Anisotropic properties of MgB$_2$ by torque magnetometry

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Abstract

Anisotropic properties of superconducting MgB$_2$ obtained by torque magnetometry are compared to theoretical predictions, concentrating on two issues. Firstly, the angular dependence of $H_{c2}$ is shown to deviate close to $T_c$ from the dependence assumed by anisotropic Ginzburg-Landau theory. Secondly, from the evaluation of torque vs angle curves it is concluded that the anisotropy of the penetration depth $\gamma$ has to be substantially higher at low temperature than theoretical estimates, at least in fields higher than 0.2 T.

Key words: MgB$_2$, anisotropy, upper critical field, penetration depth, torque
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Superconductivity in two bands of different dimensionality leads to a temperature dependent anisotropy of the upper critical field $\gamma_H = H_{c2}^{ab}/H_{c2}^{c}$ [1] in MgB$_2$, observed, e.g., by torque magnetometry [2]. Both torque results [2] and calculations [3] of $H_{c2}(\theta)$ indicate systematic deviations from the angular dependence expected within anisotropic Ginzburg-Landau theory (AGLT). However, the deviations found experimentally are most pronounced near $T_c$, while the calculations [3] predict pronounced deviations at low temperature $T$ only. Recently, new calculations of $H_{c2}(\theta)$ were carried out for the (intra-band) dirty limit [4,5]. We will show that there is good agreement in the form of the deviations of $H_{c2}(\theta)$ from AGLT between our torque results and the calculations of Ref. [5]. Calculations [6] also predicted an anisotropy of the penetration depth $\gamma_\lambda \ll \gamma_H$ at low $T$. A field $H$ dependence of an effective anisotropy [2] may be taken as an indication of such a difference between $\gamma_\lambda$ and $\gamma_H$ [7]. A recent calculation of torque $\tau(\theta)$ dependences in the London regime for the case of different $\gamma_\lambda$ and $\gamma_H$ led to the prediction of a sign reversal of the torque at low $T$ in MgB$_2$ [8]. From the comparison of the $\tau(\theta)$ dependence with the predictions of Ref. [8], we find a lower limit for $\gamma_\lambda$ at low temperatures, considerably higher than theoretical estimates [6].

For details concerning measurement apparatus and procedure, samples, and the determination of $H_{c2}$ see Refs. [2,7]. $H_{c2}(\theta)$, determined from $\tau(\theta)$ curves measured in various fields at 33 K $\simeq 0.87 T_c$, is shown in Fig. 1a). By definition, $\tau$ is 0 for $H||c$ or $||ab$, and small for field directions close. This is why there are no data close to 0° and 90°. In AGLT, $H_{c2}(\theta)$ is described by

$$H_{c2}^{AGL}(\theta) = H_{c2}^{ab}(\cos^2 \theta + \sin^2 \theta/\gamma_H^2)^{-1/2}. \quad (1)$$

The best fit of Eq. (1) to the data is indicated by the full line. Small, but systematic deviations can be seen, especially when plotting the difference between experimental data and best fit vs $\theta$ (inset): at 0.87 $T_c$, $H_{c2}(\theta)$ is not (accurately) described by Eq. (1). Deviations from Eq. (1) were not observed at lower $T$ (cf. Fig. 2 of Ref. [2]). Deviations most pronounced in the region of 0.9-0.95 $T_c$ were also found in a recent calculation [5] assuming high intraband scattering (dirty limit). In order to compare experimentally observed deviations to the predictions of Ref. [5], we calculated “AGLT
deviations” \( \alpha(\theta) \equiv \frac{H_{c2}(\theta)}{H_{c2}^{AGL}(\theta)} \). For \( \mu_0H_{c2}^{AGL} = 0.475 \text{ T} \) and \( \gamma = 3.47 \), \( \alpha(\theta) \) has form and magnitude [Fig. 1b] very similar to deviation functions for calculated [5] \( H_{c2}(\theta) \) (full line) at the same temperature [9]. Although the theoretically predicted [5] \( \gamma_H \approx 4.86 \) is higher than our data indicate, the similarity of the AGLT deviation suggests that (intraband) scattering cannot be neglected in theoretical descriptions of \( H_{c2} \).

Figure 2a) shows a \( \tau(\theta) \) curve measured (on a different crystal) in the mixed state close to \( T_c \approx 38.5 \text{ K} \). Near \( T_c \), the difference between \( \gamma_L \) and \( \gamma_H \) is small, in agreement with theoretical predictions [3,8]. The \( \tau(\theta) \) curve measured at low \( T \) [Fig. 2b)] has the same sign as the one measured close to \( T_c \), i.e., there is no sign change as expected [8] for \( \gamma_L \ll \gamma_H \). For \( \gamma_L \) moderately lower than \( \gamma_H \), Ref. [8] predicts a sign change only in an angular region close to \( 90^\circ \), illustrated with a dashed line in Fig. 2b). Such a partial sign change is also not observed, the maximum angular region where it could occur given by the irreversibility region (the slight asymmetry in the irreversibility is due to thickness variations of the crystal).

Comparing the data with curves calculated according to Ref. [8], with \( \mu_0H_{c2}^{AGL} = 3 \text{ T} \), \( \gamma_H = 6 \) [2] and various \( \gamma_L \), we conclude that \( \gamma_L \) has to be at least 2.6, considerably higher than currently available theoretical estimates [6]. Alternatively, if \( \gamma_H \) in 0.2 T is much smaller than in \( H \approx H_{c2} \) [1], the absence of a sign reversal is compatible with smaller \( \gamma_L \).

However, we should mention that the best description of the data is given by \( \gamma_L \approx \gamma_H \approx 3.3 \).

The discrepancy may be explained by the influence of the magnetic field, depressing superconductivity in the more isotropic \( \pi \) bands. This should lead to anisotropies (\( \gamma_L \) and/or \( \gamma_H \)) increasing with increasing field [2]. An anisotropy increasing with \( H \) has also been postulated based on specific heat measurements (mostly sensitive to the coherence length, i.e., \( \gamma_H \) [1]).

References

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