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Superfluid ^{3}He Confined in a Single 0.6 Micron Slab

A Phase Transition between Superfluid Phases with Hysteresis

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Abstract We present the preliminary results of our studies of superfluid ^{3}He in a 0.6 μm thick slab using NMR. Below T_c the A phase is observed, and at low pressures the region of stability of the A phase extends down to the lowest temperatures reached, as described elsewhere. At pressures above 3.2 bar another, so far unidentified phase is observed at low temperatures. In this article we focus on the behavior of this phase and the transition between this phase and the A phase, all studied at 5.5 bar. The NMR response at low temperatures exhibits two possible frequency shifts and the transition is hysteretic in temperature.

Keywords superfluid · helium-3 · confinement · slab · film · NMR · phase transition

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1 Introduction

We study superfluidity of ^{3}He confined to a single 0.6 μm thick slab inside a nanofabricated cell using SQUID based nuclear magnetic resonance (NMR). The details of the experimental setup can be found elsewhere in these proceedings [1]. As described in the cited article, ^{3}He in the slab undergoes a superfluid transition at a temperature T_c^{slab}, slightly below the bulk transition temperature T_c^{bulk}, and the A phase is observed in a wide region of the phase diagram below T_c^{slab}. However at high pressures and low temperatures, where the coherence length is shorter, we observe a transition between the A and a different phase. The investigation of this transition and of the low temperature phase is described here.

Thin slabs of superfluid ^{3}He have been examined theoretically by many workers, e.g. [2] and [3]. While considering different models, they agree that the A or planar phase (degenerate in the weak coupling limit) would stabilize in slabs a few coherence lengths thick, and the B phase with an anisotropic distortion towards the planar phase has the lowest free

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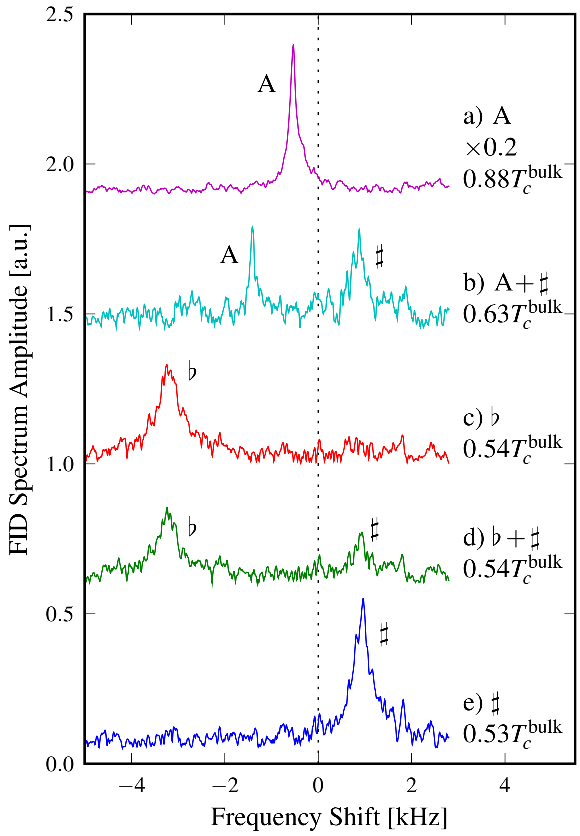

Fig. 1 (Colour online) Typical NMR spectra at 5.5 bar, for clarity shifted vertically, ordered by temperature. Three peaks observed are the A phase peak (A) and a negatively (♭) and a positively (♯) shifted peaks in the low temperature phase.
a) is a signal from the A phase, reduced by a factor of 5 to aid comparison.
b) displays a coexistence of the A phase peak with one of the low temperature phase peaks.
c), d) and e) show the two peaks observed in the low temperature phase, ♭ and ♯, and their coexistence.
The spectra c), d) and e) where observed on separate cool-downs.

energy in thicker slabs. Recent work has proposed a “stripe” phase with spontaneously broken translational symmetry in the plane of the slab to be stable in a narrow region of the phase diagram between the B and the A or planar regions [4].

2 The Low Temperature Phase

We have studied the low temperature superfluid phase at 5.5 bar, where it is stable up to $0.60T_c^{\text{bulk}}$. The pulsed NMR is performed with tipping angle of about 1° at a frequency of 1.06 MHz in a static field of 33 mT perpendicular to the slab. To improve the sensitivity we multiply NMR free induction decays (FIDs) by a $f(t) = \exp(-t/10\ \text{ms})$ apodisation function prior to a Fourier transform.

The maximum frequency shift of the bulk B phase in our NMR field and at 5.5 bar is under 14 kHz. With this number in mind we searched for NMR response from the low temperature phase in a frequency range of ±35 kHz around the Larmor frequency. We observe two possible NMR peaks in the low temperature phase, one with a negative shift (♭) and another with a positive shift (♯).

On cooling below the A phase, there is a certain probability to observe either a negatively or a positively shifted peak, or a mixture of the two. While staying in the low temperature

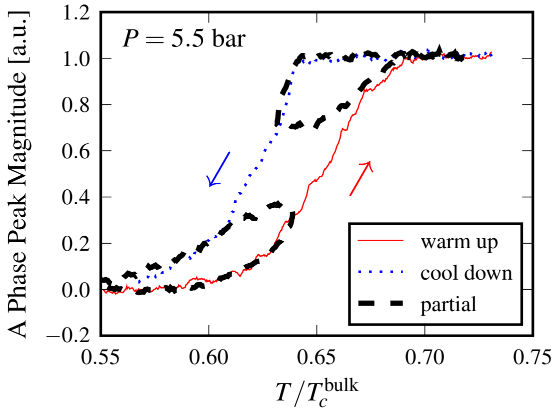

Fig. 2 (Colour online) The evolution of the A phase peak around the transition during a warm-up into the A phase and a cool-down from the A phase, and along two partial loops where the direction of temperature ramp is reversed before crossing the entire transition region

phase, we observe no spontaneous changes from one to another. However, if ^{3}He in the slab is warmed into the A phase or further into the normal state and cooled back down, a different line can be measured. Fig. 1 shows typical FID spectra recorded at 5.5 bar: the negatively shifted peak $\flat$ is represented by c). Spectrum e) shows the positively shifted peak $\sharp$, d) is a mixture of $\flat$ and $\sharp$. For comparison spectrum a) taken in the A phase is also shown. It is scaled down by a factor of 5 for clarity. The negative frequency shift in the A phase is due to the dipole-unlocked state in the slab [1].

A positive shift is predicted for the B phase with an anisotropic distortion towards the planar phase [5]. This is in a qualitative agreement with the positively shifted peak we observe in the low temperature phase. The nature of the negatively shifted peak in the low temperature phase is unidentified yet.

3 The Transition between Superfluid Phases

When warming from the low temperature phase into the A phase, we observe a gradual conversion of the NMR spectrum from the $\flat$ and $\sharp$ peaks into the A phase peak over a temperature range of 0.60 to $0.69T_c^{\mathrm{bulk}}$. Spectrum b) in Fig. 1 illustrates the coexistence of the NMR responses of the two phases in this region.

In order to characterize the size of the NMR peaks we introduce a quantity called “peak magnitude” which is the integral of the modulus of the FID spectrum over a fixed frequency range. The range is chosen such that it reliably covers the peak in question at all relevant temperatures, while excluding any of the others. For the A phase this quantity remains constant above $0.69T_c^{\mathrm{bulk}}$ all the way into the normal state, thus being a good measure of the A phase NMR peak, although not uniquely related to the magnetization.

The evolution of the A phase peak magnitude with temperature during the transition is shown in Fig. 2. During a warm-up (solid line) at a 20 μK/hour rate the development of the A phase peak happens at higher temperatures than its reduction during a cool-down (dotted line) at the same rate. Similar hysteresis loops are observed when temperature ramps are carried twice as fast or slow. We also measured partial loops, shown in the figure using thick dashed lines, where the temperature ramp is reversed before the whole transition region is crossed.

4 Conclusions

It seems that we can rule out a continuous transition between the planar phase and the planar-distorted B phase, since experiments so far show that the A phase is favoured over the planar phase [1]. Furthermore, the observed hysteresis indicates that the phase transition is first order.

We plan to conduct simple imaging experiments in the coexistence region to try and establish whether there is a single phase boundary in the cell, or multiple domains. The observation of two possible NMR signatures at low temperatures may indicate two possible phases, one of which is metastable. A new phase, such as the predicted "stripe" phase, is an intriguing possibility. The NMR response of the "stripe" phase has not yet been calculated.

Work to identify the nature of the low temperature phase and the origin of the observed hysteresis of the transition is ongoing and the next step will be to extend our studies to pressures other than 5.5 bar.

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