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Magneto-transport properties of heavy-fermion systems

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Abstract. Starting from the two-conduction-band Anderson lattice model, the magneto-transport properties of heavy-fermion systems are studied in the slave-boson mean-field theory. The residual magnetoresistivities induced by different kinds of impurity are calculated, and the experimentally detected positive maximum structure in the residual magnetoresistance of heavy-fermion systems is reproduced. The transition of field-dependent resistivity from non-monotonic to monotonic behaviour with increasing temperature can be explained naturally by including the charge fluctuation effect. The influences of applied pressure are also investigated.

1. Introduction

Of all the properties that have been revealed in the heavy-fermion (HF) compounds, the anomalous magnetoresistance (MR) is probably one of the most interesting and puzzling questions. It is found that, for most HF compounds which have non-magnetic order and non-superconducting ground states, the MR changes sign from negative to positive when the temperature decreases, and a positive maximum in a certain magnetic field h_M has been confirmed at very low temperatures [1–7]. Applied pressure also changes the magneto-transport properties of HF systems dramatically [4, 5]. All these anomalies should be related to the normal ground-state properties.

In recent years, much theoretical attention has been attracted by the anomalous low-temperature magneto-transport properties, because the correct description of the normal ground state of HF systems must contain a reasonable interpretation of these anomalies. Until now, there have been many kinds of viewpoint about the origin of the novel MR. Sumiyama *et al* [2] studied the transport properties in both single-crystal $CeCu_6$ and alloy $Ce_{1-x}La_xCu_6$ systems; they found that a positive MR could only exist in the dense case at very low temperatures, and they explained it as a sign that the material was entering the coherent state. Kawakami and Okiji [8] proposed that a positive MR is produced by a gap-like structure in the density of states (DOS) of quasi-particles as a result of coherent scattering between conduction and f electrons. Since only the charge fluctuation term was considered in [8], they failed to reproduce the experimental result of the positive residual MR. Ohkawa [9] first ascribed the positive residual MR of HF systems to local disorder of ligands around f ions, and some of the experimental results have been explained by him, but in Ohkawa's formalism, the correlation between different f sites is ignored. Therefore, the slave-boson formalism is a more appropriate approach. Recently, interesting experiments have focused on the influence of applied pressure on the MR of HF systems [4, 5]. It is believed that these results provide an effective way to probe the microscopic origin of the

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anomalous MR in HF compounds, and a theoretical study of the pressure effect is needed. The aim of this paper is to study the magneto-transport properties of the HF compounds on the basis of a two-conduction-band Anderson lattice model, where the inter-site correlation has been included. We attempt to provide a reasonable explanation for the anomalous MR of HF systems, including the effects of pressure and thermal fluctuation at finite temperatures. Our results show that there is a significant magnetic field dependence of the residual resistivity produced by the disorder of conduction–f-electron mixing and the appearance of Kondo holes. The transition from non-monotonic to monotonic behaviour of the MR with increasing temperature as well as the effects of pressure are also explained. The rest of this paper is organized as follows. The influence of the magnetic field on the normal ground state of HF systems is studied in section 2. The variation in residual resistivity caused by disorder in the magnetic field is calculated in section 3. In section 4, we discuss the field-dependent resistivity of HF compounds at finite temperatures. The effect of pressure on MR is studied in section 5. Finally, in section 6 we present the conclusions.

2. The normal ground state of HF systems in a magnetic field

In the study of the normal ground state of HF systems, the $U = \infty$ Anderson lattice model is referred to as a good starting point [10]. In order to obtain a metallic ground state, more than two conduction bands should be considered, as proposed by Ohkawa [11]. In the present article, we assume that there are two conduction bands mixed with f electrons in the system. If we make use of the slave-boson technique introduced by Barnes [12] and Coleman [13], the two-conduction-band Anderson lattice Hamiltonian can be written as [14]

$$H = \sum_{i=1,2}\sum_{k\tau}\epsilon_{ik}c^{+}_{ik\tau}c_{ik\tau} + \sum_{l\tau}E_0 f^{+}_{l\tau}f_{l\tau} + V\sum_{i}\sum_{l\tau}(c^{+}_{il\tau}f_{l\tau}b^{+}_{l} + f^{+}_{l\tau}c_{il\tau}b_{l}) \tag{1}$$

with a constraint reflecting the strong on-site f–f correlation given by

$$\sum_{\tau} f^{+}_{l\tau}f_{l\tau} + b^{+}_{l}b_{l} = 1 \tag{2}$$

where $\tau = \pm 1$ is the spin index, $c_{ik\tau}(f_{l\tau})$ is the annihilation operator of the ith conduction band (localized) electron in the Bloch (Wannier) representation. For simplicity, we introduce two conduction bands with the same dispersion ϵ_{ik} and assume that the two conduction bands are expressed as

$$\epsilon_{1,2k} = \epsilon_k \pm \epsilon_0 \tag{3}$$

with the constant DOS of the unperturbed conduction electrons given by

$$\rho(\epsilon) = \frac{1}{N}\sum_{k}\delta(\epsilon - \epsilon_k) = \begin{cases} \dfrac{1}{2D} & |\epsilon| \leqslant D \\ 0 & |\epsilon| > D. \end{cases} \tag{4}$$

We suppose that the effect of the applied magnetic field is to add a Zeeman term in the energies of both the conduction and the f electrons without changing the mixing strength V:

$$\epsilon_{ik\tau} = \epsilon_{ik} + \tau g_c \mu_B B \tag{5}$$

$$E_{0\tau} = E_0 + \tau g_f \mu_B B \tag{6}$$

where the orbital effect of the magnetic field is neglected. For simplicity, we set $g_c = g_f = g$ and define a reduced magnetic field $h \equiv g\mu_B B$; then equations (5) and (6) can be rewritten as $\epsilon_{ik\tau} = \epsilon_{ik} + \tau h$ and $E_{0\tau} = E_0 + \tau h$, respectively. In the mean-field approximation, both b and b^+ can be replaced by a c-number r. Including the constraint (2), we obtain the following effective Hamiltonian from equation (1):

$$H' = \sum_{ik\tau} \epsilon_{ik\tau} c^+_{ik\tau} c_{ik\tau} + \sum_{l\tau} E_{f\tau} f^+_{l\tau} f_{l\tau} + rV \sum_{il} \sum_{\tau} (c^+_{il\tau} f_{l\tau} + f^+_{l\tau} c_{il\tau}) + N\lambda(r^2 - 1) \tag{7}$$

where N is the number of lattice sites and

$$E_{f\tau} = E_{0\tau} + \lambda. \tag{8}$$

λ is the Lagrange multiplier. r and the mean-field parameter λ are determined by the minimum condition of free energy, which can be expressed as

$$\sum_{\tau} \langle f^+_{l\tau} f_{l\tau} \rangle + r^2 = 1 \tag{9}$$

$$2\lambda r + V \sum_{i\tau} \langle f^+_{l\tau} c_{il\tau} + c^+_{il\tau} f_{l\tau} \rangle = 0. \tag{10}$$

In our model, we assume that there are in total three electrons per site (i.e. the half-filled case), and the chemical potential μ is then determined by

$$\sum_{\tau} \langle f^+_{l\tau} f_{l\tau} \rangle + \sum_{i\tau} \langle c^+_{il\tau} c_{il\tau} \rangle = 3. \tag{11}$$

The Hamiltonian (7) can also be written in matrix form as

$$H' = \sum_{k\tau} \begin{bmatrix} c^+_{1k\tau} & c^+_{2k\tau} & f^+_{k\tau} \end{bmatrix} \tilde{\mathbf{E}}_\tau(k) \begin{bmatrix} c_{1k\tau} \\ c_{2k\tau} \\ f_{k\tau} \end{bmatrix} + N\lambda(r^2 - 1) \tag{12}$$

where

$$\tilde{\mathbf{E}}_\tau(k) = \begin{bmatrix} \epsilon_{1k\tau} & 0 & rV \\ 0 & \epsilon_{2k\tau} & rV \\ rV & rV & E_{f\tau} \end{bmatrix} \tag{13}$$

and the corresponding Green function (GF) is

$$G_\tau(k,\omega) = [\omega - \tilde{\mathbf{E}}_\tau(k)]^{-1} = (1/A_\tau) \times \begin{bmatrix} (\omega - E_{f\tau})(\omega - \epsilon_{2k\tau}) - r^2V^2 & r^2V^2 & rV(\omega - \epsilon_{2k\tau}) \\ r^2V^2 & (\omega - E_{f\tau})(\omega - \epsilon_{1k\tau}) - r^2V^2 & rV(\omega - \epsilon_{1k\tau}) \\ rV(\omega - \epsilon_{2k\tau}) & rV(\omega - \epsilon_{1k\tau}) & (\omega - \epsilon_{1k\tau})(\omega - \epsilon_{2k\tau}) \end{bmatrix} \tag{14}$$

where

$$A_\tau = (\omega - E_{f\tau})(\omega - \epsilon_{1k\tau})(\omega - \epsilon_{2k\tau}) - 2r^2V^2(\omega - \epsilon_{k\tau}). \tag{15}$$

From equations (7), (9)–(11), we can determine the variation in the mean-field parameters $r(h)$, $E_f(h)$ and chemical potential $\mu(h)$ with the magnetic field [15]. It is also easy to obtain the Kondo temperature in zero magnetic field as in [14]:

$$T_{K0} = 1.13\sqrt{D^2 - \epsilon_0^2} \exp(-D|E_0|/2V^2). \tag{16}$$

3. Residual magnetoresistivity

In a perfect lattice, there should be no residual resistivity but, in a realistic metal, there must be some impurities and defects which have little influence on the thermodynamic properties but have a large effect on the transport properties. Therefore, one must include the effect of disorder due to the impurities.

We consider now a situation where there are $c_I N$ impurities distributed randomly on the atomic sites of conduction bands in an HF compound, where c_I is the concentration of impurities. These impurities will change the cell volume of the impurity sites. From experiments it is found that the characteristic temperature T_K of HF systems changes dramatically under an applied pressure [16, 17]. So it is widely believed that the conduction–f-electron mixing strength is sensitive to the variation in cell volume, and the change in conduction–f-electron mixing strength may be significant even though the cell-volume change due to the impurity is small. Comparatively, the energy shift of both conduction and f electrons induced by the small cell-volume change can be neglected. For simplicity, we assume that the changes in the conduction–f-electron mixing strength in all the impurity sites have the same value ΔV. Therefore, the disorder Hamiltonian induced by impurities in conduction bands can be written as

$$H_{\rm dis} = \sum_{j\in\psi,\tau} \begin{bmatrix} c^+_{1j\tau} & c^+_{2j\tau} & f^+_{j\tau} \end{bmatrix} \Delta \mathbf{H} \begin{bmatrix} c_{1j\tau} \\ c_{2j\tau} \\ f_{j\tau} \end{bmatrix} \tag{17}$$

with

$$\Delta \mathbf{H} = \begin{pmatrix} 0 & 0 & r\Delta V \\ 0 & 0 & r\Delta V \\ r\Delta V & r\Delta V & 0 \end{pmatrix} \tag{18}$$

where ψ is the set of the impurity sites.

In the dilute limit of the coherent-potential approximation (CPA) when $c_I \ll 1$, the correlation of impurities is negligible, and the effect of the impurity scattering can be represented by an effective medium as [18]

$$\mathbf{\Sigma}_\tau(\omega) \equiv \begin{pmatrix} \Sigma_{11} & \Sigma_{12} & \Sigma_{1f} \\ \Sigma_{21} & \Sigma_{22} & \Sigma_{2f} \\ \Sigma_{f1} & \Sigma_{f2} & \Sigma_{ff} \end{pmatrix} = \frac{c_I \Delta \mathbf{H}}{1 - \mathbf{F}_\tau(\omega)\Delta \mathbf{H}} \tag{19}$$

where

$$\mathbf{F}(\omega) \equiv \begin{pmatrix} F_{11} & F_{12} & F_{1f} \\ F_{21} & F_{22} & F_{2f} \\ F_{f1} & F_{f2} & F_{ff} \end{pmatrix} \qquad F_{ij} = \frac{1}{N}\sum_k G_{ij}(k,\omega). \tag{20}$$

From equations (17)–(20), we obtain the solution of the effective medium as

$$\begin{aligned} &\Sigma_{11} = \Sigma_{12} = \Sigma_{21} = \Sigma_{22} = F_{ff}/B \\ &\Sigma_{1f} = \Sigma_{2f} = \Sigma_{f1} = \Sigma_{f2} = [1/(r\Delta V) - F_{1f} - F_{2f}]/B \\ &\Sigma_{ff} = (F_{11} + F_{12} + F_{21} + F_{22})/B \end{aligned} \tag{21}$$

where

$$B = [1/(r\Delta V) - F_{1f} - F_{2f}]^2 - F_{ff}(F_{11} + F_{12} + F_{21} + F_{22}). \quad (22)$$

The effective Hamiltonian including the effect of impurity scattering is

$$\tilde{H}(\omega) = \sum_{k\tau} \left[c^+_{1k\tau}\ c^+_{2k\tau}\ f^+_{fk\tau}\right] [\tilde{\mathbf{E}}_\tau(k) + \boldsymbol{\Sigma}_\tau(\omega)] \begin{bmatrix} c_{1k\tau} \\ c_{2k\tau} \\ f_{k\tau} \end{bmatrix} \quad (23)$$

and the corresponding GF reads

$$\tilde{G}_\tau(k,\omega) = [\omega - \tilde{\mathbf{E}}_\tau(k) - \boldsymbol{\Sigma}_\tau(\omega)]^{-1}. \quad (24)$$

Since the electrical conduction of HF systems arises mainly from conduction band electrons, the conductivity in the single-site CPA can be expressed as [19]

$$\sigma(T) = \frac{e^2}{3\pi\Omega m^2} \int_{-\infty}^{\infty} d\omega - \frac{\partial f}{\partial \omega} \sum_{k\tau} v_k^2 \times \left[\left\{\mathrm{Im}\left[\tilde{G}_{11\tau}(k,\omega + i0^+)\right]\right\}^2 + \left\{\mathrm{Im}\left[\tilde{G}_{22\tau}(k,\omega + i0^+)\right]\right\}^2\right] \quad (25)$$

where $f(\omega)$ is the Fermi–Dirac function. At zero temperature, the residual resistivity is determined by the relaxation time of conduction electrons on the Fermi surface, and equation (25) becomes

$$\sigma_0 = \frac{e^2}{3\pi\Omega m^2} \sum_{k\tau} \sum_{i=1,2} v_k^2(\mu) \left\{\mathrm{Im}\left[\tilde{G}_{ii\tau}(k,\mu + i0^+)\right]\right\}^2. \quad (26)$$

In the dilute impurity limit, equation (26) can be simplified as

$$\sigma_0(h) = \sigma_\uparrow(h) + \sigma_\downarrow(h) \quad (27)$$

where

$$\sigma_\tau(h) = (e^2/12\pi\Omega m^2 c_1) \{[D + E_\tau(\mu)](\alpha^2 + \beta^2)/\delta^2\} \times \left[1/\sqrt{(rV)^4 + \epsilon_0^2(\mu - E_f)^2}\right] \quad (28)$$

with

$$\alpha = (\mu - E_\tau + \epsilon_0)^2 [(rV)^2\Sigma_{ff} + 2(rV)(\mu - E_{f\tau})\Sigma_{1f} + (\mu - E_{f\tau})^2\Sigma_{11}] \quad (29)$$

$$\beta = (\mu - E_\tau - \epsilon_0)^2 [(rV)^2\Sigma_{ff} + 2(rV)(\mu - E_{f\tau})\Sigma_{1f} + (\mu - E_{f\tau})^2\Sigma_{11}] \quad (30)$$

$$\delta = [(\mu - E_\tau)^2 - \epsilon_0^2]\,\Sigma_{ff} + 2(\mu - E_{f\tau})(\mu - E_\tau)\Sigma_{11} + 4(rV)(\mu - E_\tau)\Sigma_{1f} \quad (31)$$

$$E_\tau(\mu) = \mu + (\mu - E_{f\tau})\epsilon_0^2 / \left[(rV)^2 + \sqrt{(rV)^4 + \epsilon_0^2(\mu - E_{f\tau})^2}\right]^2 - \tau h. \quad (32)$$

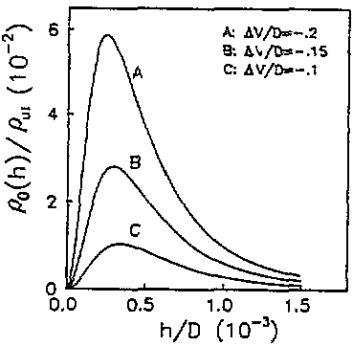

Figure 1. The residual MR induced by different parameters conduction–f mixing strength disorder ΔV, where $\rho_{u1} \equiv c_I e^2/3\pi\Omega m^2$.

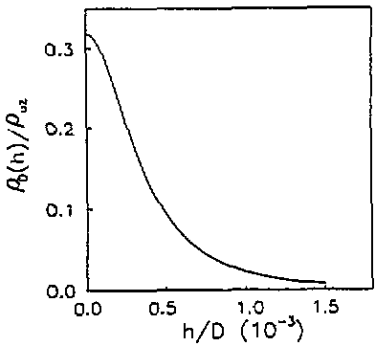

Figure 2. Kondo-hole-induced residual MR, where $\rho_{u2} \equiv c_K e^2/3\pi\Omega m^2$.

Figure 1 gives the numerical result of $\rho_0(h)$ with different values of the disorder parameter ΔV. We find that in a zero magnetic field the residual resistivity produced by the disorder of conduction–f-electron mixing strength is very small. In the presence of an external magnetic field, the residual resistivity increases dramatically, resulting in a large positive magnetoresistivity, and a maximum of magnetoresistivity emerges at non-zero magnetic field.

Besides the impurities in the conduction band, there is another kind of impurity, which is often called a Kondo hole. It is caused by substitution of non-f ions (La like) for f ions (Ce like), and it is equivalent to introducing an infinite potential in an f-electron energy level of impurity sites. Using the single-site CPA, Xu and Li [20] have studied alloy systems with this kind of substitution. They found a simple result for the effective medium [20]:

$$\Sigma(\omega) = -c_K \begin{pmatrix} 0 & 0 & 0 \\ 0 & 0 & 0 \\ 0 & 0 & 1/\Phi_{ff} \end{pmatrix} \tag{33}$$

where c_K is the concentration of Kondo holes, and

$$\Phi(\omega) = \frac{1}{N}\sum_k \left[\omega - \tilde{E}(k) - \Sigma(\omega)\right]^{-1}. \tag{34}$$

In the dilute limit, the Born approximation is valid, and equation (33) can be rewritten as

$$\Sigma_{ff}(\omega) = -c_K/F_{ff}(\omega) \tag{35}$$

where $F_{ff}(\omega)$ is the f-electron GF of the perfect lattice as shown in equation (20). Substituting equation (35) into equation (24), we may obtain the field dependence of the residual resistivity due to the effect of Kondo holes. The numerical result is sketched in figure 2. We find that the residual resistivity induced by Kondo holes decreases with increasing applied magnetic field, which is consistent with Ohkawa's [9] result.

In actual compounds, these two kinds of impurity should exist together. In the dilute limit, there is no correlation between these two sorts of disorder. From Matthiessen's rule, we have

$$\rho_0(h) = \rho_{0I}(h) + \rho_{0K}(h). \tag{36}$$

The variation in $\Delta\rho/\rho \equiv [\rho_0(h) - \rho_0(0)]/\rho_0(0)$ under zero applied pressure is shown later in figure 4 with $\Delta V = -0.2$, $c_I/c_K = 5$. We find that a positive maximum of the residual MR exists in a magnetic field h_M and also a crossover of the residual MR from positive to negative in h_X [21]; these have been observed in experiments on $CeCu_6$, $CeAl_3$, $CeRu_2Si_2$, etc [1,3–7].

4. Field dependence of the resistivity of HF compounds at finite temperatures

In the low-temperature region, the resistivity of HF systems has the form $\rho(T) = \rho_0 + AT^2$, where ρ_0 is the residual resistivity, and the T^2-term reflects the Fermi liquid behaviour. It has been proved in the $1/N_f$ expansion that the T^2-term results from charge fluctuations, and the coefficient A is proportional to $N(\mu)^2$ [10], where $N(\mu)$ represents the DOS of quasi-particles on the Fermi surface. Therefore, the field-dependent resistivity at finite temperatures takes the form

$$\rho(T,h) = \rho_0(h) + A(h)T^2 \tag{37}$$

with

$$A(h) = \eta N(\mu,h)^2 \tag{38}$$

where η is a suitable constant. In the present model, the DOS near the Fermi surface can be obtained as

$$N(\mu,h) = \sum_\tau \frac{(rV)^2}{2D(\omega - E_{f\tau})^2} \frac{\sqrt{(rV)^4 + \epsilon_0^2(\mu - E_{f\tau})^2} - r^2V^2}{\sqrt{(rV)^4 + \epsilon_0^2(\mu - E_{f\tau})^2}}. \tag{39}$$

In [15] we have shown that $N(\mu,h)$ decreases with increasing h because the quasi-particle bands with different spin orientations are split by the magnetic field. This is the so-called suppression effect of the magnetic field on the HF state, which leads to a reduction in $A(h)$ with increasing applied field (see figure 5 below). Hence, the charge fluctuations always contribute a monotonically decreasing T^2-term to the field-dependent resistivity $\rho(T,h)$ in the Fermi liquid regime. On the other hand, $\rho_0(h)$ in equation (37) represents the total residual resistivity induced by two kinds of impurity which shows a non-monotonic field dependence as discussed in section 3. The numerical results of equation (37) are given in figure 3, where the relations between the resistivity of HF systems and the magnetic field at different temperatures are presented. As the temperature increases from zero to a finite value, the resistivity curves change continuously from non-monotonic behaviour with a maximum at $h = h_M > 0$ to monotonic decreasing behaviour with $h_M = 0$. Therefore, the experimentally observed 'non-monotonic to monotonic' transition [1] of the field-dependent resistivity with increasing temperature is reproduced in our theory. We ascribe this transition to the competition between the impurity effect and charge fluctuations.

5. The influence of applied pressure

It is widely accepted that the applied pressure will increase the conduction–f-electron mixing strength dramatically because of the diminishing cell volume in the HF systems. Experimentally, an anomalously large electronic Grüneisen constant Γ of the order of 100 has been discovered [22], and Γ can be defined as

$$\Gamma \equiv -\partial(\ln T_K)/\partial(\ln \Omega) = (1/T_K\kappa)(\partial T_K/\partial P) \tag{40}$$

where κ is the compressibility.

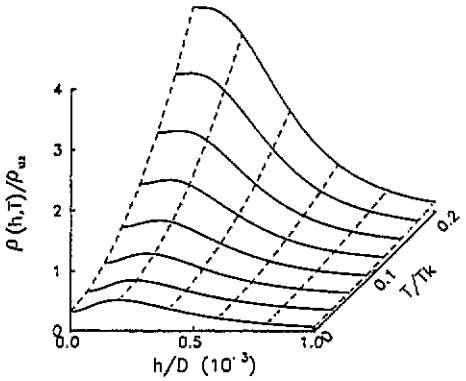

Figure 3. Field-dependent resistivity of HF systems at different temperatures, where $\rho_{\omega 2} = c_K e^2/3\pi\Omega m^2$.

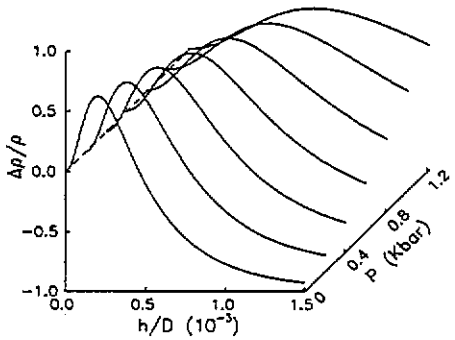

Figure 4. The variation in $\Delta\rho/\rho \equiv [\rho_0(h,P) - \rho_0(0,0)]/\rho_0(0,0)$ with magnetic field h and applied pressure P.

On the basis of this relation, we may discuss the effect of pressure. We assume that the applied pressure can change only the conduction–f-electron mixing strength $V(P)$ while E_0 and ϵ_0 remain unchanged. From equation (40), we obtain the relation between the Kondo temperature T_K and applied pressure P as

$$T_K/T_{K0} = \exp(\kappa\Gamma P). \tag{41}$$

On substitution of equation (41) into equation (16), it is easy to obtain the conduction–f-electron mixing strength $V(P)$ under an applied pressure P:

$$V(P) = V(0)\left\{1 - [2V(0)^2\Gamma\kappa/D|E_0|]P\right\}^{-1/2} \tag{42}$$

where $V(0)$ is the conduction–f-electron mixing strength under zero applied pressure, and Γ and κ can be determined from experimental data. By self-consistent calculation of equations (9)–(11) with equation (42), we may obtain the magnetic field and pressure dependence of the slave-boson mean-field parameters $r(h,P)$, $E_f(h,P)$ and $\mu(h,P)$, from which the influence of the pressure on the MR is obtained. In figure 4, we present the residual magnetoresistivity $\Delta\rho/\rho \equiv$

$[\rho_0(h,P)-\rho_0(0,0)]/\rho_0(0,0)$ of HF systems under different applied pressures where we have taken $\kappa = 2.16\times10^{-3}$ K bar^{-1} [16] and $\Gamma = 100$ [22]. Figure 4 shows that the residual MR is suppressed in a small field but enhanced in a relatively large field, and thus the values of h_M and h_X are increased by the applied pressure. These results are in good agreement with experiments [4, 5]. Furthermore, the experimentally revealed quasi-invariance of the residual resistivity ρ_0 with pressure [5] is also found in our calculation.

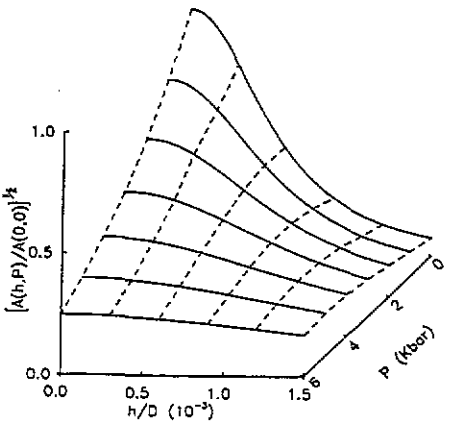

Figure 5. The variation in the T^2-coefficient of resistivity with magnetic field and applied pressure.

Figure 5 shows the variation in the T^2-coefficient A with magnetic field and pressure. In the absence of applied pressure, $A(h)$ decreases rapidly with increasing magnetic field which is consistent with the experimental data given by Amato *et al* [3]. The results in figure 5 also show that $A(P)$ decreases with increasing applied pressure in the weak-field region and then increases with the further increases in pressure when the magnetic field becomes strong enough. We think that this may be a new phenomenon due to the combined effect of the magnetic field and pressure.

6. Conclusions

On the basis of the two-conduction-band Anderson lattice model, we have studied the low-temperature magneto-transport properties of HF systems. We find that the impurity-induced disorder of the conduction–f-electron mixing strength may produce a positive residual MR with a maximum structure which is observed in experiments, whereas the residual resistivity induced by Kondo hole scattering decreases with increasing magnetic field and only a negative residual MR can be obtained from Kondo hole impurities. At finite temperature, charge fluctuations cause a T^2-term in the field-dependent resistivity, which also contributes a negative MR owing to the suppression of HF effects by the magnetic field. So the positive MR can exist only at extremely low temperatures, and there should be a continuous transition from a non-monotonic to a monotonic field-dependent resistivity with increasing temperature. Using the experimentally determined Grüneisen constant and compressibility, the influence of pressure is also investigated. The maximum point h_M and zero point h_X of the residual MR are found to increase under increasing applied pressure. All the above results are in qualitative agreement with experiments, which indicates that present theory provides a reasonable description of the MR of HF compounds.

Acknowledgments

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