Magnetoresistivity and Complete $H_{c2}(T)$ in $MgB_2$.

S. L. Bud’ko, C. Petrovic, G. Lapertot*, C. E. Cunningham†, and P. C. Canfield
Ames Laboratory, U.S. Department of Energy and Department of Physics and Astronomy
Iowa State University, Ames, Iowa 50011

M-H. Jung‡ and A. H. Lacerda
National High Magnetic Field Laboratory - Pulse Facility, Los Alamos National Laboratory, MS E536 Los Alamos, NM 87545
(March 22, 2022)

Detailed magneto-transport data on dense wires of $MgB_2$ are reported for applied magnetic fields up to 18 T. The temperature and field dependencies of the electrical resistivity are consistent with $MgB_2$ behaving like a simple metal and following a generalized form of Kohler’s rule. In addition, given the generally high $T_c$ values and narrow resistive transition widths associated with $MgB_2$ synthesized in this manner, combined with applied magnetic fields of up to 18 T, an accurate and complete $H_{c2}(T)$ curve could be determined. This curve agrees well with curves determined from lower field measurements on sintered pellets and wires of $MgB_2$. $H_{c2}(T)$ is linear in $T$ over a wide range of temperature ($7 K \leq T \leq 32 K$) and has an upward curvature for $T$ close to $T_c$. These features are similar to other high $\kappa$, clean limit, boron-bearing intermetallics: $YNi_2B_2C$ and $LaNi_2B_2C$.

I. INTRODUCTION

The recent discovery of superconductivity in $MgB_2$ has lead to a flurry of activity. Measurements of the boron isotope effect show that there is a shift in $T_c$ from 39.2 K to 40.2 K (for $Mg^{11}B_2$ and $Mg^{10}B_2$ respectively), a result consistent with electron phonon mediated BCS superconductivity. Measurements of the upper critical field, $H_{c2}(T)$, and the thermodynamic critical field, $H_c(T)$, as well as the specific heat are all consistent with $MgB_2$ being a fairly typical intermetallic superconductor with an atypically high transition temperature. Although single crystal samples are not yet available, it has recently been found that dense, very high quality, wire samples of $MgB_2$ can be made. These samples have a superconducting transition temperature above that found for $Mg^{11}B_2$, as would be expected based on the natural abundance of $^{10}B$. These samples allow for the direct measurement of electrical resistivity and, given that the width of the superconducting transition is narrower in $MgB_2$ wire than in powder or sintered pellet samples, wire samples allow for an accurate determination of the upper critical field $H_{c2}(T)$. In this communication we present data on the magneto-transport of $MgB_2$ wires for applied magnetic fields of up to 18 T and over the temperature range 1.5 - 300 K. By a careful analysis of the resistivity data we are able to conclude that $MgB_2$ behaves like a simple metal in the normal state with all of our magnetoresistance data collapsing onto a single curve in accordance to Kohler’s rule. In addition we are able to construct the full $H_{c2}(T)$ curve. We find that $H_{c2}(T)$ is linear over a much larger temperature range than would be expected, leading to a $H_{c2}(0) \approx 16.4$ T.

II. EXPERIMENTAL METHODS

$MgB_2$ wire was produced by sealing 100 µm diameter boron fiber and $Mg$ into a Ta tube with a nominal ratio of $Mg_2B$. Given that $MgB_2$ is the most $Mg$ rich binary $Mg - B$ compound known, it was felt that excess $Mg$ would aid in the formation of the proper, stoichiometric phase. The sealed Ta tube was itself sealed in quartz and then placed into a 950°C box furnace for two hours. The reaction ampoule was then removed from the furnace and quenched to room temperature. Whereas the boron fiber has a diameter of 100 µm, the $MgB_2$ wire has a diameter of approximately 160 µm. Although the $MgB_2$ wires are somewhat brittle, the integrity of the filament segments is preserved during the exposure to the $Mg$ vapor; i.e. the fibers did not decompose, fragment, or turn into powder.

The resulting wire has over 80% the theoretical density of $MgB_2$ and measurements of the temperature dependent resistivity reveal that $MgB_2$ is highly conducting in the normal state. The room temperature resistivity has a value of 9.6 $\mu$Ohm-cm; whereas the resistivity at $T = 40$ K is 0.38 $\mu$Ohm-cm. The zero field $T_c$ value for the wire sample is higher than that found for $Mg^{11}B_2$, a result consistent with the natural abundance of $^{10}B$. It should be noted that both wire and sintered pellet samples synthesized in this manner tend to have very high and sharp superconducting transitions.

Magnetoresistivity measurements utilizing a 20 T superconducting magnet were performed at the National

*On leave from Commissariat a l’Energie Atomique, DRFMC-SPSMS, 38054 Grenoble, France
†On leave from Dept. of Physics, Grinnell College, Grinnell, IA 50112
‡also at Physics Dept., New Mexico State University, Las Cruces, New Mexico
High Magnetic Field Laboratory, Pulsed Facility. A standard four-probe ac method was used, utilizing Epotek H20E silver epoxy for making electrical contacts. The contact resistance was approximately 1 Ohm. Given the well-defined geometry of the samples, accurate measurements of resistivity were possible. The ac current was applied along the wire and the magnetic field was applied perpendicular to the current direction. The sample was mounted in a flow cryostat able to regulate the temperature from 1.4 K to room temperature.

III. DATA AND ANALYSIS

Figure 1 presents temperature dependent electrical resistivity data for a MgB₂ wire sample taken at a variety of applied fields for \( H \leq 18 \) T. Two features are clearly seen: there is a suppression of the superconducting phase to lower temperatures for increasing applied field, and there is a clear, large magnetoresistivity in the normal state. Looking first at the suppression of superconductivity, the inset to Fig. 1 presents an enlarged view of the low temperature resistivity data. Using these data, three temperatures can be extracted from each curve: onset temperature, temperature of maximum \( \rho_T/\rho_0 \), and completion temperature, where onset and completion temperatures are determined by extending the maximum \( \rho_T/\rho_0 \) line up to the normal state and down to zero resistivity.

Figure 2 presents the \( H_{c2}(T) \) curve that we deduce from these data. In addition to the high field data taken at NHMFL (shown as open symbols), data taken in a Quantum Design PPMS system at lower fields on a sample from the same batch are also shown (filled symbols). Several features of this curve are worth noting. First of all it has a large temperature / field range over which it is linear (7 K \( \leq T \leq 32 \) K). Below approximately 7 K \( H_{c2}(T) \) starts to roll over and saturate. This leads to a low temperature value of \( H_{c2}(1.5 \) K) \( = 16.2 \) T, which is significantly larger than estimated based on the assumption that the low temperature \( H_{c2}(0) = 0.71 T_c \) \[ dH_{c2}(T)/dT \] = 12.5 T. Secondly, at high temperatures (\( T \geq 32 \) K) there is a distinct positive, upward curvature associated with the \( H_{c2}(T) \) curve. This is not unique to the current form of our sample but was also seen in resistively determined \( H_{c2}(T) \) for sintered pellets of MgB₂. Taken as a whole, the temperature dependence of \( H_{c2} \) for MgB₂ is remarkably similar to that recently found for other non-magnetic, intermetallic boride superconductors: \( LuNi2B2C \) and \( YNi2B2C \)

In these cases \( H_{c2}(T) \) is linear over an extended region of \( T \) and near \( T_c \) there is a distinct upward curvature. In both the case of MgB₂ as well as in the case of \( Y/LuNi2B2C \) the material is a high \( \kappa \), type-II superconductor and in both cases the as grown compounds are well within the clean limit.

Turning to the normal state magnetoresistivity, Fig. 3 shows \( \Delta \rho/\rho_0 \) vs \( H/\rho_0 \) on a log – log plot to demonstrate that all of the data presented in Fig. 1, as well as the two isothermal \( \rho(H) \) plots shown in the inset of Fig. 3, are broadly consistent with the generalized form of Kohler’s rule. The fact that all of these data fall (roughly) onto a single curve implies that there is a single salient scattering time in the normal state transport of \( MgB_2 \).

This is what would be anticipated for a simple nonmagnetic intermetallic sample. It is worth noting that such a clear magnetoresistance would be much harder to detect in samples with enhanced impurity or defect scattering.

The isothermal \( \Delta \rho(T)/\rho_0 \) data shown in the inset of Fig. 3 can be fit to \( \Delta \rho(T)/\rho_0 \propto H^\alpha \) with \( \alpha = 1.4-1.5 \). In addition, the temperature dependent normal state resistivity of sintered \( Mg^{10}B_2 \) pellets as well as the resistivity of wire samples in zero field can be fit to a power law between \( T^{2.6} \) and \( T^3 \) at low temperatures (\( T \leq 200 \) K).

Finally, there is a slight upturn observed in the low-temperature \( \rho(T) \) data taken in high applied magnetic fields (Figure 1). Although the origin of this feature is not completely understood, similar features have been observed for other high purity, nonmagnetic intermetallic compounds.

IV. CONCLUSIONS

In this communication we present detailed magnetoresistivity data on dense (over 80%), high quality samples of \( MgB_2 \). In the normal state we find that \( MgB_2 \) has a temperature and field dependent resistivity that is consistent with \( MgB_2 \) being a highly conducting intermetallic compound that can be synthesized so as to achieve very low residual resistivities. This allows the large values of \( \Delta \rho/\rho_0 \) to reveal themselves. The fact that the magnetoresistivity data follow Kohler’s rule is consistent with \( MgB_2 \) behaving like a simple metal with one dominant scattering time.

In the superconducting state we find that \( MgB_2 \) has a relatively linear \( H_{c2}(T) \) curve with slight deviations from linearity at both high and low temperatures. This leads to a relatively high value of \( H_{c2}(0) = 16.4 \) T. The linear behavior of \( H_{c2}(T) \) as well as the upward curvature in \( H_{c2}(T) \) for \( T < T_c \) is similar to behavior seen in other boron bearing intermetallic compounds (\( YNi2B2C \) and \( LuNi2B2C \)) that have large \( \kappa \) values and are within the clean limit. This similarity brings up the obvious question of whether such temperature dependencies of \( H_{c2}(T) \) are a generic feature associate with this subclass of intermetallic superconductors.

V. ACKNOWLEDGMENTS

We would like to thank D. K. Finnemore for useful discussions. Ames Laboratory is operated for the U. S. De-
partment of Energy by Iowa State University under Contract No. W-7405-Eng.-82. This work was supported by the director for Energy Research, Office of Basic Energy Sciences. Work performed at the National High Magnetic Field Laboratory was supported by the National Science Foundation, The State of Florida and the U. S. Department of Energy. One of us (M-H J) acknowledges partial support from LANSCE - LANL.

1 J. Akimiitsu, Symposium on Transition Metal Oxides, Sendai, January 10, 2001; J. Nagamatsu, N. Nakagawa, T. Muranaka, Y. Zenitani, and J. Akimitsu (to be published).
2 S. L. Bud’ko, G. Lapertot, C. Petrovic, C. E. Cunningham, N. Anderson, and P. C. Canfield, Phys. Rev. Lett. 86, 1877 (2001).
3 D. K. Finnemore, J. E. Ostenson, S. L. Bud’ko, G. Lapertot, and P. C. Canfield, cond-mat/0102114.
4 P. C. Canfield, D. K. Finnemore, S. L. Bud’ko, J. E. Ostenson, G. Lapertot, C. E. Cunningham, and C. Petrovic, cond-mat/0102283.
5 Y. Takano, H. Takeya, H. Fujii, T. Hatano, K. Togano, H. Kito, and H. Ihara, cond-mat/0102167.
6 D. C. Larbalestier, M. Rikel, L. D. Cooley, A. A. Polyanskii, J. Y. Jiang, S. Patnaik, X. Y. Cai, D. M. Feldmann, A. Gurevich, A. A. Squitier, M. T. Naus, C. B. Eom, E. E. Hellstrom, R. J. Cava, K. A. Regan, N. Rogado, M. A. Hayward, T. He, J. S. Slusky, P. Khalifah, K. Inumaru, and M. Hass, cond-mat/0102216.
7 Y. Bugoslavsky, G. K. Perkins, X. Qi, L. F. Cohen, and A. D. Caplin, cond-mat/0102355.
8 N. R. Werthamer, E. Helfand, and P. C. Hohenberg, Phys. Rev. 147, 295 (1966) and refs. therein.
9 K. D. D. Rathnayaka, A. K. Bhatnagar, A. Parasiris, D. G. Naugle, P. C. Canfield, and B. K. Cho, Phys. Rev. B 55, 8506 (1997).
10 V. Metlushko, U. Welp, A. Koshelev, I. Aranson, G. W. Crabtree, and P. C. Canfield, Phys. Rev. Lett. 79, 1738 (1997).
11 S. V. Shulga, S.-L. Drechsler, G. Fuchs, K.-H. Muller, K. Winzer, M. Heinecke, and K. Krug, Phys. Rev. Lett. 80, 1730 (1998).
12 see for example: A. B. Pippard, Magnetoresistance in metals (Cambridge University Press, Cambridge, England, 1989).
13 C. U. Jung, Min-Seok Park, W. N. Kang, Mun-Seog Kim, S. Y. Lee, and Sung-Il Lee, cond-mat/0102215.
14 S. L. Bud’ko, P. C. Canfield, C. H. Mielke, and A. H. Lacerda, Phys. Rev. B 57, 13624 (1998).
15 K. D. Myers, S. L. Bud’ko, I. R. Fisher, Z. Islam, H. Kleinke, A. H. Lacerda, and P. C. Canfield, J. Magn. Magn. Mater., 205, 27 (1999).
FIG. 3. Kohler’s plot for $MgB_2$ wires: open symbols from temperature-dependent resistivity; filled symbols from field-dependent resistivity at 45 K and 60 K. Inset $\Delta \rho(H)/\rho_0$ at 45 K and 60 K.