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Effect of the Magnetic Order on ^{3}He Crystals

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Abstract Solid ^{3}He orders magnetically into two different phases below the Néel transition depending on the magnetic field (*U2D2* or low field phase below 450 mT and *CNAF* or high field phase above 450 mT). We have performed measurements of the growth velocities and determined the step energies for different facets in both phases at $B = 0$ T and $B = 2$ T. It was found that the growth rate is much faster at $B = 2$ T than at zero magnetic field. We conclude that the interface couples strongly to the crystal lattice at zero magnetic field while it seems to couple weakly at $B = 2$ T. The ordering of the spins in the solid clearly affects the growth velocity of the crystals by an order of magnitude.

Keywords Quantum solids · Crystal growth

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1 Introduction

Due to its rich magnetic phase diagram and its superfluidity, ^{3}He is a very interesting model system if magnetic effects on the crystal growth mechanisms want to be studied. Solid ^{3}He orders magnetically into the *U2D2* phase (an antiferromagnetic phase with two planes of spins pointing up and two planes of spins pointing down in sequence) when it is cooled down to very low temperatures (below the Néel transition $\sim$1 mK). If the external magnetic field is increased above 450 mT, the solid orders into a different magnetic phase, the so-called *CNAF* phase (a normal antiferromagnetic phase, but with the spins tilted from their normal position with a significant magnetization).

It has been found experimentally [1] that the liquid/solid interface of ^{4}He couples weakly with the crystal lattice of solid ^{4}He. Due to the large zero-point motion of the ^{3}He atoms, the liquid/solid interface was expected [2] to have an even weaker coupling with the crystal lattice than ^{4}He. It was very surprising when Tsepelin et al. [3] found out that the liquid/solid interface of ^{3}He was strongly coupled to the ^{3}He crystal at zero magnetic field.

We continued with these investigations by applying an external magnetic field to ^{3}He crystals and growing them under these conditions in our sample chamber. We tried to determine whether the magnetic order has an effect on the growth kinetics of the crystals.

2 Experimental Details

The cryostat consists of a dilution refrigerator with a lowest stable temperature around 5 mK which is used for pre-cooling the nuclear demagnetization stage, to which the experimental cell is attached to. The upper Pomeranchuk part of our cell allows us to pressurize the ^{3}He volume in order to grow crystals. At the bottom part of the body of the cell two Suprasil windows are glued, which allows direct optical access to the ^{3}He crystals. Light is transmitted through an optical fiber from the experimental room to the experimental cell. After traveling through the cell, the light is recorded by a CCD camera located inside the vacuum can of the dilution refrigerator. A magnet mounted in the liquid helium bath permits us to increase the magnetic field in the center of the experimental cell up to 9 T. This is certainly more than needed for the study of the magnetic phase transition from the *U2D2* to the *CNAF* phase at 450 mT. A more detailed description of the experimental setup can be found in the work by Blaauwgeers et al. [4] and references therein.

3 Results and Discussion

At zero magnetic field, the liquid is in the superfluid B-phase and the solid is magnetically ordered in the $U2D2$ phase, while at $B = 2$ T the liquid is in the superfluid A_2-phase and the solid orders into the *CNAF* phase. We have measured the velocities

as a function of the applied overpressure of the ⟨110⟩ and ⟨100⟩ facets at zero magnetic field and a temperature of 0.65 mK, and of the ⟨110⟩, ⟨100⟩ and ⟨211⟩ facets at $B = 2$ T and $T \approx 1$ mK [6, 7].

The effective growth coefficient k_{eff} (which is the quantity to be determined) can be defined as [5]

$$k_{\mathrm{eff}} = \frac{v_{\mathrm{f}}}{\Delta\mu_{\mathrm{P}}} \tag{1}$$

where v_{f} is the velocity of the facet, and $\Delta\mu_{\mathrm{P}}$ is the chemical potential difference (per unit mass) between the liquid and the solid, which can be expressed as

$$\Delta\mu_{\mathrm{P}} = \left(\frac{\rho_{\mathrm{s}} - \rho_{\mathrm{l}}}{\rho_{\mathrm{s}}\rho_{\mathrm{l}}}\right)\Delta P \tag{2}$$

with ρ_{s} and ρ_{l} the molar densities of the solid and liquid respectively, and where ΔP is the pressure change in the system with respect to the equilibrium melting pressure. Supposing that the growth velocity does not depend on the step mobility and that the facet growth velocity becomes linearly dependent on the overpressure ΔP, the expression for the facet growth velocity v_{f} is the following

$$v_{\mathrm{f}} = \frac{d^2 v_c}{2\pi\beta}\left(\frac{\rho_s - \rho_l}{\rho_s}\right) K\Delta P, \tag{3}$$

where d is the height of the elementary step of the facet, v_{c} is the step critical velocity [3], β is the step energy of the facet, and K depends on the Burgers vector of the dislocation, and in the simplest case $K = 1$. In absence of reliable data on characteristics of dislocations in our crystals we assume in the following $K = 1$. The value of the step energy β can be derived from (3).

The surface stiffness α of ^{3}He crystals has been measured for rough crystals and it was found to be almost isotropic and temperature independent [1], $\alpha = \alpha_0 \approx 0.06$ erg/cm^2. In the case that the liquid/solid interface couples strongly with the crystal lattice, the step energy is roughly equal to the surface energy of the additional area, $\beta \sim \alpha d$. In spite of the anisotropy, the ratio $\beta/\alpha d$ is approximately equal to one. In the weak coupling limit, the distribution of the step over a number of lattice spacings reduces the step energy, $\beta/\alpha d \ll 1$.

We present our results in Fig. 1 where the step energies β of the ⟨110⟩, ⟨100⟩ and ⟨211⟩ facets have been plotted as a function of the interplanar distance d. The slope of the linear fit should correspond with the surface stiffness α in case the liquid/solid interface couples strongly with the crystal lattice. The fitted α for the step energies at zero magnetic field ($U2D2$ phase) is within the error bar of our measurements, which was about 30% for the step energies of the ⟨110⟩, ⟨100⟩ and ⟨211⟩ facets (an explanation of the error in our measurement can be found in our previous work [7]). However, at $B = 2$ T ($CNAF$ phase), the fitted slope has a value 30 times lower than the surface stiffness measured by Rolley et al. [1]. Thus in this case, the ratio $\beta/\alpha d \ll 1$. We interpreted this observation as the fact that the interface and the lattice are in the weak coupling regime at $B = 2$ T and T roughly equal to 1 mK.

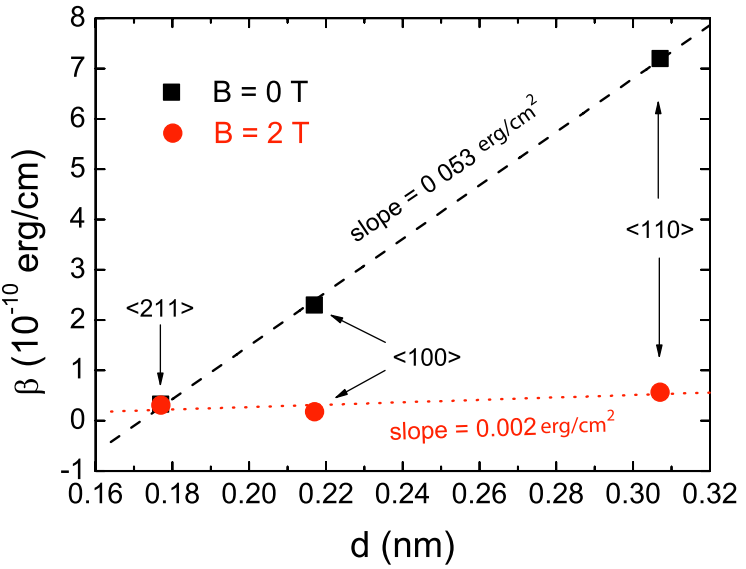

Fig. 1 (Color online) Step energies β of different facets of ^{3}He crystals are shown as a function of interplanar distance d. *Squares* and *dashed line* correspond with data taken at $B = 0$ T and $T = 0.65$ mK, and *circles* and *dotted line* correspond with data taken at $B = 2$ T and $T \approx 1$ mK. The slope of the linear fit would correspond with the surface stiffness α. Note that we never observed the $\langle 211 \rangle$ facet at zero magnetic field, therefore we used the $\langle 211 \rangle$ facet step energy measured by Tsepelin et al. [3]

One very important aspect to consider in our analysis is that we could only measure the step energies β of facets with low Miller indexes. Therefore, all our analysis was limited to few experimental points. One could argue that the coupling could change for higher Miller indexed facets. However, Tsepelin et al. [3] used up to eleven different facets in their analysis finding that the crystal and interface are in the strong coupling limit at zero magnetic field.

4 Conclusions

The step energy of different facets of ^{3}He crystals have been measured at $B = 0$ T and $B = 2$ T. The interface couples strongly to the crystal at zero magnetic field (as measured previously by Tsepelin et al. [3]), but it was surprising to find that the interface couples weakly to the crystal at $B = 2$ T. This is a completely unexpected result since there is not a big difference in the crystallographic structure between the $U2D2$ and the *CNAF* phases. We assume that this transition from the strong coupling limit in the $U2D2$ phase to weak coupling between the liquid/solid interface and the crystal lattice in the *CNAF* is related with the different magnetic ordering present in the phases.

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