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Theory of the Electrical Resistivity in YCo_2 and $LuCo_2$

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ABSTRACT

We investigated the temperature dependence of the electrical resistivity in YCo_2 and $LuCo_2$. The magnetic free energy was expanded up to the sixth-order term in the magnetization because of the metamagnetism in YCo_2 and $LuCo_2$. The self-consistent renormalization theory of spin fluctuations (the SCR theory) was applied. The SCR theory includes the effects of the electronic correlations beyond the random phase approximation. We found that the electrical resistivity had T^2-linear dependence at low temperatures. The behaviors of the electrical resistivity were consistent with the experimental data qualitatively.

Keywords

Electrical resistivity, Spin fluctuations, YCo_2, $LuCo_2$

Introduction

The magnetic properties in nearly ferromagnetic metals have intrigued many researchers [1-13]. Yoshimura et al. performed nuclear magnetic resonance experiments in YCo_2 [14,15] and $LuCo_2$ [16], both of which exhibit a maximum in the temperature dependence of the magnetic susceptibility. They found an anomaly in $1/(T_1T)$ where $1/T_1$ is the nuclear relaxation rate. Recently, we succeeded in reproducing the maximum of the temperature dependence of the magnetic susceptibility in YCo_2 and $LuCo_2$ theoretically [17-19] by using the self consistent renormalization theory of spin fluctuations (the SCR theory). The SCR theory enables us to take into account the effects of the electronic correlation beyond the random phase approximation. The behaviors of the electrical resistivity are investigated by the results of the magnetic susceptibility in YCo_2 and $LuCo_2$. Throughout this paper, we use units of energy, such that $\hbar = 1$, $k_B = 1$, and $2\mu_B = 1$, unless explicitly stated.

Formulation

Magnetic susceptibility

The reduced inverse of the magnetic susceptibility is obtained [17-19].

$$y = y_0 - y_1 A(y,t) + y_2 A^2(y,t) \tag{1}$$

where

$$y = 1/(2T_A\chi(t)), t = T/T_0, \tag{2}$$

$$A(y,t) = \frac{1}{\gamma}\int_0^1 dx\, x^3(\ln u - 1/(2u) - \psi(u)) \tag{3}$$

$$u = x(x^2 + y/\gamma)/t \tag{4}$$

$$y_0 = (1-\alpha)/(2T_A\chi_0) \tag{5}$$

where $\psi(u)$ is the digamma function and χ_0 is the non-interacting magnetic susceptibility. y_1 and y_2 are related to the coefficient of the fourth order of magnetization and the coefficient of the sixth order of magnetization of Landau expansion of magnetic free energy, respectively. γ is related to the electronic correlations.

Electrical resistivity

The electrical resistivity is obtained as follows [20].

$$R = \frac{6J^2}{e^2 n^2 \pi T N_0^2} \sum_q q_x^2 \int_{-\infty}^{\infty} d\omega n(\omega)[n(\omega)+1]\chi_c''(q,\omega) Im\chi(q,\omega) \quad (6)$$

with

$$N_0 \chi_c''(q,\omega) = \pi \sum_k \delta(\epsilon_k - \epsilon_{k-q} - \omega)(f(\epsilon_{k-q}) - f(\epsilon_k)) \quad (7)$$

where J is the exchange interaction constant between the conduction electron and spin fluctuations. N_0 is the number of magnetic atoms. n is the number of conduction electrons per magnetic atom. $n(\omega)$ and $f(\epsilon)$ are the Bose and Fermi distribution functions, respectively. $\chi''_c(q, \omega)$ is the imaginary part of the dynamical susceptibility of the conduction electrons. For small q and ω/q, it is approximated as $\chi''_c(q, \omega) \simeq \chi_c C_c \omega/q$, where χ_c is the uniform susceptibility of the non-interacting conduction electrons and C_c is the coefficient of ω/q [20]. When we use the reduced inverse of the magnetic susceptibility, the electrical resistivity is obtained.

$$R = \frac{6J^2 \chi_c C_c T_0 q_B}{e^2 n^2 T_A N_0} \int_0^{x_c} dx\, x^4 [-1 - 1/(2u) + u\psi'(u)] \quad (8)$$

$$u = x(x^2 + y/\gamma)/t, y = 1/(2T_A \chi), \quad (9)$$

where $\psi'(u)$ is the trigamma function.

Results

In the previous section, the expression of the electrical resistivity was obtained. We provide the numerical results. The spin fluctuation parameters are determined as follows: T_0 and $\chi(0)$ are fixed to the experimental values of Ref. [16], y_1 is related to T_A and T_0 through the relation $y_1 = (7/30)T_A/T_0$ derived from Takahashi's spin fluctuation theory [4], and the remaining parameters T_A and y_2 are determined so as to reproduce the observed temperature and height of the maximum of the magnetic susceptibility [16]. The relation $y_1 = (7/30)T_A/T_0$ is derived for weakly ferromagnetic metals with a positive mode-mode coupling constant, while the coupling $-y_1$ in the present systems originates from the negative fourth-order coefficient of the Landau expansion. We therefore use this relation as an explicit ansatz. We note that this ansatz fixes only the value of T_A: the calculated $\chi(T)$ and the Landau coefficients discussed below are insensitive to it, because they are determined by $\chi(0)$ and by the position and the height of the susceptibility maximum. Figure 1 shows the temperature dependence of the magnetic susceptibility in YCo_2. Figure 2 shows the temperature dependence of the electrical resistivity in YCo_2. Figure 3 shows the temperature dependence of the magnetic susceptibility in $LuCo_2$. Figure 4 shows the temperature dependence of the electrical resistivity in $LuCo_2$. In the low-temperature limit $t \ll 1$, the dominant contribution to the integral in Eq. (8) comes from the region $u \gg 1$, where the asymptotic expansion of the trigamma function is applicable:

$$-1 - 1/(2u) + u\psi'(u) \simeq \frac{1}{6u^2} + \ldots . \quad (10)$$

Then the electrical resistivity has T^2-linear dependence at low temperatures in both cases. The numerical results are consistent with the experimental data qualitatively [21].

As a consistency check with the metamagnetism, we evaluate the Landau coefficients $a = 1/\chi(0)$, $b = -2y_1T_A^2/(15T_0)$, and $c = 2y_2T_A^3/(315T_0^2)$ from the parameters given in the figure captions. The dimensionless ratio ac/b^2 is 0.40 for YCo_2 and 0.41 for $LuCo_2$, which falls inside the condition of the itinerant electron metamagnetism $3/16 < ac/b^2 < 9/20$ [13], although the metamagnetism is not used as an input of the fit. The metamagnetic transition fields estimated from the ground-state Landau free energy are about 145 T for YCo_2 and about 126 T for $LuCo_2$. They are larger than the experimental values of about 69 T and 74 T [21] by a factor of two. Since the actual transitions are assisted by the magnetovolume effect, the purely electronic estimates are consistent in this direction.

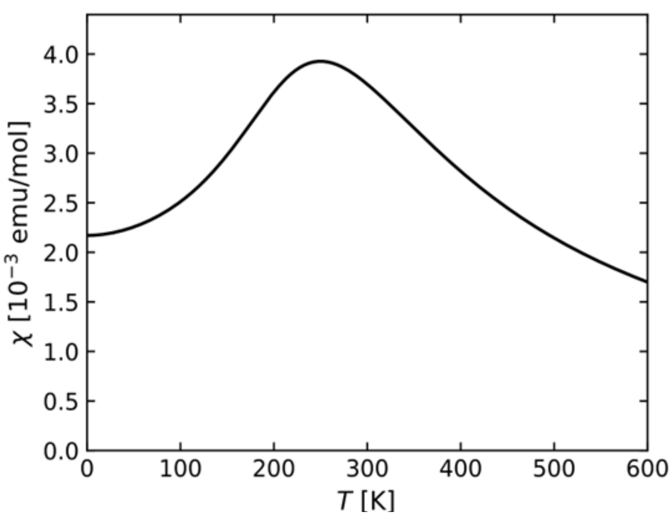

Figure 1: The temperature dependence of the magnetic susceptibility χ in YCo_2 when $\alpha = 0.90$, $\beta = 1000$, $\chi(0) = 2.17 \times 10^{-3}$ emu/mol, y_0=0.187, y_1=2.364, y_2=16.7, T_0 = 365K, T_A = 3698K.

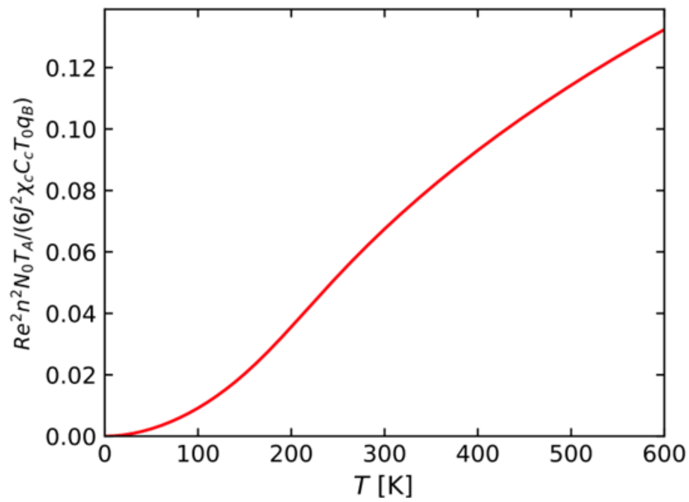

Figure 2: The temperature dependence of the electrical resistivity in YCo_2 when α = 0.90, β = 1000, χ(0) = 2.17 × 10^{-3} emu/mol, y_0=0.187, y_1=2.364, y_2=16.7, T_0 = 365K, T_A = 3698K.

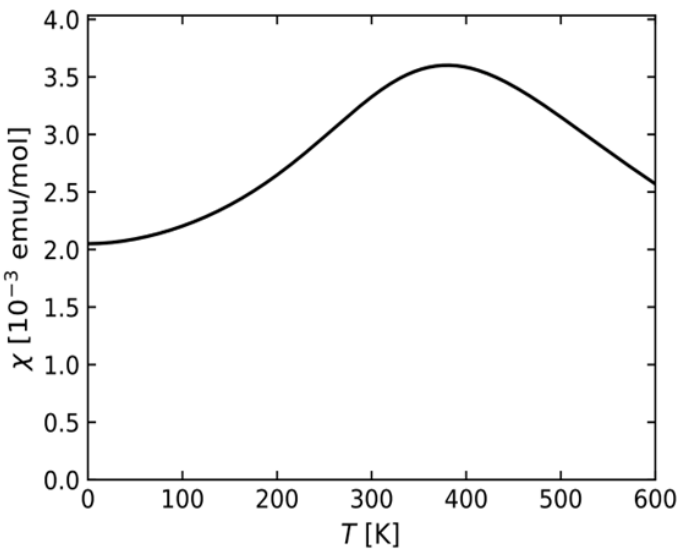

Figure 3: The temperature dependence of the magnetic susceptibility χ in $LuCo_2$ when α = 10/11, β = 1000, χ(0) = 2.05 × 10^{-3} emu/mol, y_0=0.0792, y_1=1.919, y_2=27.0, T_0 = 1124K, T_A = 9244K.

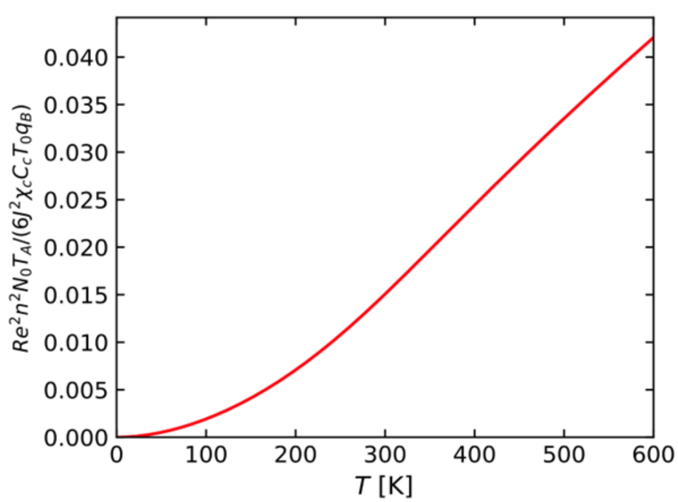

Figure 4: The temperature dependence of the electrical resistivity in $LuCo_2$ when α = 10/11, β = 1000, χ(0) = 2.05 × 10^{-3} emu/mol, y_0=0.0792, y_1=1.919, y_2=27.0, T_0 = 1124K, T_A = 9244K.

Conclusions

We have studied the temperature dependence of the electrical resistivity in YCo_2 and $LuCo_2$ by using the SCR theory that takes into account the electronic correlations beyond the random phase approximation and by taking into account the maximum of the magnetic susceptibility. The results are in qualitatively good agreement with the experimental data.

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