Reply to "Comment on 'Anisotropic impurity scattering effects on T_c and H_{c2} in $YBa_2Cu_3O_x$'"

J.-Y. Lin
Institute of Physics, National Chiao Tung University, Hsinchu 300, Taiwan, Republic of China

H. D. Yang
Department of Physics, National Sun Yat-Sen University, Kaohsiung 804, Taiwan, Republic of China

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We present discussions about the value of the transport coupling constant λ_{tr} in $YBa_2Cu_3O_y$. We have also reanalyzed our previous impurity scattering data according to the recently suggested relation between the momentum-dependent anisotropic function $f(\mathbf{k})$, the ratio of anisotropic to isotropic scattering g_I, and the normalized order parameter $e(\mathbf{k})$. Using the appropriate values of the transport properties and the plasma frequency, it is found that λ_{tr} as low as 0.2 is still a plausible value. Furthermore, we have studied the case of $\langle ef\rangle^2=0.81$, which corresponds to $f(\mathbf{k})=\pm 1$. For $\lambda_{tr}=0.2$, $g_I=0.67$ for in-plane oxygen defects and $g_I=0$ for Zn impurities, respectively. If $\lambda_{tr}=0.3$, $g_I=0.82$ for in-plane oxygen defects and $g_I=0.33$ for Zn impurities, respectively.

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We are grateful to Haraǹ[17] for comments on one of our previous papers about the anisotropic impurity scattering effects in $YBa_2Cu_3O_x$ (YBCO).[1] It is a precious opportunity for us to present important discussions that we had to omit in Ref. 1 due to the page limit. Haraǹ's comments raise two subtle issues. The first one is the interplay of $\langle ef\rangle^2$ and g_I through the equation, which describe the impurity scattering effects on T_c,[2–5]

$$\ln\frac{T_{c0}}{T_c}=\langle ef\rangle^2\left\{\psi\left[\frac{1}{2}+(1-g_I)\frac{\tau_{\mathrm{imp}}^{-1}}{4\pi T_c}\right]-\psi\left(\frac{1}{2}\right)\right\}+(\langle e\rangle^2+\langle ef\rangle^2-1)\left[\psi\left(\frac{1}{2}+\frac{\tau_{\mathrm{imp}}^{-1}}{4\pi T_c}\right)-\psi\left(\frac{1}{2}\right)\right], \quad (1)$$

where ψ is the digamma function, T_{c0} is the initial T_c of the sample, and τ_{imp}^{-1} is the isotropic component of impurity scattering rate. In this model, $f(\mathbf{k})$ is the momentum-dependent anisotropic function, g_I is the ratio of anisotropic to isotropic scattering, $e(\mathbf{k})$ is the normalized order parameter, and $\langle\cdots\rangle$ denotes the average on the Fermi surface. The other issue is the legitimacy of the value of λ_{tr} used in Ref. 1, where λ_{tr} is the transport coupling constant.[1,6,7]

We would like, first, to discuss the plausible range of the values of λ_{tr}. In Ref. 1, $\lambda_{tr}=0.2$ was used. According to Ref. 8, $\lambda_{tr}=0.246(\hbar\omega_p)^2\alpha$ in units $[\hbar\omega_p]=$eV and $[\alpha]=\mu\Omega\,\mathrm{cm\,K^{-1}}$, where ω_p is the plasma frequency and $\alpha\equiv d\rho/dT$ is the resistivity slope of the T-linear region. It was argued in the concerned comment that, using $\alpha=0.87\ \mu\Omega\,\mathrm{cm\,K^{-1}}$ in Ref. 8, $\lambda_{tr}=0.2$ would lead to $\hbar\omega_p=0.97$ eV, which was too small compared to those of YBCO in the literature. We think that this statement is probably misleading. To follow this approach prudently, it is noted that the penetration depth λ_a is the relevant parameter to derive the intrinsic plasma frequency ω_p of CuO_2 planes, in which the contribution from CuO chains is spared. Values of λ_a reported from both far-infrared spectroscopy[9] and muon spin rotation measurements[10] resulted in converging numbers of $\hbar\omega_p$ between 1.23 and 1.27 eV. More crucially, however, not noticed in Haraǹ's comment, the appropriate value of α from the high-quality samples in which the above corresponding ω_p was measured has to be taken to elucidate the reasonable value of λ_{tr}. Instead of the value of 0.87 $\mu\Omega\,\mathrm{cm\,K^{-1}}$ from much earlier samples in Ref. 8, *the corresponding* α $(=d\rho_a/dT)\leqslant 0.7\ \mu\Omega\,\mathrm{cm\,K^{-1}}$ for *high-quality untwined single crystals*.[11–13] For example, far-infrared spectroscopy in Ref. 9 revealed $\hbar\omega_p=1.23$ eV, and the corresponding single crystals prepared by the same group had α as low as 0.55 $\mu\Omega\,\mathrm{cm\,K^{-1}}$.[11] Combining these two values of $\hbar\omega_p$ and α, it would lead to $\lambda_{tr}=0.20$. Even with an intermediate value of $\alpha\approx 0.6$ and $\hbar\omega_p=1.27$ eV, $\lambda_{tr}=0.24$ well below 0.3. It is amazing that the prediction of $\lambda_{tr}\leqslant 0.3$ in Ref. 8 still holds even with the later values of $\hbar\omega_p$ and α. This is because estimates in Ref. 8 were mainly based on the absence of saturation of ρ at high temperatures, regardless of the details of other parameters.

With the plausible values of λ_{tr} better defined, we can readily discuss the other issue raised by the concerned comment. In Ref. 1, a convenient approximation of $\langle ef\rangle^2=1$ was adopted. As pointed out in Haraǹ's comment, the choice of $\langle ef\rangle^2=1$ would result in a constraint of $g_I\leqslant 0.5$ due to the non-negative scattering potential. This constraint was overlooked in some of the previous works.[1–3] With this constraint in mind, one would like to look into the data in Ref. 1 again. Let us first stick to $\langle ef\rangle^2=1$ as in Ref. 1. For $\lambda_{tr}=0.2$, $g_I=0$ well describes both the T_c suppression and the behavior of the reduced slope of the upper critical field $(dH_{c2}/dT)_{T_s}/(dH_{c2}/dT)_{T_{c0}}$ in YBCO with Zn impurities. For in-plane oxygen defects, one can choose the maximum allowed value of $g_I=0.5$ and still find the data of irradiated YBCO satisfactorily described. Therefore, none of the conclusion in Ref. 1 will be changed. Alternatively, one could adopt a simple model of $f(\mathbf{k})=\pm 1$, under which $-1<g_I$

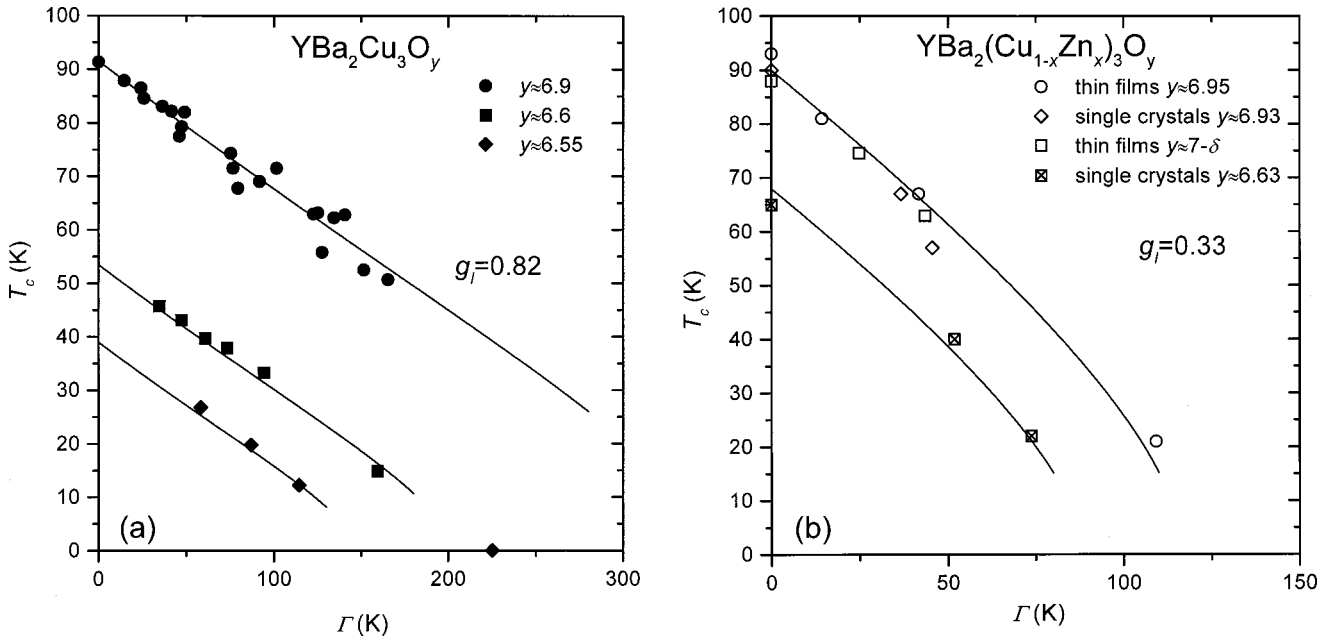

FIG. 1. (a) T_c vs $\Gamma \propto \tau_{\mathrm{imp}}^{-1}$ for irradiated YBCO. $\Gamma \equiv \rho_0/\alpha$ is experimentally determined from the transport data (Ref. 1). (b) T_c vs Γ for $YBa_2(Cu_{1-x}Zn_x)_3O_y$. All solid lines are fits to Eq. (1). $\langle ef\rangle^2 \equiv 0.81$. For $\lambda_{\mathrm{tr}}=0.2$: $g_I=0.67$ in (a) and 0 in (b), respectively. For $\lambda_{\mathrm{tr}}=0.3$: $g_I=0.82$ in (a) and 0.33 in (b), respectively. All solid lines share the same value of λ_{tr}. Some of the data were taken from references cited in Ref. 1.

<1 is guaranteed to be selfconsistent all over the Fermi surface. With a d-wave order parameter $e(\mathbf{k})$ and $f(\mathbf{k})=\mathrm{sgn}(\mathbf{e}(\mathbf{k}))$, $\langle ef\rangle^2=0.81$. One can then try to use Eq. (1) to describe the data as shown in Fig. 1. During the fitting, not only the initial slope but also the data in the whole range were considered. For $\lambda_{\mathrm{tr}}=0.2$, one obtain $g_I=0.67$ for in-plane oxygen defects and $g_I=0$ for Zn impurities, respectively. Therefore, Zn impurities resume isotropic scattering and oxygen defects show anisotropy scattering as concluded in Ref. 1. If $\lambda_{\mathrm{tr}}=0.3$, $g_I=0.82$ for in-plane oxygen defects and $g_I=0.33$ for Zn impurities, respectively. In this case, an anisotropic scattering component is assigned to both the oxygen defects and Zn impurities. However, scattering of the latter is still much more isotropic than that of the former. It is worth noting that, with a different value of $\langle ef\rangle^2$ from that in Ref. 1, the fits to Eq. (1) still indicate a constant λ_{tr} regardless of the doping levels.[13] For the previous theoretical calculations assumed $\langle ef\rangle^2=1$,[5,14] we are not able to check if the same parameters determined from T_c suppression well reproduce $(dH_{c2}/dT)_{T_c}/(dH_{c2}/dT)_{T_{c0}}$ in the case of $\langle ef\rangle^2=0.81$. Further theoretical investigation of the impurity scattering effects on $(dH_{c2}/dT)_{T_c}/(dH_{c2}/dT)_{T_{c0}}$ is surely indispensable.

In summary, in reply to the comment on Ref. 1, we have discussed in detail the plausible range of the values of λ_{tr}, and reanalyzed the data in Ref. 1. It is found that Zn impurity scattering is indeed much more isotropic than that of in-plane oxygen defects, if not completely isotropic. Impurity scattering in cuprates constantly generates new excitement in this community (e.g., Refs. 15 and 16). Therefore, we would like to thank Harań again for his comment, which stimulated more and better efforts to understand the transport properties and the role of impurities in cuprates.

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