On the origin of the conductance asymmetry in CeMIn$_5$ ($M=$Co, Rh, Ir)

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Abstract. Asymmetric differential conductance has been frequently observed in heavy fermion point-contact junctions. We report such data obtained from the Ce-based 1-1-5 compounds CeMIn$_5$ ($M=$Co, Rh, Ir). Apart from characteristics due to superconductivity or antiferromagnetism, a striking common feature is an asymmetry in the background conductance, which shows nontrivial temperature and voltage dependencies. These behaviors cannot be explained by the local heating model combined with large Seebeck effect in heavy fermions. We propose that a Fano-like interference may cause the asymmetry. The interference can occur between two conductance channels, one into the conduction band and the other into the heavy electron band formed by the hybridization of conduction electrons with localized f-electrons.

According to Harrison’s theorem [1], the electronic density of states (DOS) of a simple metal cannot be measured using tunnel junctions since it cancels out the velocity factor in the conductance kernel. This argument may also apply to simple metallic junctions without an insulating barrier. However, in many cases where electron-electron interaction is not negligible, this theorem does not appear to apply.

We adopt point-contact spectroscopic techniques to obtain differential conductance ($dI/dV$) data on the Ce-based 1-1-5 heavy fermion compounds, CeMIn$_5$ ($M=$Co, Rh, Ir). Nanometer-scale junctions are formed by bringing a sharp gold tip onto a single crystalline sample [2, 3]. Conductance spectra are taken as a function of crystallographic orientation, temperature, and magnetic field using standard lock-in techniques. The bias voltage ($V$) is referred to a sample.

Figure 1(a) displays typical normalized $dI/dV$ data over wide voltage ranges just above the phase transitions: superconducting for Co ($T_C = 2.3$ K) and Ir (0.4 K) and antiferromagnetic for Rh ($T_N = 3.8$ K). A common characteristic feature is an asymmetry in the background conductance. For Co, a similar asymmetry has been reported by us [4] and by other group [5]. The conductance asymmetry, defined as $\frac{dI}{dV}(+V) - \frac{dI}{dV}(-V)/2$, is plotted in Fig. 1(b). It is notable that the Co and Ir junctions show negative values, whereas the Rh junction shows positive. Nominally, the negative sign indicates that it is more difficult to add than to remove electrons from the f-orbital.

For a simple check of the spectroscopic nature, it is conventional to estimate the point contact size ($2a$) and to compare it with electronic mean free paths ($l$). Wexler’s formula provides a simple relationship [6]: $R_0 = \frac{4kT}{3\pi^2\alpha}[1 + \frac{3\pi}{8K}\gamma(K)]$, where $R_0$ is the resistance, $K \equiv l/a$, $\gamma(K)$ is...
Figure 1. (a) Conductance spectra for (001) junctions on CeMIn$_5$ (M=Co, Rh, Ir). The junction resistance at -20 mV is 5.4 Ω for Co and Ir and 2.3 Ω for Rh, respectively. (b) Conductance asymmetry vs. V. (c) Asymmetry in the differential resistance.

Figure 2 shows conductance spectra taken under an applied magnetic field. No field dependence in the conductance asymmetry is observed but only small magnetoconductances are seen in Co and Rh junctions. This disagrees with the strong field dependence of the Seebeck coefficient in CeCoIn$_5$ [10]. All these observations suggest the Seebeck effect model breaks down in our experiments on the 1-1-5 heavy fermions.
In search of a microscopic origin of the reduced Andreev signal in heavy-fermion superconductors, Anders and Gloos proposed a theory taking into account the strong energy-dependent quasiparticle scattering in heavy fermions [11]. Their calculation based on Green functions also shows an asymmetric conductance shape, attributed to the DOS effect in heavy fermions. Although this model provides explanations for both observations, one disadvantage is the difficulty to track down how the calculated features appear. Nowack and Klug [12] considered electronic scattering by an energy-dependent DOS in heavy fermions in their calculations based on Boltzmann transport equations. In this model, the asymmetry arises from the DOS centered at a finite energy. We have proposed [4] a two-channel model adopting the two-fluid picture [13] and a Lorentzian DOS for heavy electrons. Although our model successfully accounts for the data at the lowest temperature, it was found that a Fano [14] line shape provides significantly better fits to our data over broad ranges of temperature and voltage. This appears to imply that the two channels need to be entangled instead of being independent.

The original Fano formula is given as
\[ F(\epsilon) = \frac{(q_F + \epsilon)^2}{1 + q_F}, \]
where \( q_F \) is the Fano factor, \( \epsilon \equiv (E - E_0)/\Gamma \), \( E_0 \) and \( \Gamma \) the resonance energy and width, respectively. Simulated Fano lines are plotted in Fig. 3(a). The line shape is asymmetric for \( q_F \neq 0, \infty \), with a peak at \( \epsilon = 1/q_F \). In order to analyze the experimental data using a Fano-like interference model, we make a conjecture that the conductance at zero temperature can be expressed as follows.

\[ \frac{dI}{dV} = C \cdot F(\epsilon) + G_0, \]

where \( C \) is a prefactor for the Fano contribution and \( G_0 \) the constant background conductance. In Fig. 3(b), we plot experimental data and the best fit using this formula. The fit parameters are: \( q_F = -2.14 \), \( E_0 = 2.23 \) meV, \( \Gamma/2 = 11.13 \) meV, \( C = 0.0061 \ \Omega^{-1} \), and \( G_0 = 0.164 \ \Omega^{-1} \). It is notable that the experimental data with a peak at a negative bias voltage can be reproduced with
a negative $q_F$, placing the resonance ($E_0$) above the Fermi level. This result indicates that our data is in fact in agreement with a general belief on the Kondo resonance position in Ce-based heavy fermion systems [16]. The negative $q_F$ value can be justified as due to the phase factor in the interference. Following the two-fluid picture [13], one can imagine that the interference occurs between two channels, one into the conduction band and the other into the heavy electron band. The large $G_0$ value might imply that there exists a substantial contribution from the channel into the conduction band without interference. Our model is currently phenomenological and, thus, a more rigorous theoretical formulation is desirable. Such a theory may also provide a microscopic explanation for the reduced Andreev signal observed in heavy fermions [4].

W.K.P. and L.H.G. acknowledge the discussion with D. Pines on the two-fluid picture for heavy fermions, and the discussions with A. J. Leggett and P. W. Anderson in regard to Harrison’s theorem. Work at the UIUC was supported by the U.S. DoE, Award DEFG02-91ER45439 and DEFG02-07ER46453 and by NSF DMR 07-06013 through the FSMRL and the CMM. Work at LANL was performed under the auspices of the U.S. DoE Office of Science.

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