Experimental setup for the observation of crystallization waves in $^3$He

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Abstract. At low temperatures helium crystals can grow and melt so fast that a melting-freezing wave may propagate along the liquid-solid interface. In $^4$He these crystallization waves have been observed at temperatures below 0.5 K. The required temperature for the observation of the crystallization waves in $^3$He is predicted to be about 0.2 mK. In order to reach such low temperature at the melting pressure of $^3$He, special care has to be taken in the design of the experimental cell. Here we present the draft of the experimental cell which is designed for observation of the crystallization waves in $^3$He.

1. Introduction

At low enough temperature, where the liquid phase of helium is superfluid and the latent heat is small, the intrinsic properties of the liquid-solid interface dominate, while at high temperature they are hidden by dissipation in the bulk. An unique interface property, the existence of the melting-freezing waves in helium, was presented by Andreev and Parshin already in 1978 [1]. They suggested that at low enough temperature the crystal can grow in one place and melt in another place so easily that a wave may propagate along the crystal surface without significant dissipation.

These crystallization waves were experimentally discovered on $^4$He crystal below 0.5 K in 1979 [2] and they have been intensively studied since then. In contrast to the bosonic $^4$He, the propagation of the fermionic $^3$He crystallization waves is expected to be magnetic field dependent. In $^3$He the crystallization waves have not been observed since for such an observation a temperature as low as 0.2 mK is needed [3], when the damping of the waves is small.

In order to cool a $^3$He sample far below the superfluid transition temperature $T_c$, all possible heat leaks should be eliminated and the thermalization of the $^3$He sample should be as good as possible. Previously we have been able to cool superfluid $^3$He with an optical cell down to $0.2T_c$ or 0.5 mK at melting pressure [4], Osheroff and Yu [5] have reached $0.15T_c$ at melting pressure, Bayreuth group has cooled close to $0.17T_c$ at 0.35 bar [6] and Lancaster group has obtained temperatures below $0.17T_c$ with a nested cell structure, although at low pressure [7].

The Lancaster-type cell consists of two nested cells, one inside another, and the adiabatically demagnetized copper refrigerants are placed directly into both the inner and outer $^3$He baths [8].
Since the copper nuclear stage is placed also inside the experimental volume, the cell as a whole is exposed to the magnetic field.

Unfortunately we cannot directly use the Lancaster type cell design as the studies of $^3$He crystals require tunable and mechanically strong experimental volume which can hold the melting pressure of about 35 bar. However, Leiden group has used plastic compressible Pomeranchuk cells in high magnetic fields and under high pressure [9]. The reason to use a plastic flexible cell instead of metallic bellows is to eliminate the eddy current heating in changing the magnetic field.

Our plan is to combine the Lancaster type cell design with the plastic compressible cell developed in Leiden. The waves can be excited with a comblike interdigital capacitor because helium crystallizes more easily in high electric field. On the other hand the waves can be detected with a second interdigital capacitor since its capacitance is determined by the liquid-solid fraction touching the capacitor. For this purpose the interdigital capacitors have been used by several groups in the previous studies of the crystallization waves in $^4$He [10].

2. Cell design

The cell shown in figure 1 consists of three cylindrical volumes. The outermost $^3$He volume serves as a thermal guard for the inner volumes. The inner $^3$He volume and the $^4$He volume are separated with a thin flexible Kapton membrane which allows to vary the size of the inner $^3$He volume. Both $^3$He volumes, except the space reserved for the experiments, are filled with Cu refrigerant plates which are coated with Ag sinter for heat exchange. Heat load from $^4$He to $^3$He volumes is insignificant because at temperatures below 10 mK both the heat capacity of $^4$He and the thermal conductivity in the capillary $^4$He filling line are very small.

The experimental volume is located at the coldest place of the cell, which is the center of the inner $^3$He volume that is surrounded by Ag sinter coated Cu refrigerant plates. The temperature of liquid $^3$He can be measured with a vibrating wire viscometer placed in the upper part of the experimental volume. The two interdigital capacitors, one of which is used to excite and the other one to detect the crystallization waves, are positioned on the opposite faces of the cubic experimental volume. A sapphire plate serves as a substrate for the $^3$He crystal.

Pressure gauges are needed not only to detect the nucleation of the $^3$He crystals but also for calibrating thermometers, like vibrating wires, against the well-known melting curve of $^3$He [11]. For melting curve thermometry BeCu [12] and sapphire [13] pressure gauges have been widely used. Although the heat capacity of the BeCu pressure gauge is much larger than that of the sapphire gauge, the BeCu gauges are used owing to their high resolution. The BeCu pressure gauges are located further from the cell at the low magnetic field region to avoid eddy current heating.

In order to avoid heat release from the walls to the experimental $^3$He volume, the wall material should be suitable for low temperature studies. The material candidates are sapphire which does not release heat but is difficult to machine, plastic (Araldite, Stycast, Kapton) which releases heat but is easy to machine, and copper which can be cooled down but makes the design more complicated due to the eddy current heating which has to be avoided. Whichever material will be chosen, it is convenient to make the cell walls relatively thin. A thin cylindrical wall can hold high pressure difference only when the pressure inside the wall is larger than outside. As the pressure in the $^4$He volume runs from 0 bar up to 25 bar, the pressure in the outer $^3$He volume has to be small. The outer cell wall can be made of Araldite since the heat release requirements for the outer wall are not so strict because of the $^3$He thermal guard.

The helium filling lines should be well anchored to the Cu refrigerants in order to avoid heat leaks to the experimental cell. Due to the minimum on the melting curve of $^3$He, the $^3$He filling lines are blocked somewhere on the way to higher temperatures. However, the $^4$He filling line remains open and it can be used to compress/decompress the $^3$He cell.
Figure 1. Experimental setup. The nested cells are exposed to magnetic field up to 9 T. The pressure gauges are placed to low magnetic field region. The illustrative projection of the interdigital capacitor is not in scale (finger width and spacing few micrometers). Aluminum oxide supports, wiring and thermal links to the heat switch are not shown.

Before demagnetization all the copper refrigerants have to be precooled. The Cu refrigerants which cool the pressure gauges and the filling lines can be precooled directly via Cu wires connected to the heat switch. This allows precooling down to the temperature of 8 mK provided by the dilution refrigerator. However, only a few of the sinter plated Cu refrigerant plates in the $^3$He baths have metallic thermal link to the precooling stage and the rest of them are thermalized via precooled liquid $^3$He.

3. Operating the setup
Before cooling the setup below 1 K the $^3$He volumes should be filled up to the pressure close to the low temperature limit of the $^3$He melting pressure which is about 35 bar. This is because this pressure is about 5 bar higher than the minimum melting pressure of $^3$He at 0.3 K. On the other hand the Kapton membrane should be kept stretched during cooling by keeping the $^4$He pressure low in order to have capability to increase the pressure in the inner $^3$He volume during the experiment.

When the $^3$He in the inner $^3$He volume is cooled down, it liquefies again and a crystal can
be nucleated by pressurizing. The pressure of the flexible inner $^3$He volume can be increased by raising the pressure in the $^4$He volume towards the $^4$He melting pressure, 25 bar. The nucleation of a $^3$He crystal in the experimental volume can be ensured by applying high voltage to one of the interdigital capacitors which allows the crystal to nucleate on the side of the interdigital capacitor.

In order to avoid capillary deformation of the horizontal crystal surface near the cell walls, the contact angle can be tuned with electrical field induced by capacitors with high DC voltage. With an additional AC component applied to one capacitor it is possible to generate the waves which can then be detected by the other capacitor.

When the cell warms up, the vibrating wire thermometers can be calibrated against the melting curve of $^3$He.

4. Discussions and remarks
Since $^4$He is superfluid up to relatively high temperatures, the $^4$He filling line may cause problems. Any thermo-mechanical oscillation in the filling line at higher temperatures is a potential source for tiny pressure oscillations in the $^4$He volume at low temperature. If this is found to be a problem, then it is possible to cut the oscillations in the filling line using a cold valve. Additional cooling of $^3$He might be obtained by placing Cu refrigerant plates also to the $^4$He bath.

If the crystallization waves can be detected with the setup described here, then it would be interesting to investigate the waves optically in high magnetic fields. In addition, the NMR measurements might also be useful. However, in such studies the experimental setup seems unavoidably to be more complicated.

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