Point-contact properties of magnetic clusters in CeNi$_{0.4}$Cu$_{0.6}$

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Abstract. We present point-contact spectroscopy (PCS) study of CeNi$_{0.4}$Cu$_{0.6}$ at low temperatures (1.5 - 10 K) and in magnetic fields up to 6 T. We have observed point-contact (PC) spectra with spectroscopic features, which are probably connected with scattering of conduction electrons on clusters and quasiparticles present in this alloy. We obtained reproducible symmetric dependencies in both polarities of applied voltage.

1. Introduction

Intermetallic 3d-4f magnetic compounds with substitutions on the magnetic or nonmagnetic sites have been a very useful tool to investigate the basic magnetic interactions (i. e. RKKY, 4f-3d hybridization, crystal electric field, etc.) and the interplay between them. However, the main problem with chemical substitutions is the introduction of intrinsic structural disorder in the compounds, which sometimes gives rise to inhomogeneities that in most cases are intrinsic to the samples and cannot be avoided by means of different preparation methods or supplementary thermal treatments. The simultaneous existence of competing interactions and disorder can give rise to short-range order or to a rich variety of magnetic behaviours related to clustered magnetic states such as spin-glass phases, superparamagnetism, cluster glass or magnetic phase coexistence [1, 2, 3].

One of the best examples of a complex magnetic behaviour arising from substitution effects is the CeNi$_{1-x}$Cu$_x$ system. The complete study developed in recent years revealed puzzling and seemingly contradictory physical results [4, 5, 6, 7]. The long-range magnetic order at very low temperatures was obtained from neutron diffraction [5] (antiferromagnetism for compounds with 1 ≤ x ≤ 0.7 and ferromagnetism for compounds with 0.6 ≤ x ≤ 0.2). On the other hand, a recent report on the very low temperature ac-dc magnetization on the ferromagnetic alloys of the series shows the formation of a cluster-glass state below a characteristic freezing temperature T$_f$ above the long-range ferromagnetic state [8]. Surprisingly, there is no evidence of additional transition below T$_f$ associated to the onset of long-range ferromagnetic order. Moreover, these studies indicate the formation of an intermediate inhomogeneous magnetic state below a characteristic temperature T* (above T$_f$) which accordingly to muon spin relaxation spectroscopy (µSR) [7] corresponds to the presence of dynamic entities that progressively lose their dynamical behaviour to finally freeze at T$_f$. 

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The use of combined macroscopic and microscopic probes has been crucial to propose a complete phenomenological model able to describe the puzzling experimental results obtained from the different techniques. Such a model is based on a cluster-glass state percolating into long-range ferromagnetic ordered state at lower temperatures, observed by neutron diffraction for $T < 100 \text{ mK}$. The presence of clusters below $T_f$ has been confirmed by Small Angle Neutron Scattering (SANS) showing a correlation length of $\sim 3 \text{ nm}$ [9]. In this paper we present preliminary results of PCS study in representative ferromagnetic composition ($x = 0.6$) in order to explore the clustered magnetic state which acts as a precursor of the long-range ferromagnetic order in this series.

2. Experimental details

The sample presented in this work is polycrystalline, prepared by arc melting. The preparation of samples and their quality control were discussed in Ref. [6]. The PCS seems to be very suitable for studying this series of samples because the characteristic size of PC is in nm scale and characteristic dimension of spin-clusters is also in this range. The influence of conduction electrons on clusters below $T_f$ is expected. In order to investigate the spin-clusters formation mechanism in this system we used PCS. PCS studies the electronic scattering in conductors, taking place on the nanometer length scale.

3. Results

We have performed PC measurements in hetero-contact arrangement using Pt or Cu needle. Using some selection rules [10] and taking to account comparison with $\rho(T)$ [11] we suppose the spectroscopic regime of electron transport through PC. In order to observe developing of spin-clusters we varied temperature from 1.5 K up to temperature above $T_f$. Fig. 1 shows the $d^2V/dI^2(V)$ of hetero-contact CeNi$_{0.4}$Cu$_{0.6}$ - Pt above as well as below freezing temperature $T_f = 1.8 \text{ K}$. The spectrum at 1.5 K reveals several maxima and with increasing temperature the maxima above $\sim 10 \text{ mV}$ are suppressed. In order to identify origin of these nonlinearities we also applied the magnetic field up to 6 T. Fig. 2 displays the magnetic field behaviour of $dV/dI(V)$ for hetero-contact CeNi$_{0.4}$Cu$_{0.6}$ - Pt at $T = 1.5 \text{ K}$. The maximum at zero bias voltage is typical for spin-glass and Kondo compounds [10]. However, in the classic Kondo systems (Cu or Au with a small amount of impurities as Mn or Fe) the increasing magnetic field results in the Zeeman splitting of degenerate spin states with the energy difference $2\Delta = 2g\mu_B H$, where $\mu_B$ is the Bohr magneton. This depresses spin-flip scattering, which costs energy $2\Delta$ and decreases Kondo resistance. Without applied external magnetic field the spin-flip scattering of

![Figure 1. Characteristic temperature behaviour of $d^2V/dI^2(V)$ for hetero-contact CeNi$_{0.4}$Cu$_{0.6}$ - Pt ($R_{PC} = 1 \Omega$). The freezing temperature $T_f = 1.8 \text{ K}$.

![Figure 2. Magnetic field behaviour of $dV/dI(V)$ for hetero-contact CeNi$_{0.4}$Cu$_{0.6}$ - Pt at $T = 1.5 \text{ K}$.

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the conduction electrons on magnetic impurities is elastic, whereas in the applied magnetic field, it is accompanied by the energy change by $2\Delta$. In other words, the inelastic spin-flip processes in PC are forbidden for $|eV| < \Delta$ and for $|eV| > \Delta$ they become possible. It means that for $|eV|$ minimum appears on the $dV/dI(V)$ characteristic at zero-bias in applied magnetic field [12].

In our case for hetero-contact $\text{CeNi}_{0.4}\text{Cu}_{0.6}$ - Pt we did not observe such a behaviour and no minimum at zero bias is observed up to 6 T. In spectrum $(d^2V/dI^2(V))$ of hetero-contact $\text{CeNi}_{0.4}\text{Cu}_{0.6}$ - Pt we have observed more less periodic structure, however the amplitude of maxima is small and is difficult to determine which maximum is related to scattering of conduction electrons and which maximum is only noise. The structure near 20 mV remains unaffected by applied magnetic field and structure above $\sim30$ mV is slightly changed with increasing magnetic field. We suppose, that structure about 20 mV is connected with interaction of conduction electrons with phonons and/or CEF levels presented in $\text{CeNi}_{0.4}\text{Cu}_{0.6}$ [11, 13]. This assumption confirms also fact that low energy ($<20$ mV) maxima remain at the same position also above $T_f$ (see Fig. 1), whereas the high energy periodic structure ($>30$ mV) is suppressed above $T_f$. Taking into account the temperature behaviour of observed spectra, than the periodic structure is connected to spin-clusters presented in $\text{CeNi}_{0.4}\text{Cu}_{0.6}$ below $T_f$. We suppose that electron-induced spin flips of the clusters in the PC area is responsible for high energy structure in $d^2V/dI^2(V)$ of hetero-contact $\text{CeNi}_{0.4}\text{Cu}_{0.6}$ - Pt. Above temperature $T_f$ clusters are unstable and spins fluctuate. Therefore we observe smooth spectra without periodic structure. When temperature becomes lower than $T_f$, spin-clusters will be freeze and conduction electrons can scatter on this clusters.

Fig. 3 shows the magnetic field behaviour of $d^2V/dI^2(V)$ for hetero-contact $\text{CeNi}_{0.4}\text{Cu}_{0.6}$ - Pt at $T = 1.5$ K. Spectra exhibit periodic structure and with increasing magnetic field we observed almost no change. One would expect the destroying of clusters with increasing magnetic field, however till now it is not known the saturation magnetic field. Magnetic field of 6 T has only small effect on anomalies. On the other hand Fig. 3 demonstrates the reproducibility of observed structure and thus the low level of noise.

**4. Conclusions**

The preliminary results of PCS measurements of the spin-clusters in $\text{CeNi}_{0.4}\text{Cu}_{0.6}$ show periodic structure of $d^2V/dI^2(V)$ below $T_f$. With increasing temperature above $T_f$ this periodic structure is suppressed. We suppose that maxima at high energy are connected with the electron-induced spin flips of the clusters in the PC area. Non-linearities at lower voltages remains unaffected.
Figure 3. Magnetic field behaviour of \( \frac{d^2V}{dI^2}(V) \) for hetero-contact (CeNi_{0.4}Cu_{0.6} - Pt) at \( T = 1.5 \) K (\( T_f = 1.8 \) K). The curves are shifted for clarity.

with increasing temperature as well as magnetic field and therefore we suppose their phonon or CEF origin. In addition the application of a magnetic field up to 6 T has only a little effect on spectra. Therefore it will be interesting to use ferromagnetic needle. More detailed study is required.

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