Microcontact spectroscopy of the $CeCu_2Si_2$ Kondo lattice

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The strong electron-electron interaction causes current flow in a thermal regime in $CeCu_2Si_2$ microcontacts. The conductivity of $CeCu_2Si_2$-Cu heterocontacts is found to be asymmetric with respect to the current direction. This asymmetry is attributed to a resonance in the $CeCu_2Si_2$ state density near the Fermi level.

1. Considerable interest has recently been attracted to the kinetic phenomena in the compound $CeCu_2Si_2$, which exhibits several unusual properties at low temperatures.[1–4] This material falls in the category of so-called Kondo lattices, which constitute a new class of solids, according to Ref. 4. At temperatures $T_K \sim 10$ K (T_K is the Kondo temperature), there is a maximum in the electron energy spectrum near the Fermi level in $CeCu_2Si_2$. This maximum, known as the Abrikosov-Suhl resonance, is responsible for the anomalous properties of $CeCu_2Si_2$. The presence of a narrow resonance gives rise to quasiparticles with a large effective mass ($m^* \gtrsim 200m_0$)—"heavy fermions"—and to a low degeneracy temperature, $T_F^* \sim 10$ K. At $T < T_K$, the magnetic moments of cerium are screened by conduction electrons, and the $CeCu_2Si_2$ goes into a nonmagnetic state. There is accordingly interest in studying the properties of $CeCu_2Si_2$ by the method of microcontact spectroscopy, which has been widely used to study various mechanisms for the energy relaxation of electrons in conductors.[5]

2. Figure 1a shows the differential resistance $R_D(V) = dV/dI(V)$ of a $CeCu_2Si_2$ microcontact; there are two maxima, at 5 and 67 mV. As $V \to 0$, the function $R_D(V)$ is

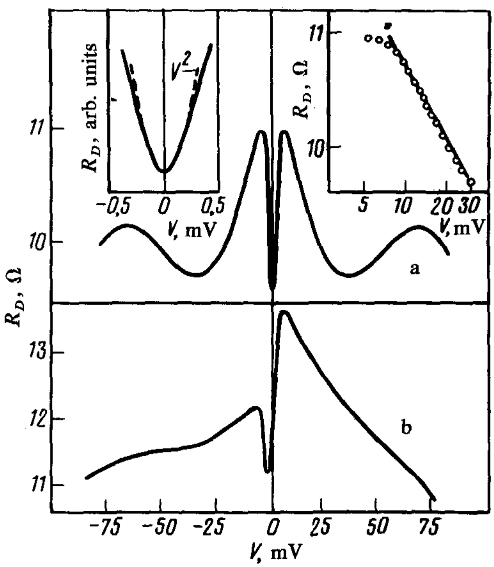

FIG. 1. The differential resistance $R_D(V)$ of a $CeCu_2Si_2$ microcontact at $T_0 = 2.4$ K (a) and of a $CeCu_2Si_2$-Cu heterocontact at $T_0 = 4.2$ K (b) (at $V > 0$, the current flows from Cu to $CeCu_2Si_2$).

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quadratic, $R_D(V) = R(0) + aV^2$, while between 7 and 30 mV it falls off logarithmically (see the inset in Fig. 1a). The function $R_D(V)$ is thus qualitatively similar to $\rho(T)$ of a bulk sample.[4] The correlation between $R_D(V)$ and $\rho(T)$ is evidence of a thermal regime for the current flow in $CeCu_2Si_2$ contacts, in which the temperature T in the contact is related to the voltage across it by[6]

$$T^2 = T_0^2 + V^2/4L, \qquad (1)$$

where T_0 is the temperature of the bath, and L is the Lorentz number.

According to the theory for the thermal regime,[6] we can use the measured curves of $R_D(V)$ to calculate the temperature dependence of the resistance of the microcontact, $R_{\rm mc}^{\rm theo}(T)$, using the linear relation (1) between T and V ($V = \alpha T$) at $T^2 \gg T_0^2$:

$$R_{\rm mc}^{\rm theo}(T) = R_{\rm mc}^{\rm theo}(V/\alpha) = \pi/2 \left[\int_0^V R_D^{-1}(v)(V^2 - v^2)^{-1/2} dv \right]^{-1}.$$

Figure 2 shows experimental results on the microcontact resistance versus the temperature,[2)] $R_{\rm mc}(T)$, in comparison with $R_{\rm mc}^{\rm theo}(T)$. In order to bring the extrema of the $R_{\rm mc}^{\rm theo}(T)$ curve into coincidence with those of the $R_{\rm mc}(T)$ curve, we need to assign L in (1) the value 1.25×10^{-7} V^2/K^2; i.e., we need $L/L_0 \approx 5$, where L_0 is the standard value for the Lorentz number. We see that there is a good correlation between the calculated and experimental curves in both shape and absolute values; the significant discrepancy at $T < 6$ K is due to a violation of the inequality $T^2 \gg T_0^2$. The value $L/L_0 \approx 5$ which we find in the interval 10–100 K agrees satisfactorily with the data of Ref. 3 in view of the strong dependence of the properties of $CeCu_2Si_2$ on the direction in the single crystal, on the structural quality, and on the stoichiometry. For a more precise comparison with experiment, we would need to correct the theory of the thermal regime for the temperature dependence $L(T)$, and we would also need to take into account the circumstance that the strong electron-electron interaction in $CeCu_2Si_2$ may make the effective temperature of the electron subsystem different from the lattice temperature.

3. The main distinguishing feature of the $R_D(V)$ curves for $CeCu_2Si_2$-Cu heterocontacts is their asymmetry with respect to the $V = 0$ axis (Fig. 1b). An asymmetry of

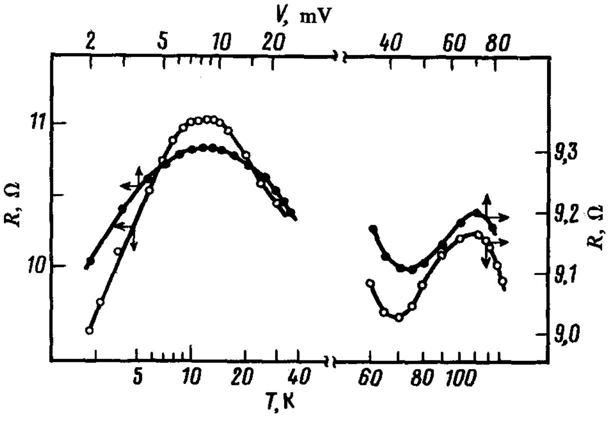

FIG. 2. Comparison of the experimental (○) temperature dependence of the resistance of a $CeCu_2Si_2$ microcontact with the theoretical (●) behavior. The V scale is drawn in accordance with Eq. (1), where $L = 1.25 \times 10^{-7}$ V^2/K^2 and $T_0 = 0$.

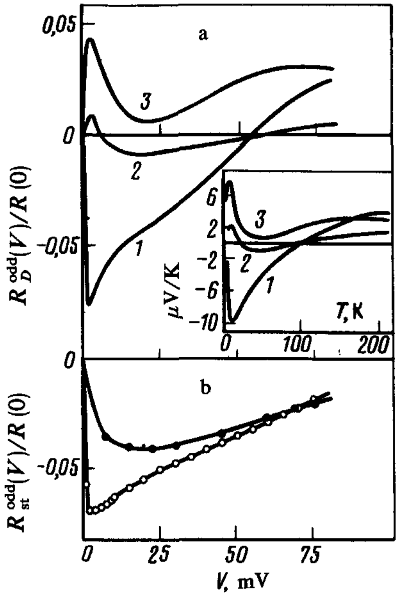

FIG. 3. a—Experimental results on $R_D^{odd}(V)$ for heterocontacts between Cu and (1) $CeCu_2Si_2$, (2) $Ce_{0.7}La_{0.3}Cu_2Si_2$, and (3) $Ce_{0.3}La_{0.7}Cu_2Si_2$. The inset shows $S(T)$ for these compounds[4]; b—comparison of the theoretical dependence $R_{st}^{odd}(V)/R(0)$, calculated from (2), for a $CeCu_2Si_2$-Cu heterocontact (●) with experimental data (○).

$R_D(V)$ curves has been observed previously for heterocontacts of Mo or Pt with a valence fluctuation compound[8,9] and, by O. I. Shklyarevskiĭ, A. G. M. Jansen,[3] I. K. Janson, and the first two of the present authors for heterocontacts of a normal metal with a ferromagnetic metal and with dilute magnetic alloys, Cu-Fe and Cu-Mn (the results are to be published). It has been suggested in these studies that the observed asymmetry may be due to a manifestation of the Seebeck and/or Peltier effect in the thermal regime. That these effects do influence the asymmetry of $R_D(V)$ is shown clearly by the correlation between the odd part of the differential resistance, $R_D^{odd}(V)=\frac{1}{2}[R_D^+(V)-R_D^-(V)]$, of heterocontacts of copper with $CeCu_2Si_2$ and of two of its alloys, and the absolute thermal emf of these substances (see Fig. 3 and the inset). This correlation has been mentioned[9] for other compounds.

Analyzing these effects, we find that we would have

$$R_{st}^{odd}(V)/R(0) \simeq \int_{T_0}^{T} [S_1(T)-S_2(T)]dT/V \qquad (2)$$

in the case of the Seeback effect or

$$R_{st}^{odd}(V) \simeq \partial R_{st}/\partial T[S_1(T)-S_2(T)]T^2/V \qquad (3)$$

in the case of Peltier effect, where $R_{st}^{odd}=(1/2)(R_{st}^+-R_{st}^-)$, R_{st}^+ and R_{st}^- are the static resistances of the microcontact for the two polarities $[R_{st}=V/I(V)=V/\int_0^V R_D^{-1}(v)dv]$, and S_1, and S_2 are the thermal emf's of the materials in the contact.

Figure 3b shows the resistance R_{st}^{odd} calculated from (2), in comparison with experimental results. In these calculations we used data from Ref. 1 on $S(T)$, and we assumed a linear relation between V and T, $V=(0.7\ \mathrm{mV/K})T$, in accordance with the conclusions of the preceding section. We see that the experimental and theoretical results agree well at $V\gtrsim 50$ mV, but at energies $eV\sim 10$ meV or at temperatures $T\sim 10$ K there is a substantial discrepancy between the curves. The Peltier effect does not improve the agreement, since its contribution is several times smaller than that of the Seeback effect according to (3) with $V\approx 5$ mV ($\partial R_{\mathrm{st}}/\partial T$ reaches a maximum value $\sim 0.1\ \Omega/\mathrm{K}$ at $R_{\mathrm{st}}\approx 10\ \Omega$).

In summary, the asymmetry of $R_D(V)$ of heterocontacts cannot be explained entirely by thermoelectric effects, especially at $T\sim 10$ K, where there is a sharp maximum in the density of electronic states of $CeCu_2Si_2$. As the temperature is raised, this maximum on the curve of $g(\epsilon)$ at $\epsilon=\epsilon_F$ becomes rounded, and (Fig. 3b) the difference between the theoretical and experimental values of $R_{\mathrm{st}}^{\mathrm{odd}}$ decreases. These circumstances indicate that the asymmetric feature on $g(\epsilon)$ in $CeCu_2Si_2$ is apparently responsible for the asymmetry of $R_D(V)$ at low energies.

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[2)]Knowing the functional dependence $R_{\mathrm{mc}}(T)$, we can estimate the size (d) of the contact and the elastic electron mean free path l_i, in accordance with Ref. 7. We find $d\sim 2000$ Å and $l_i\sim 5$ Å for the contact in Fig. 1a. Consequently, the condition $d\gg l_i$, one of the necessary conditions for the thermal regime, is satisfied.[6]

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[1]W. Franz *et al.*, Z. Phys. **B31**, 7 (1978).

[2]F. Steglich *et al.*, Phys. Rev. Lett. **43**, 1892 (1979).

[3]H. Schneider *et al.*, Solid State Commun. **48**, 1093 (1983).

[4]F. G. Aliev *et al.*, J. Low Temp. Phys. **57**, 61 (1984).

[5]A. G. M. Jansen, A. P. van Gelder, and P. Wyder, J. Phys. C **13**, 6073 (1980).

[6]B. I. Verkin *et al.*, Izv. Akad. Nauk SSSR, Ser. Fiz. **44**, 1330 (1980).

[7]A. I. Akimenko *et al.*, Fiz Nizk. Temp. **8**, 260 (1982) [Sov. J. Low Temp. Phys. **8**, 130 (1982)].

[8]B. Bussian, F. Frankowski, and D. Wohlleben, Phys. Rev. Lett. **49**, 1026 (1982).

[9]E. Paulus and G. Voss, in: Proceedings of the Fourth International Conference on Valence Fluctuations, Cologne, FRG, 1984.

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