Effect of the pressure and magnetic field on the temperature-dependent resistivity of heavy-fermion systems

Alexandre S. Rozhavsky, Alexandre M. Zagoskin,* Yurij G. Naidyuk, and Igor G. Tuluzov
Institute for Low Temperature Physics and Engineering, Ukrainian Academy of Sciences, Lenin Ave. 47, 310164 Kharkov, Ukraine
(Received 27 November 1991; revised manuscript received 16 July 1992)

The dependence of the resistivity on the pressure and magnetic field is analyzed for certain heavy-fermion compounds over a wide temperature range. The experimental data are well explained by a free-electron two-band-hybridization model, provided that a self-consistent calculation of the chemical potential is made.

Heavy-fermion systems (HFS) have been of considerable and continuing interest to physicists, since their discovery because of their anomalous transport and thermodynamic properties at moderately low temperatures. In particular, the electrical resistivity $\rho(T)$ is anomalously large compared with that in normal metals and, as a rule, there is a maximum at $T=T_{\max}$ or roll-off on the $\rho(T)$ curve in the interval $T\simeq 10-100$ K (for reviews, see, e.g., Refs. 1–3).

Treatment of these HFS anomalies traditionally appeals to a giant density of states (DOS) on the Fermi level associated with f-electron weak delocalization. The DOS enhancement finds its natural explanation within the periodic Anderson model (PAM) (see, e.g., Ref. 3). The pressure dependence of $\rho(T)$ at temperatures far from $T_{\max}$ has been calculated within the PAM in Ref. 4. However, to explain the dependence of the nonmonotonic part of the $\rho(T)$ curve upon external perturbation, it is more convenient to proceed with the mean-field version of the PAM: the two-band-hybridization model (TBHM) (see, e.g., Refs. 5–8).

In the above-mentioned model the real band structure of the HFS is simulated by the hybridized f and s (d) bands (Fig. 1). The bare width of the f band, δ, is taken to be of the order of $10-10^2$ K, and the width of the s (d) band is of the order of $\varepsilon_F \gg\delta$). The hybridization potential is assumed to be in the range 10^2-10^3 K.

The DOS is a sharp function of energy in the region $\varepsilon\simeq\delta$. This leads to a strong dependence of the chemical potential $\mu(T)$ on the temperature,[7] thus giving rise to a nontrivial temperature behavior of thermodynamic and kinetic coefficients at $T\sim\delta$. In particular, the $\rho(T)$ maximum or roll-off appears as a result of an interplay between the increase of the charge carriers' group velocity and the enhancement of electron-phonon scattering.[5,6,8] A different mechanism for $T_{\max}$ based on the idea of correlated Kondo vacuum, has been proposed in Ref. 9.

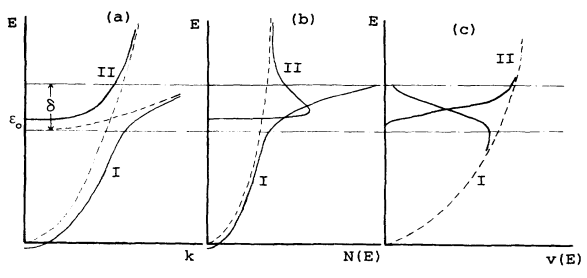

FIG. 1. Two two-band-hybridization model of HFS: The dispersion law (a), the DOS (b), and the group velocity (c).

In this paper we present correlations between the calculated shift of the chemical potential under pressure and in a magnetic field and the experimental data, and argue that the good agreement found favors TBHM.

The expressions for $T_{\max}$ and $\rho(T)$ are very cumbersome, and it is worthwhile making simple qualitative estimates based on the exact formulas given in Ref. 8.

The $\rho(T)$ maximum position is

$$T_{\max}\approx\frac{\mu(0)-\varepsilon_0}{|d\mu/dT|}\approx\frac{\delta}{|d\mu/dT|}\ , \tag{1}$$

where $d\mu/dT\approx-\text{const}\times[\varepsilon^*-\mu(0)]$ (Refs. 7 and 8), and ε^* lies inside the bare f band. The values of ε^* and of the constant prefactor can be calculated numerically for a given real band structure.

For the materials considered, $T_{\max}\simeq 5-100$ K. It follows from (1) that a variation of the chemical potential at zero temperature, $\Delta\mu$ leads to the corresponding variation of $T_{\max}$.

$$\frac{\Delta T_{\max}}{T_{\max}}\approx\frac{\Delta\mu}{\delta}\ . \tag{2}$$

This simple estimate is basic in a description of the deviation of the $\rho(T)$ dependence under pressure and in a magnetic field from the one at $P=0$, $H=0$.

Let us first discuss the effect of pressure P. To estimate $\Delta\mu(P)$, we make use of the following simple relation for a free-electron gas:

$$\frac{\Delta\mu}{\mu}=\frac{2}{3}\frac{\Delta n}{n}=\frac{2}{3}\kappa P\ , \tag{3}$$

where

$$\kappa=-\frac{1}{V}\frac{\partial V}{\partial P}\geq 10^{-3}\,\text{kbar}^{-1}$$

is the material compressibility. Taking the value $\delta/\mu(0)\approx 5\times10^{-3}$ (as it follows for $CeCu_6$ from a comparison between the heat-capacity coefficient γ of this HFS

and its non-f homolog, $LaCu_6$, Ref. 10), we obtain

$$\frac{\Delta T}{T} \approx \frac{2}{3}\frac{\mu(0)}{\delta}\kappa P \approx 0.13P(\text{kbar}) , \tag{4}$$

in good agreement with experimental data for the pressure dependence of T_{max} in $CeCu_6$ and UBe_{13}, Refs. 11–13 [Fig. 2(a)].

We can also estimate the resistivity shift under pressure at high temperature, $T \gg T_{max}$. Because the resistivity at a given temperature is proportional to the square of the DOS, we get

$$\frac{\Delta\rho}{\rho} \approx 2\frac{\Delta N(\mu(T))}{N(\mu(T))} . \tag{5}$$

It is natural to take $N(\mu(T)) \propto [\mu(T)]^{1/2}$ at $T \gg T_{max}$ and, under this assumption,

$$\left.\frac{\Delta\rho}{\rho}\right|_{T \gg T_{max}} \approx \frac{2}{3}\kappa P \geq 6\times 10^{-4} P(\text{kbar}) . \tag{6}$$

These estimates are also in reasonable agreement with the experimental data[11] [Fig. 2(a)].

Let us briefly discuss the effect of a magnetic field on $\rho(T)$. The difference between the $\rho(T)$ curves measured for CeB_6 at various magnetic fields[14] is washed out above temperatures $T(H)$. These temperatures depend linearly on the magnetic field,

$$T(H) \approx kH , \tag{7}$$

with the coefficient $k \simeq 10\mu_B$, μ_B being the Bohr magneton.

To us, Eq. (7) appears to support unambiguously the idea of spin splitting of the f band being the net effect of a magnetic field on HFS, as was claimed in Ref. 15. The quantity $g \sim 10$ is a reasonable value of the g factor.

Now substitute $\Delta\mu = g\mu_B H$ into Eq. (2). The estimate for ΔT_{max} then reads

$$\frac{\Delta T_{max}}{T_{max}} \approx \frac{g\mu_B H}{\delta} . \tag{8}$$

This equation fits the experimental data for CeB_6 both qualitatively and quantitatively if we take $g \simeq 10$ and $\delta \simeq 20$ K. This value of bandwidth δ has been deduced from tunnel point-contact experiments.[16]

Finally, it is worthwhile commenting on the point-contact-spectroscopy measurements performed on CeB_6.[17] The ratio $\Delta V_{max}/V_{max}$ for the symmetric and antisymmetric parts of the differential resistance $R_D(V)$ of the point heterocontact are plotted on Fig. [2(b)]. These two contributions to $R_D(V)$ straightforwardly reflect the temperature dependence of the bulk resistivity and thermopower coefficient because of the direct connection between the voltage applied to the point contact and the temperature of the contact region.[17] Results concerning the thermopower temperature dependence in point contacts, based on the TBHM model, will be given elsewhere.

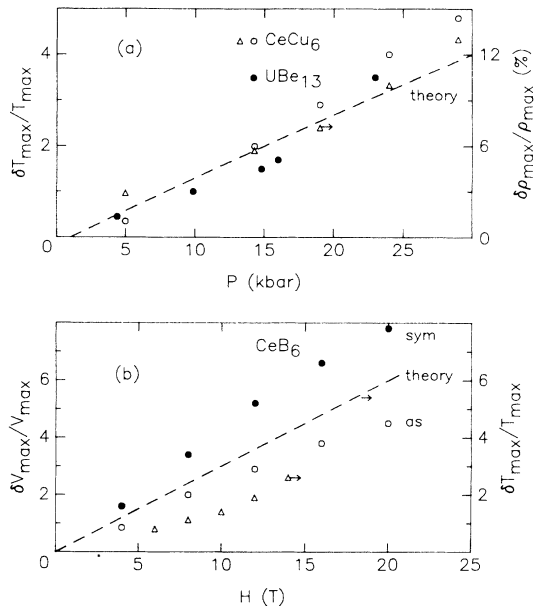

FIG. 2. (a) Experimental data for the pressure dependence of $\Delta T_{max}/T_{max}$ for $CeCu_6$ (Ref. 11) and UBe_{13} (Refs. 12 and 13), and $\Delta\rho/\rho$ (at 200 K) for $CeCu_6$, (Ref. 11) together with theoretical curve plotted according to Eqs. (4) and (6) with $\kappa = 10^{-6}\,\text{bar}^{-1}$, $\delta/\mu(0) = 5\times 10^{-3}$. (b) Experimental data for the magnetic field dependence of $\Delta T_{max}/T_{max}$ for CeB_6 (Ref. 14) and $\Delta V_{max}/V_{max}$ for the symmetric and antisymmetric parts of R_D in a point contact (Ref. 17) together with the theoretical curve plotted according to Eq. (7) with $g = 10$, $\delta \approx 2$ meV.

We have presented here a direct comparison of the theoretically estimated $\rho(T)$-curve shifts under pressure and in a magnetic field with the experimental data. The results favor the TBHM.

We are grateful to Professor I. O. Kulik and Professor I. K. Yanson for support and fruitful discussions.

*Present address: Institute of Theoretical Physics, Chalmers University of Technology, S-412 96 Göteborg, Sweden.

[1] P. A. Lee, T. M. Rice, J. W. Serene, L. J. Sham, and J. W. Wilkins, Comments Condens. Matter Phys. XII, 99 (1986).
[2] G. R. Stewart, Rev. Mod. Phys. **56**, 775 (1984).
[3] D. M. Newns and N. Read, Adv. Phys. **36**, 799 (1987).
[4] A. Auerbach and K. Levin, Phys. Rev. B **34**, 3524 (1986).
[5] P. Entel, B. Muhlschlegel, and Y. Ono, Z. Phys. B **38**, 227 (1980).
[6] F. Marabelli, P. Wachter, and J. J. M. Frause, J. Magn. Magn. Mater. **62**, 287 (1986).
[7] A. S. Rozhavsky and I. G. Tuluzov, Fiz. Nizk. Temp. **16**, 172 (1990) [Sov. J. Low Temp. Phys. **16**, 95 (1990)].
[8] A. M. Zagoskin, A. S. Rozhavsky, and I. G. Tuluzov, Fiz. Nizk. Temp. **17**, 1176 (1991); **18**, 265 (1992) [Sov. J. Low Temp. Phys. **17**, 617 (1991); **18**, 138 (1992)].
[9] H. Schweitzer and G. Czycholl, Phys. Rev. Lett. **67**, 3724 (1991).
[10] M. Springford and P. H. P. Reinders, J. Magn. Magn. Mater. **76&77**, 11 (1988).

[11]A. Shibata, G. Oomi, Y. Onuki, and T. Komatsubara, J. Phys. Soc. Jpn. **55**, 2086 (1986).
[12]J. D. Thompson, M. W. McElfresh, J. O. Willis, Z. Fisk, J. L. Smith, and M. B. Maple, Phys. Rev. B **35**, 48 (1987).
[13]S. Y. Mao, D. Jaccard, J. Sierro, Z. Fisk, and J. L. Smith, J. Magn. Magn. Mater. **76&77**, 241 (1988).
[14]A. Takase, K. Kojima, T. Komatsubara, and T. Kasuya, Solid State Commun. **36**, 461 (1988).
[15]F. Marabelli and P. Wachter, J. Magn. Magn. Mater. **70**, 364 (1987).
[16]S. Kunii and O. Kagaya, J. Magn. Magn. Mater. **52**, 165 (1985).
[17]Yu. G. Naidyuk, M. Reiffers, A. G. M. Yansen, P. Wyder, and I. K. Yanson, Z. Phys. B **82**, 221 (1991).