NON-FERMI LIQUID SCALING IN CeRhSn*

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We have recently shown that CeRhSn exhibits non-Fermi liquid temperature dependences in its low-temperature physical properties. Here we suggest that the non-Fermi liquid behavior observed in CeRhSn may be due to the existence of a Griffiths phase in the vicinity of a quantum critical point, based on electrical resistivity, magnetic susceptibility, and specific heat measurements. For CeRhSn, the low-temperature scaling of bulk properties ($C/T \propto \chi \propto T^{-1+\lambda}$, where $\lambda < 1$) is masked by an anomaly at about 6 K, which is of magnetic origin.

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Theoretical models of the non-Fermi liquid (NFL) behavior based on single impurity mechanisms include a multichannel Kondo effect of magnetic [1,2] or electric origin [3] and a conventional Kondo effect with a distribution of Kondo temperatures due to chemical disorder [4, 5]. Theoretical models which incorporate interionic interactions include fluctuations of an order parameter in the vicinity of a second-order phase transition at 0 K (quantum critical point (QCP)) [6–12] and an inhomogeneous Griffiths phase [13]. The Griffiths phase [14] consists of magnetic clusters in a paramagnetic phase and forms as a result of the competition between the Kondo effect and the RKKY interaction in the presence of disorder. Castro Neto *et al.*, [13] conclude that the specific heat and magnetic susceptibility follow a power law $\gamma \equiv C(T)/T \propto \chi(T) \propto T^{-1+\lambda}$ (where $\lambda < 1$), due to the existence of a Griffiths phase close to a QCP. We recently investigated the compound

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CeRhSn which exhibits NFL behavior [15–17]. The electrical resistivity and magnetic susceptibility have power law temperature dependences at low temperatures with small exponents $\rho(T) \propto T^{0.75}$ and $\chi(T) \propto T^{-0.5}$, and $\gamma \equiv C(T)/T \propto -\ln T$ (the latter over a limited temperature range). Experimental comparisons to the theory of Castro Neto *et al.*, have been made and will be discussed below.

The specific heat data for non-annealed CeRhSn (sample (a)) and for CeRhSn samples annealed for 4 days (sample (b)) and 8 days (sample (c)) are displayed as C/T *versus* $\ln T$ in Fig. 1. The high temperature specific heat data are very similar for all the samples investigated [16] while, at temperatures lower then about 6.2 K, the magnetic contribution to the specific heat is strongly dependent on the amount of atomic disorder. Assuming that the crystalline electric field ground state is a doublet, the total magnetic entropy per formula unit of CeRhSn is $R\ln 2 = 5.76$ Jmol^{-1}K^{-2}. The small peak in the specific heat of CeRhSn observed at $T_{\rm N}$ represents an extremally small fraction $\gamma T_{\rm N}/R\ln 2$ which is respectively ~ 0.12, 0.06, and 0.02 of entropy $R\ln 2$ at the phase transition for sample $(a), (b),$ and (c). At present, we do not know whether the observed anomalies reflect long-range order of the small magnetic moments or whether they should be attributed to the other correlation effects, *e.g.*, spin-glass behavior. We have not seen any magnetic order within a limit for an ordered moment of about 0.25 $\mu_{\rm B}$, using a high-resolution neutron spectrometer [16]. Some type of static magnetic order in CeRhSn with tiny ordered moments less than 0.1 $\mu_{\rm B}$ is probably due to subtle structural defects.

Fig. 1 reveals that C/T varies as T^{-n} below 2 K for sample (a) and (b) (see Table I), while it varies as T^{-n} between 1.5 K and 5 K for CeRhSn annealed for 8 days (sample (c)). The best fit of the expression $C(T)/T = cT^{-n}$ to the data yields $n = 0.54$ for sample (a), $n = 0.39$ for sample (b) and

TABLE I

Comparison of electrical resistivity $\Delta\rho$, magnetic susceptibility χ, and specific heat C data for CeRhSn polycrystalline samples: unannealed (a), annealed for 4 days (b), and for 8 days (c).

CeRhSn	$\Delta\rho = \Delta\rho(0)[1 + (T/T_0)^n]$				$\chi \propto T^{-1+\lambda}$		$C/T \propto T^{-1+\lambda}$	
	$\Delta\rho(0)$ [$\mu\Omega$cm]	T_0 [K]	n	T-range [K]	λ	T-range [K]	λ	T-range [K]
(a)	47.50	6.8	0.73	1.8–25	0.60	1.8–6	0.46	0.6–2
(b)	32.0	3.6	0.75	1.8–25	0.65	1.8–6	0.61	0.6–2
(c)	30.38	3.5	0.71	1.8–25	0.49	0.4–4.2	0.65	1.5–5

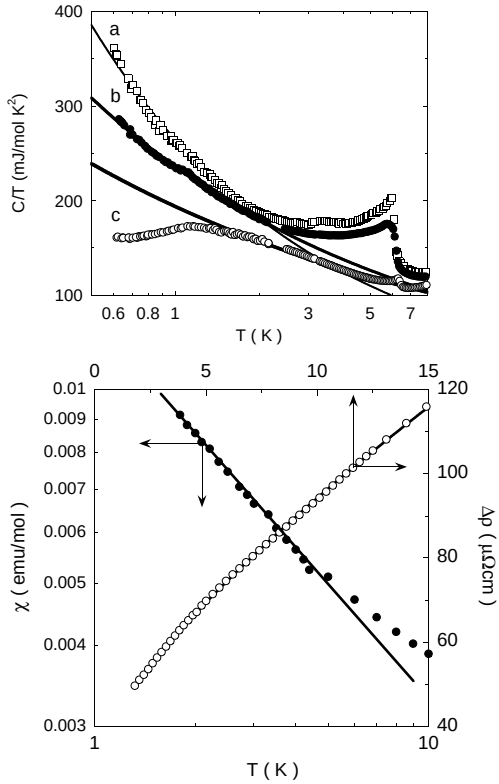

Fig. 1. Upper part: Specific heat C divided by T, C/T, *versus* $\ln T$ for three CeRhSn samples (sample (a) unannealed; samples (b) and (c) annealed for 4 and 8 days, respectively) [16]. The C/T data were fitted by the formula $C(T)/T = cT^{-n}$ in the range $T < 2\,\mathrm{K}$ for samples (a) and (b), and in the range $1.5 < T < 5\,\mathrm{K}$ for sample (c). The fits are represented by solid lines. The values of c are, respectively: 246.4 $\mathrm{mJmol^{-1}K^{-3}}$, 235.9 $\mathrm{mJmol^{-1}K^{-3}}$, and 195.8 $\mathrm{mJmol^{-1}K^{-3}}$ for samples (a), (b), and (c). The n values are listed in Table I. Lower part: Magnetic susceptibility χ *versus* T on a double logarithmic plot and the incremental electrical resistivity $\Delta\rho = \rho(\mathrm{CeRhSn}) - \rho(\mathrm{LaRhSn})$ *versus* T for a CeRhSn sample annealed for 8 days (sample (c)). The solid line represents the fit of the expression $\Delta\rho(T) = \Delta\rho(0)\,[1 + a(T/T_\mathrm{K})^n]$ to the data with $n = 0.74$, $\Delta\rho(0) = 32.2\ \mu\Omega\mathrm{cm}$, $a = 13.9$ and $T_\mathrm{K} = 145\,\mathrm{K}$ (T_K is the Kondo temperature). The straight line represents the relation $\chi \propto T^{-n}$.

$n = 0.35$ for sample (c). A noticeable deviation of the C/T data from linearity in $\log T$ at $T < 1.5\,\mathrm{K}$ (sample (c)) is not expected for a NFL. However, a number of systems have been reported (*e.g.*, $\mathrm{Ce(Ru_{0.7}Rh_{0.3})_2Si_2}$ [18], $\mathrm{U(Pt_{0.94}Pd_{0.06})_3}$ [19], $\mathrm{UCu_3Al_2}$ [20]) which show NFL behavior coexistent with magnetic order. These systems show magnetic behavior in the middle

or even above the temperature range where $C/T \propto \ln T$ or T^{-n}, and do not fit the picture of the QCP [8]. It is possible that the NFL temperature dependences of $\rho(T)$, $\chi(T)$, and $C(T)$ for disordered CeRhSn in the low-temperature region are related to the proximity of a magnetically ordered state that depends on the degree of atomic order. The parameters obtained from the best fits (Table I) are consistent with the presence of a Griffiths phase at very low temperatures *i.e.* $C/T \propto \chi \propto T^{-1+\lambda}$, with $\lambda < 1$.

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