Vol. 34 (2003) *ACTA PHYSICA POLONICA B* No 2

ANISOTROPIC CRITICAL FIELDS of MgB_2 SINGLE CRYSTALS *

T. Dahm

Universität Tübingen, Institut für Theoretische Physik
Auf der Morgenstelle 14, 72076 Tübingen, Germany

A.I. Posazhennikova

Laboratorium voor Vaste-Stoffusica en Magnetisme
Katholieke Universiteit Leuven, 3001 Leuven, Belgium

and K. Maki

Max-Planck-Institute for Physics of Complex Systems
Nöthnitzerstr. 38, 01187 Dresden, Germany

and

Department of Physics and Astronomy, University of Southern California
Los Angeles, CA 90089-0484, USA

(Received July 10, 2002)

The recently discovered superconductivity in MgB_2 has created the world sensation. In spite of the relatively high superconducting transition temperature $T_c = 39\,K$, the superconductivity is understood in terms of rare two gap superconductor with energy gaps attached to the σ and π-band. However, this simple model cannot describe the temperature dependent anisotropy in H_{c2} or the temperature dependence of the anisotropic magnetic penetration depth. Here we propose a model with two anisotropic energy gaps with different shapes. Indeed the present model describes a number of peculiarities of MgB_2 which have been revealed only recently through single crystal MgB_2.

PACS numbers: 74.20.Rp, 74.25.Bt, 74.70.Ad

---

[*] Presented at the International Conference on Strongly Correlated Electron Systems, (SCES 02), Cracow, Poland, July 10–13, 2002.

1. Introduction

The discovery of new superconductivity in $\mathrm{MgB_2}$ took the world by surprise [1]. Early studies based on polycrystalline samples lead to a two gap model [2–4]. On the other hand the anisotropy in $H_{\mathrm{c}2}(t,\Theta)$ suggested an anisotropic s-wave model [5–9]. Further it is clear that the simple two gap model cannot describe the strong temperature dependence of $\gamma(t) = H_{\mathrm{c}2}^{ab}(t)/H_{\mathrm{c}2}^{c}(t)$ observed in single crystal $\mathrm{MgB_2}$ [6, 9]. For this we need an order parameter $\Delta(\vec{k})$ of oblate shape [9]. On the other hand, it is well known that $H_{\mathrm{c}2}^{ab}(t)/H_{\mathrm{c}2}^{c}(t) > 1$ and $H_{\mathrm{c}1}^{ab}(t)/H_{\mathrm{c}1}^{c}(t) > 1$ for single crystal experiments [10–12], which contradicts the Ginzburg–Landau phenomenology. Further, both magnetic penetration depth data and $H_{\mathrm{c}1}^{c}(t)$ data suggest a prolate order parameter as in [7,8]. Indeed, an earlier STM study suggested a prolate order parameter as well [13].

Is the order parameter prolate or oblate? The answer is that we need both. We suggest, that the oblate order parameter is attached to the σ-band while the prolate order parameter to the π-band. In the following we shall describe salient features of single crystal $\mathrm{MgB_2}$ within the present model.

2. Upper critical field

We just point out two features in the upper critical field which are outside of the Ginzburg–Landau phenomenology: *(a)* the strong temperature dependence of the anisotropy parameter $\gamma(t) = H_{\mathrm{c}2}^{ab}(t)/H_{\mathrm{c}2}^{c}(t)$ [9]; *(b)* the deviation from the effective mass model $H_{\mathrm{c}2}(t,\Theta)/H_{\mathrm{c}2}(t,0) \neq (\cos^2\Theta + \gamma\sin^2\Theta)^{-1/2}$ [6].

For example $\Delta(\vec{k}) \sim 1/\sqrt{1+az^2}$, where $z = \cos\Theta$ and $a \sim 100$ can describe the temperature dependence of $\gamma(t)$, as has been shown in Ref. [9]. Also, by fitting the experimental data we obtained $v_a \simeq 2.7 \times 10^7$ cm/sec and $v_c/v_a \simeq 0.48$. We point out that these values are very consistent with the ones for the σ-band [2].

By fitting experimental data for $H_{\mathrm{c}2}(\theta)$ [14] close to T_{c} we can deduce the ratio $v_c/v_a \simeq 0.73$, implying $a = 10$, for example. This result is greater than that estimated in our previous analysis of $H_{\mathrm{c}2}(T)$ [9]. Next order correction in $(T - T_{\mathrm{c}})/T_{\mathrm{c}}$ leads to the increase of the ratio v_c/v_a for the same values of the parameter a. In the future we are going to elaborate our study of the upper critical field behavior in $\mathrm{MgB_2}$ by taking into account impurity scattering, what we believe will improve the agreement with experiment.

3. Lower critical field

From c-axis oriented films and single crystals, the superfluid density $\rho_{\mathrm{s},a}$ and the lower critical fields $H_{\mathrm{c}1}^{c}$ and $H_{\mathrm{c}1}^{ab}$ have been extracted reliably [11,12]. It is clear this time that we need a prolate order parameter to fit these data.

We choose $\Delta(\vec{k}) = 1/\sqrt{1-az^2}$ with $a \simeq 0.92 \sim 0.95$. These values give a good fit of penetration depth data [11]. The magnetic penetration depths are related to the lower critical fields via the formulas

$$H_{c1}^{c}(t) = \frac{\Phi_0}{2\pi\lambda_a^2(t)} \ln\frac{\lambda_a(t)}{\xi_a(t)}, \tag{1}$$

$$H_{c1}^{ab}(t) = \frac{\Phi_0}{2\pi\lambda_a(t)\lambda_c(t)} \ln\sqrt{\frac{\lambda_a(t)\lambda_c(t)}{\xi_a(t)\xi_c(t)}}, \tag{2}$$

where $\lambda_a(t)$ and $\lambda_c(t)$ are the magnetic penetration depth with the supercurrent in the ab-plane and in parallel to the c-axis, respectively. They are related to the superfluid density via $\rho_{s,a}(t) = \lambda_a^2(0)/\lambda_a^2(t)$ and $\rho_{s,c}(t) = \lambda_c^2(0)/\lambda_c^2(t)$. Taking $a = 0.95$, which fits $\rho_{s,a}(t)$ from Ref. [11], we calculate $\rho_{s,c}(t)$ and obtain the temperature dependences of H_{c1}^{c} and H_{c1}^{ab} from Eqs. (1) and (2), neglecting the temperature dependence of the logarithms. The result is shown in Fig. 1 along with the experimental results from Ref. [12]. From these fits we obtain $H_{c1}^{c}(0) = 24$ mT and $H_{c1}^{ab}(0) = 32$ mT. From this the ratio of the relevant Fermi velocities can be estimated as $H_{c1}^{ab}(0)/H_{c1}^{c}(0) \approx v_c/v_a = 1.3$. In other words, the corresponding Fermi surface is more isotropic and further $v_c > v_a$. This strongly suggests that the prolate order parameter we are considering has to be associated with the π-band.

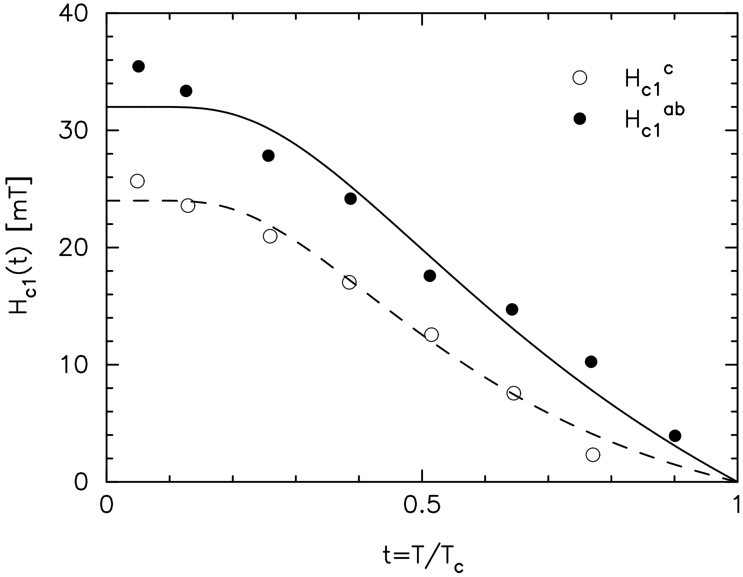

Fig. 1. Temperature dependence of the lower critical fields H_{c1}^{c} (dashed line) and H_{c1}^{ab} (solid line) along with the corresponding experimental data from Ref. [12].

4. Syntheses

We have seen so far that we need two energy gaps of different shape in order to describe $H_{c2}(t,\Theta)$ and $H_{c1}(t,\Theta)$. The temperature dependence of $\gamma(t)$ indicates that an oblate order parameter ($\Delta(\vec{k}) = 1/\sqrt{1+az^2}$) dominates the behavior at high magnetic field. Also we need $v_c/v_a = 0.48$. This suggests the cylindrical Fermi surface associated with the σ-band as the carrier of this order parameter. On the other hand, for $H_{c1}(t,\Theta)$ we need a prolate order parameter ($\Delta(\vec{k}) = 1/\sqrt{1-az^2}$). Also, the anisotropy in $H_{c1}(t,\Theta)$ suggests the π-band as the carrier of this order parameter. In other words, if we assume that the high field properties are controlled by the oblate order parameter attached to the σ-band, while the low field properties are due to the prolate order parameter attached to the π-band, we have a consistent picture for superconductivity in MgB_2.

We believe that this picture will be crucial to understand also a variety of anomalies observed in the vortex state in MgB_2.

We would like to thank M. Angst, F. Bouquet, S. Haas, A. Janossy, A. Junod, B.B. Jin and N. Klein for useful discussions on MgB_2.

REFERENCES

[1] J. Nagamatsu *et al.*, *Nature* **410**, 63 (2001).

[2] S.V. Shulga *et al.*, `cond-mat/0103154`.

[3] J.M. An, W.E. Pickett, *Phys. Rev. Lett.* **86**, 4366 (2001).

[4] A.Y. Liu, I.I. Mazin, J. Kortus, *Phys. Rev. Lett.* **87**, 087005 (2001).

[5] O.F. de Lima *et al.*, *Phys. Rev.* **B64**, 144517 (2001).

[6] M. Angst *et al.*, *Phys. Rev. Lett.* **88**, 167004 (2002).

[7] Y. Chen, S. Haas, K. Maki, *Curr. Appl. Phys.* **1**, 333 (2001).

[8] S. Haa, K. Maki, *Phys. Rev.* **B65**, 020502(R) (2002).

[9] A.I. Posazhennikova, T. Dahm, K. Maki, `cond-mat/0204272`, to appear in *Europhys. Lett.*.

[10] C. Buzea, T. Yamashita, *Supercond. Sci. Technol.* **14**, R115 (2001).

[11] B.B. Jin *et al.*, `cond-mat/0112350`, to appear in *Phys. Rev.* **B**.

[12] M. Xu *et al.*, *Appl. Phys. Lett.* **79**, 2779 (2001).

[13] P. Seneor *et al.*, *Phys. Rev.* **B65**, 012505 (2002).

[14] Yu. Eltsev *et al.*, *Physica* **C**, proceedings of ISS2001, Kobe, Japan, Sept. 24–26, 2001, in press.