when the temperature goes down. The model describes the low-frequency *ac* experiments (Ref. 8) well. Application of the model to *dc* flow experiments fails to explain the increase of α. In fact it predicts a small decrease of α. We propose here an extension to this model.

In *dc* flow experiments the rate of phase slippage (Josephson frequency) at applied pressures of 1.0 Pa is 75 kHz. The arrival rate of ballistic ^{3}He atoms from a ^{3}He solution of concentration 10^{-7} used in our experiments to a nucleation site of the size, derived from measurements in Ref. 8 is of the order of 1 MHz. Each vortex nucleated in the process of the phase slip carries the trapped ^{3}He atom(s) away from the nucleation center. When the phase slip rate approaches the arrival rate, the ^{3}He concentration at the site becomes depleted. We carried out calculations of the phase slip rate taking into account multi-^{3}He atom processes and parameters provided by Ref. 8. The calculations do show the increase in α, qualitatively consistent with that observed in our experiments. They also predict steps in the $v_c(P)$ dependence, which are not observed. This may indicate presence of several nucleation sites. This could not be resolved in low frequency measurements.

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