Tunneling spectroscopy studies of CePt$_3$Si

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Abstract. Electronic structure around the Fermi energy of noncentrosymmetric superconductor CePt$_3$Si in the normal state in the vicinity of the magnetic phase transition was investigated using low temperature electron tunneling spectroscopy. A pronounced $E^{1/2}$ anomaly observed in the density of states at the Fermi level indicates an interplay of correlation and localization. A dip in the low bias voltage region resembling a narrow correlation pseudogap of the width $\approx 2$ meV is believed not to originate from magnetic interactions. The results are consistent with the assumption that two sets of electrons are present in CePt$_3$Si.

1. Introduction

CePt$_3$Si, the first known heavy-fermion superconductor without inversion center in the crystal structure [1], orders antiferromagnetically at $T_N = 2.25$ K [2, 3] and undergoes a superconducting phase transition at $T_c = 0.75$ K [1]. Some experiments show two superconducting jumps indicating two distinct superconducting phases with different transition temperatures below about 0.5 K [2–7].

The absence of inversion symmetry in the CePt$_3$Si crystal lattice gives rise to splitting the Fermi surface due to an antisymmetric spin-orbit coupling [2] and the broken inversion symmetry also triggers a mixing between spin-singlet and spin-triplet states in the superconducting condensate [8], yielding line nodes in the electronic gap structure [2]. An intriguing coexistence of both superconductivity and long-range magnetic order on a microscopic scale, evidenced e. g. by $\mu$SR spectroscopy [9], is believed to be a consequence of two different sets of electrons [1]. Also paramagnetic properties of the system result from several competing interactions due to correlation effects.

Since the remarkable effects due to parity-violation in CePt$_3$Si are strongly enhanced by electron correlations [10], an information about the electronic density of states (DOS) in the vicinity of the Fermi level could advance an understanding of this peculiar compound. In the present paper we report on the DOS of CePt$_3$Si in the normal state probed by electron tunneling spectroscopy at temperatures close above and below $T_N$.

2. Experiment

Polycrystalline CePt$_3$Si samples were prepared by argon arc melting and subsequent heat treatment under high vacuum. Further details about the preparation process and structural properties of the samples can be found in Ref. [1]. Tunneling measurements were performed
by electron tunneling spectroscopy using mechanically controlled tunnel junctions. An annealed gold tip was used as a counter electrode. Differential conductance, $dI/dV$, as well as its derivative, $d^2I/dV^2$, were numerically calculated from the measured current-voltage characteristics. It should be mentioned that due to a formation of an oxide layer on the sample surface, the tunnel junction electrodes were in a direct mechanical contact, separated just by a native surface-insulating barrier.

3. Results and discussion

A characteristic differential-conductance vs. bias-voltage curve of CePt$_3$Si/Au tunnel junction at 4.2 K is depicted in Fig. 1(a). A typical tunnel resistance corresponding to the behavior was about 10 MΩ. The data reveal a pronounced V-shaped zero-bias anomaly in the bias voltage region $|V| < 100$ mV. The position of the dip minimum precisely at the Fermi energy suggests that the dip is a consequence of correlation effects. A decrease of the conductance in the minimum in comparison to the values at ±100 mV is less than ∼20%. As demonstrated in Fig. 1(b), the studied conductance is proportional to $V^{1/2}$ on both sides of the Fermi level, except at the lowest bias. We regard this as a proof that both correlations and localization occur in CePt$_3$Si.

![Figure 1. Typical differential-conductance curve of CePt$_3$Si at 4.2 K (a), and the same data replotted in $dI/dV$ vs. $V^{1/2}$ coordinates (b). A characteristic tunnel resistance was ~10 MΩ. The straight red lines represent linear fits.](image)

We have analyzed the obtained data within the context of early studies of disordered systems [11, 12]. According to the scaling model [12] that includes both localization and correlation on equal footing, the one-electron DOS, $N(E)$, in the vicinity of the Fermi energy is given by

$$N(E) = N(0)[1 + (E/\Delta)^{1/2}],$$

(1)

where $N(0)$ is the DOS at the Fermi energy, $E_F$, the energy $E$ is measured from $E_F$, and $\Delta$ is a (pseudo)-correlation-gap parameter, which decreases as localization becomes stronger [12, 13]. Taking into account that the differential conductance is proportional to $N(E)$ and that the voltage scale in millivolts represents in fact an energy scale in millielectronvolts, the parameter $\Delta$ could be estimated in accordance with Eq. (1) from least squares fits. Such an analysis of the data from Fig. 1, provides, however, an extremely large value, $\Delta \approx 1.2$ eV. In view of the relatively small decrease of the conductance, this may indicate either a very weak localization, or might be a sign of the presence of two (at least) different sets of electrons.
in the system: localized electrons, which obey the above mentioned $E^{1/2}$ law, and say, non-localised ones, with constant or only very weakly varying DOS. In fact, the latter interpretation would be in qualitative agreement with the presumption of the coexistence of superconductivity and long-range antiferromagnetism with two different electron subsystems [2, 14]. Supposing that also non-localized electrons contribute to the tunneling current, the fitting coefficient $N(0)$ represents an integral value of the DOS at $E_F$ and the analysis yields a larger value of $\Delta$ than the real value corresponding to the localized electrons.

**Figure 2.** Differential conductance curves of CePt$_3$Si/Au tunnel junction in low voltage limit at several temperatures near the magnetic phase transition temperature, $T_N = 2.2$ K (a), and the corresponding $d^2V/dI^2$ curves (b). The typical tunnel resistance was $\sim$200 kΩ.

More detailed studies were done at the low-bias region, $|V| < 20$ mV. In this case a typical tunnel resistance was about 200 kΩ. Because of better mechanical stability of such (low resistance) contacts we were able to measure almost the same contact at several temperatures in the interval 1.8 K - 3.5 K. Differential-conductance curves corresponding to temperatures 1.8 K, 2 K and 3.4 K are shown at Fig. 2(a). All spectra exhibit a presence of a dip at the lowest-bias voltage. Since the dip is centered exactly at $E_F$, it can be regarded as a consequence of correlation effects. As with respect to the reproducibility of the measurement we have not observed any significant change of the spectra when crossing the temperature of antiferromagnetic ordering, $T_N = 2.2$ K, we believe that the dip does not originate from magnetic interactions. The finite value of the dip minimum is considered as an indication of a pseudogap. To substantiate whether an electron pairing is responsible for the correlation pseudogap formation, an experiments down below $T_c$ should be of profit.

Fig. 2(b) depicts derivatives of the data from Fig. 2(a), $d^2V/dI^2$. The width of the pseudogap determined as an energy difference between the positions of the most pronounced local extrema in $d^2V/dI^2$ dependences is $\approx 2$ meV.

**4. Summary**

We have performed tunneling spectroscopy studies of CePt$_3$Si in the normal state. The high-tunnel-resistance tunneling spectra at 4.2 K reveal the presence of an $E^{1/2}$ dependence in the bias voltage region $|V| < 100$ mV. We consider this observation as a proof of localization and correlation effects in the system. An analysis of the conductance data in terms of Eq. 1 yields an unexpectedly high value of the (pseudo)-correlation-gap parameter, $\Delta_{est} \approx 1.2$ eV. We interpret this as a sign of the presence of (at least) two electron subsystems with different degrees of localization. The studies at low bias voltage, $|V| < 20$ mV, reveal a dip, suggesting a narrow
correlation pseudogap of the width ≈ 2 meV at the Fermi energy. As the dip remains practically unchanged in the temperature range 1.8 K - 3.4 K, we conclude that it has a non-magnetic origin. A deeper understanding of the origin of the dip (e.g. whether it is formed in the set of electrons responsible for superconductivity) requires further studies, especially at lower temperatures and in magnetic fields.

5. Acknowledgments
This work was supported by the Slovak Scientific Grant Agency (VEGA 7184), the Slovak Research and Development Agency (APVV-0346-07), the Austrian FWF (P18054), and by the European Science Foundation (COST P16). The low-temperature STS-head and STS control electronics were provided by Laboratories of Applied Research [15].

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