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Short Communication

Solid ^{4}He : search for superfluidity

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Résumé. — L'existence d'une superfluidité pour un solide de bosons a été proposée par plusieurs théoriciens. Aucune expérience ne l'a jusqu'à présent révélée. Nous présentons un argument qui nous a incités à explorer la gamme de température 1 mK-20 mK. Nous avons tenté de détecter un courant de masse à travers du ^{4}He solide à 4 mK. L'absence d'effet abaisse encore la borne supérieure pour la température de superfluidité de ce solide.

Abstract. — Theoreticians agree that superfluidity can exist in a Bose solid. The experiments to detect such an effect have failed up to now. We present here an argument that justifies the exploration of the 1 mK-20 mK temperature range. We have carried out an experiment to detect a mass flow through the solid ^{4}He down to 4 mK. No anomalous effect occurred, and this result therefore further reduces the upper limit for the occurrence of superfluidity in solid ^{4}He to below 4 mK.

The idea that a solid could be superfluid has two different origins. Questions about unusual effects in quantum crystals led Andreev and Lifshitz [1] to propose a mechanism by which vacancies could undergo Bose-condensation (B.C.). On the other hand, questions about the relation between B.C. and superfluidity led Chester [2] to remark that B.C. should occur in Bose solids, due to the atomic quantum exchange. He considered it as an example of the lack of a direct connection between B.C. and superfluidity. However Leggett [3] has shown that phenomena associated with superfluidity, such as Non Classical Rotational Inertia (NCRI) are possible in periodic crystals.

In the following decade, there were several theoretical attempts [4-17] to determine the conditions under which superfluidity of a solid might be observed. No definitive conclusion has been

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drawn and we are left with the statement from Leggett that "it is impossible to exclude the occurrence of NCRI in insulating solids".

The first experiments attempted to demonstrate the possibility of shear flow without stress in solid ^{4}He [18-20]. More in the spirit of Leggett's paper were the experiments of Greywall [21] and of Bishop *et al.* [22]. Both groups failed to observe any indication of superfluidity down to a temperature of 25 mK. This led them to consider two possibilities :

- the solid is not superfluid above 25 mK ;
- the solid is superfluid above 25 mK but the critical velocity is too small for superfluidity to be detected.

Following the second hypothesis, both experiments give the same upper limit for the product of the superfluid fraction $\frac{\rho_s}{\rho_c}$ and the critical velocity v_c,

$$\frac{\rho_s}{\rho_c} \, v_c \; \leq \; 0.25 \; \text{Å/s}$$

(ρ_c is the solid density) .
Bishop *et al.* were able to state separately :

$$v_c \; \leq \; 5 \, \mu/\text{s} \;\; \text{and} \;\; \frac{\rho_s}{\rho_c} \leq 5 \times 10^{-6}$$

We report here on a new search for superfluidity in solid h.c.p. ^{4}He. Our motivation for this experiment was our belief that realistic temperatures where B.C. can occur in hcp ^{4}He are smaller than 25 mK, while still being accessible. Our idea is that, as B.C. is a property of indistinguishable particles, it can only occur when $k_B T < \hbar \omega_E$ where ω_E is the exchange frequency.

To estimate this exchange frequency, we can refer to solid ^{3}He. In b.c.c. ^{3}He, exchange between atoms yields (magnetic) order. The low transition temperature $T_c = 1$ mK results from a large cancellation between odd and even exchange cycles [23]. Without this cancellation (which does not occur for a Bose system) the exchange temperature should be 20 mK at the melting molar volume. Taking into account the molar volume dependence, but not the mass difference, gives 2 mK as an estimate of the exchange temperature in solid ^{4}He. The range of temperature between 2 mK and 20 mK is thus interesting to explore and easily achievable with a dilution refrigerator.

The experimental cell is placed in the mixing chamber of a dilution refrigerator. This cell (Fig. 1) essentially consists of three cylinders. When the solid has grown up to the base of the middle one, the cell is divided in two parts, inner and outer. More helium can only be admitted in the outer part through a filling capillary. Further growth in the inner part needs some mass flow through the solid. The levels of the solid in the inner and outer part are recorded by measuring the electrical capacitance between the cylinders. These cylinders are made out of copper and are independently thermalized by sintered silver powder. We have verified that in a similar geometry, a resistive thermometer immersed in the ^{4}He can be cooled down to 5 mK, the only thermal contact being achieved through the ^{4}He. Clearly, the ^{4}He temperature can be considered to be that of the mixing chamber in our experiment.
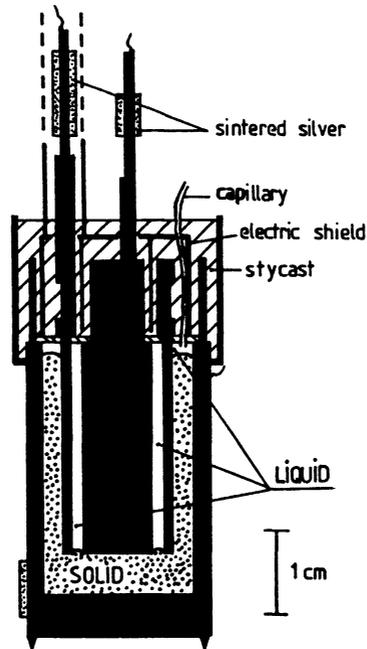
Fig. 1.— The experimental cell.

Figure 2 shows a typical recording of both capacitances during the filling of the cell with solid. Note that the inner capacitance see the approach of the solid, until growth is stopped at its bottom. This little variation δC will be of important use below.

We have made two attempts. In the first one, the solid was grown in the bcc phase at 1.6 K and then cooled down along the melting curve. We remained at 4 mK for 3 days without any detectable change (< 0.1 mm) of the inner level. In this run the solid contains a large number of dislocations.

In the second run, the solid was grown at low temperature (4 mK). It took 8 hours to fill the outer part up to 90%. We then waited for 6.5 days at 4 mK, again without any detectable change of the inner level.

In order to avoid drift problems of the capacitance bridge on such a long period of time, we melted the crystal at the end of the run. We could then record the variation of the inner capacitance before it reaches the full liquid value, and compare it to the corresponding variation δC at the beginning of the run, on growing (Fig. 3). These variations were equal within the experimental uncertainty, which corresponds to 0.1 mm.

With these two attempts two different types of flow were tested. As recently suggested by Shevchenko [24], superfluidity could occur in the dislocation cores. For testing this theory we needed a higher dislocation density as in the first attempt.

On the other hand, bulk flow can be hindered by stresses (solid parahydrogen could be an example of this effect [25]). In our second run, the solid was grown slowly at low temperature and thus has the lowest possible stresses. Moreover, as the ³He solubility in the solid is nearly zero at
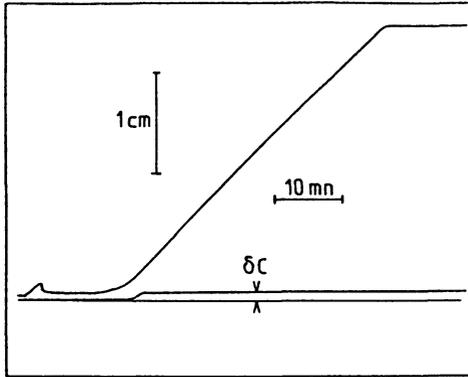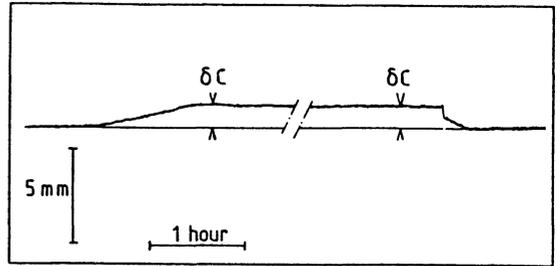
Fig. 2.

Fig. 3.

Fig. 2.— A typical record of the capacitances during the growth of a crystal. Upper curve : outer level. Lower curve : inner level. In this case, nucleation first occurs in the outer capacitance, then the crystal fell down to the bottom of the cell. Note the variation δC of the inner capacitance before blocking.

Fig. 3.— The variation δC of the inner capacitance, a) on growing ; b) on melting, 6.5 days later (second run, see text).

this temperature, it should be free of ^{3}He impurities (we use standard commercial ^{4}He).

We will now show, using Leggett's result, that our null result is due very probably to the fact that the transition temperature is lower than 4 mK and not to a critical velocity problem.

Our upper limit for the interface velocity v_l in the second run is :

$$v_l < 1.8 \times 10^{-10} \text{ m/s}$$

which gives :

$$\frac{\rho_s}{\rho_c} v_c = \frac{\rho_c - \rho_L}{\rho_c} v_l < 1.8 \times 10^{-11} \text{ m/s} = 0.18 \text{ Å/s}$$

ρ_L is the liquid density, $\frac{\rho_s}{\rho_c}$ is the superfluid fraction in the crystal, and v_c the critical velocity.

On the other hand, from the work of Leggett one can understand that the zero temperature value of ρ_s is controlled by the minimum value of the wave function, along an exchange path. Leggett estimates ρ_s to be :

$$\frac{\rho_s}{\rho_c} \simeq \frac{J}{\left(\hbar^2/ma^2\right)}$$

where J is the exchange energy and a the distance between neighbouring atoms. We think that a more realistic value for the denominator should be $k_B\theta_D$ where θ_D is the Debye temperature. This would take into account the atomic hard cores and the fact that kinetic and potential energies are of the same order in solid ^{4}He. As for the numerator, we can remark that, at temperatures higher than J/k_B, ^{4}He particles can be considered as classical, not bosons. Thus the transition temperature T_0 must be lower or of the order of J/k_B. Taking the equality gives a lower limit for ρ_s :

$$\frac{\rho_s}{\rho_c} \gtrsim \frac{T_0}{\theta_D}$$

On the other hand, the critical velocity should be of order [26] :

$$v_c \cong \frac{\hbar}{md} \ln \frac{d}{\xi}$$

where d is a typical free distance in the cell ($d \cong 3$ mm) and ξ the coherence length. Taking the logarithmic factor equal to unity gives a lower limit for v_c. The same order of magnitude can be extracted from the paper of Leggett [3]. He argues that the moment of inertia of an annulus should be periodic in angular velocity, with period :

$$\omega_0 = \hbar/\alpha m R^2$$

Later in the discussion, he shows that α should be 1. If we interpret this periodicity as due to the fact that the critical velocity is obtained for an angular velocity ω_0, then :

$$v_c = \frac{\hbar}{mR}$$

The conclusion is that, if T_0 is larger than 4 mK, then :

$$\frac{\rho_s}{\rho_c} v_c \gtrsim 10^{-9} \text{ m/s} = 10 \text{ Å/s}$$

which is in contradiction with our experimental upper limit. Therefore, it can be concluded that :

$$T_0 < 4 \text{ mK}$$

In conclusion, we have measured the growth velocity of solid ^{4}He in a geometry where additional mass must flow through the solid. This allows us to give a new upper bound to the temper-

ature of superfluidity of solid hcp ^{4}He :

$$T_0 \lesssim 4 \text{ mK}$$

well below the limit given by the preceeding attempts (25 mK) .

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