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NUCLEAR INDUCED FERROMAGNETISM IN \( \text{PrCu}_5 \)

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Résumé.— Nous avons observé dans le composé de Van Vleck \( \text{PrCu}_5 \), l'apparition à basse température d'un ordre ferromagnétique nucléaire ; la température de Curie \( T_C \) est de 24 mK. Au-dessus de \( T_C \), l'énorme décroissance du renforcement de la constante de Curie nucléaire d'un facteur 180 avec le champ appliqué ne peut être expliquée qu'en tenant compte d'interactions indirectes entre les noyaux de Pr.

Abstract.— In the Van Vleck compound \( \text{PrCu}_5 \), we have observed, at low temperature, a nuclear ferromagnetic ordering with a Curie temperature of 24 mK. Above \( T_C \), to explain the huge decrease by a factor 180 of the enhanced nuclear Curie constant with the applied magnetic field, one has to take into account indirect interactions between Pr nuclei.

1. INTRODUCTION.— Among Van Vleck compounds of Praseodymium, \( \text{PrCu}_5 \) is of particular interest. The ionic ground state is a singlet with another singlet at about 30 K. As a result, \( \text{PrCu}_5 \) exhibits, at helium temperature, a Van Vleck susceptibility enhanced by near-critical ferromagnetic exchange interactions between Pr ions. Ferromagnetic nuclear ordering occurs between 20 and 50 mK /1/.

2. EXPERIMENTS.— Polycrystalline samples were used for this study. The magnetization measurements were performed as described earlier /2,3/, the sample being cooled with a paramagnetic salt. The susceptibility measurements were performed using an A.C. mutual inductance bridge ; the sample was placed in the mixing chamber of a dilution refrigerator. The lowest attainable temperature, with a single continuous heat exchanger, was 17 mK.

3. EXPERIMENTAL RESULTS AND DISCUSSION.— The total magnetization of \( \text{PrCu}_5 \) at low temperature is shown on figure 1. From curve a, in low field, we deduce a Van Vleck susceptibility of 0.5 emu/mole Pr giving an enhancement factor \((1 + K)\) equal to 95. It is, to our knowledge, the largest one observed in Pr compounds. Curves b and c were measured at low temperature; curve c, obtained with decreasing applied field after cooling the sample in 60 kOe, shows a saturated magnetization of 1000 emu/mole, characteristic of ferromagnetic nuclear ordering. This value is in good agreement with the calculated one, at zero \( K \), by \( M_{\text{ns}} = (1 + \eta) (1 + K) N g_{\text{n}}^n \mu_{\text{n}}^n \)

\[ I = 1260 \text{ emu} \] (We recall that \( K = h_b g_{\text{n}}^n H_{\text{n}} \), \( \eta = h_b \frac{dM}{dH} \), and \( h_b = A g_{\text{J}}^n B g_{\text{n}}^n \mu_{\text{n}}^n \), \( A \) being the hyperfine constant).

Fig. 1: Magnetization of \( \text{PrCu}_5 \) versus field at low temperature.

The susceptibility (figure 2), measured with an A.C. technique shows also a sharp peak at 24 mK. The inverse of the D.C. susceptibility (figure 2), measured in a 200 Oe field, follows a Curie Weiss law with a paramagnetic Curie temperature of also 24 mK. This temperature is close to the 35 mK predicted by a molecular field theory /5/. Also we made, a full study of the nuclear magnetization above \( T_C \) as a function of magnetic field and temperature. In every field, the susceptibility follows a Curie law (figure 3). The most striking fact is the huge variation of the nuclear Curie constant (deduced from these Curie laws) with the applied field. While the calculated one, using our previous model /3,4/, by \( C_{\text{n}} = (1 + \eta) (1 + K) (C_{\text{n}}^0 \text{ being the bare Curie constant of Pr}) \) varies by a factor of 60, the measured one \( C_{\text{n}} \) varies by a factor of 180 (Table I).

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In our previous model the enhanced nuclear magnetization was given by,

\[ M_{en} = (1+n) N g_n \mu_n J I \sum_{n=1}^{\infty} \frac{H_n}{h} \frac{I+K}{kB} \].

It was considered that the electronic magnetization \( M' \) induced by the nuclear field \( H_n /3/4 \) was small compared to the electronic magnetization \( M \) induced by the applied field. This is the case in Pr \( Cu_5 \) for high fields (over 65 kOe) but not in lower fields. One has to consider the total electronic magnetization \( M+M' \) and indirect interactions between the nuclei via the electronic moment \( /6/ \). We take the molecular field as being also proportional to the total electronic magnetization say \( \alpha (M+M') \). This gives a nuclear Curie constant which is

\[ C_{en} = C_n (1+n) (I+K) h \].

Values of \( \alpha \), taken as a parameter, are shown in Table I. More details about this study will be published elsewhere.

The A.C. susceptibility measurements were performed on the dilution refrigerator of Service National des Champs Intenses.

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**Fig. 2**: A.C. susceptibility and inverse of susceptibility as a function of temperature

**Fig. 3**: Enhanced nuclear susceptibility measured in different fields versus \( 1/T \)

<table>
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<th>Table I</th>
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<tbody>
<tr>
<td>( H (kOe) )</td>
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<tr>
<td>( C_{en} \times 10^9 )</td>
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<tr>
<td>( [{C_n(1+n)(1+K)} \times 10^4] )</td>
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<td>( \alpha )</td>
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