The self-consistent renormalization theory of anisotropic spin fluctuations in nearly ferromagnetic metals

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We investigated the temperature dependence of the inverse of the magnetic susceptibility, the nuclear magnetic relaxation rate, and the T-linear coefficcient of the specific heat in nearly ferromagnetic metals by using the self-consistent renormalization theory of anisotropic spin fluctuations. At low temperatures, the inverse of the magnetic susceptibility has T^2-linear dependence. In elevated temperatures, the inverse of the magnetic susceptibility has T-linear dependence. The nuclear magnetic relaxation rate has T/y_ν-linear dependence where y_ν is the inverse of the reduced magnetic susceptibility. The T-linear coefficient of the specific heat has $\ln(1+1/y_{0\nu})(\nu=\parallel\ or\ \perp)$ where $y_{0\nu}$ is the inverse of the reduced magnetic susceptibility at the zero temperature.

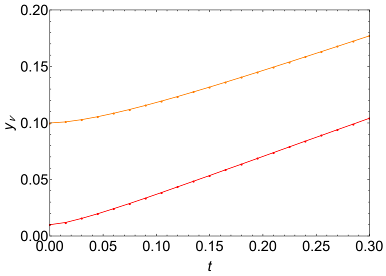

Fig 1:The temperature dependence of the inverse of the reduced magnetic susceptibility $y(\nu=\parallel$, or $\perp)$ when $y_{0\parallel}$=0.01(the red line), $y_{0\perp}=0.1$(the orange line), $y_{1\parallel}$=$y_{2\parallel}$=3, $y_{1\perp}$=$y_{2\perp}$=1, respectively.

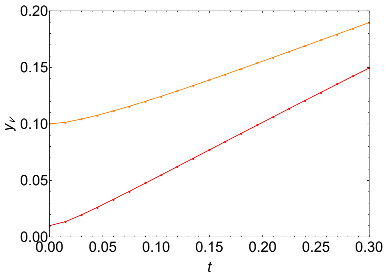

Fig 2: The temperature dependence of the inverse of the reduced magnetic susceptibility $y_\nu(\nu=\parallel$, or $\perp)$ when $y_{0\parallel}$=0.01(the red line), $y_{0\perp}=0.1$(the orange line), $y_{1\parallel}$=$y_{2\parallel}$=6, $y_{1\perp}$=$y_{2\perp}$=1, respectively.

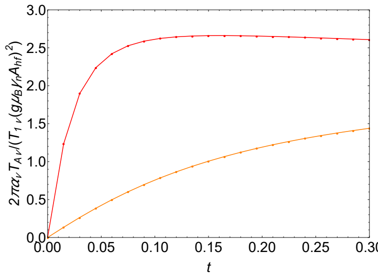

Fig 3: The temperature dependence of $\dfrac{2\pi\alpha_\nu T_{A_\nu}}{T_{1\nu}(\gamma_n A_{hf})^2(g\mu_B)^2}(\nu=\parallel\ or\ \perp)$ when $y_{0\parallel}$=0.01(the red line), $y_{0\perp}$=0.1(the orange line), $y_{1\parallel}=y_{2\parallel}=3$, $y_{1\perp}=y_{2\perp}=1$, respectively.

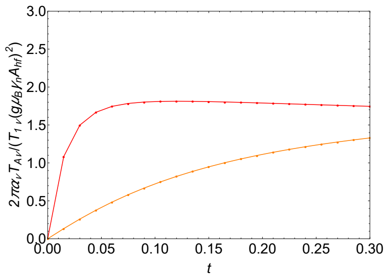

Fig 4: The temperature dependence of $\dfrac{2\pi\alpha_\nu T_{A_\nu}}{T_{1\nu}(\gamma_n A_{hf})^2(g\mu_B)^2}(\nu=\parallel\ or\ \perp)$ when $y_{0\parallel}$=0.01(the red line), $y_{0\perp}$=0.1(the orange line), $y_{1\parallel}=y_{2\parallel}=6$, $y_{1\perp}=y_{2\perp}=1$, respectively.

1. Purpose

It seems to us that the effects on anisotropically ferromagnetic spin fluctuations have been unanswered in nearly ferromagnetic metals, however. We extend the SCR theory to the anisotropic spin fluctuation case in nearly ferromagnetic metals. Throughout this paper, we use units of energy, such that $\hbar=1$, $k_B=1$, and $2\mu_B=1$, unless explicitly stated. We assume that c-axis is the axis of easy magnetization.

2. The inverse of the magnetic susceptibility with the SCR theory

The inverse of the reduced magnetic susceptibility are obtained.

$$y_\parallel = y_{0\parallel} + (3/2)y_{1\parallel}\int_0^1 dx x^3[\ln u_\parallel - 1/(2u_\parallel) - \psi(u_\parallel)] + (2/2)y_{1\perp}\int_0^1 dx x^3[\ln u_\perp - 1/(2u_\perp) - \psi(u_\perp)] \quad (1)$$

$$y_\perp = y_{0\perp} + (1/2)y_{2\parallel}\int_0^1 dx x^3[\ln u_\parallel - 1/(2u_\parallel) - \psi(u_\parallel)] + 4y_{2\perp}\int_0^1 dx x^3[\ln u_\perp - 1/(2u_\perp) - \psi(u_\perp)] \quad (2)$$

At low temperatures $t << 1$, we use the following asymtotic expansion of the digamma function in the integrand of Eqs. (1) and (2).

$$\ln u_\nu - 1/2u_\nu - \psi(u_\nu) \simeq \frac{1}{12u_\nu^2} + \dots . \quad (3)$$

At low temperatures the inverse of the magnetic susceptibility has T^2-linear dependence. In elevated temperatures, it has T-linear dependence.

3. The nuclear magnetic relaxation rate

The nuclear magnetic relaxation rate is studied by using the dynamical susceptibility in the nearly ferromagnetic metals. It is obtained:

$$\frac{1}{T_{1\nu}} = (g\mu_B)^2(\gamma_n A_{hf})^2 t \frac{3}{2\pi\alpha_\nu T_{A_\nu}}[\frac{1}{y_\nu} - \frac{1}{1+y_\nu}](\nu=\parallel\ or\ \perp) \quad (4)$$

where $T_{1\nu}(\nu=\parallel$ or $\perp)$ is a nuclear magnetic relaxation time, A_{hf} is the hyperfine coupling constant. γ_n is the nuclear gyromagnetic ratio, and N_0 is the number of the magnetic atom. g is the g-factor of the conduction electron, and μ_B is the Bohr's magneton.

4. The T-linear coefficient of the specific heat

The specific heat of spin fluctuations is

$$\frac{C_m}{T} = -\frac{\partial^2 F_{sf}}{\partial T^2}. \quad (5)$$

The T-linear coefficient of the specific heat γ_m is obtained

$$\gamma_m = \frac{N_0}{4T_0}\ln(1+\frac{1}{y_{0\parallel}}) + \frac{N_0}{2T_0}\ln(1+\frac{1}{y_{0\perp}}). \quad (6)$$

From Eq.(6), γ_m increases when $y_{0\nu}$ decreases. In contrast to nearly ferromagnetic metals, γ_m increases in nearly antiferromanetic metals when y_{s0} increases where y_{s0} is the inverse of the reduced staggered magnetic susceptibility at the zero temperature.

5. Conclusions

We have made the self-consistent renormalization theory of anisotropic spin fluctuations in three dimensional nearly ferromagnetic metals beyond the random phase approximation. We have investigated the temperature dependence of the inverse of the magnetic susceptibility, nuclear magnetic relaxation rate, and the T-linear coefficient of the specific heat in nearly ferromagnetic metals. We have found that the temperature dependence of the inverse of the magnetic susceptibility has T^2-linear behavior at low temperatures. With increasing temperatures it has T-linear dependence. The nuclear magnetic relaxation rate has t/y_ν-linear dependence. The anisotropy appears in the inverse of the magnetic susceptibility and the nuclear magnetic relaxation rate by anisotropic spin fluctuations. The T-linear coefficient of the specific heat increases when the inverse of the magnetic susceptibility decreases.

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