Kondo effect in low-dimensional disordered systems

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Abstract

We investigate the Kondo effect in two-dimensional disordered electron systems using a finite-temperature quantum Monte Carlo method. Depending on the position of a magnetic impurity, the local moment is screened or unscreened by the spin of the conduction electron. On the basis of the results, we show that the distribution of the Kondo temperature becomes wide and the weight at $T_K = 0$ becomes large as randomness increases. The average susceptibility shows a weak power-law or logarithmic divergence at low temperature, indicating a non-Fermi-liquid behavior.

Key words: Kondo effect, Anderson localization, susceptibility, Kondo temperature

The Kondo effect in disordered systems has attracted attention both theoretically and experimentally. Using perturbative expansion, the Kondo effect in the weakly localized regime was investigated [1]. It was shown that the Kondo logarithmic terms are modified into the product of new anomalous terms and the Kondo logarithmic ones, and that the latters are scaled into the same Kondo temperature as that without randomness [2]. The Kondo effect in strongly disordered systems was studied by taking account of the Coulomb interaction among conduction electrons [3]. It was shown that the Kondo temperature has a spatial distribution, which leads to divergence behaviors of physical quantities as temperature approaches zero. Such a spatial distribution in the Kondo temperature was suggested from experimental results of strong broadening of the Cu NMR line of $\mathrm{UCu_{5-x}Pd_x}$ [4]. In spite of these findings, the effects of strong randomness itself on the behavior of a magnetic impurity have not yet been fully investigated from a microscopic viewpoint.

In this paper, we study the Kondo effect in two-dimensional (2D) strongly disordered electron systems using a finite-temperature quantum Monte Carlo (QMC) method [5]. Let us consider the single-impurity Anderson model with on-site random potentials described by the Hamiltonian

$$H = \sum_{i\sigma} \epsilon_i c^\dagger_{i\sigma} c_{i\sigma} - t \sum_{<ij>\sigma} c^\dagger_{i\sigma} c_{j\sigma} + \epsilon_d \sum_{\sigma} n_{d\sigma} + V \sum_{\sigma} (d^\dagger_\sigma c_{0\sigma} + \text{H.c.}) + U n_{d\uparrow} n_{d\downarrow} \quad (1)$$

where random on-site potentials ϵ_i are chosen to be a flat distribution in the interval $[-W, W]$ under the condition $\sum_i \epsilon_i = 0$, $< i, j >$ denotes the summation of the nearest-neighbor sites, and $n_{d\sigma} = d^\dagger_\sigma d_\sigma$. The system consists of a 41×41 square lattice with a magnetic impurity. For $W \geq 3.0$, the conduction electron is localized with the localization length $\xi(W) \leq 37.5$ [6]. Thus, the system for $W \geq 3.0$ is probably in the strongly localized regime in low temperature. We set the condition $\epsilon_d + (1/2)U = 0$ and use the parameters $U = 2.0$ and $V = -1.0$ in units of t.

Shifting the position of a magnetic impurity twenty-four times around the center in the same realization of the random potential, we calculate the susceptibility of a magnetic impurity in $0 \leq W \leq 3.5$. Depending on the position of a magnetic impurity in given W, its local moment can be screened or unscreened by the spin of the conduction electron. In the former case the sus-

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ceptibility shows a local Fermi-liquid behavior, while in the latter case the susceptibility shows a power-law or a logarithmic divergence. The results indicate that the Kondo temperature T_K has a spatial distribution down to $T_K = 0$, since $T_K = [2\pi\chi(0)]^{-1}$ with $\chi(0)$ being the susceptibility at zero temperature. We extrapolate $\chi(0)$ and evaluate the distribution of the Kondo temperature. The results are summarized in Fig. 1. As W increases, the distribution of the Kondo temperature becomes wider and the weight at $T_K = 0$ increases considerably. We have shown that the spatial distribution of the Kondo temperature can be caused only by the effects of a random potential.

To obtain the local information on Kondo screening, we calculate the correlation function between the local moment and the spin of the conduction electron. When the local moment is unscreened, the antiferromagnetic correlation at the magnetic impurity is suppressed noticeably in contrast with the results for the screened case. This suppression of the antiferromagnetic correlation at the magnetic impurity probably cause incomplete screening and a divergence behavior of the susceptibility.

In the disordered systems with dilute magnetic impurities, where each magnetic impurity acts as a single magnetic impurity, the observable susceptibility may be obtained by averaging over the susceptibility at each

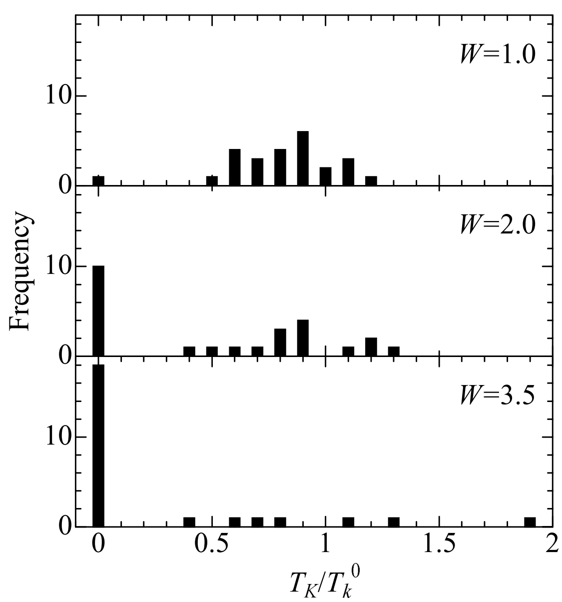

Fig. 1. Distribution of the Kondo temperature for $W = 1.0$, $W = 2.0$ and 3.5. Twenty-five positions of a magnetic impurity is used around the center. T_K^0 is the Kondo temperature without randomness.

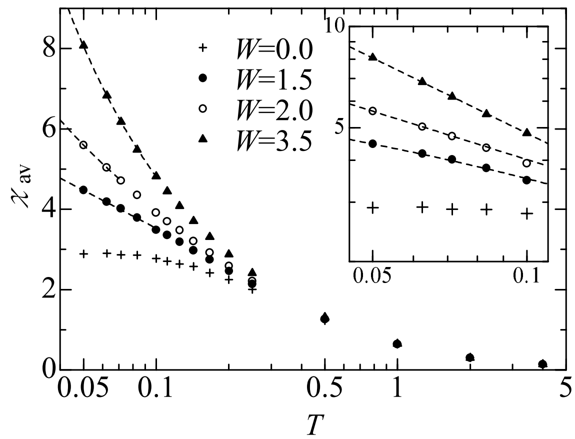

Fig. 2. Average susceptibility for $W = 1.5$, 2.0, and 3.5. The broken lines are fitted by the least-squares method. For W=1.5, 2.0, and 3.5, $\chi_{\rm av} = -1.36 \log T + 0.397$, $1.34\,T^{-0.477}$, and $0.867\,T^{-0.744}$, respectively. Inset: $\log \chi_{\rm av}(T)$ versus $\log T$.

position of a magnetic impurity. We thus take an average over the susceptibility at twenty-five positions around the center of the system. The results are shown in Fig. 2. For $W = 1.5$, the average susceptibility $\chi_{\rm av}$ shows a logarithmic divergence in $0.05 \le T < T_K^0 \sim 0.14$. For 2.0 and 3.5, $\chi_{\rm av}$ shows a weak power-law divergence $\chi_{\rm av} \sim T^{-\alpha}$ with $\alpha \sim 0.477$ ($W = 2.0$) and $\alpha \sim 0.744$ ($W = 3.5$). Therefore, in 2D disordered electron systems with dilute magnetic impurities, the observable susceptibility shows a non-Fermi-liquid behavior in low temperature.

Numerical computation was partly carried out at Supercomputer Center, the Institute for Solid State Physics, University of Tokyo. This work was partly supported by a Grant-in-Aid for Scientific Research from the Ministry of Education, Culture, Sports, Science, and Technology, Japan.

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