

Thermodynamic and Transport Properties of Superconducting Mg^{10}B_2

D. K. Finnemore, J. E. Ostenson, S. L. Bud'ko, G. Lapertot,* and P. C. Canfield

Ames Laboratory, U.S. Department of Energy and Department of Physics and Astronomy, Iowa State University, Ames, Iowa 50011
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Transport and thermodynamic properties of a sintered pellet of the newly discovered MgB_2 superconductor have been measured to determine the characteristic critical magnetic fields and critical current densities. Both resistive transition and magnetization data give similar values of the upper critical field, H_{c2} , with magnetization data giving $dH_{c2}/dT = 0.44$ T/K at the transition temperature of $T_c = 40.2$ K. Close to the transition temperature, magnetization curves are thermodynamically reversible, but at low temperatures the trapped flux can be on the order of 1 T. The value of dH_c/dT at T_c is estimated to be about 12 mT/K, a value similar to classical superconductors like Sn. Hence, the Ginzburg-Landau parameter $\kappa \sim 26$. Estimates of the critical supercurrent density, J_c , using hysteresis loops and the Bean model, give critical current densities on the order of 10^5 A/cm². Hence the supercurrent coupling through the grain boundaries is comparable to intermetallics like Nb_3Sn .

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I. Introduction.—With the discovery of superconductivity in MgB_2 at about 39 K by Akimiitsu and co-workers [1], there is an opportunity to study superfluid transport and phase locking of conduction electrons in a whole new class of materials. In early studies of the B isotope effect [2], Bud'ko and co-workers found the superconducting transition temperature, T_c , increased from 39.2 K for Mg^{11}B_2 to 40.2 K for Mg^{10}B_2 giving a partial isotope exponent $\alpha_B = 0.26$ for the isotope relation $T_c \sim M^{-\alpha_B}$ where M is the isotope mass. This is a clear indication that the phonons are playing an important role in the superconducting interaction. Calculations by Kortus and co-workers [3] have predicted an electron-phonon mechanism for this material and a rather isotropic electrical transport in spite of the very layered appearance of honeycombed boron and hexagonal magnesium networks in the material.

The purpose of this Letter is to report measurements of the critical fields of this material to get an estimate of the characteristic length and energy scales for comparison with the classical superconductors like Nb and the high temperature superconductors, like $\text{YBa}_2\text{Cu}_3\text{O}_{7-\delta}$. A second goal is to obtain some measure of the supercurrent transport through grain boundaries for comparison with the high temperature superconductors where there are serious weak link problems with the grain boundaries.

II. Experiment.—A sintered pellet of Mg^{10}B_2 was made by sealing a stoichiometric mixture of Mg and ^{10}B in a Ta tube and heating to 950 °C for 2 h [2]. Magnetization was measured with a Quantum Design SQUID magnetometer with a 60 mm scan length on a 14.22 mg piece from the same batch of Mg^{10}B_2 material reported previously [2]. Electrical resistance between 1.9 and 300 K in applied magnetic field up to 9 T was measured in a Quantum Design PPMS-9 apparatus on another piece from the same Mg^{10}B_2 batch using standard four probe ac resistance technique at $f = 16$ Hz and a current density of 0.1–0.3 A/cm². Electrical contacts were made with Epo-tek H20E silver epoxy. As was shown [2] these samples have

powder x-ray diffraction patterns consistent with single phase MgB_2 , manifest full diamagnetic shielding in low field, zero-field-cooled-warming susceptibility data, and have a jump in specific heat at T_c of $\Delta C/(\gamma T_c) \approx 1$: i.e., the samples used for this study are single phase bulk superconductors.

III. Results and discussion.—The temperature-dependent electrical resistance of the material from 300 to 1.9 K, shown in Fig. 1, roughly obeys $R = R_0 + R_1 T^3$ power law in the normal state ($40 \text{ K} \leq T \leq 200 \text{ K}$). The residual resistance ratio is approximately 20, which is relatively high for a sintered polycrystalline sample. A rough estimate of resistivity gives $\rho(40 \text{ K}) \approx 1 \mu\Omega \text{ cm}$, but given that the sample is less than 100% dense this represents an upper limit. Near T_c , the data show considerable flux-flow broadening as shown by the inset of Fig. 1 where the scans range from 0 to 9 T. Transition widths gradually broaden from 0.5 K at 0 field to 9.5 K at $\mu_0 H = 9 \text{ T}$ indicating a broad region of flux-flow resistivity [4]. The extent of this flux-flow regime is delineated

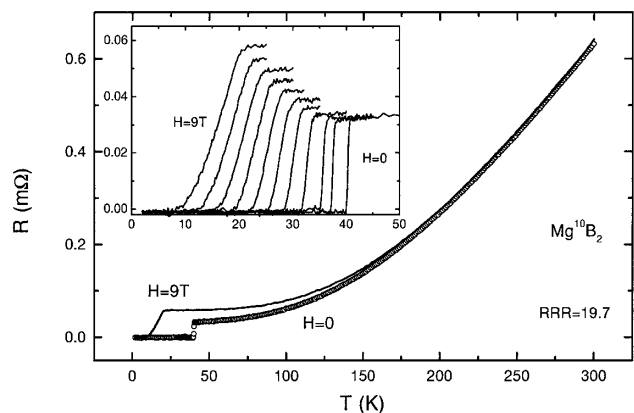


FIG. 1. Resistance of Mg^{10}B_2 sample in zero and in 9 T applied field. Inset: Resistive superconducting transition in different applied fields (right to left): 0 T, 0.5 T, and from 1 T to 9 T in steps of 1 T.

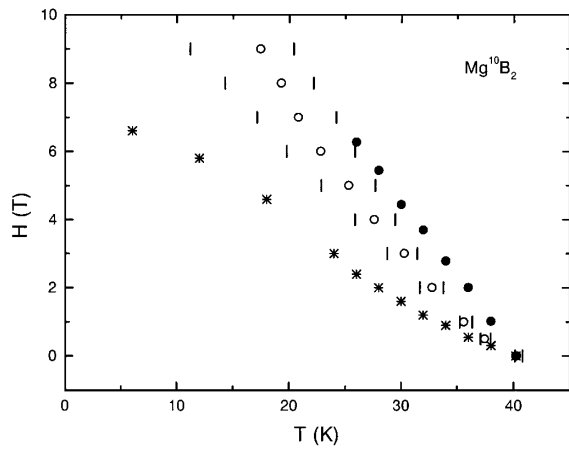


FIG. 2. Upper critical field of $Mg^{10}B_2$ determined resistively (onset and offset are vertical bars and maximum slope points are the open circles) and from magnetization (filled circles). Asterisks show H_{irr} .

by the onset and completion temperatures shown in Fig. 2 by the vertical dashed lines.

Possibly the most interesting aspect of these data is the strong magnetoresistance which shows the resistance at 45 K rising approximately 80% in 9 T. If these data are plotted on a Kohler plot shown in Fig. 3, the $\Delta\rho/\rho_0$ vs H/ρ_0 curve is a straight line for the change of temperature at constant field (open circles) and for changing field at constant temperature (solid triangles). This observation is consistent with the observed magnetoresistance being a band effect and intrinsic to the sample.

Magnetization data are exemplified by the 36 and 30 K runs in Fig. 4. For the 30 K run, the magnetization abruptly departs from the background at $H_{c2} = 4.4$ T and is reversible to an accuracy of 1% of the magnetization down to $H_{irr} = 1.6$ T. Because the background magnetization is very small, linear in magnetic field, and independent of temperature between 42 and 50 K, this

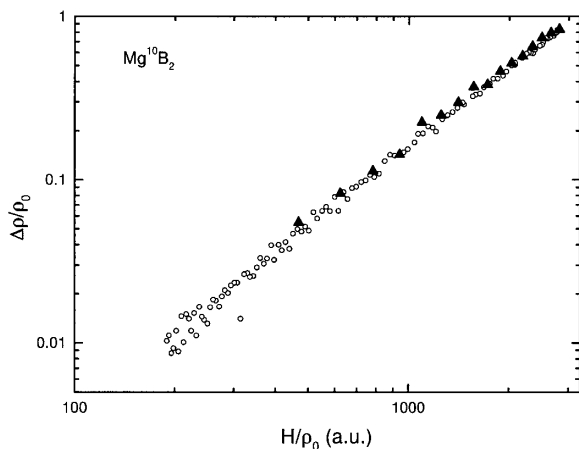


FIG. 3. Kohler plot for $Mg^{10}B_2$: Open circles from temperature-dependent resistance from 0 T to 9 T and filled triangles from field-dependent resistance at 45 K.

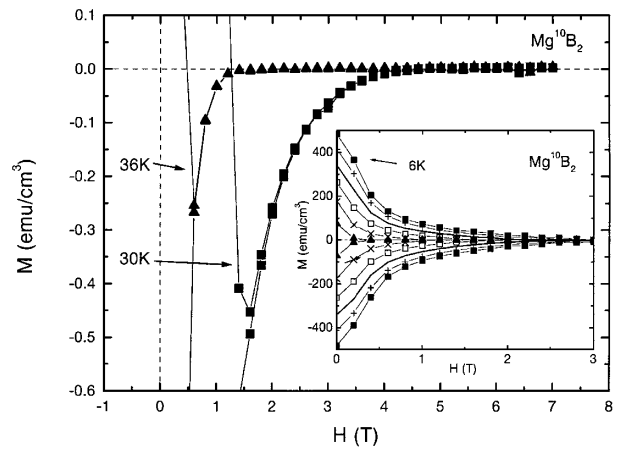


FIG. 4. Expanded view of magnetization vs field to show the reversible range and the H_{irr} region. Inset shows the full range of magnetization up to 3 T at temperature intervals of 6 K.

correction is easily made and H_{c2} and H_{irr} are fairly easy to measure. At 7 T, the magnitude of the background is about 0.13 emu/cm^3 and the correction can be made to an accuracy of 0.01 emu/cm^3 . The inset shows the irreversible magnetization over a fuller temperature range. In the inset, the \times symbols show the 30 K data and show that about 200 emu/cm^3 or about 0.2 T flux is trapped at zero field. At 6 K, shown by the solid squares of the inset, the trapped flux at zero applied field for this rather porous granular pellet is 500 emu/cm^3 or over 0.5 T.

Using the Bean [5] model with $J_c = 17\Delta M/r$, the critical current densities of Fig. 5 can be derived. Here J_c is in A/cm^2 , ΔM in emu/cm^3 , and the sample radius, r , in cm. These J_c values are not as high as a sintered pellet of Nb_3Sn [5], but the grain-to-grain supercurrent coupling is rather promising. A scanning electron microscope picture of a fracture surface of the pellet shows grain size running from about 0.5 to $5 \mu\text{m}$. The grains are somewhat faceted plates and many small grains are equiaxed. From the magnitude of the measured screening currents, it is

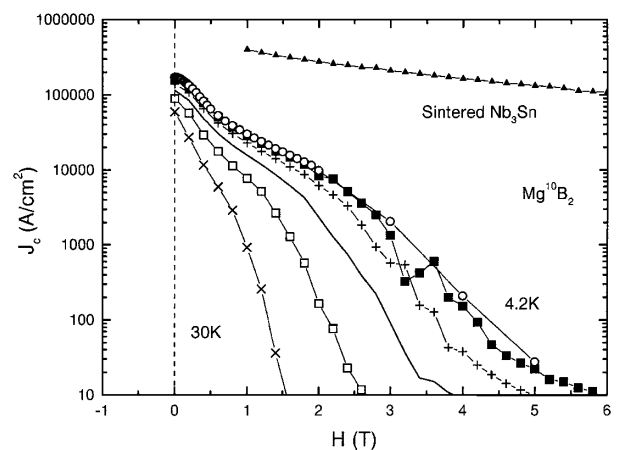


FIG. 5. Comparison of $J_c(H, T)$ up to 30 K with published data for a sintered Nb_3Sn sample at 4.2 K.

clear that the proper r to put in the Bean model is the full sample diameter and not the grain size. The sample radius is about 1 mm.

Close to T_c , there is a reasonable range of thermodynamic reversibility, so an estimate has been made of H_c vs T . To do this, it is assumed that the flux pinning in decreasing magnetic field is the same as in increasing magnetic field and an equilibrium magnetization is defined as the average of the increasing field magnetization and the decreasing field magnetization by $M_{\text{eq}} = (M_{\text{inc}} + M_{\text{dec}})/2$. Willemin and co-workers [6] have shown the validity of this procedure. A plot of M_{eq} vs T in Fig. 6 shows behavior close to that predicted by Abrikosov [7]. Integrating the area under these magnetization curves gives the H_c vs T curve shown in the inset of Fig. 6. From the slope of $dH_c/dT = 119$ Oe/K, one can calculate the jump in specific heat at T_c to be $\Delta C = [VT_c/4\pi][dH_c/dT]^2 = 79$ mJ/mol K. This is consistent with the direct specific heat measurements published earlier [2] from which ΔC can be estimated to be about 84 mJ/mol K.

IV. Conclusions.—The transport and magnetization studies of Mg^{10}B_2 give very consistent measures of $H_{c2}(T)$ for this material with magnetization data giving a slope at T_c of $dH_{c2}/dT = 0.44$ T/K. The magnetization H_{c2} agrees with the onset of the resistive transition, and the broadened resistive transitions seem to reflect a flux-flow resistivity phenomenon. Close to T_c , the values of the H_c can be estimated and the slope is found to be $dH_c/dT = 0.012$ T/K. This then means that the Ginsburg-Landau parameter $\kappa = H_{c2}/[0.707H_c] \approx 26$. By estimating $H_{c2}(T=0) = 0.71T_c[dH_{c2}/dT]_{T_c}$ to be 12.5 T, the low temperature coherence distance, $\xi_0 = \phi_0/[2\pi H_{c2}]^{1/2}$, is found to be 5.2 nm. Using the relation $\kappa = \xi_0/\lambda$, the penetration depth, $\lambda = 140$ nm.

The critical current densities for this rather porous sintered sample are on the order of 10^5 A/cm² at 6 K. This would seem to indicate that MgB_2 grain boundaries can transmit rather large supercurrents.

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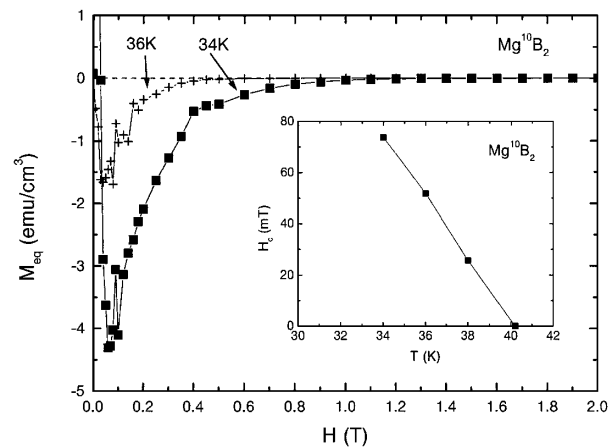


FIG. 6. $M_{\text{eq}} = (M_{\text{inc}} + M_{\text{dec}})/2$ vs T plot to show the extension of the reversible magnetization into the irreversible range assuming that flux pinning is the same for increasing and decreasing fields. The inset shows the resulting values of H_c .

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*On leave from Commissariat à l'Énergie Atomique, DRFMC-SPSMS, 38054 Grenoble, France.

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