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Melting of polarized ^3He : interpretation of recent experiments

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Résumé. — Nous proposons un scénario pour interpréter les expériences récentes de fusion de ^3He solide polarisé. En fusion permanente, le liquide est formé avec l'aimantation du solide loin de l'interface. Avec cette interprétation, tous les résultats à basse aimantation sont en accord avec ce que l'on peut prédire, les susceptibilités magnétiques des deux phases étant bien connues.

Abstract. — We propose a scenario for interpreting the recent experiments on melting of polarized solid ^3He . During a permanent melting, the liquid is formed with the polarization of the bulk solid. Within this interpretation, all the low polarization results agree with the predictions deduced from the well known magnetic susceptibilities of both phases.

1. Introduction.

Two recent experiments [1, 2] have thrown a new light on the magnetic properties of the dense phases of ^3He at low temperatures. In both cases equilibrium between solid and highly polarized liquid was obtained by decompressing the solid phase, previously polarized in a magnetic field at low temperature. The measured depression ΔP of the melting curve gives information on the magnetic properties of both phases.

For the interpretation of all these experiments, it is essential to know the magnetizations of both the solid and liquid phases at the interface, where it actually determines the depression ΔP . Nevertheless, what is really measured is the total magnetization, that is in practice that of the bulk solid phase (only a small fraction of the solid is melted). The interpretation thus depends on the model which relates this global magnetization m to those of the interfacial solid and liquid. Moreover, at low polarizations the depression ΔP depends only on the magnetic susceptibilities of both phases, which are known. This gives an important check of the validity of the interpretation.

In [1] evidence is given for the proportionality of ΔP with the square of the measured relative magnetization m , in the final part of the relaxation. Assuming that the solid is finely cracked, the

authors assume that m is the magnetization of the solid at the interface. Equalling the effective fields in the liquid and the solid at the interface then gives the theoretical slope :

$$\frac{\Delta P}{m^2} = 1.7 \text{ bar}$$

while that one observed is :

$$\frac{\Delta P}{m^2} = (6 \pm 1) \text{ bar (at } T = 105 \text{ mK)} .$$

In order to reconcile these results, Bonfait *et al.* [1] suggest the existence of an instability, which makes the total magnetization to have three components, while only one is measured by the NMR. In the absence of a more precise scenario, it is impossible to analyse further the higher m results.

On the other hand, A. Dutta and C. Archie [2] recently performed « slow » decompressions of polarized solid, having thus experimental access to the whole process. However they do not measure the evolution of the magnetization. They point out that the preceding analysis is unable to explain their results, which is actually not surprising since it was developed only to explain the end of the decompression curve. They are then led to the hypothesis that the equilibrium between liquid and solid corresponds to equal polarizations (and not equal effective fields) at the interface.

We disagree with this interpretation and the purpose of this paper is to propose a scenario of melting which explains both experiments, without invoking either instability of the transverse magnetization or different effective fields at the interface.

2. New analysis : permanent melting.

We first discuss the consequences of the hypothesis of Dutta *et al.* Assuming that the effective field in both phases are not equal is equivalent to saying that, during a time characteristic of the experiment, these phases cannot exchange magnetization. However, since these authors assume the equality of chemical potentials, and thus the free exchange of atoms, their hypothesis would imply that atom exchange can only occur by pairs with opposite spins. Nevertheless this does not ensure the equality of magnetizations at the interface, which should then be attributed to some unknown mechanism.

The alternative scenario we propose is based on the picture of permanent melting with a plane interface given by Nozières and one of the authors [3]. Figure 1, which is taken from this paper sketches the process : in the permanent regime the liquid is formed at the bulk solid magnetization. A diffusion profile connects the solid magnetization at the interface (which insures the equality of effective fields with the liquid) with that of the bulk solid. The typical thickness of this profile is $\frac{D}{u}$, where D is the diffusion constant in the solid and u the velocity of the interface. This picture is correct as far as this thickness is much smaller than the radius of curvature of the interface. This implies that the diffusion profile occupies a negligible volume in the sample. This is not contradictory with the idea of dendritic melting proposed in [1]. We simply assume now that the size of the dendrites is larger than the diffusion profile thickness, while the opposite was assumed smaller in [1]. A discussion of what would be *a priori* the good limit to take is beyond the scope of this paper. We shall simply remark here that the first one gives very good agreement with the experiments.

The consequence of this scenario is that the mean measured magnetization, which is that of the bulk solid (occupying at least 90 % of the volume) is also that of the *liquid at the interface* and not of the solid as assumed in [1].

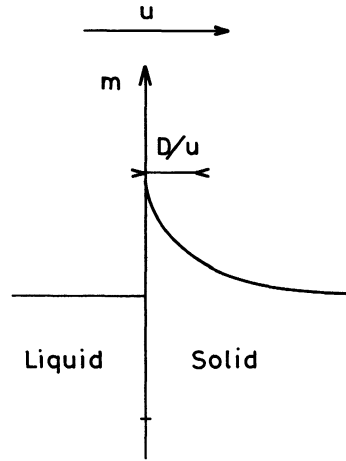


Fig. 1. — When the radius of curvature of the interface is larger than the diffusion profile, the liquid is formed with the magnetization of the bulk solid.

3. Comparison with experiments.

As a comparison, let us now see what are the predictions of the model for the low magnetization slope $\frac{\Delta P}{m^2}$ in each scenario. Following Bonfait *et al.*, we express the effective field in kelvin and measure the magnetization relative to the saturated one (in these units the Curie constant is equal to 1).

i) Assuming, as Bonfait *et al.*, that the measured magnetization is that of the *solid at the interface* gives :

$$\Delta P \cdot \Delta v = \frac{R}{2} \frac{\chi_s - \chi_L}{\chi_s^2} m^2 \tag{1}$$

where Δv is the difference between molar volumes.

ii) For the mechanism proposed by Dutta *et al.* the simplest way is to write :

$$F_s(m) + P(m) v_s - (F_L(m) + P(m) v_L) = 0 = F_s(0) + P(0) v_s - (F_L(0) + P(0) v_L)$$

where F_i and v_i are the molar free energies and volumes at temperature T . For the lowest values of m : $F_i(m) - F_i(0) = R \frac{m^2}{2 \chi_i}$ and thus :

$$\begin{aligned} \Delta P \cdot \Delta v &= \frac{Rm^2}{2} (\chi_L^{-1}(T) - \chi_s^{-1}(T)) \\ \Delta P \cdot \Delta v &= \frac{R}{2} \frac{(\chi_s - \chi_L)}{\chi_s \chi_L} m^2 . \end{aligned} \tag{2}$$

iii) Finally, our model here consists in replacing in the denominator of equation (1) χ_s by χ_L :

$$\Delta P \cdot \Delta v = \frac{R}{2} \frac{(\chi_s - \chi_L)}{\chi_L^2} m^2 : \tag{3}$$

Table I. — Comparison of the various interpretations with experiment. m is the global measured magnetization. m_s and m_l are the solid and liquid ones at the interface. In the last column is given the correction factor applied to the data of Dutta and Archie (see text).

T	(i) $m = m_s$	(ii) $m = m_s = m_l$	(iii) $m = m_l$	Experiment	Correction factor
50 mK	1.16 bar	4.2 bar	15.4 bar	16.9 bar	1.16
75 mK	1.5 bar	3.9 bar	10.1 bar	10.7 bar	1.25
100 mK	1.7 bar	3.6 bar	7.5 bar	8.3 bar	1.375
105 mK	1.7 bar	3.5 bar	7 bar	$6(\pm 1)$ bar	

The values given for $\frac{\Delta P}{m^2}$ by the three formulae above are summarized in table I. The fourth column gives the experimental results. Those corresponding to the data of Dutta *et al.* have been deduced from their last figure which gives the ΔP at different temperatures, starting with a solid polarized under different fields. Unfortunately, the corresponding magnetizations have not been given; it may be inferred by assuming that the starting temperature is always the same. Then $m = \text{th} \frac{B}{B_0}$. As $m = 0.65$ with $B = 8$ tesla, we have $B_0 = 10.2$ T. The 2 tesla data thus correspond to $m(2 \text{ T}) : 0.19$ and for 1 tesla : $m(1 \text{ T}) = 0.097$. We then obtain an estimation of the slope $\frac{\Delta P}{m^2}$ by :

$$\frac{\Delta P}{m^2} = \frac{\Delta P(2 \text{ T}) - \Delta P(1 \text{ T})}{m^2(2 \text{ T}) - m^2(1 \text{ T})}$$

The ΔP values are corrected to take into account the drop shown in their figure 4, which is due to the relaxation of m between the time the decompression starts and the time one reaches the corresponding temperature.

It is clear that formula (3) gives the best agreement with experiment. It seems thus clear that both experiments, are made in the regime of thin diffusion profile, occupying a negligible volume, by contrast with the thick diffusion profile limit, assumed in reference [1].

4. Conclusion.

Owing to the recent data of Dutta *et al.* a coherent scenario of the decompression can be proposed which accounts for all the experimental results : the solid is continuously melting, forcing the magnetization of the liquid at the interface to be that of the bulk solid (and *not* of the solid at the interface).

These decompression experiments can now provide valuable information about the high magnetization phases.

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