

# Magnetoresistance

*Ralph C. Dougherty\**

*Received*

**DOI:**

*\*Department of Chemistry and Biochemistry, Florida State University, Tallahassee FL  
32306-4390: e-mail: ralphd@chem.fsu.edu*

When an external magnetic field interacts with a conductor it changes the motion of the conducting electrons unless the electrons are traveling precisely along the polar axis of the magnetic field or in a molecular wire. In the most general case, where the magnetic field axis crosses the crystal axis of the conductor at an arbitrary angle, other than  $0^\circ$  or  $\pi/2$ , the electron orbital angular momentum of the conducting electrons will change by a small arbitrary increment, as the electrons in a Hall effect cyclotron orbit move from one atomic plane to another to complete the cyclotron circuit. In general this will result in a shift in the conduction bands for the electrons to  $s$  basis set conduction bands. The reason for this is that  $s$  basis set bands are the only bands that can support arbitrary small changes in electron orbital angular momentum. The orbital angular momentum in  $s$  bands is always exactly zero, as are the arbitrary small increments. Understanding the need for shifts in conduction bands caused by external magnetic fields provides a direct explanation for the angular anisotropy of magnetoresistance in crystalline samples. Crystalline samples gave the first example of the quantum Hall effect, but it was not recognized as such at the time. The Meissner Ochsensfeld effect illustrates the exclusion of an external magnetic field by a superconductor. This exclusion comes from the required band shift to  $s$  basis set conducting bands to permit electron cyclotron motion in response to an arbitrary external magnetic field orientation. Any conduction in  $s$  basis conducting bands would resistively quench a superconductor through Fermi contact, the system free energy will also increase, so the external field is excluded as long as possible. Electron orbital angular momentum in the conduction bands of metals has major effects on the resistivity of metals. Like the preceding and following papers the treatment here is qualitative and based on simple quantum mechanical

arguments. The development of quantitative treatments along these lines has begun and appears to require only reasonable extensions of existing theory.

## I. INTRODUCTION

The Hall effect,<sup>1</sup> the quantum Hall effect,<sup>2,3</sup> angular anisotropy of magnetoresistivity,<sup>4,5</sup> and the Meissner Ochsensfeld effect,<sup>6</sup> are four phenomena that are important to developing an understanding of magnetoresistance in metals. The sources of insight are the effect of magnetic fields on resistivity, and the relationship that has to conducting electron orbital angular momentum.

Hall's original experiments measured the electrical potential at right angles to the current, in a thin metal sheet that was perpendicular to a magnetic field.<sup>1</sup> The measured potential is generated in these experiments by cyclotron motion of the electrons in the magnetic field and the electric field that drives the current. The electron cyclotron motion changes the path length for the current which results in the observed increase in resistivity with applied magnetic field.<sup>5</sup> The electron orbital angular momentum can also be influenced by the external magnetic field because of its connection with cyclotron motion.

If the current is flowing in a single atomic plane (that is, perpendicular to the magnetic field, in an oriented crystal), we know from the quantum Hall effect<sup>3,7</sup> that there will be no influence of the external magnetic field strength on the electron orbital angular momentum. Orbital angular momentum is the quantum number that changes in the quantum Hall effect.

When polycrystalline samples (or arbitrary angles of the applied magnetic field to the atomic planes) are used in the Hall experiment it is necessary for electrons to cross from one atomic plane to another in order to complete a cyclotron orbit. In crossing from one atomic plane to the next an electron will necessarily experience a small, arbitrary, change in orbital angular momentum. These changes are not

quantized, and so can be accommodated only in  $s$  basis wave functions. In  $s$  basis wavefunctions the orbital angular momentum is exactly zero, and all increments of the orbital angular momentum are zero. If the original conduction band in the metal had orbital angular momentum were greater than zero, a band shift will occur because of the requirement of small changes in electron orbital angular momentum as the electron shifts from one atomic plane in the lattice to the next in the Hall experiment (see the discussion of angular anisotropy of magnetoresistivity below).

Changes in electron orbital angular momentum in metals are quantized. Understanding this, is essential to understanding magnetoresistivity. For  $s$  basis wave functions the value of  $l$  is zero. No matter that the cyclotron motion of an electron is due to the presence of an external magnetic field, the orbital angular momentum for that electron in a  $s$  basis conduction band is zero. For wave functions with  $l > 0$ , angular momentum is quantized in units of  $\hbar$ . It is only possible to change orbital angular momentum only by the quantal increment, small, arbitrary, changes in electron orbital angular momentum are not possible in these conducting bands. The influence of magnetic fields on electron orbital angular momentum and conducting electron path length are two major factors in magnetoresistance.

## II. MAGNETORESISTANCE

Placing a conductor at an arbitrary orientation in a magnetic field induces a (thermally generated) current in the conductor that produces a magnetic field opposed to the inducing field. The change in electron path length is the major factor associated with the increase in resistivity observed when an active conductor is

placed in a magnetic field.<sup>5</sup> If the macroscopic nominally circular Hall current is confined to a single atomic plane in the metal lattice, the electron motion will generate a quantum Hall effect. The orbital angular momentum of the circulating electrons will be determined by the quantum state of the system, see, e.g., ref. 8.

We have analyzed the data in Figures 1 and 2 using the assumption that the electron current is confined to the metal-metal bonds in the lattice.<sup>4</sup> When the cyclotron plane of the Hall current is at a significant angle to one of the atomic planes of the lattice, electrons in cyclotron motion must jump from one atomic plane to another to complete their cyclotron orbit. In a classical view, these jumps between atomic planes would contribute small components of orbital angular momentum to the electrons in the conducting bands. In a quantum mechanical view, the electron orbital angular momentum for the jump from plane to plane can only happen in  $s$  basis function conduction bands because those bands have zero orbital angular momentum. Here the small arbitrary changes in electron orbital angular momentum are all exactly zero. This happens only in  $s$  basis wavefunctions.

The data in Figures 1 and 2 show that placing a conducting crystal in a magnetic field produces a change in resistivity that is dependent upon sample orientation of the crystal.<sup>4</sup> The resistivity of the sample is not observed to decrease below the zero external field resistivity. The resistivity sharply increases and decreases as a function of the sample orientation. (Figure 1).<sup>4</sup> We interpret this change in resistivity as reflecting a band shift for the conducting bands in the metal.

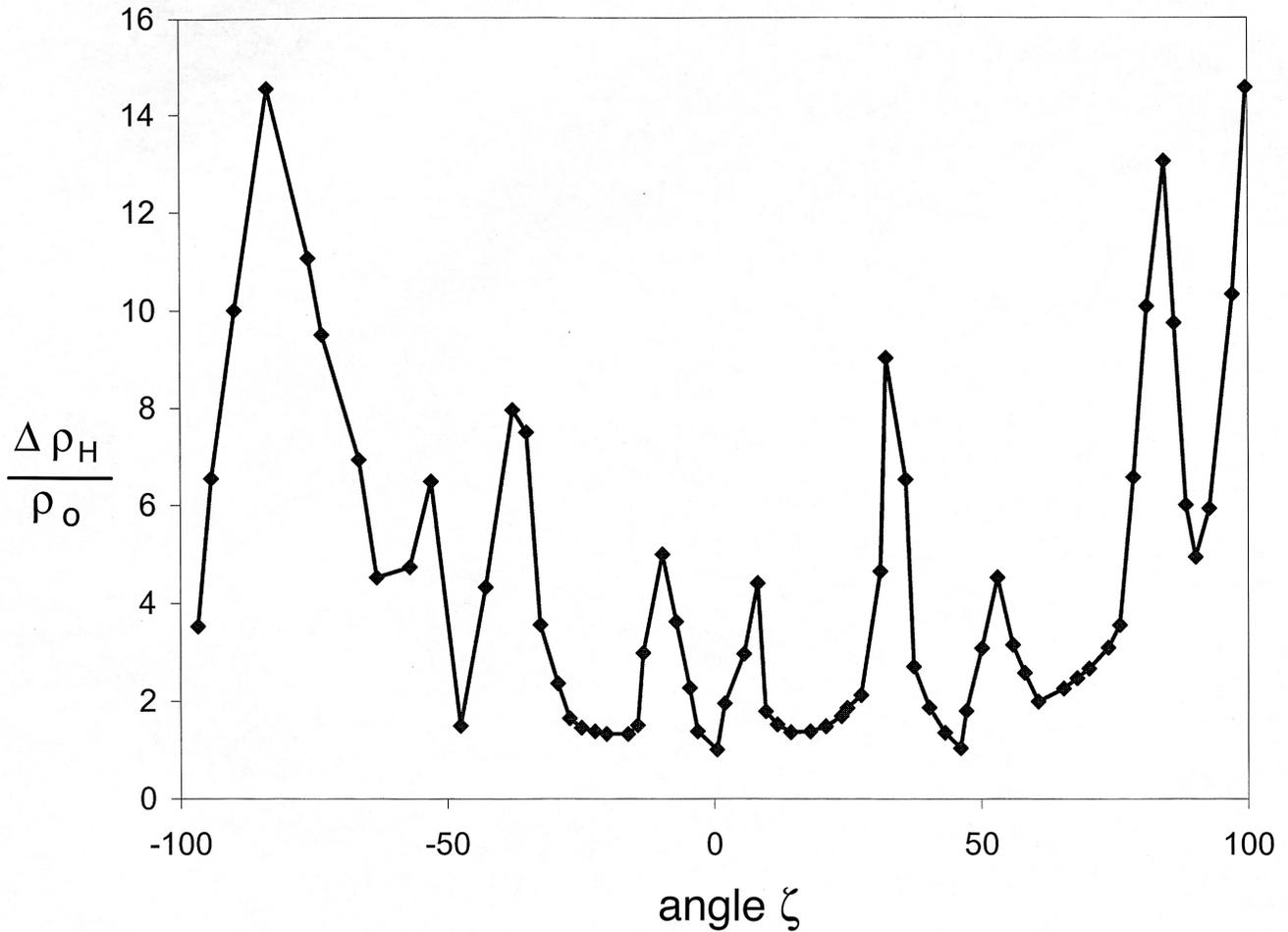


Figure 1: Magnetoresistance anisotropy of single crystal silver at 4.3 K.<sup>4</sup>

The magnetic field intensity for Figure 1 was 23,500 Oe, or 2.35 T. This is the saturation field strength of a conventional iron core electromagnet. The relative change in resistance is

$$\Delta Q_H / Q_0 = Q_H / Q_0 - 1.$$

Figure 1 shows that there are apparent shifts in the conduction bands as the axis of the crystal is rotated with reference to the static external magnetic field. The resistivity of a metal depends upon the basis sets for the conduction bands, the conduction path, and the absolute temperature.<sup>9</sup> The change in electron travel path

length for a small angle change in a crystal taken over a macroscopic length of the order of 1 cm would not be expected to be larger than a few percent. The maximum change in resistivity in Fig. 1 is of the order of a factor of 7. A shift in the conducting bands must have occurred. The peaks in Fig. 1 are double peaks. The minimum between the two peaks is coincident with the location of a plane of atoms at that particular angle.

The ratio of  $p/s$  scattering amplitude at 10 K using expression (8) of Ref. 9, is  $2 \times 10^{-6}$ . Using this number, it would take a very small shift from a  $p$  conduction band to a  $s$  conduction band to account for the observed factor of 10 or so increase in resistivity that occurred on either side of  $0^\circ$ ,  $45^\circ$ , and  $90^\circ$  in the data in Figure 1. The increase in resistivity with the angle, at constant magnetic field, is due to the increase in electron path length associated with electron cyclotron orbits that involve more than one plane of atoms in the crystal, and the necessary band shifts to  $s$  basis conduction bands. Electron motion from one plane of atoms to another requires arbitrary small increments of electron orbital angular momentum, as explained above. When this happens the motion is not quantal and must be continuous to include the arbitrary orbital angular momentum increments. When the angle closely approaches an atomic plane being perpendicular to the magnetic field, some of the cyclotron current can complete its circuit in a single plane of atoms and become a quantal motion. Under these conditions there is no need for a band shift, from  $l > 0$  to  $l = 0$ , in the conducting band, because all of the orbital angular momentum increases are quantal, and identical with the cyclotron quantal changes. In this

regime both the Hall effect and the quantum Hall effect operate at the same time for silver. This will be true at 10 K and at 300 K.

When the Hall effect operates in a plane of atoms, as in the case of 0, 45 and 90 degrees in Fig. 1, there is no change in the conduction band structure from the zero field case. It is possible for the Hall effect to operate as a quantum Hall effect in these situations. In the quantum Hall effect<sup>10,11</sup> there is no need for a shift in the conduction band during cyclotron motion of the electron because the changes in electron orbital angular momentum are quantal and are directly associated with the Hall effect quanta. The electron motion in the quantum Hall effect can be either dissipative or dissipation-less. If the motion is dissipative, the apparent mass of the electron decreases in a predictable way because of partial wave electron nuclear scattering.<sup>9</sup> Graphene shows a dissipative quantum Hall effect at 300 K.<sup>12</sup> Resistivity of bilayer graphene near zero carrier concentration as a function of temperature had an approximately zero slope.<sup>13</sup> This indicates that un-doped graphene is conducting using *s* basis set conduction bands,<sup>9</sup> in accord with molecular orbital expectations. At a temperature of 30 mK graphene has demonstrated a bipolar supercurrent as part of a Josephson junction.<sup>14</sup> Supercurrents and superconductivity are discussed in the preceding manuscript.<sup>15</sup>

The coexistence of the quantum Hall effect and the Hall effect occurs in GaAs-Ga<sub>1-x</sub>Al<sub>x</sub>As heterojunctions at 1.1 K.<sup>16</sup> This does not represent a breakdown of dissipationless conduction, but rather a continuous phase transition to simultaneous dissipationless and dissipative conduction. The phase transition is caused by the density of conducting electrons in the sample. In the specific case in ref. 16, heterojunction (7), the critical current was ~325  $\mu$ A. The device was prepared by

molecular beam epitaxy, and was a GaAs-Ga<sub>1-x</sub>Al<sub>x</sub>As (x=0.29) heterojunction. There are several complications in calculating the number of electrons required to saturate the conduction band with  $l > 0$  in these devices. The most significant one is the fact that the layer thickness for the heterojunction was not reported. The magnetic field effect on the conducting electron trajectory, and thus residence time, is another complication.

Once the conduction bands with  $l > 0$  have been fully occupied, further contributions to the conductivity, and the Hall effect in these devices will necessarily occur in the next higher energy bands,  $s$  basis wave functions. In these wave functions the conduction will be inescapably dissipative.<sup>9</sup> Once the transition has been made the device will be both a dissipationless quantum Hall effect and a dissipative Hall effect device, all in one package. This observation accounts for the fact that the observed resistive dissipation was smaller than expected for the total current passed in the case of GaAs heterostructures.<sup>16</sup> The voltage spikes observed at the critical current,  $\sim 325 \mu\text{A}$ , reflect switching noise, a consequence of the inhomogeneous surface of the device.<sup>16</sup>

When the angle of the crystal to the magnetic field moves a plane of atoms away from perpendicular to the magnetic field, some of the orbiting electrons will not be able to complete their cyclotron orbit in a single plane of atoms. A shift from one atomic plane to the next plane will require non-quantal changes in orbital angular momentum and will necessitate a band shift to  $s$  basis conduction bands.<sup>9</sup> This will increase the resistivity of the sample (because of the increased partial wave scattering for  $s$  basis bands as compared to bands with  $l > 0$ ), and switch the system from a

quantum to a continuum regime. These effects produce the graph seen in Fig. 1. The original authors estimated the uncertainty in the angle as  $\pm 5^\circ$ . The minima in Fig. 1 correspond to the angular positions of the atomic planes in the face centered cubic crystal of silver, within those error limits.

The sharply peaked features in Fig. 1, and similar figures for other metals<sup>4</sup> are directly related to the crystal structure of the metal and the conducting bands as a function of magnetic field orientation. The distinct features in Fig. 1 correspond to planes of silver atoms in the crystal structure.<sup>4,17</sup> Fig. 1 shows resistance increases larger than a factor of 10 for silver.

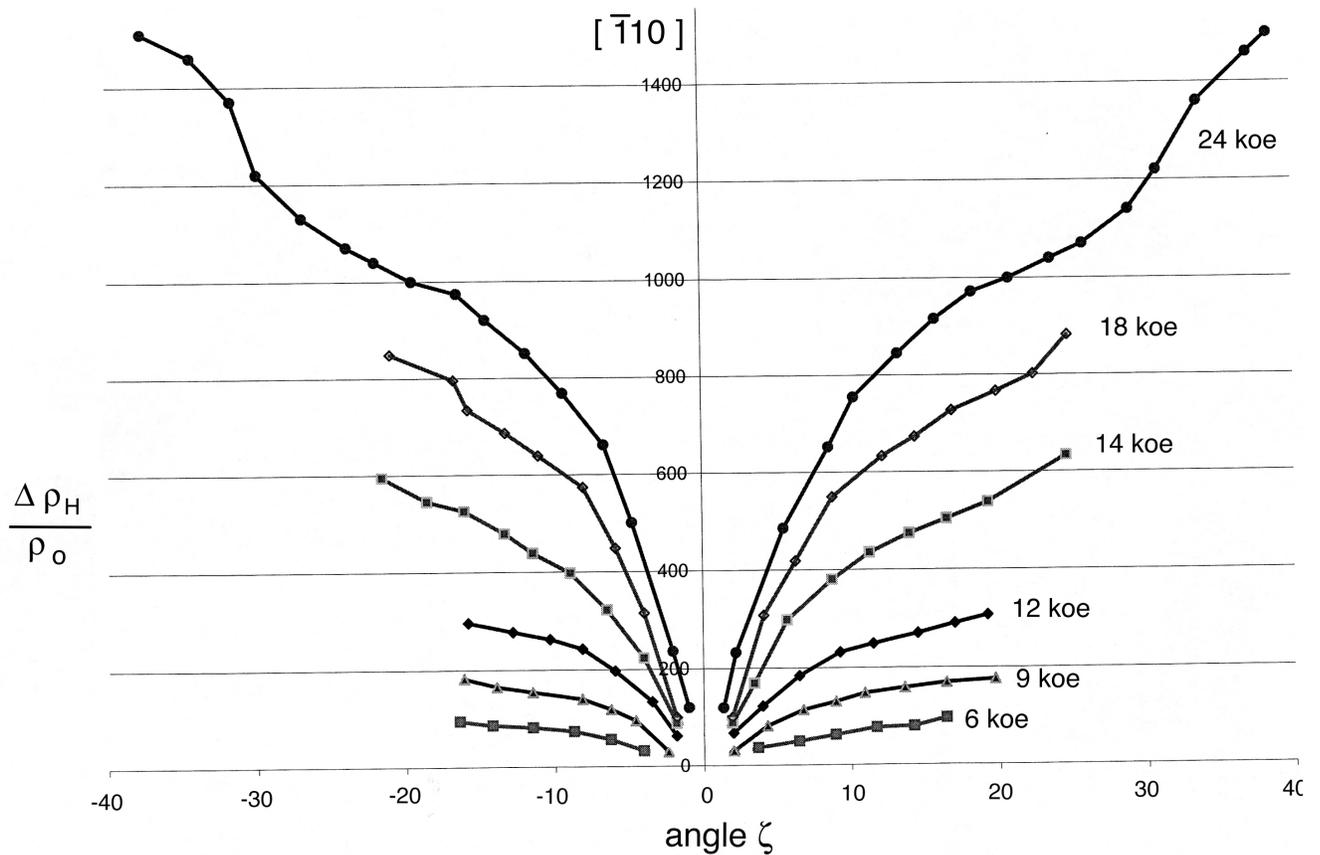


Figure 2. Lead crystal relative resistance as a function of magnetic field and angle,

$\zeta$ .<sup>4</sup>

For the same magnetic field as used for silver (Fig. 1), lead has a magnetoresistance ratio ( $\Delta\rho_H/\rho_0$ ) larger than 1400,<sup>4</sup> see Fig. 2. The variations in the shape of the relative resistivity curves with magnetic field and orientation angle in Fig. 2 are due to primarily to the conducting band structure of lead crystal as compared to that of silver in Fig. 1. The changes in slope of the curves in Fig. 2 at  $\sim 15^\circ$  and at  $\sim 28^\circ$  suggest the importance of interactions beyond the nearest neighbor atoms in the fcc crystal lattice in producing the changes in magnetoresistance.

### **THE MEISSNER OCHSENFELD EFFECT AND RELATED PHENOMENA**

When a magnetic field penetrates a metallic conductor, it changes the resistivity of the metal, generally by increasing it.<sup>5</sup> This is the the result of induction of a cyclotron current that has an associated magnetic field dependent electron orbital angular momentum. The only basis functions that can accommodate an arbitrary magnetic field dependent electron orbital angular momentum are *s* basis functions.<sup>9</sup> In orbitals formed from *s* basis functions, the electron orbital angular momentum is exactly zero regardless of the applied magnetic field. If any of the conducting electrons in a superconductor are shifted to *s* basis wavefunctions, superconductivity will quench because of resistive electron scattering in the *s* basis conduction bands.<sup>9,15</sup> The energy gap that forms on the creation of the superconductor is the factor that controls external magnetic field penetration of a superconductor.<sup>15</sup>

As long as a superconducting state persists, an applied magnetic field, at an arbitrary angle, will not be capable of penetrating the metal of the superconductor.

As soon as an applied magnetic field penetrates the metal of a superconductor, the material will revert to normal resistive conduction. This is the Meissner Ochsensfeld effect.<sup>6</sup> Popularly, the Meissner Ochsensfeld effect is known as magnetic levitation. In this phenomenon a normal magnet will float, for example, above a disk of a cuprate superconductor that is kept at temperatures below the  $T_c$ . Another feature of the Meissner Ochsensfeld effect is the expulsion of magnetic flux from a superconductor as the temperature is lowered below  $T_c$ .<sup>6</sup> The origin of this phenomenon is the same as above. Central to this part of the Meissner Ochsensfeld effect is the generation of a superconducting magnetic field that is in opposition to the applied magnetic field. This kind of magnetic action and reaction has been known for many years. One well known example is the ring current effect in magnetic resonance experiments with small molecules.<sup>18</sup> In these cases the magnetically generated ring current in molecules like benzene, for example, always opposes the applied magnetic field in the experiment. In the Meissnerr Ochsensfeld effect the field opposition is sufficient to keep the probe field from penetrating the superconductor. In the paramagnetic Meissner Ochsensfeld effect,<sup>19</sup> a superconducting material demonstrates paramagnetism when cooled below  $T_c$  in the presence of a magnetic field. This effect appears to be easiest to demonstrate in small samples of planes of atoms. Geim and co-workers utilized micro-disks of aluminum approximately 2.5  $\mu\text{m}$  in diameter by 0.1  $\mu\text{m}$  thick.<sup>19</sup> The Geim group found evidence that the effect was quantal.<sup>19</sup> The applied magnetic field induces a cyclotron current with its associated electron orbital angular momentum in a superconducting band. Additions to the superconducting current occur by addition of single magnetic flux quanta, a quantum Hall

phenomenon.<sup>19</sup> This restriction satisfies the requirements for changes in the electron orbital angular momentum in the superconducting bands ( $l > 0$ ) of Al.

Recently field fluctuations in mesoscopic aluminum rings at the critical temperature for superconductivity have been documented.<sup>20</sup> These quantum fluctuations are directly related to the Little Parks effect,<sup>21</sup> another variation on the quantum Hall effect.

The magnetic field-induced superconductivity in the ferromagnet URhGe<sup>23</sup> is another example of the paramagnetic Meissner Ochsenfeld effect. The same is true for other examples of the coexistence of ferromagnetic and superconducting magnetic fields in the same sample.<sup>24</sup>

The fundamental reason that external magnetic fields are excluded from a superconductor in the Meissner Ochsenfeld effect is that the free energy of the entire system is lower when the external magnetic field remains exclusively external. This statement is tautological, and provides no insight into the origins of the effect. In this regard it is like the London equations.<sup>25</sup> An intruding external magnetic field in a superconductor would induce an arbitrary (resistive) Hall current in the superconductor if it were allowed entrance. The current will necessarily be resistive, since an arbitrary angle of metal crystal planes to the magnetic field will require that the conducting band for the current be formed from  $s$  basis functions. The result will be quenching of the supercurrent, and a loss of the negative free energy associated with the stabilizing energy gap for the current.

The critical magnetic field,  $H_c$ , in a Meissner Ochsenfeld experiment is the field that will penetrate a given active superconductor and quench the superconducting state.<sup>26</sup> This field and the critical temperature,  $T_c$ , define the region of stability on a

plot of  $H$  v.  $T$  for any superconducting system. Both of these critical endpoints are directly connected to the process that creates the superconducting state in the first place. This process generally involves a breakdown in the Born-Oppenheimer approximation for the metallic lattice and is discussed in greater detail in the preceding manuscript.<sup>15</sup>

The recent demonstration of low temperature coupled ferromagnetism and superconductivity in  $\text{CeCoIn}_5$ ,<sup>27</sup> is dramatic evidence for the existence of unpaired electron spin within the boundaries of a superconductor. The experiment by Kenzelmann, *et al.*, is convincing evidence that the Meisner Ocsenfeld does not require a “pure diamagnetic” system as BCS theory assumes.<sup>26</sup> Two other recent reports one on unusual isotope effects,<sup>28</sup> and one on an unusual phase transition,<sup>29</sup> fall outside the capacity of BCS theory for explanation.

The following paper discusses a model for resistivity in electron transport in metals that is based on the quantum mechanics of partial wave scattering.<sup>9</sup> This purely quantum mechanical model for resistivity is an essential basis for the ideas discussed in this and the preceding manuscript.

## SUMMARY

Magnetoresistivity in metals arises from the increased path length of electrons traveling in metals as a consequence of the Hall effect. In polycrystalline metals there is also an increase in resistivity due to band shifts to  $\delta$  basis conducting bands in appropriate cases to accommodate small arbitrary changes in orbital angular

momentum required for changing atomic planes in completion of Hall cyclotron orbits. The angular anisotropy of magnetoresistance<sup>4</sup> is a consequence of alignment of atomic planes in a crystal perpendicular to a magnetic field axis. When an atomic plane is perpendicular to the magnetic field axis, both the Hall effect and the quantum Hall effect operate, depending on the conducting band structure of the metal. As the atomic plane moves from perpendicular to the magnetic field, the resistance in the sample increases. At the same time the quantum Hall effect shifts to the continuum Hall effect because of the circuitous electron path required to complete cyclotron motion through the maze of atomic planes. This same transfer from the quantum Hall effect to the continuum Hall effect occurs at the current critical point in heterojunctions that exhibit the quantum Hall effect.<sup>8</sup> The onset of dissipative conduction in these devices<sup>8a</sup> is due to saturation of the conducting bands with  $l > 0$  in the heterojunction. At that point the device will demonstrate both quantum and continuum Hall effects.

The Meissner Ochsensfeld effect<sup>9</sup> is an example of magnetoresistance in which an external magnetic field is excluded from a superconducting system. The primary basis for this effect is protection of the superconducting system from the continuum Hall effect caused by arbitrary cyclotron motion of electrons. Perfectly arbitrary cyclotron motion of electrons requires that the electrons be in  $s$ -basis wave functions where electron orbital angular momentum is zero, and electron nuclear scattering is maximized. The secondary basis for the Meissner Ochsensfeld effect is action and reaction between the probe magnetic field and the induced superconducting magnetic field that prevents the probe field's penetration of the superconductor.

**ACKNOWLEDGMENT:** J. Daniel Kimel and Louis N. Howard have been patient and careful listeners and critics during the development of these ideas. It is a pleasure to express my deep gratitude to them for their help. Stephan von Molnar read and clearly critiqued an early version of this manuscript. Stephanie R. Dillon digitized the graphics of reference 3. I am most grateful for all of this assistance.

## REFERENCES

- 1 E.H. Hall, *Amer. J. Math.*, **1879**, 2.
- 2 J. Wakaayashi, and S. Kawaji, *J. Phys. Soc. Japan*, **1978**, 44, 1839-1849.
- 3 K. von Klitzing, G. Dorda, and M. Pepper, *Phys. Rev. Lett.*, **1980**, 45, 494-497.
- 4 N.E. Alekseevskii and Y.P. Gaidukhov, *Soviet Phys., J. Exper. Theor. Phys.*, **1960**, 17, 481-484.
- 5 P.L. Kapitza, *Proc. Roy. Soc. A*, **1929**, 123, 292-341.
- 6 W. Meissner and R. Ochenfeld, *Naturwissenschaften*, **1933**, 23, 787-788.
- 7 Lu Li, J. G. Checkelsky, Y. S. Hor, C. Uher, A. F. Hebard, R. J. Cava, and N. P. Ong, *Science*, **2008**, 321, 547-550. This paper describes experiments with electrons in single planes of a Bi crystal with application of a high magnetic field.
- 8 K. Behnia, L. Balicas, Y. Kopelevich, *Science*. **2007**, 317, 1729-1731.

- 9 R.C. Dougherty, **2009**, *submitted*.
- 10 D. Yoshioka, *The Quantum Hall Effect*, **2002**, Springer, Heidelberg.
- 11 K.N. Shrivastava, *Introduction to Quantum Hall Effect*, **2002**, Nova, New York.
- 12 K. S. Novoselov, Z. Jiang, Y. Zhang, S. V. Morozov, H. L. Stormer, U. Zeitler, J. C. Maan, G. S. Boebinger, P. Kim and A. K. Geim, *Science*, **2007**, *315*, 1379-1379.
- 13 K. S. Novoselov, E. Mccann, S. V. Morozov, V. I. Fal'ko, M. I. Katsnelson, U. Zeitler, D. Jiang, F. Schedin and A. K. Geim, *Nature Phys.*, **2006**, *2*, 177-180.
- 14 H. B. Heersche1, P. Jarillo-Herrero, J. B. Oostinga, L. M. K. Vandersypen and A. F. Morpurgo, *Nature*, **2007**, *446*, 56-59.
- 15 R.C. Dougherty, **2009**, *submitted*.
- 16 M.E. Cage, R.F. Dziuba, B.F. Field,.E.R. Williams, S.M. Gossard, D.C. Tsui and R.J. Wagner, *Phys. Rev. Lett.*, **1983**, *51*, 1374-1377.
- 17 M.P. Marder, *Condensed Matter Physics*, **2000**, J. Wiley & Sons, New York.
- 18 H. Friebolin, *Basic one- and two-dimensional NMR spectroscopy*, *3rd Rev. Ed.*, **1998**, Wiley-VCH, New York, p. 49.
- 19 A.K. Geim, S.V. Dubonos, L.G.S. Lok, M. Henini and J.C. Maan, *Nature*, **1998**, *396*, 144-146.
- 20 N.C. Koshnick, H. Bluhm, M.E. Huber, K.A. Moler, *Science*, **2007**, *318*, 1440-1443.
- 21 W.A. Little and R.D. Parks, *Phys. Rev. Lett.*, **1962**, *9*, 9-12.

- 22 F. Le´vy, I. Sheikin, B. Grenier, A. D. Huxley, *Science*, **2005**, *413*, 1343-1346.
- 23 D. Aoki, A. Huxley, E. Ressouche, D. Braithwaite, J. Flouquet, J.-P. Brison, E. Lhotel, C. Paulsen, *Nature*, **2001**, *413*, 613-616.
- 24 S. S. Saxena, P. Agarwal, K. Ahilan, F. M. Grosche, R. K. W. Haselwimmer, M. J. Steiner, E. Pugh, I. R. Walker, S. R. Julian, P. Monthoux, G. G. Lonzarich, A. Huxley, I. Sheikin, D. Braithwaite and J. Flouquet, *Nature*, **2000**, *406*, 587-592.
- 25 F. and H. London, *Proc. Roy. Soc. A*, **1935**, *149*, 71-88.
- 26 M. Tinkham, *Introduction to superconductivity, second edition*, **1996**, Dover, New York.
- 27 M. Kenzelmann, Th. Strässle, C. Niedermayer, M. Sigrist, B. Padmanabhan, M. Zolliker, *Science*. **2008**, *321*, 1652-1654.
- 28 M. Riccò, F. Gianferrari<sup>1</sup>, D. Pontiroli<sup>1</sup>, M. Belli<sup>1</sup>, C. Bucci<sup>1</sup>, and T. Shiroka, *EPL*, **2008**, *81*, 57002 (6pp).
- 29 Y. Takabayashi, A. Y. Ganin, P. Jeglič,<sup>3</sup> D. Arčon, T. Takano, Y. Iwasa, Y. Ohishi, M. Takata, N. Takeshita, K. Prassides, M. J. Rosseinsky, *Science*, **2009**, *323*, 1585-1590.