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# TEMPERATURE DEPENDENT KONDO SCALE IN THE HEAVY FERMION SYSTEMS WITH $T=0$ ANTIFERROMAGNATIC PHASE TRANSITION

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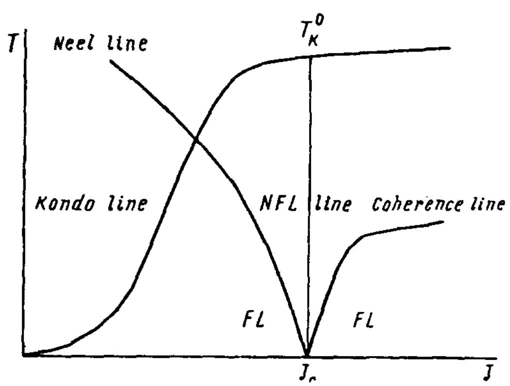
We describe the anomalous temperature dependence of the transport and thermodynamic properties observed near the $T=0$ antiferromagnetic phase transition as a result of a power law type temperature dependence of the characteristic Kondo scale which is originated from self-similarity of the ground state.

During the last decades the interparticle 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 demonstrated, through anomalous linear vs temperature dependence of the resistivity, marginal Fermi liquid type excitations in the normal state, the question arised if a non-Fermi liquid (NFL) behaviour 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 of the value of the localised electron spin $S$ (i.e. $n > 2S$). The Hamiltonian of this model could describe electron assisted tunnelling [2] as well as a specific case of electron scattering on the U atom having a non-Kramers ground state doublet. The last case (called quadrupolar Kondo effect) was proposed by Cox [3] to describe the origin of heavy mass formation in the uranium based HF compounds. For 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 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 self-consistently describe main low temperature properties of the system with $T=0$ antiferromagnetic phase transition: namely the logarithmic divergence of the linear term in heat capacity, square root *vs* $T$ asymptotic in the magnetic susceptibility and the linear *vs* temperature dependence of the electrical resistivity experimentally observed in the $CeCu_{5.9}Au_{0.1}$ compound [7]. Our important suggestion is that in the class of the systems under consideration there are two characteristic Kondo temperatures: the first one, $T_K^0$ , is independent on temperature and corresponds to the local correlations and the second one, $T_K$, is varying with $T$, and corresponds to the temperature dependent Kondo scale.

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

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




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

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

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

It was shown recently that in both mentioned above NFL ground state models the KE scale should be characterized by the *self-similarity* property [9], therefore $\xi$ may satisfy equation 1. The Kondo length is related to the Kondo temperature $T_K$ in the following way: $\xi \approx h v_F / k_B T_K$ [10] where $v_F$ is a Fermi velocity. Therefore, $T_K \sim (T - T_N)^{\alpha}$ and for $T_N = 0$ one has $T_K \sim T^{\alpha}$.

Using this relation let us now analyse the temperature dependence of the resistivity in the $T = 0$ magnetic phase transition conditions. If we decrease the temperature along the NFL line (see Figures) and suppose that for every fixed temperature the Fermi liquid type renormalization of the interactions is possible (i.e. one may use the relation $\Delta\rho \sim (T/T_K)^2$), then we get: $\Delta\rho \sim T^{2(1-\alpha)}$ and to satisfy the experiment [7] one should put $\alpha = 1/2$. Therefore, the linear *vs* $T$ dependence of the "magnetic" part of resistivity may be understood as a consequence of the power law decrease of the Kondo temperature when approaching zero temperature, i.e.

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

In our approach the Kondo length will be characterized by the following temperature dependence:

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

Now in the approximation of non-interacting spins one simply obtains the asymptotic behaviour 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 when $T \to 0$. In fact, if $T_0$ is some variable parameter with dimension of the energy, then the dominated for corresponding scale $\xi_0$ excitations will be characterised by a linear term in the heat capacity $\gamma_0 \sim 1/T_0$ . To obtain the total linear term at temperature $T$ due to the asymptotic *self-similarity* of the ground state [9] we may integrate $\gamma_0$ over $T_0$ between $T$ and $T_K^0$ . Therefore, the electronic specific heat $\Delta C$ is:

$$\Delta C \sim T \int_T^{T_K^0} \frac{1}{T_0} dT_0 \sim T \ln \frac{T_K^0}{T} \qquad (6)$$

By using the obtained above correlation length exponent $\alpha = 1/2$ one can understand also scaling behaviour which shows the antiferromagnetic transition when suppressed under the pressure [11]. Continentino [12] supposes that $T_N \sim\mid J - J_c \mid^{\nu \cdot z}$ ($\nu$ is correlation length exponent in the relation $\xi \sim\mid J - J_c \mid^{-\nu}$ and $z$ – dynamic critical exponent). Recently, by tuning NFL ground state with pressure $p$, a linear behaviour $T_N \sim (p - p_c) \sim\mid J - J_c \mid$ was experimentally observed in the antiferromagnetic HF alloy $CeCu_{5.7}Au_{0.3}$ . Therefore $\nu z = 1$ and if we use obtained above value $\alpha = \nu = 1/2$ then one finds $z$=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] to construct the phenomenological theory of non-Fermi liquid behaviour in HF compounds through an analysis of the expression for the free energy in the form $F = -Tf(T/T_K^0, H/T^\delta)$. Contrary to the present work, the $T_K^0 \to \infty$ limit and finite external magnetic fields $H$ disturbing the self-similar ground state were considered. On the other hand, the temperature dependent Kondo scattering process was proposed before only in respect to the possibility of a non-uniform spread of the $T_K^0$ values in the sample volume [15].

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

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