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INFLUENCE OF HIGH MAGNETIC FIELDS ON THE COEXISTENCE CURVE OF He^3 AT 1.2 K

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Résumé.- Des mesures préliminaires de l'influence de champs magnétiques intenses sur la courbe de coexistence de ^3He à des températures allant de 1,22 à 1,25 K montrent que à température constante le changement de la pression de vapeur avec le champ a une pente positive de zéro à 5 ou 6 T. La pente devient ensuite négative jusque vers 15 ou 17 T, puis elle devient fortement positive jusqu'à 19,2 T. Le changement total de pression par rapport à l'équilibre est de l'ordre de 0,1% de la pression totale.

Abstract.-Preliminary measurements of the influence of high magnetic fields on the coexistence curve of He^3 at temperatures between 1.22 K and 1.25 K show that under isothermal conditions the change in the vapor pressure as a function of field has a positive slope from zero to 5 or 6 T. The slope then becomes negative up to about 15 or 17 T whereupon it becomes strongly positive up to 19.2 T. The total change in the pressure from equilibrium is of the order of 0.1% of the total pressure.

We report here the results of preliminary measurements of the influence of high magnetic fields on the vapor pressure of He^3 at temperatures between 1.22 and 1.5 K and magnetic fields up to 19.25 T. These data are the initial results of an experimental program to study He^3 in high magnetic fields. Because of the small pressure differences (about 0.1%) and the long spin lattice relaxation times observed, the findings reported here should be viewed as preliminary and subject to further exploration and verification. However, the results seem to warrant this report because of the observed dependence of the vapor pressure of He^3 on the magnetic field.

The apparatus used is shown in Fig. 1. The He^3 sample chamber, 25 mm long and 12 mm diameter, made of stainless steel, was situated inside a He^4 Dewar at the center of a Bitter solenoid which supplied the magnetic field. The inhomogeneity in the field across the sample was less than 0.2% of the total. Care was taken to fill the chamber so that no liquid reached into the fill line. The He^3 fill line, a 3 mm diameter stainless steel tube, was vacuum-jacketed starting 45 mm

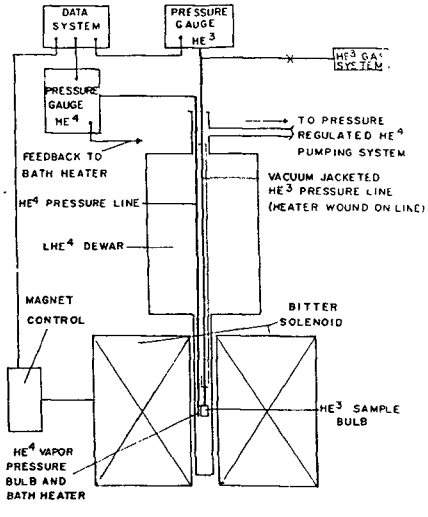

Figure 1.

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above the sample chamber up to the top Dewar neck, with a heater wound on the fill line inside the vacuum jacket. He^3 pressure was monitored by a capacitance diaphragm gauge capable of detecting pressure changes of about 0.01 μ on its most sensitive scale and the ability to measure pressures up to 100 mm with the above precision. (1 μ = 10^{-3} mm = 0.133 Pa.)

The temperature of the He^4 bath in which the He^3 sample chamber was immersed was monitored by a pressure gauge similar to the He^3 gauge but with a sensitivity greater by a factor of ten. That gauge was attached to a He^4 vapor pressure bulb in which He^4 liquid was condensed. The He^4 pressure gauge was also part of a feedback loop for the regulation of the bath. During a typical run the long term temperature drift was never more than 0.1 mK with short term fluctuation of about the same order.

The He^3 sample was in good contact with the He^4 bath as evidenced by any short term bath temperature fluctuation being reflected in the He^3 pressure and the good agreement of the He^3 and He^4 temperatures obtained from vapor pressure tables. The thermal relaxation time between the He^3 and He^4 baths was less than a second as opposed to the long magnetic relaxation times in He^3 . No eddy current heating due to the ripple in the magnetic field was observed as evidenced by the absence of any effect when a field ripple compensator was turned on, although some heating was observed when the field was swept very fast, 10 T/min.

Figure 2. shows our raw data with the dashed line representing equation /1/. Figures 3 and 4 show typical results of our experimental runs at temperatures between 1.22 and 1.25 K with no observable effect at 1.5 K. They

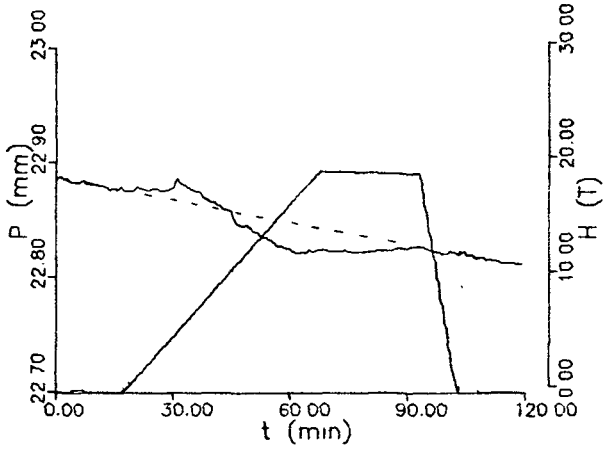

Figure 2.

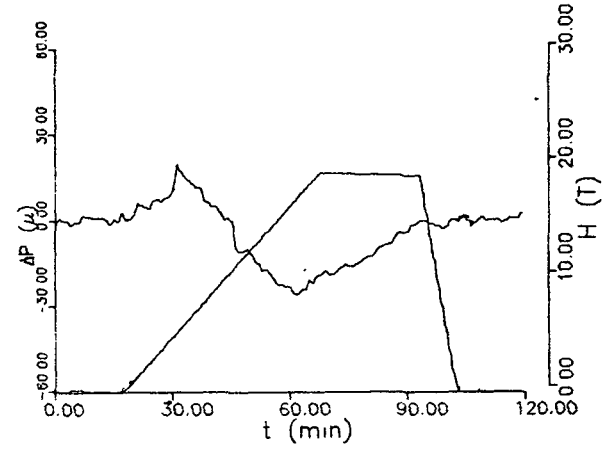

Figure 3.

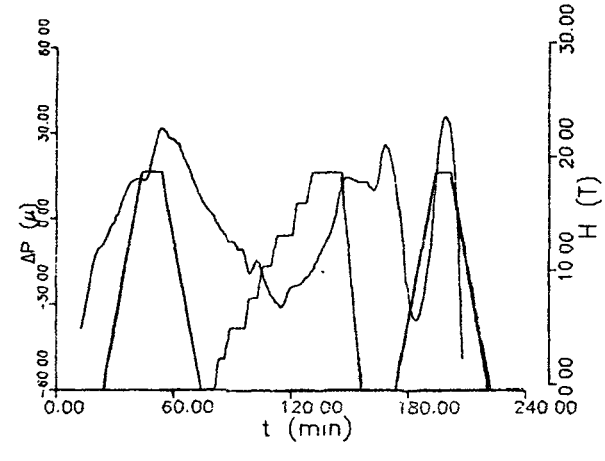

Figure 4.

represent the pressure change ΔP in He^3 as well as the applied magnetic field as a function of time. ΔP, represented by the irregular line and referring to the left hand scale in terms of microns μ was obtained by subtracting out the long term pressure drift which was assumed to have the form

$$P = P_o + at + b \exp(-t/\tau') \qquad (1)$$

where P_o, a, b, and τ' are constants obtained from a fit to the points at zero magnetic field. The straight lines represent the magnetic field in Tesla and refer to the right hand scale.

Several features became apparent. When the field is applied to a previously unmagnetized sample, Figure 3, the pressure initially rises. This rise continues to about 5 T where it has a tendency to level off and start decreasing. At about 10 T it crosses the zero line and again levels off between 14 T and 17 T. Thereafter it increases. The changes in pressure range from approximately +30 μ to -30 μ with the changes depending on the rapidity with which the field is swept. This suggests a long time constant. If the field is swept from zero to 19.25 T in 20 min. as shown in Figure 4, the pressure does not have time to respond to the field and one sees only a suggestion of the above response. A 50-minute sweep or a stepping of the field will more closely approximate an equilibrium situation. Moreover, we were never able to stay at the highest field for a long enough time to be sure that we are close to equilibrium (because of the time constraint on our runs), and thus ΔP at 19.25T could be much higher than that indicated on the graph. Subsequent magnetizations and demagnetizations evoke smaller effects because the long magnetic time constant will keep the pressure from reaching equilibrium before a change is effected in the magnetic field, but the tendencies observed above are apparent. A phenomenological description of the time dependent behavior of the change of pressure $\Delta P(t)$ with an exponential relaxation time τ_m can be written as

$$\Delta P(t) = \int_{-\infty}^{t} \frac{1}{\tau_m} \exp\left(-\frac{t-t'}{\tau_m}\right) \Delta P_o(t')dt' \qquad (2)$$

The observed pressure is thus a function of past history /1/. For a linearly varying $\Delta P_o(t)$ where

$$\begin{aligned} \Delta P_o(t) &= At \qquad t>0 \quad A \text{ constant} \\ &= 0 \qquad t<0 \end{aligned} \qquad (3)$$

$$\Delta P(t) = A\left\{t - \tau_m\left[1 - \exp(-t/\tau_m)\right]\right\} \qquad (4)$$

From equation (4) we see that unless $\Delta P_o(t)$ reverses direction or $\tau_m = 0$, we have the classic Zeno problem where $\Delta P(t)$ never catches up with $\Delta P_o(t)$. If $\Delta P_o(t)$ reverses direction, $\Delta P(t)$ is equal to $\Delta P_o(t)$ whenever $\frac{d\Delta P(t)}{dt} = 0$. In our case the problem may be more complicated because τ_m itself might depend on the magnetic field or He^3 polarization.

Figure 5. summarizes our best estimated measured ΔP, assumed close to equilibrium, as a function of the magnetic field. The arrows attached to the points indicate the estimated possible excursion from the measured points since the true equilibrium value would be

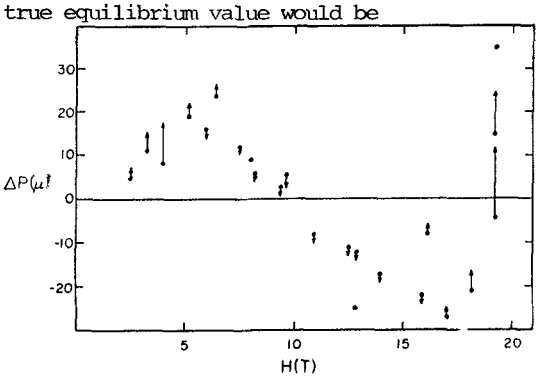

Figure 5.

$$\Delta P_o(t) = \tau_m \frac{d\Delta P(t)}{dt} + \Delta P(t) \qquad (5)$$

Although we have no explanation for the behavior of He^3 in high magnetic fields described above, several factors must be considered in order to set the stage for an explanation. To begin with, one has to realize that at our temperatures He^3 is a diamagnetic substance, and the force due to the magnetic field gradient will give rise to a change in the pressure reading of our gauges to compensate for the change in pressure at our sample due to that force under isothermal conditions.

The diamagnetic susceptibility of He^3 is

$$\chi_d \simeq -1.9 \times 10^{-6} \text{ cm}^3/\text{mol}$$

while the nuclear paramagnetic susceptibility is

$$\chi_p \simeq \frac{1.3 \times 10^{-7}}{T} \text{ cm}^3/\text{mol}$$

and thus the magnitudes of the two susceptibilities become equal only at about 67 mk. It is easy to show /2/ that the change in pressure due to this effect is

$$P = \frac{1}{2} \frac{\chi}{\bar{V}} (H_o^2 - H_f^2) \qquad (6)$$

where H_o and H_f are the highest and lowest fields at the sample, and χ and V are the molar susceptibility and molar volume respectively. In our case this contribution would amount to about $\Delta P \simeq +6\mu$ at the highest fields.

If one assumes with Goldstein /3/ that the portion of Fermi liquid in the liquid He^3 is proportional to the deviation of the susceptibility from Curie's law, then only 3.5% of our liquid sample is in the Fermi state /4/. Moreover, if one considers He^3 as a nuclear paramagnet and ignores the small contribution due to nuclear spin diamagnetic orbit coupling in a magnetic field /1/, the polarization in a magnetic field will be proportioned to $\frac{\mu H}{kT}$ or $.78 \times 10^{-3} \frac{H}{T}$ with H in Tesla and T in K. At the highest fields in our case the polarization is about 1.25%.

Beyond the change in pressure due to the magnetic field gradient discussed above, any explanation of the pressure change at the coexistence curve has to depend on the change in the differences in the molar entropies and volumes of the vapor and liquid with the magnetic field through the Clausius Clapeyron equation

$$\frac{dP}{dT} = \frac{S_v - S_l}{V_v - V_l} = \frac{L}{T(V_v - V_l)} \qquad (7)$$

where the subscripts v and l refer to the vapor and liquid respectively and L is the latent heat. Generally V_l is neglected, S_v is assumed to be that of a paramagnet, and V_v is assumed to be unaffected by the field. This equation is then integrated with respect to T to obtain ΔP. A more explicit expression giving the magnetic field dependence is

$$(V_v - V_l)\, dP = (S_v - S_l)\, dT + (M_v - M_l)\, dH \qquad (8)$$

where the M's are the molar magnetizations.

Castaing and Nozières /5/ conclude from the above arguments that "the vapor curve will move upward as the magnetic field is increased." They also suggest the possibility that the liquid phase may become unstable in high magnetic fields. Lhuillier and Laloë /6/ obtain an equation for the ratio of pressures of the polarized $P\uparrow$ and unpolarized liquid

$$\frac{P\uparrow}{P} = \exp\left(\frac{\Delta E(He^3\uparrow)}{kT}\right)$$

With their estimate of $\Delta E(He^3\uparrow) = 0.2K$, $P = 22$ mm and a polarization of 1.25%, we obtain

$$\Delta P = 1.25 \times 10^{-2} (P\uparrow - P) \simeq 50\mu$$

Although this is close to the total change in ΔP it predicts only an increase. Goldstein, /7/ on the other hand, predicts a decrease in pressure upon the application of a magnetic field whose magnitude is a fraction of a micron (μ).

It is tempting to speculate that the decrease in pressure, if real, is due to the destruction of the Fermi liquid fraction by the magnetic field. Indeed, the value of $\frac{\mu H}{k}$ at the first possible inflection point at $H = 4T$ is about 3mK, which is also close to the superfluid transition point /8/. We believe that further investigation of the influence of high magnetic fields on the behavior of He^3 at this and lower temperatures will illuminate the nature of this Fermi liquid.

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/1/ We are indebted to Ernesto Corinaldesi for clarifying these points.

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