One-Loop Corrections to the Susceptibility and the Specific Heat in the Periodic Coqblin-Schrieffer Model

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Abstract

We investigate the periodic Coqblin-Schrieffer model in terms of the functional integral formalism, taking into account the one-loop corrections. We determine the order parameter corresponding to heavy fermion state for the symmetric case with isotropic hybridization, and calculate the thermodynamic quantities such as specific heat and susceptibility. We show how the one-loop corrections modify the thermodynamic quantities.

Key words: heavy fermion; one-loop approximation; periodic Coqblin-Schrieffer model; susceptibility; specific heat

In order to describe the heavy-fermion state, we have investigated the periodic Coqblin-Schrieffer (PCS) model by applying the mean-field approximation (MFA)[1] and the one-loop approximation (1LA).[2]

In ref. [1], we have shown that the metamagnetic-like behavior of $CeRu_2Si_2$ and the non-Fermi-liquid-like behavior of $CeNi_2Ge_2$ can be described from the same origin, the singularity of $|\omega|^{-1/2}$ in the density of quasi-particle states for the case with anisotropic c-f hybridization. In the MFA, there appears the phase transition between the heavy-fermion state and the localized state. Such a transition however has not been observed experimentally. It is therefore of great interest to examine how the transition is modified by corrections to the mean-field solution.

In ref. [2], we have developed the renormalized perturbation theory with respect to the coupling constant J employing the functional integral method. We considered the simple case with the isotropic mixing at no applied magnetic field, for which the free energy and the self-consistent equation for the order parameter were examined by the 1LA. We have shown that, if phase fluctuations are gauge fixed by Anderson-Higgs mechanism similarly to superconductivity, [2–4] the heavy-fermion state is more stabilized due to the corrections. In this paper we present the temperature dependence of the specific heat and susceptibility in the 1LA and discuss the fluctuations effects on these quantities.

We make a brief summary of our perturbation expansion for the PCS model in ref. [2] and use the same notations therein. The PCS model is given as[1,5]

$$H = \sum_{k\sigma} \varepsilon_k c^\dagger_{k\sigma} c_{k\sigma} + \sum_{iM} (\varepsilon_f + E_M) f^\dagger_{iM} f_{iM} - J \sum_{iMM'} f^\dagger_{iM} c_{iM} c^\dagger_{iM'} f_{iM'} . \tag{1}$$

We employ the auxiliary field method, in which Fermi fields are integrated out and then Bose fields are parametrized as $\phi_i = \sigma_0 + (\rho_i + \mathrm{i}\pi_i)/\sqrt{2}$, where σ_0, ρ_i and π_i are the mean-field value, the amplitude and the phase components of the fluctuations, respectively. Then we obtain the Helmholtz free energy as

$$F = \mu N_\mathrm{e} + JN\sigma_0^2 - k_B T \,\mathrm{tr} \log \hat{G}_0^{-1} - k_B T \log \langle \mathrm{e}^{\mathrm{tr}\log(1+\hat{G}_0 \hat{M}_f)} \rangle, \tag{2}$$

where N_e is the total number of the electrons, and the functional integrals over the Bose fields should be

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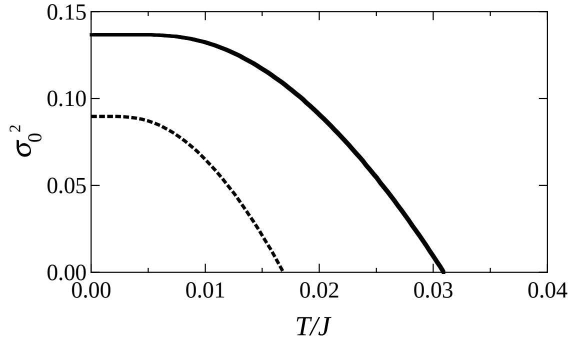

Fig. 1. Order parameter σ_0^2 as a function of T. The solid line shows $\{\sigma_0^{(1)}\}^2$ in the one-loop approximation and the dashed line $\{\sigma_0^{(0)}\}^2$ in the mean-field approximation.

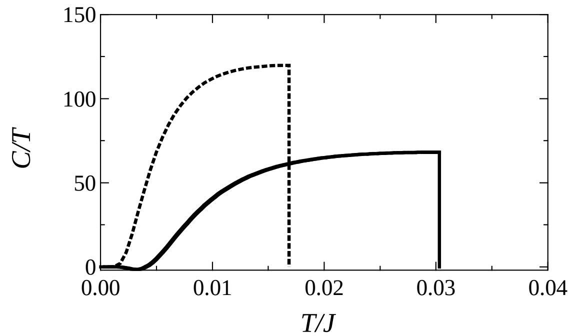

Fig. 2. Specific heat divided by temperature C/T as a function of T. The solid line shows $C^{(1)}/T$ in the one-loop approximation and the dashed line $C^{(0)}/T$ in the mean-field approximation. We set $k_B = 1$.

performed, which is denoted by $\langle \cdots \rangle$. Here we consider the one-loop corrections to the free energy, which is given by

$$\Delta F^{(1)}(\sigma_0) = \frac{1}{2} k_B T \langle \mathrm{tr}(\hat{G}_0 \hat{M}_f)^2 \rangle. \tag{3}$$

The ρ and the π fluctuations contribute separately to give

$$\Delta F^{(1)}_{\rho,\pi}(\sigma_0) = NJ[1 \mp \frac{1}{4}\sigma_0^2 K_M^2(\sigma_0^2)], \tag{4}$$

$$K_M(\sigma_0^2) = \sum_{k,\eta} z^{gap}_{kM}(\omega_\tau) f(\omega_\tau), \tag{5}$$

$$z^{gap}_{kM}(\omega_\tau) = \frac{J(\omega_\tau - E_M) I_k}{(\omega_\tau - E_M)^2 + J^2 \sigma_0^2 I_k}, \tag{6}$$

where $-$ of eq. (4) is for the ρ mode, whereas $+$ for the π mode, and $f(\omega_\tau)$ the Fermi distribution function. Note that $K_M^2(\sigma_0^2)$ is an increasing function with respect to σ_0. Therefore, if only the radial (ρ) fluctuations are effective, the self-consistent order parameter σ_0 increases from the mean-field solution.

We consider here the simple symmetric case ($E_M = 0$) with an isotropic mixing ($I_k = 1$), and take $J/D = 1/6$, where D is the half width of the conduction band. Figure 1 shows the temperature dependence of the square of order parameter $\{\sigma_0^{(1)}\}^2$, which is proportional to the hybridization gap, in comparison with that of the mean-field solution $\{\sigma_0^{(0)}\}^2$. The critical temperature $T_c^{(1)}$ in the 1LA is higher than $T_c^{(0)}$ in the MFA. The critical index of $\{\sigma_0^{(1)}\}^2$ is 1, which is as same as 1 for $\{\sigma_0^{(0)}\}^2$. Note that this result differs from that in ref. [2], in which we made a mistake in numerical calculation.

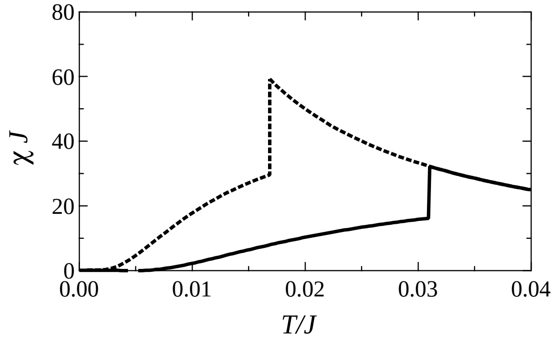

Fig. 3. Susceptibility χ as a function of T. The solid line shows $\chi^{(1)}$ in the one-loop approximation and the dashed line $\chi^{(0)}$ in the mean-field approximation. We set $g_J = \mu_B = M_J = 1$.

We obtain thermodynamic quantities by differentiating free energy with respect to temperature and magnetic field. The temperature dependence of the electronic specific heat coefficient C/T for the 1LA and the MFA are shown in Fig. 2 in comparison with that in the MFA. Note that the integration of C/T over T from 0 to T_c is $2\log 2$ for both the cases. Figure 3 shows the temperature dependence of the susceptibility χ.

We observe that the one-loop correction term $\Delta F^{(1)}_\rho$ is effective to increase σ_0, whereas it scarcely contributes to C/T and χ; namely, the behaviors of C/T and χ in the 1LA are dominated from the expressions of the MFA with the dressed σ_0, and the correction terms of the 1LA are negligibly small.

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