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Physica B 241-243 (1998) 859-861

PHYSICA B

Quantum critical scattering in uranium non-Fermi liquid compounds

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Abstract

Our recent observation of universal scaling in ω/T of the magnetic response of the non-Fermi liquid compound $UCu_{5-x}Pd_x$ provides evidence of single-impurity quantum critical fluctuations of the uranium 5f-electrons. The scaling is observed over a wide range of frequencies from ~ 1 to 25 meV, and a wide range of temperatures from ~ 10 to 300 K, with evidence of a cross-over to more conventional moment fluctuations above 25 meV. We now have evidence from measurements with full polarization analysis of the development of antiferromagnetic correlations below 10 K in UCu_4Pd, but not in $UCu_{3.5}Pd_{1.5}$, indicating the cross-over from the quantum critical regime to a low-temperature quantum-disordered regime as predicted by phenomenological theories of quantum phase transitions.

Keywords: Non-Fermi liquids; Quantum phase transitions

In recent years, a new class of metallic compounds has been identified with remarkable scaling properties inconsistent with the behaviour of normal Fermi liquids [1]. These non-Fermi liquids, which usually contain uranium or cerium ions, exhibit weak power law, or logarithmic divergences of their bulk thermodynamic and magnetic properties at low temperatures without showing evidence of long-range ordering [2,3]. In a series of neutron scattering investigations of non-Fermi liquid uranium compounds, we have shown that the bulk properties are associated with an unusual scaling of the magnetic response, in which temperature provides the only energy scale [4,5]. In other words, over a wide range of temperatures (30–300 K) and energy transfers (0.5–25 meV), the dynamic susceptibility can be described as a universal function in ω/T.

There are a number of microscopic models of non-Fermi liquid behaviour [6–8]. Amongst those that predict scaling in ω/T are phenomenological

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0921-4526/98/$19.00
PII S0921-4526(97)00854-5

models of quantum critical scattering, associated with the proximity to a quantum ($T = 0$) phase transition [9]. These occur in systems in which magnetic long-range order has been suppressed by quantum disorder, such as may be produced by doping. Although the quantum phase transition occurs at a unique value of dopant concentration, the quantum critical regime is predicted to extend over a range of compositions around this point above a cross-over temperature. Below this temperature, non-universal behaviour is expected.

In our earlier measurements of the $UCu_{5-x}Pd_x$ series, the magnetic response at $x = 1$ and 1.5 was remarkably similar with no evidence of any Q-dependence apart from the uranium form factor. In order to see if magnetic correlations developed at low temperature, we performed diffuse neutron scattering experiments with full polarization analysis using the D7 spectrometer at the ILL. With an incident wavelength of 4.83 Å, the measurements on polycrystalline samples of UCu_4Pd and $UCu_{3.5}Pd_{1.5}$ covered a Q-range from 0.2 to 2.4 $Å^{-1}$. By installing a disk chopper, we also measured with energy analysis from about −25 to 3 meV but the data had to be summed over all angles to compensate for the additional loss of intensity.

Fig. 1 shows a comparison of the paramagnetic $S(Q)$ of the two compounds at 1.5 K. While the $x = 1.5$ sample shows just a form factor dependence within the statistical accuracy of the data, the $x = 1$ sample displays a peak at 0.95 $Å^{-1}$. This corresponds to the $[\frac{1}{2}\frac{1}{2}\frac{1}{2}]$ wave vector that characterizes the magnetic ordering in the heavy fermion antiferromagnet UCu_5 [10]. UCu_4Pd is close to the dopant concentration at which the magnetic order is suppressed, and our results therefore indicate that magnetic correlations persist at low temperature into the non-Fermi liquid regime but are no longer present at $x = 1.5$.

We also performed measurements with time-of-flight analysis (Fig. 2). The results confirmed our earlier observation that the scattering in energy loss does not change significantly with temperature, while the energy gain scattering increases as required by detailed balance. The spectral weight which is lost with decreasing temperature does not get transferred to the elastic channel. This is an important observation, because some models of

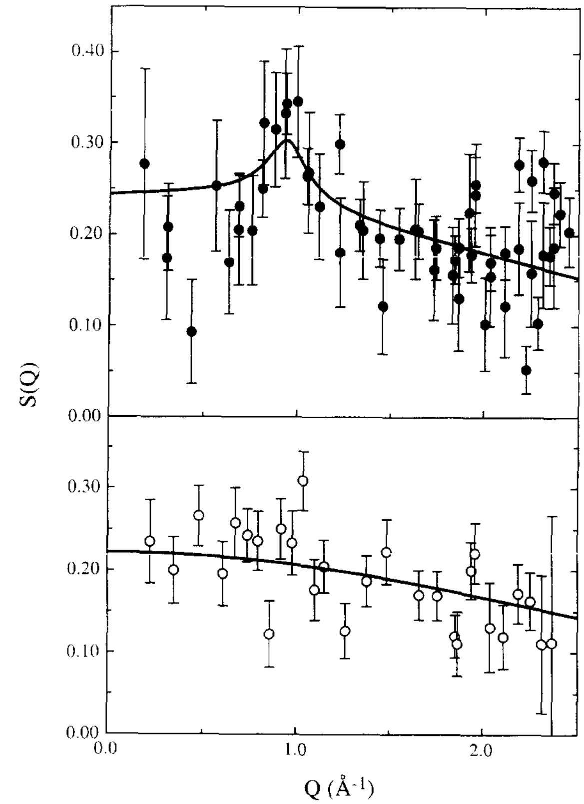

Fig. 1. Paramagnetic $S(Q)$ from UCu_4Pd (filled circles) and $UCu_{3.5}Pd_{1.5}$ (open circles). The solid lines are fits to a spherically averaged Lorentzian peak at 0.945 $Å^{-1}$ and an incoherent background, both modulated by the uranium form factor.

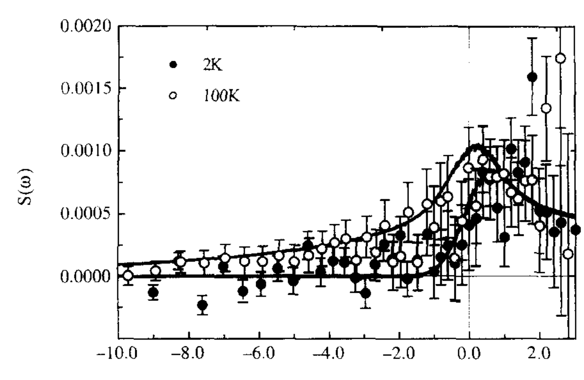

Fig. 2. $S(\omega)$ of UCu_4Pd summed over all detectors and measured with an incident energy of 3.5 meV at 1.5 K (filled circles) and 100 K (open circles).

non-Fermi liquid behaviour based on unconventional moment screening (multi-channel Kondo models) predict that, at low temperature, a proportion of the spins are uncompensated and would produce elastic paramagnetic scattering (and residual entropy at low temperature) [7]. There is no evidence for such an effect here.

In conclusion, we have performed polarized diffuse neutron scattering measurements of the non-Fermi liquid compounds, $UCu_{5-x}Pd_x$, with $x = 1$ and 1.5. Whereas our earlier investigations showed nearly identical scaling in these compounds, the new results show departures from this universal behaviour at low temperatures, with the $x = 1$ sample showing evidence of antiferromagnetic correlations. These observations are qualitatively consistent with phenomenological models of quantum critical scattering [9].

This work was supported by US DOE, BES-MS, contract W-31-109-ENG-38, NSF grant no. DMR97-05454, and a NATO Collaborative Research Grant.

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