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FERMI LIQUID DESCRIPTION FOR TEMPERATURE INDUCED FERROMAGNETISM

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Abstract. — Temperature induced ferromagnetism in Y$_2$Ni$_7$ is not explained by existing theories where the free energy is expanded in even powers of magnetization. The Fermi liquid model is shown to explain essential features of temperature induced ferromagnetism because of the logarithmic temperature- and magnetization dependence of the free energy arising from the Fermi liquid effect.

Peculiar itinerant ferromagnetism, so-called thermally induced or temperature induced ferromagnetism (TIF), has been recently observed in Y$_2$Ni$_7$ [1]; Y$_2$Ni$_7$ is ferromagnetic for a temperature range between 7 K and 58 K and paramagnetic otherwise. This phenomenon was originally called thermal spontaneous magnetism [1]. Such a possibility had been earlier predicted by Shimizu [2] within the Stoner model of itinerant electron magnetism. Moriya [3] has shown, however, that either theory based on the Stoner model or his spin fluctuation theory can hardly explain this anomalous behaviour.

Most existing theories [2-4] are based on the assumption that the free energy of the system can be expanded in even powers of magnetization $M$. Moriya [3] has considered the energy up to order $M^4$ which leads him to the above conclusion. Shimizu and Inoue [4] have taken terms up to $M^8$ to reexamine this problem; within this form of the free energy, however, a quantitative explanation of the problem is shown to be difficult.

If the interaction between electrons is properly considered, the above assumption loses its grounds; the energy of the system at absolute zero is known to contain terms such as $M^4$ in $M$ [5, 6] and hence it cannot be expanded in powers of $M$. According to the Fermi liquid model [7] more generally, since the energy is a functional of the quasiparticle distribution function which manifests itself in the sharp Fermi surface (discontinuity), the energy contains, as a reflection of the discontinuity, various logarithmic terms with respect to temperature $T$ and magnetization. There exist terms of the form $T^4 \ln q \left( T^2, M^2 \right)$, $T^2 M^2 \ln u \left( T^2, M^2 \right)$, $M^4 \ln v \left( T^2, M^2 \right)$, $T^4 M^2 \ln w \left( T^2, M^2 \right)$ etc., where functions $q, u, v, w$ etc. satisfy $q(0,0) = u(0,0) = v(0,0) = 0$. If we try to describe TIF precisely, we have to consider all these terms. However, here our aim is to show the validity of the Fermi liquid model [7] to this problem, and also the system (Y$_2$Ni$_7$) is weakly magnetized, we have only to consider the $T^2 M^2 \ln u$ term.

At low $T$ and low $M$, $u \left( T^2, M^2 \right)$ can be approximated as $u = \left( T/T^* \right)^2 + \left( M/M^* \right)^2$, where $T^*$ and $M^*$ are constants. Now the free energy, $F$, is given by

$$F = F_0 - \frac{1}{2} \gamma_0 T^2 + \frac{M^2}{2 \chi_0} + \frac{1}{2} f_1 T^2 M^2 \ln \left\{ \left( \frac{T}{T^*} \right)^2 + \left( \frac{M}{M^*} \right)^2 \right\} + \frac{1}{\lambda} + \tau^2 \ln \left( \tau^2 + \sigma^2 \right) + \frac{\tau^2 \sigma^2}{\tau^2 + \sigma^2} = 0,$$

where $\chi_0$ is the susceptibility at absolute zero and $F_0$, $\gamma_0$ and $f_1$ are constants. It is known that $f_1 > 0$ because of thermodynamic stability [7]. In the absence of a magnetic field, from $\partial F/\partial M = 0$ we obtain the $M$ vs. $T$ relation; either

$$M = 0 \quad (2a)$$

or

$$\frac{1}{\lambda} + \tau^2 \ln \left( \tau^2 + \sigma^2 \right) + \frac{\tau^2 \sigma^2}{\tau^2 + \sigma^2} = 0, \quad (2b)$$

where $\lambda = f_1 x_0 T^2$, $\tau = T/T^*$ and $\sigma = M/M^*$. Assume that $\lambda$ is finite and the system is paramagnetic at $T = 0$. If $\lambda/\epsilon > 1$, relation (2b) has two solutions $\tau = \tau_s$ and $\tau_c$ for $\sigma = 0$; we thus obtain $\sigma > 0$ for $\tau_s < \tau < \tau_c$ and $\sigma = 0$ otherwise. Thermally induced ferromagnetism appears at $T_s = \tau_s T^*$ and disappears at $T_c = \tau_c T^*$. The condition for the appearance of TIF is given by $f_1 x_0 T^2 / \epsilon > 1$.

In the presence of a magnetic field $H$, the magnetization curve, the $M$ vs. $H$ relation, is obtained from (1) through the relation $H = \partial F/\partial M$;

$$\eta = \sigma \left\{ \frac{1}{\lambda} + \tau^2 \ln \left( \tau^2 + \sigma^2 \right) + \frac{\tau^2 \sigma^2}{\tau^2 + \sigma^2} \right\}, \quad (3)$$

where $\eta = H/H^* = H/f_1 T^2 M^*$. The susceptibility in the paramagnetic region, $\chi(T) = M/H$, is thus given by

$$\chi(T)/\chi(0) = \left[ 1 + 2\lambda (T/T^*)^2 \ln (T/T^*) \right]^{-1}. \quad (4)$$

For Y$_2$Ni$_7$, using the observed data $T_s = 7$ K and $T_c = 58$ K, we obtain $T^* = 59.8$ K and $\lambda = 17.0$. For these values of parameters the $\sigma$ vs. $\tau$ ($M$ vs. $T$) and $\chi(T)/\chi(0)$ vs. $\tau = T/T^*$ relations, (2b) and (4), are plotted in figure 1; magnetization curves, $\sigma$ vs. $\eta$ ($M$ vs. $H$) relations, at various values of reduced temperature $\tau$, (3), are plotted in figure 2. These curves
in figures 1 and 2 reproduce essential features of the observed facts [1] in $Y_2Ni_7$. As mentioned before, at higher temperatures $\tau \sim 1$ ($T \sim T^*$) terms which have been ignored here become important.

It will be seen that TIF is not a rare phenomenon. Generally, substances exhibiting the susceptibility maximum [8] with relatively high peaks are nearly temperature induced ferromagnets. Such examples are found in transition metals [8], Rh ($\lambda/e = 0.34$) and W ($\lambda/e = 0.42$), and in Laves phase compounds [9], $YCo_2$ ($\lambda/e = 0.44$). Metallic iridium is surely a candidate for TIF. We fit the observed data of $\chi (293 \text{ K} < T < 1833 \text{ K})$ for Ir [10] to the formula

$$\frac{\chi (0)}{\chi (T)} = 1 + \left( \frac{T}{1841} \right)^2 \ln \frac{T}{3508} - \left( \frac{T}{2265} \right)^4 \ln \frac{T}{2223}$$

from which we predict $\chi (T)^{-1} = 0$ at $T = 2745 \text{ K}$. If the susceptibility does not change at the melting point (2727 K), Ir should exhibit TIF at 2745 K. Although this estimate should not be taken too serious, it is very probable to see TIF at such high temperatures.

The origin of TIF can be attributed within the Stoner model [2], to particular forms of the density of states (DOS) curve for which the susceptibility increases with increasing temperature. With the same forms of DOS, the entropy of the system, which is given by

$$S \propto - \sum_i n_i \ln n_i + (1 - n_i) \ln (1 - n_i)$$

($n_i$ = Fermi distribution function), becomes greater when the system is magnetized; this favours the occurrence of TIF and the argument here agrees with the thermodynamic relation $\partial S/\partial M = (M/x^2) (\partial x/\partial T)$. However, Moriya [3] has argued that, even if the criterion for DOS is satisfied within the Stoner model, TIF hardly appears because of the spin fluctuations.

In the Fermi liquid model [7], on the contrary, TIF may be attributed to the presence of the interaction; the interaction acts to increase entropy through the excitation of the single particle states near the Fermi surface. As seen from (1), we always have $\partial S/\partial M > 0$ at sufficiently low $T$ and low $M$, for $f > 0$ because of thermodynamic stability [7]. Since the term concerned is associated with the Fermi surface (discontinuity), it becomes a logarithmic function which produces the $T^2 \ln T$ variation of $\chi$ and hence the susceptibility maximum [7, 8]. In conclusion, Fermi liquid effect which causes universally the susceptibility maximum also favours the occurrence of TIF.