Temperature-dependent kondo scale in the heavy fermion systems with $T=0$ antiferromagnetic phase transition

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Anomalous temperature dependence of the transport and thermodynamic properties is described. This temperature dependence was observed near the $T=0$ antiferromagnetic phase transition as a result of a power-law temperature dependence of the characteristic Kondo scale which is originated from self-similarity of the ground state. © *1995 American Institute of Physics.*

During the last decades the particle-particle interactions in the heavy fermion systems (HFS) were taken into account by means of effective-mass renormalization in the frame of the Fermi liquid model. With the discovery of high-T_c superconductivity it was demonstrated, through anomalous linear-vs-temperature dependence of the resistivity, that there are marginal Fermi-liquid-type excitations in the normal state. The question arises whether non-Fermi-liquid (NFL) behavior is also possible in HFS. It should be noted that already in 1980 Nozieres and Blandin[1] predicted the possibility of observing the NFL ground state in the multichannel Kondo effect (KE) when the number of free-electron channels n is more than double the value of the localized electron spin S (i.e., $n>2S$). The Hamiltonian of this model could describe electron-assisted tunnelling[2] and a specific case of electron scattering on the U atom with a non-Kramers ground state doublet. The last case (called the quadrupolar Kondo effect) was proposed by Cox[3] to describe the origin of heavy mass formation in the uranium-based HF compounds. For the quadrupolar two-channel KE the exact solution[4] gives the low-temperature dependences of the thermodynamic and transport properties: resistivity $\Delta\rho \sim \sqrt{T}$, heat capacity $\Delta C \sim T\cdot\ln(T_K^0/T)$ (T_K^0 is a characteristic Kondo scale in the high-temperature limit), and magnetic susceptibility $\Delta\chi \sim \sqrt{T}$. All these asymptotic expressions were found recently in the $U_{0.9}Th_{0.1}Be_{13}$ compound.[5]

It is necessary to point out that at present there is also another approach to describe the NFL ground state in HF, which is based on the assumption that the system undergoes a second-order, three-dimensional, magnetic phase transition at zero temperature.[6] This problem was not resolved exactly by the moment. In this letter we present a scaling approach, which allows for the first time a self-consistent description of the main low-temperature properties of the system with a $T=0$ antiferromagnetic phase transition: namely the logarithmic divergence of the linear term in heat capacity, square root vs T asymptotic behavior of the magnetic susceptibility and the linear-vs-temperature dependence of the electrical resistivity observed experimentally in the $CeCu_{5.9}Au_{0.1}$ compound.[7] Our important suggestion is that in the class of the systems under consider-

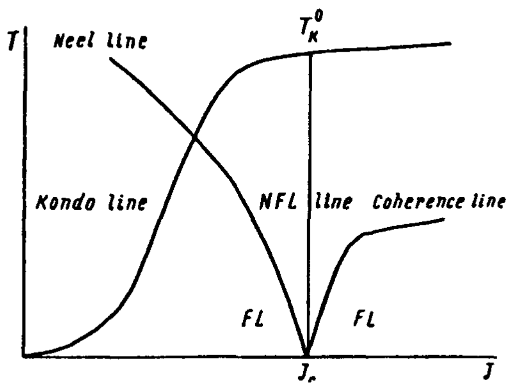

FIG. 1. Phase diagram of the Kondo lattice (J—exchange interaction). Along the dotted (NFL) line the temperature-dependent Kondo scale T_K is less than the single-ion Kondo scale T_K^0.

ation there are two characteristic Kondo temperatures: the first one, T_K^0, is independent of the temperature and corresponds to the local correlations and the second one, T_K, varies with T, and corresponds to the temperature-dependent Kondo scale.

It is well known that the presence of a magnetic correlation in a Kondo system may result in the competition between two coherent effects: indirect RKKY interaction and KE (see the phase diagram in Fig. 1). If $T_N>0$, then at $T<T_N$ the KE should be suppressed and its corresponding Kondo characteristic length ξ increases to infinity. The physical reason for such behavior may be a close relationship between the optimal scattering length for the Kondo process and the magnetic correlation scale. It can be assumed, therefore, that at $T>T_N$ in the vicinity of the critical point the KE scattering length is given by

$$\xi \sim (T-T_N)^{-\alpha}. \tag{1}$$

Power-law dependences successfully describe some characteristics in the vicinity of the phase transition temperature in the frame of the scaling theory. For example, near the temperature of the metal-insulator transition (T^*) the conductivity and localization radius change as a power of $(T-T^*)$ (Ref. 8). An analogous dependence describes the statistical percolation properties near the percolation threshold. In addition, the power function $f(\tau)=\mathbf{b}\cdot\tau^{\alpha}$ [here $\tau=(T-T_N)$] is a simple dependence which satisfies the homogeneous principle for positive λ; i.e.,

$$f(\lambda\tau)=\lambda^{\alpha}f(\tau). \tag{2}$$

It was shown recently that in both NFL ground-state models mentioned above the KE scale should be characterized by the *self-similarity* property,[9] so ξ may satisfy Eq. (1). The Kondo length is related to the Kondo temperature T_K in the following way: $\xi \approx hv_F/k_BT_K$ (Ref. 10), where v_F is the Fermi velocity. Therefore, $T_K \sim (T-T_N)^{\alpha}$ and at $T_N=0$ we have $T_K \sim T^{\alpha}$.

Using this relation, we will now analyze the temperature dependence of the resistivity under the conditions of the $T=0$ magnetic phase transition. If we decrease the temperature along the NFL line (see Fig. 1) and assume that for every fixed temperature the Fermi-liquid-type renormalization of the interactions is possible [i.e., we can use the relation $\Delta\rho \sim (T/T_K)^2$], we obtain $\Delta\rho \sim T^{2(1-\alpha)}$. To satisfy the experiment[7] we should set $\alpha=1/2$. Therefore, the linear-vs-T dependence of the "magnetic" part of the resistivity can be understood as the result of the power law decrease of the Kondo temperature upon approaching zero temperature; i.e.,

$$T_K(T) \sim T^{1/2}. \tag{3}$$

In our approach the Kondo length is characterized by the temperature dependence

$$\xi(T) \sim T^{-1/2}. \tag{4}$$

In the approximation of the noninteracting spins we now simply obtain the asymptotic behavior of the magnetic susceptibility:

$$\Delta\chi \sim N/T \sim 1/\xi^3 T \sim \sqrt{T} \tag{5}$$

(here N is the number of magnetic moments per volume $V \sim \xi^3$) and a logarithmically divergent linear term in the heat capacity as $T \to 0$. In fact, if T_0 is a variable parameter with the dimension of energy, then the excitations for the corresponding scale ξ_0 will be characterized by a linear term in the heat capacity, $\gamma_0 \sim 1/T_0$. To obtain the total linear term at a temperature T due to the asymptotic *self-similarity* of the ground state,[9] we will integrate γ_0 over T_0 between T and T_K^0. Therefore, the electron specific heat ΔC is

$$\Delta C \sim T \int_T^{T_K^0} \frac{1}{T_0}\, dT_0 \sim T \ln \frac{T_K^0}{T}. \tag{6}$$

Using the correlation length exponent obtained above $\alpha=1/2$, we can also understand the scaling behavior which shows the antiferromagnetic transition upon suppression under pressure.[11] Continentino[12] assumed that $T_N \sim |J-J_c|^{\nu\cdot z}$ (ν is the correlation length exponent in the relation $\xi \sim |J-J_c|^{-\nu}$ and z is the dynamic critical exponent). By tuning the NFL ground state with pressure p, a linear behavior $T_N \sim (p-p_c) \sim |J-J_c|$ was recently observed experimentally in the antiferromagnetic HF alloy $CeCu_{5.7}Au_{0.3}$. Therefore $\nu z=1$, and if we use the value obtained above $\alpha=\nu=1/2$, then we find $z=2$, which exactly corresponds to the dynamic critical exponent for the bulk antiferromagnetic transition.[13]

More complicated scaling arguments were employed by Tsvelik and Reizer[14] in order to construct the phenomenological theory of the behavior of non-Fermi liquid in HF compounds through an analysis of the expression for the free energy in the form $F=-Tf(T/T_K^0, H/T^\delta)$. In contrast with our study, they considered the $T_K^0 \to \infty$ limit and the finite external magnetic fields H which disturb the self-similar ground state. On the other hand, the temperature-dependent Kondo scattering process was proposed before only with respect to the possibility of a nonuniform spread of the T_K^0 values in the bulk of the sample.[15]

In summary, by using scaling analysis the main anomalous asymptotic behavior of the transport and thermodynamic characteristics of the $T=0$ antiferromagnetic phase transition of the NFL ground-state model were self-consistently described for the first time. Our important suggestion is that two Kondo energy scales (one T_K^0—independent and the other one T_K—dependent on the temperature) may describe the low-temperature properties of the system.

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