Doiron-Leyraud and Taillefer Reply: In our recent Letter [1], we reported a study of how the thermal conductivity κ of $YBa_2Cu_3O_y$ (YBCO) changes as its doping is made to cross the superconducting critical point at $p_c = 0.05$, i.e., from $p_i < p_c$ to $p_f > p_c$. For the same crystal with the same contacts, we showed that the difference $\Delta\kappa = \kappa(p_i) - \kappa(p_f) = \beta T^3$ up to 500 mK. This observation, free from any analysis and confirmed on several specimens, is attributed to heat-carrying bosons with a T^3 conductivity analogous to the magnons in the undoped cuprate antiferromagnet Nd_2CuO_4 (NCO) [2].

Twin-boundary scattering.—Ando [3] points out that YBCO has a structural transition at p_c from tetragonal (tetra) ($p < p_c$) to orthorhombic (ortho) ($p > p_c$). He suggests that in twinned samples like ours, twin-boundary scattering will cause a drop in phonon conductivity (κ_p) when crossing into the ortho phase. While this may be true, it does not explain the T^3 difference we observe because κ_p in (twinned or untwinned) cuprate crystals never goes as T^3. This was shown in our study of NCO [2] where the magnon conductivity goes precisely as T^3 while κ_p goes as $T^{2.6}$. Below 0.5 K or so, the mean free path of magnons is limited by the rough sample edges (quasi-2D) while that of phonons is limited by the sample faces (3D) which, in as-grown crystals, are mirrorlike and cause specular reflection. The resulting T-dependent phonon mean free path leads to κ_p being no longer cubic in T, as shown in our recent study of as-grown and roughened samples of NCO [4]. Therefore, additional phonon scattering for $p > p_c$ cannot give $\Delta\kappa \propto T^3$ as we observe in YBCO up to 0.5 K. (In their measurements on YBCO, Ando and coworkers claim to see $\kappa_p \propto T^3$ at low T [5]. However, this is always limited to below 150 mK or so.)

Although mentioned in our Letter [1] but not shown, we have data on samples (labeled M, N, O) whose entire doping evolution took place in the tetra phase below p_c. In Fig. 1, we show the change in conductivity between $p_0 = 4.3\%$ and $p_1 = 4.6\%$ for the most underdoped sample (sample O, with $y = 6.31$). Here, the T^3 dependence cannot come from twin-boundary scattering because sample O never entered the ortho phase. Invoking strains that build up as the tetra-ortho transition is approached from below also does not work, as scattering from strain fields is known to vary linearly with phonon frequency and so causes $\kappa_p \propto T^2$, not T^3.

Wiedemann-Franz law.—In our Letter, we fit our $\kappa(T)$ data to a sum of three terms: $\kappa(T) = aT + \beta T^3 + r(T)$ coming from fermions, bosons, and phonons, respectively. Ando argues that we should have explicitly included an additional term for charge conduction. But the only way one can do this *a priori* is to use the Wiedemann-Franz (WF) law: $\kappa_e = L_0 T\sigma = L_0 T/\rho$, where L_0 is the Sommerfeld constant and σ the electrical conductivity.

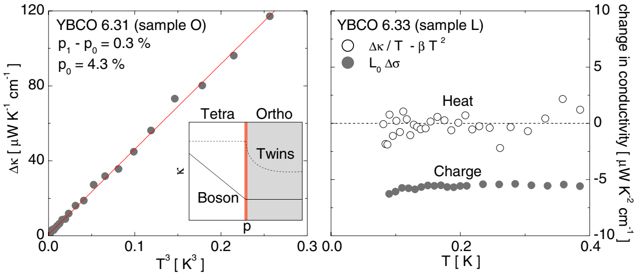

FIG. 1 (color online). Left: Boson—Change in the thermal conductivity κ of YBCO sample O ($y = 6.31$) between $p_0 = 4.3\%$ and $p_1 = 4.6\%$. The reduction in κ, giving $\Delta\kappa \propto T^3$, occurs entirely within the tetragonal phase below p_c. Inset: Sketch of κ if twin-boundary scattering of phonons were causing a reduction (dashed line) and of the measured κ (solid line) (see Fig. 2 in [1]). Right: Fermion—Change in κ of YBCO sample L ($y = 6.33$) between $p_0 = 4.7\%$ and $p_1 = 5.0\%$, with the βT^3 contribution subtracted, plotted as $\Delta\kappa/T - \beta T^2$ vs T. The corresponding change in electrical conductivity σ (see Fig. 3 of [1]) is plotted as $L_0\Delta\sigma$ vs T.

Moving away from arguments over fitting procedure, the best way to compare charge and heat conductivities is to directly examine how they change with doping. In Fig. 1, we plot the difference in κ for sample L between $p_0 = 4.7\%$ and $p_1 = 5.0\%$, without the T^3 term, i.e., $\Delta\kappa/T - \beta T^2$ vs T. We compare this with the corresponding change (on the same sample at the very same dopings) in electrical conductivity, $L_0\Delta\sigma$ [1]. Because κ/T does not change with doping while σ does, the WF law is violated, independently of the fitting procedure. This shows that Ando's suggestion of including an explicit κ_e term leads to an inconsistency, in the sense that it relies on the WF law which does not hold here.

Nicolas Doiron-Leyraud[1] and Louis Taillefer[1,*]
[1]Département de physique and RQMP
Université de Sherbrooke
Sherbrooke, Canada

Received 5 October 2007; published 14 January 2008
DOI: 10.1103/PhysRevLett.100.029702
PACS numbers: 74.72.Bk, 72.15.Eb, 74.25.Fy

---

[*] Louis.Taillefer@USherbrooke.ca

[1] N. Doiron-Leyraud *et al.*, Phys. Rev. Lett. **97**, 207001 (2006).
[2] S. Y. Li *et al.*, Phys. Rev. Lett. **95**, 156603 (2005).
[3] Y. Ando, preceding Comment, Phys. Rev. Lett. **100** 029701 (2008).
[4] S. Y. Li *et al.*, arXiv:0709.3075.
[5] X. F. Sun *et al.*, Phys. Rev. Lett. **93**, 107001 (2004).