Reply to "Comment on 'Superconducting anisotropy and evidence for intrinsic pinning in single crystalline MgB_2' "

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We respond to the Comment by Angst *et al.* and report the analysis that our assumption of the upper critical field ηH_{c2} is reasonable.

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In our recent paper,[1] torque data measured on an MgB_2 single crystal in fields from 10 to 60 kG at 10 K were presented. It has been revealed that the MgB_2 crystal exhibits an intrinsic pinning[2] like a high-T_c cuprate.[3] This is consistent with a theoretical picture that the superconductivity in MgB_2 occurs in the boron layers.[4,5]

In the three-dimensional anisotropic London model in the mixed state, the angular dependence of the torque is given by Kogan[6] as

$$\tau_{rev}(\theta_c) = \frac{\phi_0 HV}{16\pi\lambda^2}\frac{\gamma_c^2-1}{\gamma_c^{1/3}}\frac{\sin 2\theta_c}{\epsilon(\theta_c)}\ln\left\{\frac{\gamma_c \eta H_{c2}^{\parallel c}}{H\epsilon(\theta_c)}\right\}, \qquad (1)$$

where $\epsilon(\theta_c)=(\sin^2\theta_c+\gamma_c^2\cos^2\theta_c)^{1/2}$, θ_c is the angle between the applied field and the c axis, $\gamma_c=\sqrt{m_c/m_{ab}}$, $H_{c2}^{\parallel c}$ is the upper critical field perpendicular to the ab plane $(\eta\sim 1)$, and V is the sample volume. The computer fitting of τ_{rev} to the Kogan model[6] gives the anisotropy parameter $\gamma_c=2.8-4.8$, where $\eta H_{c2}^{\parallel c}$ is fixed to 60 kG.[7] The results showed that the anisotropy is rather field-independent, $\gamma_c\simeq 4.3$ in fields above 20 kG. Angst *et al.*[8] claimed that the above conclusion on anisotropy does not hold, because the theoretical expression Eq. (1) used is not applicable to the torque data measured in fields close to or above the upper critical field $H_{c2}^{\parallel c}$.

A strict theoretical argument on the applicability of Eq. (1) by Angst *et al.* is correct, but it has also been well recognized by researchers in this field. To the authors' knowledge, we do not have an alternative formula, which is applicable for the whole regime of the mixed state.

The authors of Ref. 8 criticized the assumption $\eta H_{c2}^{\parallel c}=60$ kG in Ref. 1 which was simply cited from the experimental fact given in Ref. 7, and inferred that a possible discrepancy is an overestimation of $H_{c2}^{\parallel c}$ by Xu *et al.*[7] due to alignment problems. However, it is impossible for us to attribute the difference to an inevitable misalignment. Our crystal was grown under identical conditions to the first MgB_2 crystal[7] reported in the literature. The authors of Ref. 8 assume the relation $H_{c2}^{\parallel c}\simeq \eta H_{c2}^{\parallel c}$ while the explicit value of η is not analyzed in the Comment.[9] Therefore, the criticism is not thoroughly convincing without mentioning η. It is useful to note that the torque does not behave intricately but is always a simple monotonic function of increasing angle near $\theta_c\sim 0$ degrees where Angst *et al.*[10] explore the applicability of the formula. In our opinion, this makes it possible to apply the Kogan formula extensively in estimating an anisotropy parameter γ_c and $\eta H_{c2}^{\parallel c}$ without being affected by fatal flaws.

The difficulty in determining H_{c2} comes from the criterion. For example, Angst *et al.*[11] use the torque as a sensitive means of determining H_{c2} as a function of angle θ_c. In addition, the determination of H_{c2} is dependent on the criterion of the torque onset. The critical angle θ_{c2} in Fig. 1 of Ref. 12 could be either 74.4 degrees as marked in the figure or 60 degrees as the very onset. The difference is huge when one estimates the $H_{c2}(\theta_c)$ value. Figure 2 of Ref. 11 also shows that the very onset yields much higher H_{c2}, although the authors actually used an artificial finite criterion to determine the $H_{c2}(\theta_{c2})$ from the torque signal. The entire torque curve can be used to determine θ_{c2} with the aid of the Kogan model when $\eta H_{c2}^{\parallel c}(\theta)<H$ without any criterion difficulty. The procedure has successfully been applied for an electron-doped cuprate $Nd_{1.85}Ce_{0.15}CuO_4$ crystal to obtain $\eta H_{c2}^{\parallel c}$ with a reasonable γ_c.[12]

Angst *et al.*[8] cited some literature which report lower $H_{c2}^{\parallel c}$ in the region of 30-35 kG. However, the $H_{c2}^{\parallel c}$ of a superconductor definitely depends on the microscopic nature of the sample. They do not discuss such possibilities, but seem to believe in a universal H_{c2} for the various different single crystals. We note some examples. Pradhan *et al.*[13] showed that $H_{c2}^{\parallel c}$ is about 50 kG at 10 K. Lee *et al.*[14] showed that $H_{c2}^{\parallel c}$ is approximately 60 kG at 10 K. Kim *et al.*[15] showed that $H_{c2}^{\parallel c}$ is far beyond 60 kG at 10 K. It is very impressive to read a report by Gurevich *et al.*[16] that $H_{c2}^{\parallel c}(0)$ is extremely high (340 kG). We consider that our sample has a higher $H_{c2}^{\parallel c}$ compared to a sample used in Ref. 8.

Angst *et al.*[8] mentioned that even the data obtained in $H=30$ kG (Fig. 1 of Ref. 1) may not be sufficiently below H_{c2}

to yield a proper value from Eq. (1). We fixed a parameter $H_{c2}^{\|c}$ because our data have a poor signal-to-noise ratio due to the smallness of the crystal.[1] We obtained $\gamma = 4.23 \pm 0.29$ and $\eta H_{c2} = 62.9 \pm 8.0$ kG by a free parameter fitting to data in 30 kG of Ref. 1, which are relatively superior to other data in view of the signal-to-noise ratio. This reinforces the validity of our assumption of $\eta H_{c2}^{\|c} = 60$ kG at 10 K in analyzing γ_c.

In conclusion, we note that the anisotropy of the MgB_2 crystal might be dependent on the sample status.

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