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SURFACE INDUCED FERROMAGNETISM IN ^3He

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Résumé.- La susceptibilité et les temps de relaxation transverses et longitudinaux des noyaux d' ^3He dans une poudre de charbon (ϕ 9 nm) ont été mesurés jusqu'à 0.4 mK par RMN pulsée. Les résultats indiquent que l' ^3He près de l'interface solide-liquide a une tendance ferromagnétique aux plus basses températures.

Abstract.- Pulsed NMR measurements of the susceptibility and of the transverse and longitudinal relaxation times of ^3He intermixed with 9 nm carbon particles down to 0.4 mK show that the solid-liquid system near the surfaces favours ferromagnetic order below 10 mK and approaches a ferromagnetic transition at the lowest temperatures.

Recent measurements on ^3He at millidegree temperatures inside a stack of mylar plates 4 μm apart /1/ and intermixed with ultrafine carbon particles /2/ showed a pronounced enhancement of the susceptibility as compared with that of normal bulk Fermi-liquid. The excess susceptibility exhibited a ferromagnetic Curie-Weiss behaviour $\chi = 1/(T - \theta)$ with θ roughly 0.7 mK. We report here pulsed NMR measurements on ^3He intermixed with 9 nm carbon particles at 0, 6, 15 and 25 bar bulk pressure well below that temperature as well as above the onset of the ferromagnetic trend of the susceptibility. The apparent transverse relaxation time τ_2^* was also determined at the various pressures; the longitudinal relaxation time τ_1 was measured only at 0 bar. All measurements were performed in a magnetic field of 28 mT.

Our sample consisted of a cylindrical NMR coil, 5 mm in diameter and 6 mm long, filled to 6 % with carbon black /3/. The characteristic surface area of the carbon powder was measured with the BET-method to be 350 m^2/g yielding for the total surface area of our sample 4.9 m^2 . The temperatures were determined by measuring the susceptibility of powdered platinum confined in a similar coil and in contact with the ^3He sample; the Korringa relation was employed for calibration of the thermometer.

The amplitude of the free induction signal, extrapolated to time $t = 0$, is proportional to the susceptibility of the sample. The measured signals appeared to be composed of two contributions, one decaying much slower ($\tau_2^* \approx 400 \mu\text{s}$) than the other

($\tau_2^* \approx 40 \mu\text{s}$). We call the extrapolated quantities χ_1 and χ_2 , respectively.

Our data on χ_2 show no pressure dependence within the scatter and susceptibility follows a Curie Weiss law $\theta = -0.09 \text{ mK}$. This is in accordance with an antiferromagnetic interaction with $J/k_B = \frac{4}{z} \theta = -0.06 \text{ mK}$ if we use $z = 6$ as the number of nearest neighbours. Bulk solid ^3He ordinarily exhibits an antiferromagnetic exchange interaction; the measured J would correspond to a molar volume of 21 cm^3/mole for solid ^3He . The antiferromagnetic nature of the signal, its insensitivity to the applied pressure, and its short and constant τ_2^* suggest that χ_2 is associated with a well-localized sheet of ^3He atoms on the surfaces. We estimate the thickness of the layer to be ≈ 1.2 atomic layers.

Figure 1 shows the inverse of the major contribution, χ_1 , as a function of temperature at $p = 0$. Assuming that χ_1 originates from the next few surface layers, with a density $> \rho_{\text{bulk}}$ and a Curie-Weiss type susceptibility, and from the Fermi-liquid in the centre of the voids, we may write:

$$\chi_1 = \frac{c_1}{T - \theta} + c_2, \quad (1)$$

where c_1 and c_2 are constants. The bulk liquid contribution can be separated by plotting χ_1 vs. $T^{-1} \rightarrow 0$. The c_2 's at different pressures scale within $\pm 20 \%$ as the susceptibilities of bulk liquid ^3He . In terms of the above model ($\chi_1 - c_2$) is ferromagnetic and weakly pressure dependent; the θ 's range from 0.35 to 0.50 mK. The ratios of ($\chi_1 - c_2$)'s and c_2 's yield for the thickness of the intermediate solid liquid region 4.5 - 5.5 atomic layers. The deviation of the temperature dependence of

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$(\chi_1 - c_2)$ from the Curie-Weiss law already at approximately $2\theta_1$ may reflect the two-dimensional nature of the system.

Fig. 1 : The inverse susceptibility χ_1^{-1} as a function of temperature at $p = 0$.

The resemblance of the data in figure 1 to the solid ^3He susceptibility data of Prewitt and Goodkind /4/ suggests another way of interpreting our data. If we assume that at temperatures between 10 and 20 mK the antiferromagnetic susceptibility dominates and fit those data to the first term in eq. (1), we obtain $\theta = -2.6 \dots -2.8$ mK at the different pressures. In this case, within the scatter of our data, the "excess" susceptibility appears to be proportional to T^{-2} .

Our data on the apparent transverse relaxation time τ_2^* are shown in figure 2. τ_2^* is seen to be linear, slowly declining function of temperature down to ~ 10 mK. At about 5 mK it becomes constant and then grows rapidly towards the lowest temperatures. This is characteristic of a ferromagnet close to the transition /5/.

Of the suggestions for explaining the observed ferromagnetic behaviour in the solid-liquid system of ^3He /6/, /7/, /8/, we consider the theory of vacancy induced ferromagnetism as the most appealing one. The onset temperature of the ferromagnetic trend in the susceptibility of both low-density solid and solid-liquid ^3He (we note in passing that it coincides with the inflection point of the melting curve) and of the anomalous Kapitza resistance $R_K \propto T^{-1}$ below ~ 10 mK seems to indicate that these two phenomena are related and their common origin may be established within the framework of the vacancy theory.

Fig. 2 : The apparent transverse relaxation time τ_2^* as a function of temperature at 0, 6, 15, and 25 bar.

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