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Observation of non-Fermi liquid behaviour in new Yb-based alloys

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In this contribution, after presenting the existing theoretical models, we discuss the evidence for non-Fermi liquid behaviour in $Yb(Cu_{1-x}Si_x)_{2-y}$ that have been investigated for the last years in our Institute. The alloys crystallize in the hexagonal AlB_2 type structure and exhibit a dramatic change in the electronic properties upon change of the electron concentration. Undoped $YbSi_{2-y}$ is an intermediate valent system, whereas the doping with 10% Cu ensures $\chi(T) \propto T^n$, $\rho(T) \propto T$ and $C_p \propto T^{-1/2}$ dependences. Comparison of the data with the Griffiths phase model shows that this model can describe some of the observed results. We present also a study of the Hall effect. The Hall coefficient at 7 T is found to follow a $\ln T$ dependence below 10 K, thus showing the behaviour opposite to that in Fermi-liquid heavy-fermion systems.

Key words: *non Fermi liquid; Yb-based intermetallic; Hall effect*

1. Introduction

For over half a century, the Landau Fermi liquid (LFL) theory has been successfully applied to describe the low-temperature properties of metals and intermetallic compounds [1]. In particular, this theory is useful in understanding the behaviour of strongly correlated electron systems (SCES) in which the particle–particle interaction is significant [2]. For instance, the application of LFL theory helps us to explain the enormous enhancement of effective electron masses m^* and other coefficients of physical quantities, observed in heavy fermion (HF) compounds. Other predictions of the theory (quadratic temperature dependence of the electrical resistivity, linear temperature dependence of the electronic specific heat and temperature independence of the magnetic susceptibility) are also valid in a number of SCES. There is, however, a growing number of systems showing an anomalous behaviour which distinctly deviates from the behaviour of the Landau theory. These non-Fermi liquid (NFL) systems

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are mainly Ce-, U- and Yb-based intermetallics, that are identified as systems closely related to magnetic instability, superconductivity state and quantum critical point. Some macroscopic properties characteristic of the NFL behaviour are as follows [3]: (i) weak power law and logarithmic divergences in temperature of the specific heat, $C(T)/T \propto \gamma_0 \ln(T_0/T)$ or $\propto T^{-1+\lambda}$, $\lambda < 1$, (ii) diverging magnetic susceptibility, $\chi^{-1}(T) \propto T^{\beta}$, $\beta < 1$, $\propto -\ln(T/T_0)$, (iii) quasi-linear temperature dependence in the electrical resistivity, $\rho(T) \propto T^n$, $n < 2$, (iv) frequency scaling of the dynamic spin susceptibility, $\chi(\varpi, T) \propto \varpi^{-\alpha} Z(\omega, T)$, $\alpha < 1$.

At present, there exist no theoretical models giving a universal description of the NFL behaviour. Several researches consider fluctuations around quantum critical point as a suitable mechanism leading to the NFL behaviour [4], [5]. This point of view can be supported by the recognition that the NFL properties emerge at either the magnetic instability in a typical Doniach phase diagram for HF compounds or near to a quantum critical point (QCP) where superconducting phase transition may occur. Within the Doniach lattice model [6], magnetic order vanishes when the energy of the single-ion Kondo scattering, $k_B T_K$ becomes larger than that of the Ruderman –Kasuya–Kittel–Yosida (RKKY) interaction, $k_B T_{RKKY}$. Therefore, a suitable substitution (chemical pressure) or application of hydrostatic pressure may force the system to pass through the critical value at $T_K \sim T_{RKKY}$. This may be the case for very small doping $CeCu_{6-x}Au_x$ with $x = 0.1$, where the exact quantum critical point seems to exist [7]. Other examples are undoped NFL systems like as U_2Pt_2In [8] and $CeNi_2Ge_2$ [9]. The most pronounced QCP–NFL examples are superconductors under pressure $CePd_2Si_2$ [10] and UGe_2 [11].

However, there are other NFL systems, those with large contents of substituted elements. It seems that these alloys are not related to QCP at all. Instead, the role of crystallographic disorder becomes crucial. Here, two examples: $UCu_{5-x}Pd_x$ with $x = 0.7$ [12] and $U_2Cu_{17-x}Al_x$ with $x = 5$ [13] one may mention. In this class of NFL materials, it is not possible to define exact Kondo temperature, since the existing disorder creates a very wide distribution of Kondo temperatures. According to Bernal et al. [14], Kondo temperatures depend exponentially on the Kondo coupling parameter λ via $T_K \propto \exp(-1/\lambda)$ and are distributed by the probability $P(T_K) = |d\lambda/dT_K|P(\lambda)$. Furthermore, Miranda et al. [15] have considered the correlations between unquenched magnetic moments and conduction electrons. As the main result, the authors predicted a linear temperature dependence of electrical resistivity of such NFL systems. Neto et al. [16] discussed how disorder and the competition between RKKY and Kondo interactions lead to the formation of the Griffiths phase. The latter authors have shown that due to a crystallographic disorder, magnetic clusters appear in the paramagnetic phase close to a QCP, and this is the reason why NFL properties have been observed.

The NFL features have also been observed in alloys with a large dilution, like $Y_{0.8}U_{0.2}Pd_3$ [17] and $U_{0.2}Y_{0.8}Pd_2Al_3$ [18]. Owing to the fact that the amounts of magnetic ions in these materials are small, one may regard the magnetic ions as single Kondo ions. To explain the NFL behaviour of these systems, theoretical models have

included the multichannel Kondo effect of either magnetic or electric nature [19], [20]. Both an underscreening and overscreening of the impurity spin by the conduction electrons cannot ensure a singlet ground state. As a consequence, power laws emerge for the spin contribution to the resistivity $\rho(T) \propto T^{1/2}$ and to susceptibility $\chi(T) \propto T^{1/2}$, whereas a logarithmic upturn to the specific heat appears: $C(T)/T \propto \ln(T)$ [21]–[23].

The aim of the short description of the NFL phenomenon above is to show that a great deal of the interest in NFL systems simply results from the unusual temperature, magnetic field and pressure dependences of the physical quantities of NFL materials, for which one needs a new physics. Besides, due to a close relationship between NFL materials and unconventional superconductors, it will also be desirable to investigate in more detail the NFL behaviour. Such a study certainly will not only serve the interpretation of the behaviour of excited electrons in the strongly correlated electron systems but will also contribute to understanding of the nature of these superconductors. Recently, we discovered two new NFL systems, $Yb(Cu_{1-x}Si_x)_{2-y}$ [24] and $URh_{1-x}Ru_xGe$ [25]. In the present contribution, we attempt to summarize the low-temperature NFL characteristics of the former system. We report also the results of the Hall effect measurement. Selected data of the latter system are given in the paper by Miiller and Tran [26]. In short, the substitution of Rh by Ru in the ferromagnetic URhGe (T_C = 9.5 K) suppresses ferromagnetic order in the alloy $URh_{1-x}Ru_xGe$ at x = 0.30. The vanishing of ferromagnetism accompanies short-range magnetic correlations for x = 0.3–0.35, preceding the formation of a NFL phase around x = 0.4. It was also observed that the NFL behaviour in the investigated system ($\chi(T) \propto T^n$, $\rho(T) \propto T$) is easily depressed by the application of a magnetic field. The results of magnetization, electrical resistivity and magnetoresistance measurements strongly imply that the NFL $URh_{1-x}Ru_xGe$ alloys locate nearby a magnetic instability.

2. Non-Fermi liquid behaviour in Cu-doped alloy $Yb(Cu_{0.151}Si_{0.849})_{1.883}$

Among NFL materials, there are as few as two Yb-based alloy systems such as $YbRh_2(Si_{1-x}Ge_x)_2$ [27] and $Yb(Cu,Al)_5$ [28] so far well studied. Thus, a discovery of a new Yb-based NFL material is highly requested. In recent years, our investigation has been focused on the Yb-based intermetallics. Amongst them, the binary compound $YbSi_{2-x}$ seems to be of interest for scientists searching for new NFL materials. This compound crystallizes in the hexagonal AlB_2 type structure with a great deficit in the Si sites, even with x up to 0.3 [29]. The system was also reported to show an intermediate valence behaviour [30]. We thought it would be worth to investigate the effect of electron doping on the behaviour of the Yb ions. We put the Cu atoms in the vacancies, thus increasing electron content in the system. It turned out that as many as 10% of the Cu atoms can be doped into the binary $Yb(Cu/Si)_{2-x}$ compounds. Keeping

the hexagonal AlB_2 type structure, the doping increases the unit-cell volume V from 50.82 Å^3 in $YbSi_{2-x}$ to 53.25 Å^3 in $Yb(Cu_{0.151}Si_{0.849})_{1.883}$, and simultaneously decreases the concentration of vacancies. This change apparently reduces the exchange constant J, equivalent to a weakening in the hybridization between the 4f and conduction electrons. In the framework of the Doniach lattice diagram [6], such a doping may bring the alloy about the critical regime with $T_K \sim T_{RKKY}$.

The procedure of synthesis and sample characterization was described in details in [24]. The investigated sample adopted the AlB_2 type crystal structure with the lattice parameters a = 0.3981 nm and c = 1.3720 nm. In Figure 1, we show low-temperature data of $Yb(Cu_{0.151}Si_{0.849})_{1.883}$, which demonstrate the NFL characteristics of the compound.

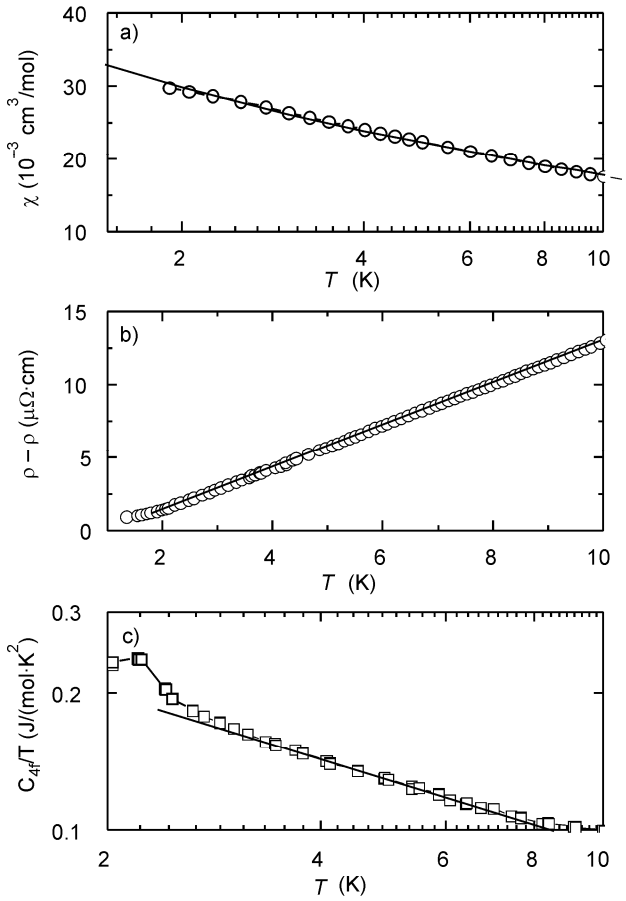

Fig. 1. The temperature dependences of: a) magnetic susceptibility obtained at 0.5 T, b) electrical resistivity, c) Yb contribution to the specific heat of $Yb(Cu_{0.151}Si_{0.849})_{1.883}$

The susceptibility data below 10 K, displayed in Fig. 1a, have been fitted by the power dependence $\chi(T) = 37.2T^{-1+\lambda}$ with $\lambda = 0.68$ (solid line). The non-Curie behav-

iour of the susceptibility indicates a contribution of electron correlations to the NFL phenomenon. It should be noted that a similar power exponent was found in other NFL materials like several solid solutions $UCu_{5-x}Pd_x$ with x = 0.7–1.5 [12]. In the context of the Griffiths phase model [16], the exponent λ describes the power-law decay of the cluster magnetization.

The resistivity data shown in Fig. 1b can be described by the linear dependence $\rho(T) - \rho_0 \propto AT$ in the temperature range 2–10 K. Such a behaviour represents the temperature dependence of resistivity based on the Kondo disorder model [14] but an alternative explanation for the linear resistivity may be the scattering due to spin fluctuations [31]–[33]. Therefore, such a dependence of resistivity may occur in number of NFL materials with different physical origins ($YbRh_2Si_2$, $CeCu_{5.9}Au_{0.1}$, $U_{0.9}Th_{0.1}Ni_2Al_3$, $U_{0.2}Y_{0.8}Pd_2Al_3$ [3]).

The low-temperature data of specific heat of the Yb ions (Fig. 1 c) exhibit a power-law behaviour, $C_{4f}/T \propto T^{-1/2}$. Neto et al. [16] in the framework of the Griffiths model predicted power-law behaviour for the specific heat $C/T \propto T^{-1+\lambda}$. Though there are some Yb_2O_3 impurities present in the sample that manifest themselves as a small anomaly at 2.2 K, we believe that the upturn in the specific heat data below 10 K is intrinsic, since in the specific heat measured at 0.5 T no peak structure can be detected.

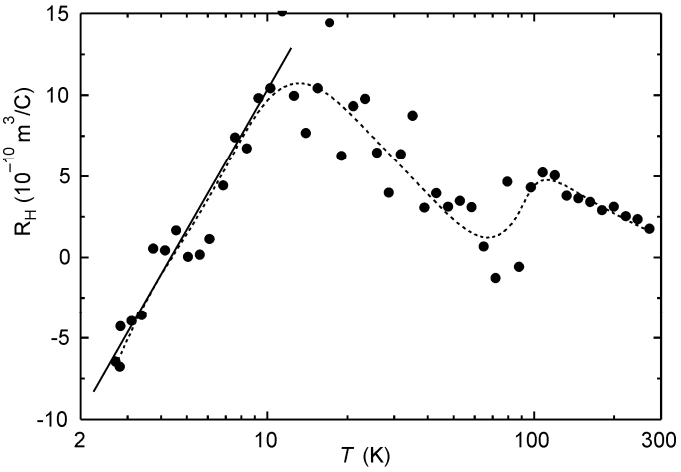

Fig. 2. Temperature dependence of the Hall coefficient at 7 T for $Yb(Cu_{0.151}Si_{0.849})_{1.883}$. The dashed and solid lines are guides for the eye

Figure 2 shows the temperature dependence of the Hall coefficient at 7 T for $Yb(Cu_{0.151}Si_{0.849})_{1.883}$. At room temperature, the Hall coefficient is positive and weakly varies with decreasing temperature. At about 12 K we observe a clear maximum, below which R_H follows a ln$T$ dependence. Accordingly to the theory developed by Fert and Levy [34] for the Hall effect of heavy fermion systems, one expects a maximum on the $R_H(T)$ curve at the coherence temperature T_0, and below which R_H levels off

due to a reduction of the skew scattering and formation of the coherent ground state. The lack of any stabilization in the Hall coefficient of $Yb(Cu_{0.151}Si_{0.849})_{1.883}$ suggests a strong correlation between magnetic ions and conduction electrons. Thus the Hall effect in $Yb(Cu_{0.151}Si_{0.849})_{1.883}$ in the studied temperature range distinctly deviates from that expected in conventional heavy-fermion systems.

3. Conclusions

We have shown selected data of the magnetic, thermodynamic and electron transport properties of $Yb(Cu_{0.151}Si_{0.849})_{1.883}$. The observed power-law dependences in the susceptibility and specific heat, as well as the linear dependence of resistivity strongly indicate the NFL behaviour of the investigated system. The remarkable finding is the ln$T$ dependence of the Hall coefficient. Since, to our knowledge, no theoretical studies of the Hall effect for the NFL ground state have been reported yet, the R_H behaviour of $Yb(Cu_{0.151}Si_{0.849})_{1.883}$ will be useful in the development of a universal model which would be able to describe anomalous physical properties observed in NFL materials.

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