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Point-contact spectroscopy of competing/coexisting orders in Cd-doped CeCoIn₅

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Abstract. Differential conductance spectra are taken from metallic point-contact junctions on Cd-doped CeCoIn₅. For (100) junctions with nominal 10% doping, we observe signatures for subsequent antiferromagnetic and superconducting transitions in qualitative agreement with bulk measurements. In the superconducting state, two conductance channels compete, both with enhanced subgap conductance, one due to superconductivity and the other antiferromagnetism. The conductance data exhibit variances for different doping levels and crystallographic orientations and junction to junction. This issue will be addressed further in terms of surface inhomogeneity or intrinsic nonuniform phase formation.

The recently discovered heavy fermion family of Cd-doped 1-1-5 compounds have attracted great interest from the community [1]. They provide unique opportunities to investigate a variety of interesting subjects in condensed matter physics. For example, one can study the interplay between antiferromagnetism and superconductivity in Cd-doped CeCoIn₅ as Cd-doping induces an antiferromagnetic order. At the nominal doping level of 10%, superconductivity and antiferromagnetism coexist. The antiferromagnetic ordering in this compound is observed commensurate with the lattice [2], in contrast with the incommensurate order in CeRhIn₅ [3]. It is of great significance to address the question what drives antiferromagnetic ordering in these heavy electron materials: Fermi surface instability such as a spin density wave, incomplete screening of local moments, or other mechanisms. Here, we report conductance spectra obtained from Cd-doped CeCoIn₅ in order to address these issues.

All samples studied in this work are single crystalline. Samples with the surface normal along three different crystallographic orientations are prepared [4]. Nanometer-scale metallic junctions are formed by bringing a sharp gold tip into contact with the sample using our home-built Cantilever-Andreev-Tunneling rig [5]. Differential conductance data are taken as a function of temperature and magnetic field using standard lock-in techniques. In the data presented below, the bias voltage is referred to the sample, i.e., the Cd-doped CeCoIn₅ electrode.

Cadmium is known to substitute indium sites, adding holes [1]. Here we refer to nominal values for the doping content as suggested in the original report. For 10% Cd doping, the compound undergoes subsequent antiferromagnetic and superconducting transitions at $T_N \sim$

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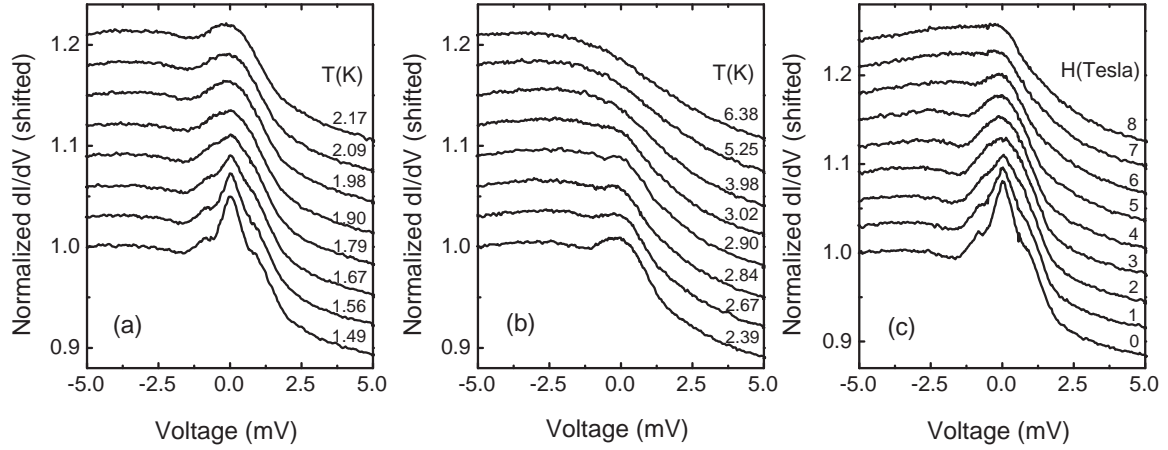


Figure 1. Conductance spectra taken from a (100) junction on 10% Cd-doped CeCoIn₅ (a) & (b) Temperature dependence. (c) Magnetic field dependence at 1.45 K. The magnetic field is applied perpendicular to the *ab*-plane.

2.9 K and $T_C \sim 1.3$ K, respectively, as confirmed by bulk measurements such as specific heat and magnetic susceptibility [1]. Previously, we reported complicated conductance behaviors in a (100) junction on 10% Cd-doped CeCoIn₅ [6]. The zero-bias conductance as a function of temperature exhibited characteristic slope changes at those transition temperatures. While the conductance enhancement in the superconducting state is clearly due to Andreev reflection [7], the origin of the broad conductance peak observed below T_N was not clear. It was conjectured that similar charge transport might occur in our normal-metal/antiferromagnet junction, as predicted by recent theoretical investigations [8, 9]. The conductance vs. bias voltage data revealed much more intriguing behaviors, indicating that there exists competing or coexisting orders below T_C . Detailed measurements as a function of temperature and magnetic field suggest that the narrower peak arises from superconductivity whereas the broad one due to antiferromagnetism [6].

We have extended the point-contact spectroscopy measurements to other crystallographic directions and Cd doping levels. Figure 1 shows conductance data taken from a (100) junction on 10% Cd-doped CeCoIn₅. The temperature dependence of the conductance is qualitatively similar to what we reported earlier [6]. Namely, the conductance near zero-bias begins to be enhanced below $T_N \approx 3.0$ K, forming a broad peak at lower temperatures. This indicates that its origin has something to do with the antiferromagnetism. According to the theoretical calculations by Andersen *et al.* [9], density of states effects can be observed in a normal-metal/antiferromagnet junction, depending on the detailed configuration. In tunnel junctions on antiferromagnets, conductance spectra with gapped structures similar to that in superconducting tunnel junctions were reported [10]. The conductance enhancement around zero-bias is seen in all our measurements independent of the doping content and crystallographic orientation, although detailed characteristics such as energy scale and magnitude vary from junction to junction. As the temperature is lowered below ≈ 1.8 K, an additional structure grows on top of the broad peak as shown in Fig. 1(a). Noting that the resistive transition for superconductivity occurs around this temperature, we attribute the central peak to Andreev reflection. This narrow peak is quenched by the applied magnetic field of 3 Tesla but the broad peak survives up to 6 Tesla,

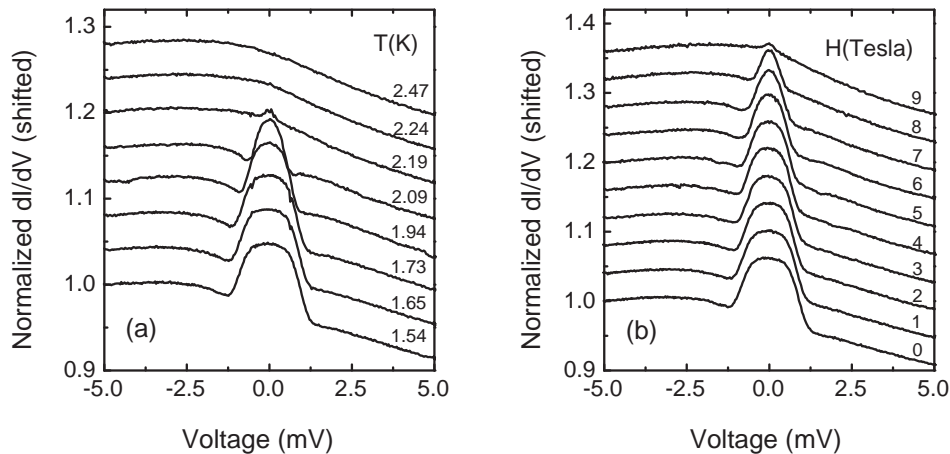


Figure 2. Conductance spectra taken from a (001) junction on 10% Cd-doped CeCoIn₅. (a) Temperature dependence. (b) Magnetic field dependence at 1.52 K. The magnetic field is applied parallel to the *ab*-plane.

as shown in Fig. 1(c). This behavior is similar to our earlier observation [6].

Conductance data for a (001) junction on 10% Cd-doped CeCoIn₅ are displayed in Fig. 2. Here the conductance enhancement begins at ≈ 2.2 K, much lower than the bulk T_N , well above the resistive T_C . This broad conductance peak is suppressed gradually by the applied magnetic field but survives up to 9 Tesla, which is above H_{c2} of undoped CeCoIn₅ at the measurement temperature of 1.52 K [11]. Combining these observations, the conductance enhancement is more likely due to antiferromagnetism but the possibility of surface inhomogeneity is being investigated.

Although we observe a broad conductance peak from most of the junctions measured, a double peak structure is seen in some cases. In Fig. 3(a), the conductance data on a (001) junction of 10% Cd show that the double peak structure might be due to the zero-bias dip structure apparent in the normal state. Currently the origin of this dip is not clear. We note the data shown in Fig. 3(b) for a (100) 20% Cd junction do not have such a normal state anomaly, implying that it might have a different origin. Naidyuk *et al* attributed the zero-bias peak in the differential resistance data on URu₂Si₂ to the decrease of Fermi surface due to antiferromagnetic ordering [12]. This might be the case if the ordering causes the Fermi surface to be gapped partly or completely.

Urbano *et al.* recently reported NMR measurements on Cd-doped CeCoIn₅ and proposed a droplet model for the origin of antiferromagnetism in this compound [13]. According to their picture, global order occurs when antiferromagnetic droplets nucleate around local Cd-dopants, increase, and coalesce. The dependence of the point contact conductance on the doping level and geometrical configuration of the junction could reveal such phase and chemical inhomogeneities. Further investigations are underway.

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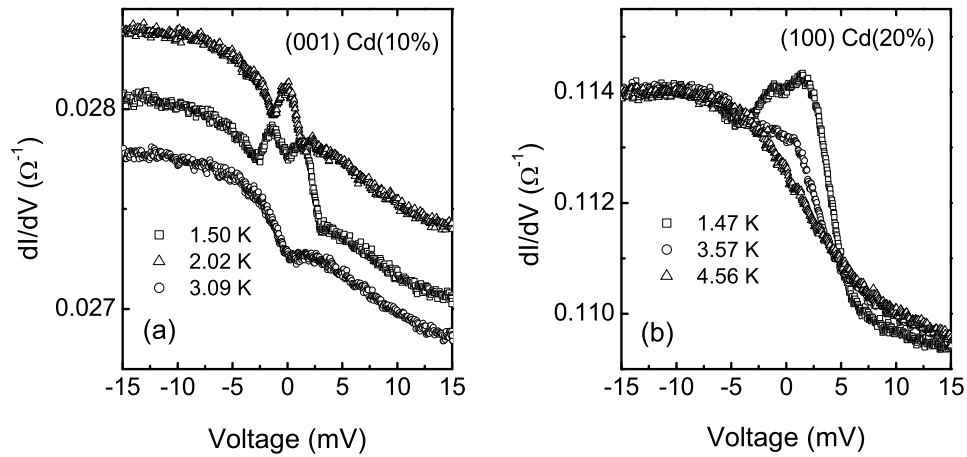


Figure 3. Conductance spectra showing a double-peak structure. (a) A (001) junction on 10% Cd-CeCoIn₅. (b) A (100) junction on 20% Cd-CeCoIn₅.

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