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PHASE TRANSITIONS IN PARTIALLY SPIN-POLARIZED ^3He

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Résumé

Nous présentons les diagrammes d'équilibre liquide-gaz pour l'hélium trois partiellement polarisé. A basses températures, nous trouvons des phénomènes intéressants tels que le métamagnétisme en phase liquide ou une surpolarisation du liquide.

Abstract

We present liquid-gas equilibrium phase diagrams for partially spin-polarized ^3He . At low temperatures, interesting phenomena such as liquid metamagnetism and liquid overpolarization have been found.

Introduction

The study of phase transitions in spin polarized ^3He is a subject of growing interest. At high pressures, the results so far obtained (1) might indicate the existence of a metamagnetic, or near it, transition in the liquid phase. In this contribution, we want to investigate the properties of polarized ^3He at lower pressures, in particular at the vapor pressure. This study has been prompted by some experiments on the liquid-gas phase transition which are now in progress at the Ecole Normale de Paris (2).

To investigate liquid-gas (and liquid-liquid) phase transitions, we resort to a simple model already employed in Nuclear Physics (3). It is based on the use of Skyrme-like forces in the framework of a mean field approach (4). A more detailed description of the method as well as further results can be found in refs 5 and 6.

The formalism

A convenient thermodynamic potential to describe the system is the free energy density that per unit volume reads

$$f(\rho, M, T) = f_{n_i}(\rho, M, T) + f_v(\rho, M, T) \quad (1)$$

where ρ is the number density, $\rho = N/V$, T is the temperature and M the magnetization

$$M = (\rho^\uparrow - \rho^\downarrow) / \rho \quad (2)$$

$\rho^\uparrow$ and $\rho^\downarrow$ are the spin up (down) partial densities. In expression 1, f_{n_i} is the free energy density of a non-interacting Fermi gas (7) and f_v is the contribution due to the interactions. This is the key ingredient for which we have taken the following function:

$$f = 1/2(b_0 + b_1 M^2 + b_2 M^4) \rho^2 + 1/2(c_0 + c_1 M^2 + c_2 M^4) \rho^{2+\sigma} \quad (3)$$

To fix the coefficients entering eq. 3 we have used as much experimental information as possible, which is mainly available for M around 0.

First of all, the values of b_0 , c_0 and σ at $T=0$ were fixed in order to reproduce the experimental values of the energy per particle E_0 , equilibrium density ρ_0 and compressibility χ of unpolarized liquid ^3He (5). Next, the coefficient b_0 was made T -dependent and fixed to exactly reproduce the vapor pressure of unpolarized ^3He . To obtain $b_1(T)$ and $c_1(T)$, we have used the magnetic susceptibility χ

$$\frac{C}{\chi} = \frac{1}{\rho^2} \left. \frac{\partial^2 f}{\partial M^2} \right|_T \quad (4)$$

for which there are experimental results at $M=0$. In eq. 4, C is the Curie's constant.

The necessity of at least M^4 terms in eq. 3 stems from experimental facts and theoretical arguments. Indeed, at $M \sim 0$ it is known experimentally that it is easier to magnetize the vapor than the liquid. Consequently, in the liquid-gas equilibrium, near $M=0$ the phase diagram would be that of fig. 1, where we show the pressure P as a function of M for a given T (L reads for the liquid, G for the gas in equilibrium with it). If $P(M)$ were always an increasing function of M , as it is the case of fig. 1, eq. 3 without M^4 terms would be fine. However, it is easy to show that this is not so for all T .

Figure 1

To see how it comes about, let us consider a very low T and write the pressures $P(P^\uparrow)$ of the $M=0(1)$ vapor as a function of the energy per particle $E_0(E_0^\uparrow)$:

$$P = A T^{5/2} \exp(E_0/T)$$

$$P^\uparrow = 2 A T^{5/2} \exp(E_0^\uparrow/T) \quad (5)$$

where A is a constant. Since $|E_0^\uparrow| < |E_0|$, at T low enough we have $P^\uparrow > P$. But when T increases, there is a temperature T^* for which both pressures are the same

$$T^* = (E_0^\uparrow - E_0) / \ln 2 \approx \Delta E / \ln 2 \quad (6)$$

and from T^* up, $P > P^\uparrow$. Recent calculations (8) show that $E_0 \sim E_0^\uparrow$ and $g_0^\uparrow \sim g_0$. That makes T^* rather small. For example, if $\Delta E = 0.2$ K, $T^* \sim 0.3$ K, much smaller than the critical temperature of ^3He (5) (T^* estimated from eq. 6 can be accurate only if T^* is not very high. For $\Delta E = 0.2$ K our calculations yield $T^* \sim 0.5$ instead of 0.3 K). We thus conclude that in order to bend down the $P(M)$ curve, we do need M^4 terms. Finally, the values of $b_2(T)$ and $c_2(T)$ are essentially fixed by the values of the experimentally unknown quantities $E_0^\uparrow$ and $g_0^\uparrow$ (6) which are the free parameters of our model.

The presence of M^4 terms in eq. 3 makes the phenomenon of liquid metamagnetism (divergence of $\chi(M)$ for some values of M) possible. For given values of P and T , the function $\chi(M)$ becomes negative in some range of values of M . Regions of negative χ or negative compressibility K are instability regions and the system has to separate in several phases that differ in density and/or magnetization.

Figure 2

Figure 3

Results

Typical phase diagrams for selected values of T are shown in figs. 1-5. Figures 1 to 3 correspond to $E_0^\dagger = -2.3$ K (this energy is the more recent theoretical estimate, see ref. 8; the results are rather insensitive to the value of $S_0^\dagger$ which is also estimated in that ref. to be smaller than S_0), whereas figs. 4 and 5 correspond to $E_0^\dagger = -2.4$ K.

In fig. 1 we present the situation $T < T^*$ whereas figs. 2 and 3 correspond to $T > T^*$. One may see in fig. 3 that for $M \geq 0.4$ the liquid is more magnetized than the vapor, in contradistinction with fig. 1. The same phenomenon of liquid overpolarization is presented in fig. 4 (T^* for $E_0^\dagger = -2.4$ K is ~ 0.2 K).

Figure 5 is the result of combining magnetic ($\chi < 0$) and mechanical ($K < 0$) instabilities. At low pressures we have a liquid-gas equilibrium that shows again liquid overpolarization. At high pressures, two liquids with rather different magnetizations and similar densities are in thermodynamical equilibrium. When P decreases, there is a point where two liquids are in equilibrium with a common vapor of intermediate M (triple line). We have not found a quadruple point in the calculations performed with our model functional, eq. 3.

Finally, figure 6 shows $\chi(M)$ for $E_0^\dagger = -2.3$ K at $T = 0.6$ K. In this figure, the curve labeled CL corresponds to the classical gas, which is a good approximation for the vapor at this temperature. NIFG represents the non-interacting Fermi gas susceptibility and the solid line is $\chi(M)$ calculated from eqs. 1, 3 and 4. Notice that near $M=0$, the magnetic susceptibility of the gas is larger than that of the liquid, whereas near $M=1$ the opposite occurs. This is so because $T > T^*$ and is in agreement with the situation shown in figures 2 and 3.

Figure 4

Figure 5

Figure 6

Conclusions

Our simple model predicts interesting physical situations and shows the key role played by $E_0^\uparrow$ in the thermodynamics of partially polarized ^3He . Our predictions can be of some relevance for future experiments. We have found that one has to go beyond $M \sim 0.5$ to find the most interesting effects.

Even if metamagnetism does not show up, situations near it might well be met (figs. 2 and 3), playing an important role (9). One could imagine purely thermal overpolarization methods taking advantage of the particular shape of these diagrams.

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