Temperature and Field Dependence of the Anisotropy of MgB₂

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The anisotropy γ of the superconducting state of high quality single-crystals of MgB₂ was determined, using torque magnetometry with two different methods. The anisotropy of the upper critical field was found to be temperature dependent, decreasing from γ ≈ 6 at 15 K to 2.8 at 35 K. Reversible torque data near Tc reveal a field dependent anisotropy, increasing nearly linearly from γ ≈ 2 in zero field to 3.7 in 10 kOe. The unusual temperature dependence is a true bulk property and can be explained by non-local effects of anisotropic pairing and/or the k-dependence of the effective mass tensor.

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The discovery of superconductivity at Tc ≈ 39 K in MgB₂ [1] has caused a lot of interest into its physical properties (for a review see Ref. [2]). Measurements of the anisotropic Ginzburg-Landau (GL) theory γ = (m∗ c/meff)1/2 = λc/λab = ξab/ξc = Hc2/δHc2, where δHc2 indicates the field H perpendicular(parallel) to the c-axis of the sample and m∗, λ, ξ and Hc2 are the GL effective mass, the coherence length, and the upper critical or bulk nucleation field, respectively. Most values reported for the anisotropy of polycrystalline or thin film MgB₂ span the range of values of γ = 1.1 – 3 [3], but there are also reports with γ ≈ 6 – 9 [3, 4]. Up to now, there are only four reports on transport measurements of the upper critical field anisotropy performed on single crystals, giving values of 2.6 [3], 2.7 [6] and 3 [3]. Magnetic measurements of the angular dependence of Hc2(θ), yielding γ = 1.6, were reported only on aligned crystallites [11].

Here, we report magnetic torque measurements on single crystals of MgB₂, performed in a wide range of temperatures from 15 K to 36 K in magnetic fields of up to 90 kOe. We provide evidence that the bulk anisotropy γ is not universally constant, but is temperature dependent down to at least 0.4 Tc and shows a pronounced field dependence near Tc. Microscopic origins of the unusual T-dependence of γ in MgB₂ are discussed.

We have grown single crystals of MgB₂ with a high pressure cubic anvil technique, similar to the one described in Ref. [6]. The details of crystal growth will be published elsewhere. In brief, a mixture of Mg and B was put into a BN container and a pressure of 30 – 35 kbar was applied. Growth runs consisted of heating during 1 h up to the maximum temperature of 1700 – 1800°C, keeping the temperature for 1 – 3 h and then cooling to room temperature during 1 – 2 h. Flat crystals were up to 0.8 × 0.6 × 0.05 mm³ in size, with sharp transitions to the superconducting state at about 38 – 39 K.

Measurements were performed on miniaturized piezoresistive cantilevers specifically designed for torque magnetometry [20]. The torque τ = m ⋅ B ≈ m ⋅ H, where m is the magnetic moment of the sample, was recorded as a function of the angle θ between the applied field H and the c-axis of the crystal for various fixed temperatures and fields. For measurements close to Tc, in fields up to 14 kOe, a non-commercial magnetometer with very high sensitivity was used. For part of these measurements, a vortex-shaking process was employed to speed up the relaxation of the vortex lattice [21]. The observation of a well-resolved lock-in effect in τ(θ) (see upper inset of Fig. 3) indicates there are no variations of crystallographic alignment throughout the samples. A crystal with a volume of about 4 × 10⁻⁴ mm³ (sample A) was measured in this system. Another crystal with a volume of about 8 × 10⁻³ mm³ (sample B) was measured in a wider range of temperatures down to 15 K in a Quantum Design PPMS with torque option and a maximum field of 90 kOe.

An example of a torque vs. angle curve is given in the inset of Fig. 3. For small angles θ the torque is essentially zero. Only when H is nearly parallel to the ab-plane there is an appreciable torque signal. The curve can be
interpreted in a straight-forward way: for $H$ parallel to the $c$–axis the sample is in the normal state, while for $H$ parallel to the $ab$–plane it is in the superconducting state. The crossover angle $\theta_{c2}$ between the normal and the superconducting state is the angle for which the fixed applied field is the upper critical field. The inset of Fig. 1 also shows hysteretic behaviour due to irreversibility. The irreversibility field $H_{irr}(T, \theta)$ determined from the torque measurements is very high, close to $H_{c2}$. Preliminary SQUID measurements on similar crystals indicate a much lower $H_{irr}$, an extended discussion of the irreversible properties of MgB$_2$ will be published elsewhere.

The crossing between straight lines through the background and the superconducting torque signal was used to define $\theta_{c2}$. This definition is not unambiguous. Taking the analysis of the data more strict we have to apply the appropriate scaling rules. The magnetization $M$ of a 3D system in the GL theory of fluctuations in the vicinity of the transition temperature $T_c(H)$ in high magnetic fields is given by a universal function $F$ of the distance from $T_c(H)$ [23]:

$$ M = \frac{T^{2/3}}{H^{1/3}} F \left( \frac{A(T-T_c)}{(TH)^{2/3}} \right), \quad (1) $$

where $A$ is a material constant. Combining the above dependence with the angular dependence of the torque [2] we find that the rescaled torque signal

$$ P = -\epsilon^{1/3}(\theta) \left( \sin \theta \cos \theta H^{5/3}(1 - 1/\gamma^2)T^{2/3} \right) \quad (2) $$

with $\epsilon(\theta) = (\cos^2 \theta + \sin^2 \theta/\gamma^2)^{1/2}$, is a universal function of the distance from $T_c$ with a fixed value $F(0)$ at $T = T_c(H)$. Taking into account the $F(0)$ value for the theoretical dependence of the universal function for a 3D system [2] we can estimate that for a volume of the sample of $8 \times 10^{-3}$ mm$^3$ $P$ reaches at $T = T_c(H)$ a value of about $2 \times 10^{-10}$ dyn cm Oe$^{-5/3}$ K$^{-2/3}$. The inset in Fig. 2 presents the angular dependence of the rescaled torque $P$ in different magnetic fields at 22K. The crossing of the $P(\theta)$ dependence for each field with the line of the constant value of $2 \times 10^{-10}$ dyn cm Oe$^{-5/3}$ K$^{-2/3}$ determines the $H_{c2}(\theta)$ dependence as it is shown in the main panel of Fig. 2. It is important to stress that the results obtained depend not very sensitively on the criterion chosen and it will be shown later (see Fig. 3) that even with a three times higher criterion we get very similar temperature dependences of $H_{c2}$ and $\gamma$. Additional $\tau(H)$ measurements at fixed angle give $H_{c2}(\theta)$ values corresponding well to those from $\tau(\theta)$ measurements.

Within the applicability of the anisotropic GL theory the angle dependence of the upper critical field is predicted to be [26]

$$ H_{c2}(\theta) = H_{c2}^\parallel (\cos^2 \theta + \sin^2 \theta/\gamma^2)^{-1/2}. \quad (3) $$

A fit of Eq. (3) to the data at 22 K yields $\gamma = 5.1(1)$ and $H_{c2}^\parallel = 17.2(1)$ kOe. This fit ($\gamma = 5.1$) describes the data well, while alternative fits with $\gamma$ fixed to 4 and 6 are clearly incompatible with the data, as shown in Fig. 2.

Figure 3 shows the angular dependence of $H_{c2}$ scaled by $H_{c2}^\parallel$ to directly compare the anisotropy at different temperatures. The 15 K data are well described by the line corresponding to $\gamma = 6$, while the 34 K data lie below the line for $\gamma = 3.5$. The data indicate an anisotropy systematically decreasing with increasing temperature. To show this is not an artifact related to fitting, we present the angular dependence of the rescaled torque $P$ for fixed $H/H_{c2}^\parallel$ in the inset. The curves clearly shift to higher angles with increasing temperature. Furthermore, we directly checked $\tau(\theta)$ raw data in fields above and below $H_{c2}^\parallel$ and $H_{c2}^{lab}$ to give absolute limitations of $\gamma$. We find...
that at 22 K, the anisotropy must be higher than 4.4, while at 34 K, it must be lower than 3.5.

All data are summarized in Fig. 4. The $H_{c2}^{ab}$ data obtained from fits to Eq. (3) do not vary much with the criterion used for the determination of $\theta_{c2}$, and agree well with $H_{c2}^{ab}$ calculated from thermal conductivity data [28] measured on a single crystal grown with the same technique. The $T$-dependence of $H_{c2}^{ab}$ is in agreement with calculations by Helfand et al. [29]. The corresponding $H_{c2}^{ab}(0) \approx 31 \text{kOe}$ is relatively small compared to literature values, which may indicate that the crystals investigated are relatively free of defects. The $H_{c2}^{ab}$ values were obtained from the two fit parameters $H_{c2}^{ab}$ and $\gamma$.

There is a slight positive curvature of $H_{c2}^{ab}(T)$, which can be attributed to the $T$-dependence of $\gamma$. The $\gamma(T)$ dependence may also be the origin of the positive curvature of $H_{c2}$ observed in other measurements of bulk, thin film and single crystal measurements [3]. Due to the lack of low temperature data and the variation of $\gamma$, only a rough estimation $H_{c2}^{ab}(0) \approx 230 \text{kOe}$ can be given. The anisotropy data show that $\gamma$ systematically decreases with increasing temperature. A change of the criterion used for the determination of $\theta_{c2}$ leads to small shifts of the magnitude of $\gamma$, but the temperature dependence is always the same. The highest upper critical field anisotropy $\gamma \approx 6$ was obtained at 15 K, the lowest anisotropy $\gamma \approx 2.8$ at 35 K. From Fig. 3 we estimate $\gamma(0) = 7 - 8$ and $\gamma(T_c) = 2.3 - 2.7$.

Small systematic deviations from Eq. (3), observed near $T_c$, indicate that the field influence on $\gamma$ may be important as well. To clarify this point, we have measured the reversible torque $\tau$ as a function of angle $\theta$ for various fields and temperatures near $T_c$. The data were analyzed with an equation derived by Kogan et al. [27], based on the anisotropic London model, which contains the GL anisotropy $\gamma$ as a parameter.

Without shaking, the irreversibility of the torque was relatively large and a clear lock-in effect was observed. The inset of Fig. 3 shows an example of shaken torque data, together with the fitted curve. An evaluation of the data measured for various $T$ and $H$ up to 10 kOe with the Kogan formula [27] reveal that $\gamma$ is field-dependent with larger $\gamma$ in larger fields, while temperature variations do not affect $\gamma$ appreciably (see Fig. 3). Indications of a field dependence of the coherence length $\xi$ (a precondition of a field dependence of it’s anisotropy) have been observed by specific heat [30] and muon spin rotation [31] measurements on NbSe$_2$. We should stress that Kogan’s formula assumes equivalence of the anisotropies of the coherence length $\xi$ and the penetration depth $\lambda$. Since the anisotropy of $\lambda$ might be different from the one of $\xi$ in our case, the two different methods used in this work can lead to different effective values of $\gamma$. The field dependence of $\gamma$ may be related to the peculiar double gap structure of MgB$_2$ with a large gap of two-dimensional
nature and a small three-dimensional gap, which is very rapidly suppressed in a magnetic field \(H\).

A temperature dependent \(H_{c2}\) anisotropy was previously observed, e.g. in NbSe\(_2\) \cite{34} and LuNi\(_2\)B\(_2\)C \cite{35}. However, in MgB\(_2\), the effect is much more pronounced. It was shown that any theory capable of explaining a temperature dependence of \(\gamma\), needs to take into account non-local effects \cite{34,35}, which can be pronounced in samples of high purity. In the vicinity of \(T_c\), non-locality is not important \cite{34}. Therefore, \(m^{*}_{ab}/m^{*}_{ab} = \gamma^2(T_c) \approx 5 - 7\) corresponds to the standard GL effective mass anisotropy. We note that this is significantly higher than the calculated \(\gamma\) anisotropy of the band effective mass (BEM) averaged over the Fermi surface (1.0 – 1.2). The microscopic theories \cite{34,35} show that the \(T\) – dependence of \(\gamma\) cannot be attributed to an anisotropy of the BEM tensor, unless it is also a wave-vector dependent. An anisotropic energy gap, caused e.g. by an anisotropy in the electron-phonon coupling (EPC), can also lead to variations of \(\gamma\) with temperature.

In MgB\(_2\), first principles calculations suggest both a pronounced wave-vector dependence of the BEM tensor \cite{36} and a strong anisotropy of the EPC (see e.g. \cite{34,37}). The latter leads naturally \cite{36} to the observed double energy gap and was suggested \cite{38} to be responsible for the unusually high \(T_c\) of MgB\(_2\). To our knowledge, there is only one theory calculating a temperature dependent \(H_{c2}\) anisotropy of MgB\(_2\) \cite{39}, which predicts, however, \(H_{c2}^{\parallel ab}/H_{c2}^{\parallel c}\) to increase with increasing \(T\). A quantitative explanation of the measured \(\gamma(T)\) apparently needs to take into account both the wave-vector dependence of the BEM tensor and the anisotropic EPC, and is beyond the scope of this work.

In conclusion, the upper critical field anisotropy \(\gamma\) of MgB\(_2\), determined by torque magnetometry, decreases with increasing temperature. Measurements of the reversible torque near \(T_c\) reveal an almost linear field dependence of the anisotropy of the coherence length and/or the penetration depth as well. Our results imply a breakdown of standard anisotropic GL theory with a (temperature and field independent) effective mass anisotropy. The temperature dependence of \(\gamma\) can be approximated tentatively by \(\gamma(T) = \gamma^* + \tilde{\gamma}(1 - T/T_c)^n\) with \(n\) close to 1. Here, \(\gamma^* \approx 2.3 - 2.7\) is the band effective mass anisotropy and \(\tilde{\gamma} \approx 4.5 - 5.5\) arises from the anisotropy of the attractive electron-electron interaction and/or the wave-vector dependence of the effective mass tensor.

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