Study of the Anomalous Hall Effect in MnSi Under Pressure

Max Grossnickle

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The Anomalous Hall Effect (AHE) is a phenomenon which consists of an extra 'anomalous' transverse voltage developing when current is passed through a ferromagnet in a magnetic field. This paper focuses on the behavior of magnetoresistance and the AHE in the ferromagnet MnSi when placed under pressures up to 1.5kbar, with the ultimate goal of the project being the study of MnSi from ambient pressure to above the critical pressure of 14.6kbar, at which point spontaneous ferromagnetic order disappears.

1 Introduction

1.1 The Hall and Anomalous Hall Effects

In the normal Hall Effect, a transverse voltage develops across a current-carrying wire which sits in a magnetic field. This is because the electrons in the wire are subjected to the Lorentz force, $F_{mag} = qv \times B$, with q equal to the electron charge, v the velocity of the electron, and B the magnetic field strength. The cross term in this force causes the electrons to move perpendicular to both their velocity and the magnetic field and pushes the electrons to one side of the wire. This process continues until the development of a transverse voltage large enough to prevent further electron movement across the wire, this voltage is known as the Hall voltage. The expression for this Hall voltage ends up as

$$V_H = \frac{R_H I B}{d}$$

with I as the current, B as the magnetic field strength, d the depth of the sample, and R_H a material specific constant known as the normal Hall coefficient. The normal Hall coefficient is given by

$$R_H = \frac{1}{ne}$$

with n equal to the charge carrier density of the material and e as the magnitude of the electron charge. These two equations are very important, as they offer one of the few methods to experimentally determine charge carrier density. The first states that the magnitude of the Hall voltage is directly proportional to the strength of the B-field, meaning that if one know the values of I and d they can vary the value of B and determine R_H, giving the charge carrier density of the material. Additionally, the sign of the Hall voltage can be used to determine

whether the charge carrier in a specific material are "electron-like" or "hole-like." The magnitude of the Hall voltage is often discussed in terms of a "Hall resistivity" obtained by dividing the Hall voltage by the current and multiplying it by the depth, the results in the relation $\rho_{xy} = R_H B$.

In ferromagnetic conductors, the Hall resistivity gains an additional contribution due to the spontaneous magnetization of the material below it's Curie temperature T_c, resulting in the expression

$$\rho_{xy} = R_H B + \mu_0 R_S M$$

The new term is the source of the AHE and the reason why it is only observed in materials which can spontaneously magnetize. This second term is anomalous in that it is more than an order of magnitude greater than the normal Hall term near the ferromagnetic transition temperature and usually has the opposite sign of the normal Hall effect.

1.2 Properties of MnSi

Manganese silicide (MnSi) is a ferromagnetic conductor with a Curie temperature of $T_c = 29.5K$. Below this temperature, MnSi forms a helical magnetic state due to the lack of an inversion symmetry in its B20 crystal structure[6]. Increasing pressure on MnSi causes the T_c to decrease until it reaches 0K at 14.6kbar. Above this pressure, MnSi enters a non-Fermi-liquid region characterized by a $T^{1.5}$ dependence of the resistivity.

In MnSi, two additional AHE signals have been observed, they are the topological Hall effect [5] and "chiral" AHE [3]. The topological Hall effect manifests itself at ambient pressure in the form of a small bump in the Hall resistivity just below T_c in the region between 0.1T and 0.2T and stems directly from the presence of a topologically quantized Berry phase. This Berry phase in turn

points to the existence of a Skyrmion lattice in the A phase of MnSi. The chiral AHE, which appears as a sharp peak in the Hall resistivity, has been observed near T_c between 6kbar and 12kbar and between 0.1T and 0.45T. A Berry phase acquired as electrons interact with the chiral spin structure in MnSi has been identified as the possible source of this peak. The eventual goal of this project is to study these two phenomena and see if they persist at higher pressures in order to determine how they are related to interactions between electrons and chiral-spin textures. Some evidence points to the existence of a magnetic state above T_c which persists above the p_c [1], which will be another focus of this study.

2 Measurement Specifications

Hall and magnetoresistance measurements were performed on an 80-micron thick MnSi sample using the four-probe method. Cooling to 4.2K was accomplished by placing the sample in a cryostat which was lowered into a liquid helium bath. Additional cooling down to 300mK was done by condensing He-3 using a charcoal sorption pump. The sample was pressurized using an anvil cell with Fluorinert (FC-77) as the pressure medium. For the data present in this paper, the pressure was estimated based off the transition temperature of MnSi. Future measurements will determine the pressure by observing the superconducting transition temperature of a lead chunk wrapped in a wire coil. Temperatures were measured from room temperature to 4.2K using a Cernox 1030 resistor and from 4.2K to 300mK using a RuOx resistor. Magnetic field sweeps greater than 10T total were carried out at a rate of 0.2T/min, while magnetic fields sweeps of 2T were swept at 0.1T/min. Magnetoresistance data was obtained by measuring the longitudinal resistance of the sample and then symmetrizing the raw data, while Hall data was acquired by antisymmetrizing

raw transverse resistance data.

3 Data

3.1 MnSi at 300bar

At 300bar, the T_c of MnSi is 29.1K. In Figure 2(b) a prominent shoulder near 0.6T is visible for the curve at 25.7K. The two curves significantly above T_c show much weaker shoulders due to reduced AHE magnitude. Hall resistance data shown in Figure 5 confirm that the T_c of our sample was above 25.7K, as a sharp transition can be seen at 0.55T in this curve. The broader transitions in the higher temperature data are characteristic of being above T_c, as at these temperatures some magnetization can still be forced by applying a strong magnetic field.
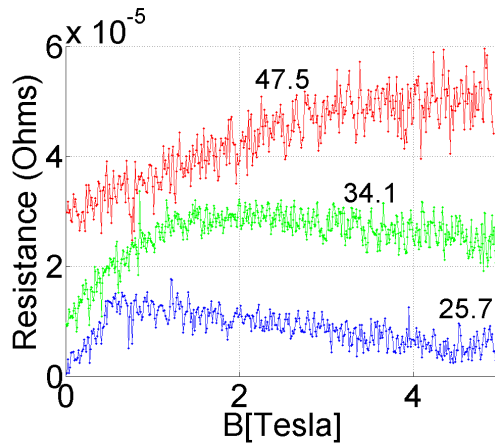
Figure 1: Hall resistance of MnSi at 300 bar. Temperatures given in K, the 47.5K curve is offset by $30\mu\Omega$ and the 34.1K curve is offset by $10\mu\Omega$ for the purpose of clarity.

3.2 MnSi at 1.5kbar

At 1.5kbar the shift in T_c is much more apparent. The 29.5K magnetoresistance curve in Figure 4 does not show the sharp shoulder expected of a curve close to T_c, while the three curves near 27K all have shoulders near 0.6 T.

(a) Magnetoresistance of MnSi at 300 bar from 0 to 5 T.
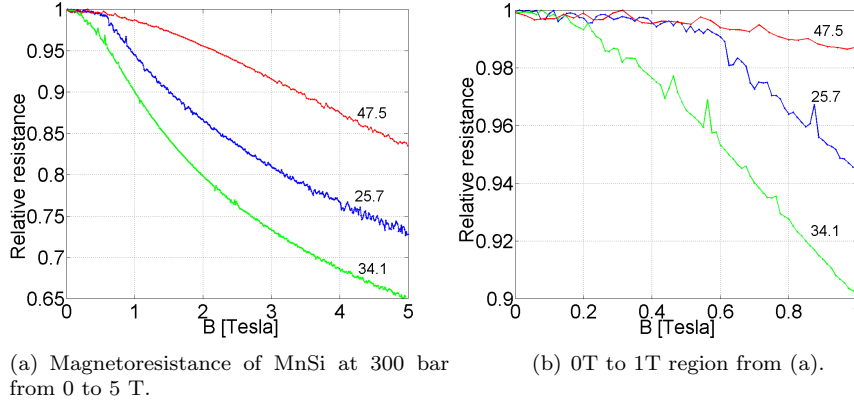
(b) 0T to 1T region from (a).

Figure 2: Magnetoresistance of MnSi at 300bar. Temperatures given in Kelvin.

The Hall data in Figure 5(a) is an even better indicator of the location of the T_c, as close inspection of the 27.5K curve reveals a smooth transition from the AHE region to the normal Hall region, meaning that at 27.5K magnetization is not yet spontaneous. However, the transition at 26.9K is sharp, meaning the sample spontaneously magnetized above that temperature. The behavior of the AHE at low temperature is shown in Figure 5(b). The Anomalous Hall coefficient discussed in the introduction of this paper has been shown to de-
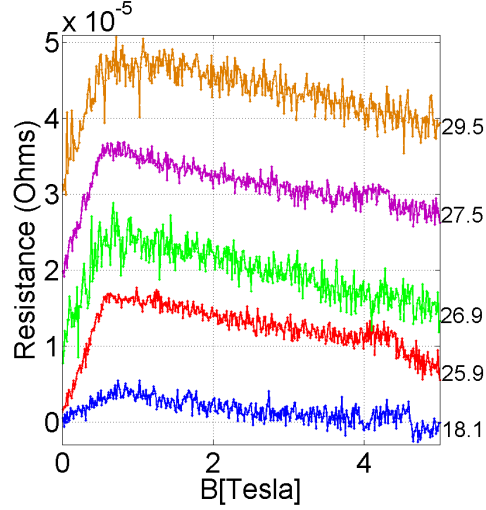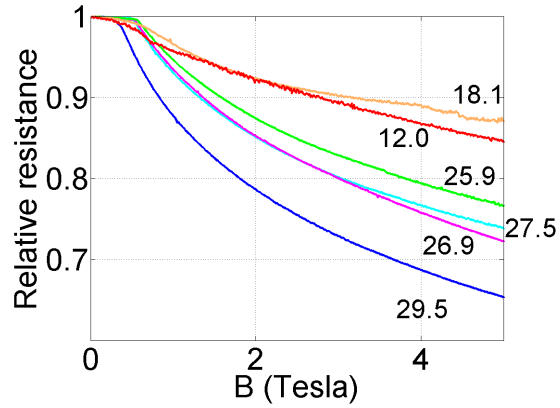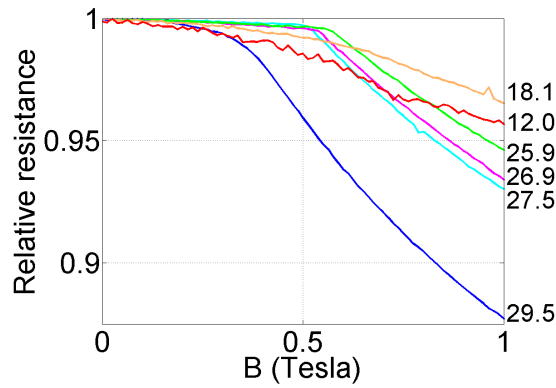

Figure 3: Hall resistance of MnSi at 300 bar. Temperatures given in K, the 47.5K curve is offset by $30\mu\Omega$ and the 34.1K curve is offset by $10\mu\Omega$ for the purpose of clarity.

pend on the squared resistivity of the material, causing the AHE signal to rapidly diminish as temperature decreases[2]. At 12.3K, the AHE signal is barely distinguishable, while below this temperature the Hall resistance is completely dominated by the normal Hall Effect.
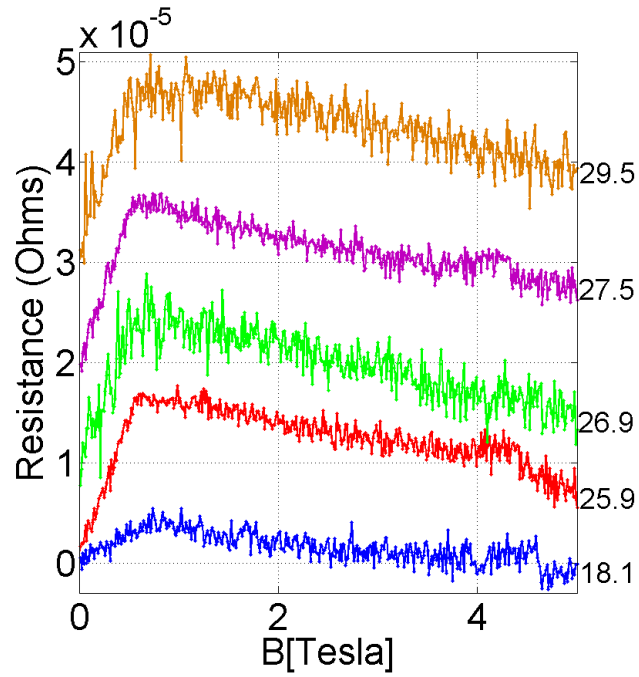

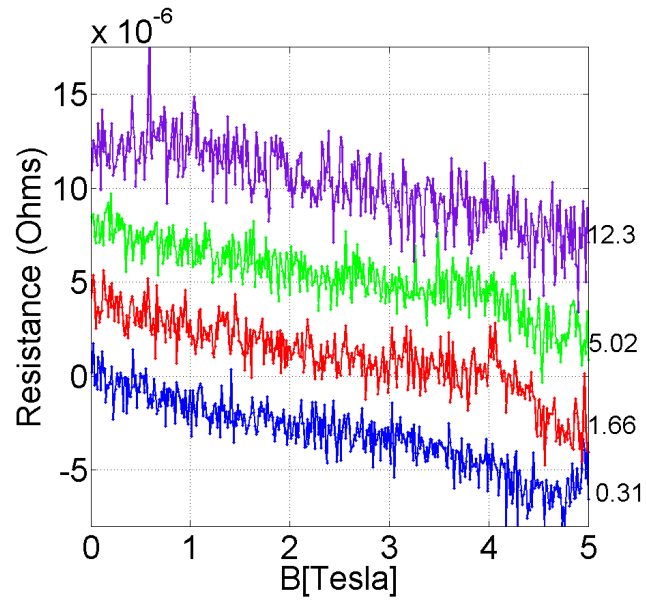(a) Magnetoresistance of MnSi at 1.5kbar from 0 to 5 T.

(b) 0T to 1T region from (a).

Figure 4: Magnetoresistance of MnSi at 1.5kbar. Temperatures given in Kelvin.

(a) Hall resistance of MnSi at 1.5kbar above 18K from 0 to 5 T.

(b) Hall resistance of MnSi at 1.5kbar below13K from 0 to 5 T.

Figure 5: Hall resistance of MnSi at 1.5kbar. Temperatures given in Kelvin.

4 Future Work

We have produced magnetoresistance and Hall resistance curves up to 5T at multiple temperatures at both 300bar and 1.5kbar. Our results are in agreement with previous findings[4], establishing a soild baseline to use in future work. Our next step will be to continue performing magnetoresistance and Hall measurements at higher pressures to find the lower and upper ranges at which the "chiral" AHE exists. These higher pressure measurements will also be used to check for the existence of the topological Hall effect, which so far has only been observed at ambient pressure. Additionally, we will take measurements above the p_c of MnSi to observe the magnetic state which may exist above T_c.

References

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