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Hall effect in the normal state of high-T_c cuprates

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Abstract

We propose a model for explaining the results of the Hall effect measurements of high-T_c cuprates in the normal state, in various materials. They all show common features: a decrease of the Hall coefficient R_H with temperature and a universal law, when plotting $R_H(T)/R_H(T_0)$ versus T/T_0 where T_0 is defined from experimental results. This behaviour is explained by using the well known electronic band structure of a CuO_2 plane, showing saddles points at the energies E_S in the directions $[0, \pm\pi]$ and $[\pm\pi, 0]$. This is well confirmed by photoemission experiments. We remark that for the energies $E > E_S$ the carrier orbits are hole-like and for $E < E_S$ they are electron-like, giving opposite contributions to R_H. We are able to fit all experimental results for all doping, and to fit the universal curve. For us $k_B T_0$ is simply $E_F - E_S$, where E_F is the Fermi level varying with the doping.

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1. Introduction

Many measurements of the Hall effect in various high-T_c cuprates have been published [1–4]. The main results are the following:

(i) At low temperature T, $R_H \approx 1/p_{h0}e$, where p_{h0} is the hole doping. When T increases R_H decreases, and for slighty overdoped samples becomes even negative [1].
(ii) These authors are also able to define a temperature T_0, where R_H changes is temperature behaviour, and such $R_H(T)/R_H(T_0)$ versus T/T_0 is a universal curve for a large doping domain (from $p_{h0} = 0.10$ to $p_{h0} = 0.27$).

We show that we can explain these results by using the band structure for carriers in the CuO_2 planes, which are present in all these compounds.

2. Calculation of the Hall coefficient

The constant energy curves of carriers in the CuO_2 planes are well known both theoretically and experimentally [5–7]. From ARPES experimental results, it is very clearly seen [7] that the Fermi level (E_F) crosses the saddle points at E_S (or Van Hove singularities level) for a hole doping of $p_{h0} = 0.22$. For $E > E_S$ the orbits are hole-like, and for $E < E_S$ they are electron-like. To compute the Hall coefficient we use the formula obtained by solving the Boltzmann equation. In the limit of low magnetic fields B, perpendicular to the CuO_2 plane, $\mu_B \ll 1$, where μ is an average mobility of the carriers, R_H is given by:

$$R_H = \frac{\sigma_{xy}}{\sigma_{xx}^2}\frac{1}{B} \tag{1}$$

where σ_{xy} and σ_{xx} are the components of the conductivity tensor. We follow the approach given by Ong [8]:

$$\sigma_{xy} = \int_{E_{min}}^{E_{max}} \left(-\frac{\partial f_0}{\partial E}\right)\sigma_{xy}(E)\,\mathrm{d}E \tag{2}$$

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where f_0 is the Fermi Dirac distribution function, $E_{\min}$ and $E_{\max}$ are the bottom and the top of the band, and $\sigma_{xy}(E)$ is σ_{xy} computed on a constant energy surface. For metals, where $k_B T \ll E_F$, σ_{xy} is usually chosen as $\sigma_{xy} = \sigma_{xy}(E_F)$, computed on the Fermi surface only, this is done by Ong [8]. In our case, $k_B T$ is not small compared to $E_F - E_S$, so when T increases the electron-like orbits as well as the hole-like orbits are populated. The electron-like orbits give a negative contribution to R_H, so that R_H decreases with temperature. This is our original approach to the problem. To compute R_H, we use the following method: we compute first $\sigma_{xy}(E)$ using the Ong approach. The idea is to draw the $\vec{l}$ curve swept by the vector $\vec{l} = \vec{v}_k \tau_k$ as $\vec{k}$ moves around the constant energy curve (CEC). Then σ_{xy} reduces to:

$$\sigma_{xy} = \frac{2e^3}{\hbar^2} A_e B \tag{3}$$

where A_e is the area embraced by CEC curve. There may be secondary loops in the $\vec{l}$ curve. When the CEC is non-convex, the $\vec{l}$ curve presents several parts where the circulation are opposite (see Ref. [8], Fig. 2). Then the effective density of carriers that must be taken in computing R_H is $n'_e = \Gamma n_e$ for the electron-like orbits with $\Gamma < 1$, and $p'_h = p_h$ for the hole-like orbits, because for the hole-like orbits we can see that the CEC have no non-convex parts. Finally we obtain:

$$R_H = \frac{1}{e} \frac{p_h - b^2 n'_e}{(p_h + b(p_{h0} - p_h))^2} \tag{4}$$

where $b = \mu_e/\mu_h$ is the ratio of the mobilities on the electron (e) and hole (h) like orbits. To compute Γ, we must know the scattering mechanisms and evaluate Γ. Γ was computed by Ong [8] assuming a constant $\vec{l}$, but this is not valid in our case because $\vec{l}$ is very small near the saddle points (hot spots). So we estimated a much smaller value of Γ.

($\Gamma \approx 0.2$ for E near E_S). We also take $b = 1$.

3. Results

We present one of our results in Fig. 1. More complete results will be presented later. We see that the agreement of our fits with the experiments is excellent.

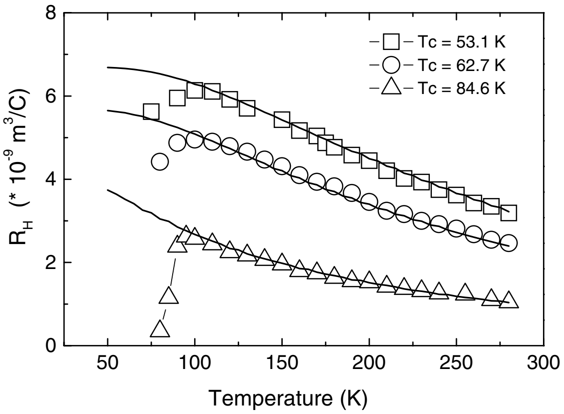

Fig. 1. Squares, circles, up-triangles: experimental values (Ref. [4]); Full lines: theoretical fits (hole doping from the top to the bottom $p_{h0} = 0.10, 0.12, 0.16$).

4. Conclusion

In conclusion, we find that the electronic structure of CuO_2 planes, with hole-like and electron-like orbits can explain the values of R_H for the high-T_c cuprates in the normal state and its behaviour with temperature, with practically no adjustable parameters.

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