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SPECIFIC HEAT OF $Mg^{11}B_2$ IN MAGNETIC FIELDS: TWO ENERGY GAPS IN THE SUPERCONDUCTING STATE

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We present specific-heat measurements on $Mg^{11}B_2$ in magnetic fields to 9 T. The anomaly at T_c is rapidly broadened and attenuated in fields, as expected for an anisotropic, randomly oriented superconductor. At low temperature there is a strongly field-dependent feature that shows the existence of a second energy gap. The Sommerfeld constant, γ, increases rapidly and non-linearly with magnetic field, which cannot be accounted for by anisotropy. It approaches γ_n = 2.6 mJ K^{-2} mol^{-1}, the coefficient of the normal-state electron contribution, asymptotically for fields greater than 5 T. In zero magnetic field the data can be fitted with a phenomenological two-gap model, a generalization of a semi-empirical model for single-gap superconductors. Both of the gaps close at the same T_c; one is larger and one smaller than the BCS weak coupling limit, in the ratio ~ 4:1, and each accounts for ~ 50% of the normal-state electron density of states. The parameters characterizing the fit agree well with those from theory and are in approximate agreement with some spectroscopic measurements.

Soon after the discovery of superconductivity in MgB_2 with T_c ~ 40 K [1], it was shown that the specific heat, C, provides compelling evidence for the existence of two distinctly different energy gaps. In this paper we will describe briefly how specific-heat measurements in magnetic fields, H, can be used to identify and quantify these energy gaps [2-4].

The electronic specific heat, $C_e(H)$, for various H is plotted in Fig. 1 as $C_e(H)/T$ *vs*. T for a polycrystalline sample of $Mg^{11}B_2$, where $C_e(H)$ was evaluated from the difference $C(H)$ – C(9 T) [2-4]. The anomaly at T_c is rapidly broadened and attenuated in H, as expected for an anisotropic, randomly oriented superconductor in the mixed state. In addition, two things are striking about the plot: 1). For $H = 0$ C_e increases much more rapidly with T than for a BCS superconductor. 2). At low T and $H \neq 0$, there is a very rapid, non-linear (nearly exponential) increase in C_e/T, with increasing H, which cannot be accounted for by anisotropy (see below). Two other reports of specific-heat measurements [5,6] give similar results, confirming that this behavior is intrinsic. The behavior is conspicuously different from that of any other known superconductor. It gives the appearance of a transition to the superconducting state in two stages that are associated with two energy gaps, one much smaller than the other.

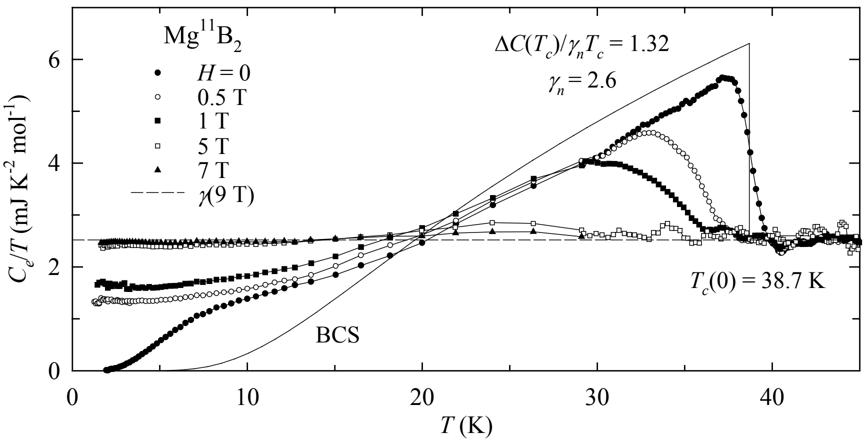

Figure 1. C_e/T *vs*. T in magnetic fields to 9 T.

Figure 2a is a plot of $\gamma(H)$ *vs*. H, where γ is the Sommerfeld constant, showing the non-linear increase. The normal state γ_n was obtained by extrapolating the data to the upper critical field $H_{c2}(0) = 16$ T [7]. Anisotropy in H_{c2} cannot explain the dramatic increase in $\gamma(H)$ at low H. The dashed curve is a calculation using the effective-mass model with an anisotropy of 10, which is larger than reported values [8,9], but $\gamma(H)$ cannot be fitted with *any* value of anisotropy. The rapid increase in $\gamma(H)$ at low H can be explained by the presence of a second energy gap with a small magnitude and associated small condensation energy.

In Fig 2b the presence of a second, smaller energy gap is shown clearly in the exponential T dependence of C_{es} for $H = 0$, where C_{es} is the electronic specific heat in the superconducting state. C_{es} is well represented by a simple exponential over a much wider range of T, $4 < T_c/T < 17$, than for a BCS superconductor. This corresponds to the fact that the smaller gap, which determines C_{es}, is much smaller than the BCS gap. A comparison of the fitted parameters, shown in Fig. 2b, with BCS expressions valid in this temperature interval gives as a rough approximation to the $T = 0$ gap parameter $\Delta_2(0) = 0.44\ k_B T_c$, about one quarter of the BCS value. For a two-band, two-gap super-

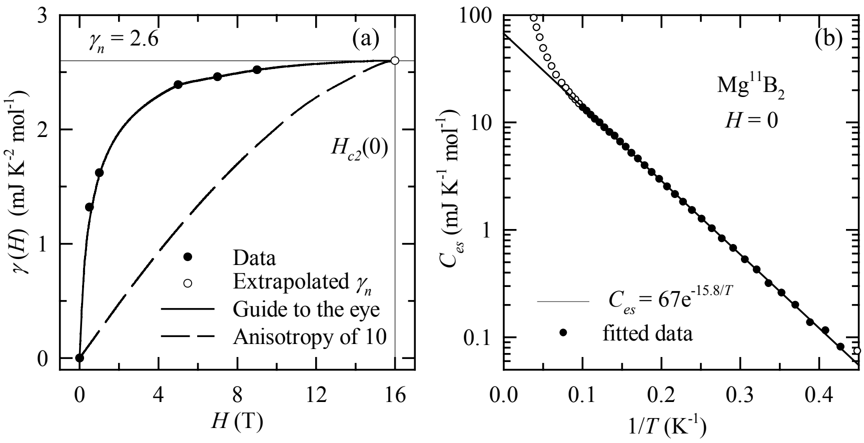

Figure 2. (a) $\gamma(H)$ *vs*. H. (b) The low-temperature exponential dependence of C_{es} *vs*. $1/T$ for $H = 0$.

conductor, interband coupling ensures that both gaps open at the same T_c [10]. If the electron-phonon coupling is weaker in one band than the other the two gaps are likely to have similar T dependences [11] but C_{es} will be determined by the smaller gap at low T [10]. Qualitatively, the T dependence of C_{es} is consistent with the expectations for such a two-gap superconductor.

A phenomenological model for a two-gap superconductor [4], which is a generalization of a semi-empirical model for single-gap superconductors [12] – generally referred to as the "α-model"– provides the basis for a quantitative interpretation of C_{es} for $H = 0$. In a two-band, two-gap model the total C_{es} is taken as the sum of the specific heats calculated independently for each band. C_{es} is fitted with four parameters: The two gaps Δ_1 and Δ_2 plus their normalizing factors γ_1/γ_n and γ_2/γ_n, which are subject to the constraint that $\gamma_1 + \gamma_2 = \gamma_n$. Figure 3 shows the results of such a fit, with the four fitted parameters given in the figure. The two gaps are in the ratio ~ 4:1, and each accounts for ~ 50% of the normal-state electron density of states (see Fig. 3 for the exact fitted values of the parameters). These results are consistent with constraints imposed by the general theory of two-gap superconductors: In the low-T limit C_{es} is determined by the smaller gap [10]; $\Delta C(T_c)/\gamma_n T_c$ must be less than the BCS value (the experimental value is 1.32 and the BCS value is 1.43); one gap must be larger than the BCS gap and one smaller [11]. The derived values of the parameters are in remarkably good agreement with band-structure calculations [13]. The agreement of the parameters derived from the two-gap

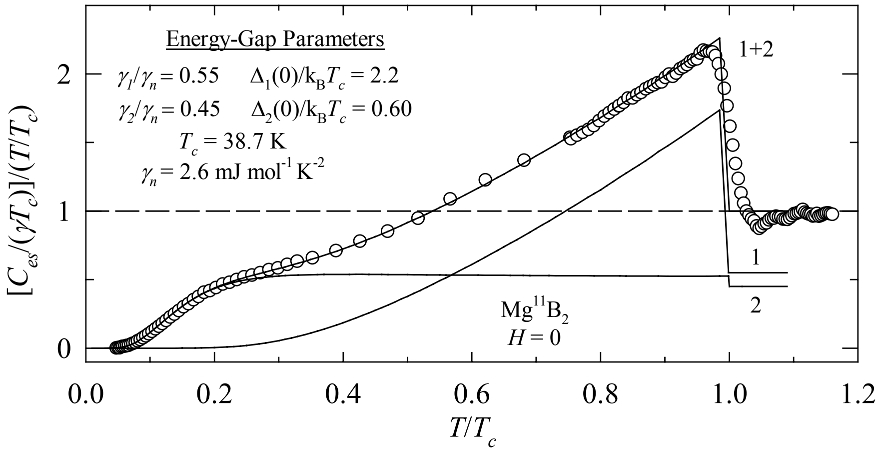

Figure 3. Results of a fit to C_{es}, for $H = 0$, with a phenomenological two-gap model.

model with the theoretical band-structure calculations argues persuasively for both the existence of two-gaps in MgB_2 and its relation to the high value of T_c.

The phenomenological two-gap model fit of the data of Ref. [5] gives results [4] that are similar to ours, while the data of Ref. [6] has a low-temperature exponential behavior that is very similar to that shown in Fig. 2b.

The majority of spectroscopic determinations of the gap parameters for MgB_2 identify only one gap (some large, some small), but a significant number do show two gaps, which in some cases [14-18] are in approximate agreement with those derived from the two-gap model C_{es} fit [3,4] and band-structure calculations [13].

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References

1. Nagamatsu J. *et al.*, *Nature* **410** (2001) 63.
2. Bouquet F. *et al.*, *Phys. Rev. Lett.* **87** (2001) 47001.

3. Fisher R. A. *et al*., *Studies of High Temperature Superconductors* **38**, ed. by A. V. Narlikar (Nova Science, Commack, NY, 2001) in press, cond-mat/0107072 (2001).
4. Bouquet F. *et al*., *Europhys. Lett*., in press, cond-mat/0107196 (2001).
5. Wang Y. *et al*., *Physica C* **355** (2001) 179.
6. Yang H. D. *et al*., *Phys. Rev. Lett*., in press, cond-mat/0104574 (2001).
7. Bud'ko S. L. *et al*., *Phys. Rev. B* **63** (2001) 220503R.
8. An J. M. *et al*., *Phys. Rev. Lett*. **86** (2001) 4366.
9. deLima O. F. *et al*., *Phys. Rev. Lett*. **86** (2001) 59741.
10. Geilikman B. T. *et al*., *Sov. Phys. Solid State* **9** (1967) 642.
11. Kresin V. Z. and Wolf S. A., *Physica C* **169** (1990) 476.
12. Padamasee H. *et al*., *J. Low Temp. Phys*. **12** (1973) 387.
13. Liu A. Y. *et al*., *Phys. Rev. Lett*. **87** (2001) 87005.
14. Giubileo F., *et al*., cond-mat/0105592 (2001).
15. Szab\ P. *et al*., cond-mat/0105598 (2001).
16. Laube F. *et al*., cond-mat/0106407 (2001).
17. Tsuda S. *et al*., *Phys. Rev. Lett*. **87** (2001) 177006.
18. Chen X. K. *et al*., *Phys. Rev. Lett*. **87** (2001) 157002.