The Interface Instability of Melting Magnetized Solid ^{3}He

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Abstract

We report on our observations that the solid-liquid interface of highly magnetized solid ^{3}He becomes instable during melting. The liquid penetrates in the solid in the form of cellular dendrites. One-dimensional magnetic resonance imaging of the magnetization profile shows clearly the magnetization gradients in the solid and the liquid during melting, as well as enhanced magnetization at the interface. This enhanced magnetization disappears when the instability is complete. We discuss the results with the melting scenario of Castaing and Nozières [1], and determine the spin diffusion coefficient of solid ^{3}He.

Key words: polarized 3He; interface instability; melting;

1. Introduction

It was first shown experimentally by Marchenkov et al [2] that the interface of solid ^{3}He shows a Mullins-Sekerka type instability upon melting the solid in a magnetic field strong enough to cause significant magnetization in the solid. This instability was predicted by Puech et al [3] by doing a linear stability analysis on the melting scenario, predicted by Castaing and Nozières [1]. Our later experiments [4] revealed directly the enhanced magnetization in the solid near the interface by a one-dimensional magnetic imaging technique. This also allowed us to explain the delay between the start of the melting and the onset of the instability. Here we report on some new measurements with improved NMR techniques, which allowed us to look at the magnetization profiles while melting more rapidly than before [4].

2. Experimental

Compared to the previous experimental set-up [4,5] we changed some parts of the experimental cell. The outer wall of the ^{4}He space of the Pomeranchuk cell is made of Kapton and the inside of the cylindrical PtAg sinter in the ^{3}He chamber is filled with a quartz bar to increase the maximum relative volume change. The temperature of the ^{3}He is measured with a carbon resistor thermometer in the lower part of the cell, where we look at the melting process.

In 9 Tesla the ^{3}He NMR line is centered at 284 MHz and has a width of 10 kHz. When a vertical magnetic field gradient of 0.3 T/m is applied, the width increases till about 50 kHz. This corresponds to the height (5 mm) of the ^{3}He volume inside the NMR coil around the optical part of the cell. The vertical magnetic field gradient is used to determine the magnetization in a horizontal slice dz of the sample cell, and especially at the liquid-solid interface.

The polarized solid ^{3}He is grown in about 4 hours. The magnetization at the liquid-solid interface can only be measured properly if the interface, which has an area of 3 mm by 5 mm, is horizontal. This was the case in about 80 percent of our crystals. The interface was always made in the visible part of the cell, thus in the NMR pick up coil [5].

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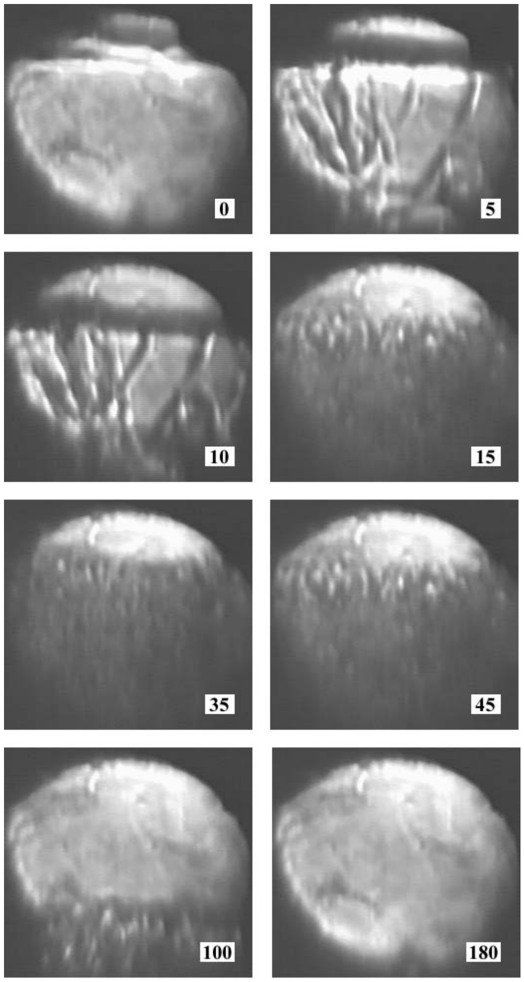

Fig. 1. Optical images of a rapid melting experiment of magnetized solid ^{3}He. The melting is rather fast compared to the aperture time, giving blurred pictures. It is clear from the images that initially rather thick cell-shaped dendrites appear, followed by a complete breaking up of the solid. The numbers give the time in seconds after the start of the melting.

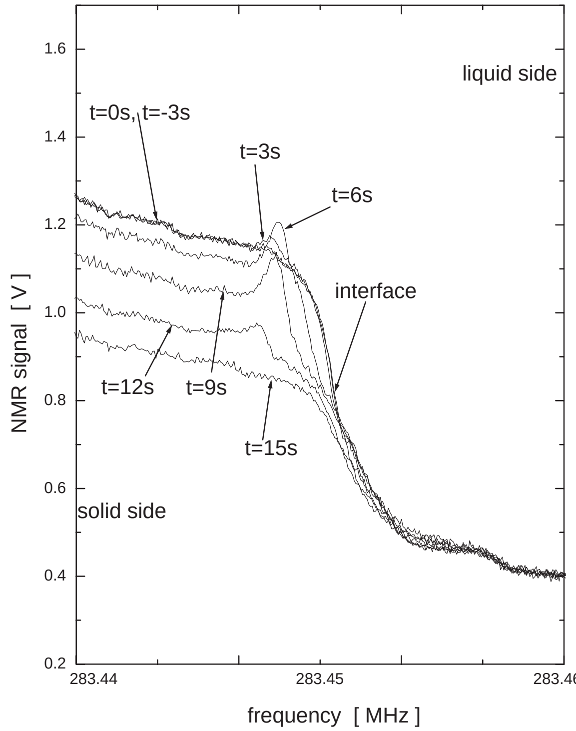

Fig. 2. NMR waveforms giving the magnetization profile during the initial stages of the rapid melting experiment as shown in Fig. 1.

3. Results

Figure 1 shows the images of the solid ^{3}He during melting. The liquid-solid interface is at the bottom of the horizontal black stripe. In the top of the image is liquid ^{3}He, in the bottom solid ^{3}He or a liquid-solid mixture (from t=15 s). The diameter of each image is 4 mm. Starting at t=0 the pressure in the ^{3}He space decreases from 34 to 30 bar in 15 seconds. Due to the inverse Pomeranchuk effect the temperature increases from 10 to 150 mK. After 5 seconds an instability is visible; cellular-like liquid pockets penetrate into the solid. Between t=5s and t=10s the ^{3}He liquid-solid interface is horizontal, which is important for our NMR spectra. After 15 seconds the instability is complete and a liquid-solid ^{3}He mixture is left. Now the images are darker because most of the light is diffracted on solid pieces. After 180 seconds all solid is gone.

The NMR waveforms obtained during this melting are shown in Fig. 2. Only the section close to the interface is shown. The signal change at f=283.45MHz results from the difference in magnetization of liquid and solid ^{3}He. The slope on the solid side is due to the different sensitivity of the NMR coil and the distribution of ^{3}He inside the coil. At t=3s the magnetization of the solid close to the interface increases. Within our resolution the images do not yet show any movement of the interface. Solid ^{3}He is really melting at t=6 s and the increase of the magnetization in the solid at the interface is clear. At t=9 s the magnetization of the bulk solid, away from the interface, is decreasing due to the temperature increase, and the magnetization of the interface solid is still enhanced. The enhancement is much less than at t=12s. We assume that the instability is already complete at this time. No enhanced magnetization is seen after t=15s.

4. Discussion

Castaing and Nozières[1] already predicted an enhanced magnetization in the solid at the interface. When the magnetized solid melts into liquid, the magnetization of the liquid increases. This corresponds to a strongly enhanced effective magnetic field, i.e. the magnetic field needed to get the same polarization of the liquid ^{3}He in equilibrium. This field could easily have a value of 100 T [1]. Inside the solid ^{3}He the (effective) magnetic field is 9 Tesla. The effective magnetic field (B_{eff}) cannot drop instantaneously from 100 to 9 Tesla since the diffusion of magnetization in solid ^{3}He is finite. Thus B_{eff} penetrates from the liquid into the solid. This higher B_{eff} results in a higher magnetization of the solid magnetization close to the interface.

During melting the width of the boundary layer with enhanced magnetization is given by the magnetization diffusion length $\ell_s = D_s/v$ with D_s the spin diffusion coefficient in the solid, and v the melting velocity. Between t=6 s and t=12 s the melting velocity is about 13 $\mu m/s$. Because B_{eff} at the interface is very high, the magnetization of the first solid layers is 100 percent. The magnetization falls off exponentially with ℓ_s. From the area of the enhancement in Fig. 2 ℓ_s is calculated: $\ell_s = 10\mu m$. For the ^{3}He spin diffusion coefficient we get: $D_s = 1.2 \cdot 10^{-10} m/s^2$. This is one order of magnitude higher than the D_s measured in by G. Deville et al. [6]. We assume that this is caused by a large amount of vacancies inside the solid ^{3}He during melting.

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