Point-contact spectroscopy of the normal state excitations in PrOs$_4$Sb$_{12}$

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Abstract

Point-contact (PC) investigations of the heavy-fermion (HF) superconductor PrOs$_4$Sb$_{12}$ in the temperature range between 1.5 and 4.2 K and in a magnetic field up to 8 T are presented. The main feature in PC spectra, the second derivative of the I-V curves, in the normal state is a peak at about 1-3 mV. This low energy peak is smeared by the temperature rise and suppressed (or splitted) by a magnetic field. The origin of the peak is likely excitation of the Pr$^{3+}$ ion from the ground $\Gamma_1$ state to the upper $\Gamma_5$ state, considering the generally accepted crystalline electric field (CEF) schema in PrOs$_4$Sb$_{12}$. Absence of the visible features of other CEF transitions in the PC spectra testifies to the dominant coupling of the conducting electrons with this low-lying (about 1 meV in energy) excitation. Thus, this interaction is important for ascertainment of the nature of HF and superconducting state in PrOs$_4$Sb$_{12}$.

Key words: PrOs$_4$Sb$_{12}$, crystalline electric field, point-contact spectroscopy

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PrOs$_4$Sb$_{12}$ appears to be the first Pr-based heavy-fermion superconductor ($T_c \approx 1.85$ K) with an effective quasiparticle mass $m^* \approx 50 m_e$ according to the enhanced electronic specific heat coefficient $\gamma [1]$. Crystal-electric-field (CEF) splitting of the Pr$^{3+}$ multiplet influences the physical properties of PrOs$_4$Sb$_{12}$ as widely accepted, first of all, the heavy-fermion phenomena and superconducting pairing mechanism in this compound. According to the recent specific heat, magnetization, elastic and inelastic neutron scattering measurements [2] CEF schema in PrOs$_4$Sb$_{12}$ tends to be as follows: magnetic $\Gamma_5$ and $\Gamma_4$ triplets, nonmagnetic $\Gamma_3$ doublet separated from the ground $\Gamma_1$ state by 10K, 100K and 300K respectively. Thus, as it is commonly believed, mass enhancement would arise from inelastic exchange scattering of the conduction electrons by the well-localized hybridized $4f^2$ electrons of the Pr$^{3+}$ ion.

Point-contact spectroscopy (PCS) turns to be a successful tool for the direct study of energy-dependent interactions between conducting electrons and different quasiparticle excitations in metals [3]. In [4] a PCS theory for the $f$-localized states was evolved. It was shown that nonlinear conductivity of PC is determined by the inelastic scattering of the conducting electrons on the $f$-shell, what allows to probe the CEF levels of the rare-earth ion. PCS was used successfully to study the CEF levels of the Pr$^{3+}$ ion in PrNi$_5$ and their Zeeman splitting [5]. In the case of heavy-fermion materials obtaining of the spectroscopic information is restricted by their very high resistivity that leads to violation of the ballistic condition and transition to the thermal regime and dominance of the self-heating effects in the PC spectra. Only PC’s on relatively "low resistivity" specimens (≤ 10$\mu$Qcm) which we believe our PrOs$_4$Sb$_{12}$ samples belong to, may have at low
voltage inelastic electron mean free path exceeding the PC size and spectra with spectroscopic features.

We have used the PrOs$_4$Sb$_{12}$ single-crystal samples ($T_c=1.75$ K) of a sub-millimeter size. To produce PC’s a Cu electrode had a gentle touch to ‘as grown’ PrOs$_4$Sb$_{12}$ surface in liquid He$^\text{3}$. The first and second derivatives of the I-V curves as function of bias voltage were recorded using a standard lock-in technique.

In Fig.1 the $dV/dI(V)$ characteristics of PC between PrOs$_4$Sb$_{12}$ and Cu taken at $T=1.5$ K are presented for the magnetic field range between 0 and 8 T. The ‘quasi’ parabolic $dV/dI(V)$ curves show also a minimum around $V\approx 0 \text{ mV}$. Magnetic field somewhat degrades the zero-bias minimum.

Figure 2 displays PC spectra $d^2V/dI^2(V)$ corresponding to Fig. 1. Zero magnetic field spectrum shows sharp peak at about 0.8 mV, which is suppressed by magnetic field of 0.5 T. Traces of superconductivity are likely responsible for this feature.

The most prominent peculiarity of the spectra is a maximum at about 1.8 mV. Increasing temperatures (not shown) as well as magnetic fields lead to its broadening, reduction and finally even splitting is seen at high magnetic fields. This maximum can be connected with the allowed CEF transition $\Gamma_1 \rightarrow \Gamma_5$ with energy about 0.7 meV, according to the level scheme determined in [6]. Next allowed CEF transition (around 11 meV [6]) is not displayed in the PC spectra pointing out to the dominant coupling of the conducting electrons with the low-lying $\Gamma_1 \rightarrow \Gamma_5$ excitation. Moreover, no features due to phonon maxima of Cu (around 16 meV) as well as PrOs$_4$Sb$_{12}$ phonons were enucleated (top inset in Fig. 2). This may be associated with the small contribution from phonon compared to the CEF excitations and transition of the PC region in the thermal regime at higher voltages (> 10 mV) due to decrease of the inelastic mean free path.

Figure 2 (bottom inset) shows a calculation according to the CEF theory [4] compared to the experimental curve taken at 1 T to suppress the mentioned 0.8 mV peak. The main parameter of the calculation is the position of the CEF peak taken at 1.1 meV to fit the experimental curve what is in a reasonable agreement with the neutron data [6]. Contrary, calculation of the spectrum in the thermal regime according to Eq.(3.23) in [3] (Fig. 2, upper inset) exhibits a maximum at 0.6 mV with a shallow hump around 20 mV.

Finally, we have presented the first results of PCS for the skutterudite PrOs$_4$Sb$_{12}$. For low bias a pronounced maximum in the PC spectra is well resolved. This maximum is suppressed, broadened and splitted by a magnetic field what points out to its CEF excitation nature. To reinforce this, measurements at lower temperature and higher magnetic field are desirable.

References

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