Antiparamagnons and the thermal conductivity of $YBa_2Cu_3O_{7-\delta}$

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We calculate the electronic contribution to the thermal conductivity and find a peak below T_c in agreement with experiment. In our model, the quasiparticle damping is due to inelastic scattering from antiparamagnons. Our results support the recent conjecture by Yu *et al.* that some sort of suppression of quasiparticle damping is responsible for this peak. The correlation between these measurements, the microwave conductivity, and many others strongly supports the view that antiferromagnetic spin fluctuations in the CuO_2 planes dominate the quasiparticle lifetime.

Recently, Yu *et al.*[1] reported data and an interpretation of the low-temperature peak in the thermal conductivity $\kappa(T)$ observed in high-temperature superconductors below T_c. They argue that $\kappa(T)$ is composed of phonon and electronic contributions of the same order of magnitude above T_c, but the electronic contribution $\kappa_e(T)$ increases dramatically below T_c due to the suppression of quasiparticle damping. In this paper, we show that these data above $\sim$20 K can be understood using our recent simple model[2] for quasiparticle damping due to inelastic scattering from antiparamagnons (antiferromagnetic spin fluctuations in the CuO_2 planes).

Our approximate starting expression for the electronic thermal conductivity is given by[3]

$$\kappa_e = \frac{n}{mT}\int_\Delta^\infty d\omega\,\omega^2 \left[-\frac{df}{d\omega}\right] \frac{[N^2(\omega)-M^2(\omega)]}{\Gamma(\omega)N(\omega)} ,$$

where we omit vertex corrections. Here $[N^2(\omega)-M^2(\omega)]$ gives the coherence factor and the quasiparticle lifetime $\tau(\omega)=1/2\Gamma(\omega)$. These are computed as in Ref. 2, which requires that we know the spin response function $\chi(\mathbf{q},\omega)$ below T_c. Above T_c, we assume $\chi(\mathbf{q},\omega)$ is given by the form used to describe the spin-lattice relaxation data. Below T_c, the antiparamagnon spectrum for ω below the pair-breaking gap at $2\Delta(T)$ is taken to be suppressed by a factor $f(T)=\exp[(T-T_c)/T_0]$, where $T_0=13$ K (obtained from NMR data[4]). The spectrum at $\omega>2\Delta(T)$ is unchanged, which is a slightly improved version of the ansatz we used in Ref. 2, although it has only a minor effect on the calculated lifetimes. This kind of suppression of the spin fluctuations at low frequencies is indeed what is directly observed experimentally[5] by inelastic neutron scattering. We emphasize that the $\chi(\mathbf{q},\omega)$ we use in our analysis is built on experimental NMR data from above and below T_c, and not on unproven microscopic models.

Our results for the thermal conductivity are presented in Fig. 1(a). Note that our value at T_c, $\kappa_e(T_c)=2.9$ W/mK, is in good agreement with 3.9 W/mK obtained by Yu *et al.*[1] Qualitative agreement below T_c is all that can be reasonably expected due to the difficulty in substracting the phonon contribution to $\kappa(T)$ from the data (see below). The analogous results for the microwave conductivity σ_n are shown in Fig. 1(b), where we have used the same input parameters. Our calculated magnitude of σ_n agrees well with the data at T_c, in addition to reproducing the enhancement below T_c. In both cases, our calculations reproduce the peak at the correct temperature. This low-temperature peak arises from a competition between the increasing quasiparticle lifetime on the one hand and the decreasing number of excited quasiparticles on the other as $T\rightarrow 0$. Coherence effects mani-

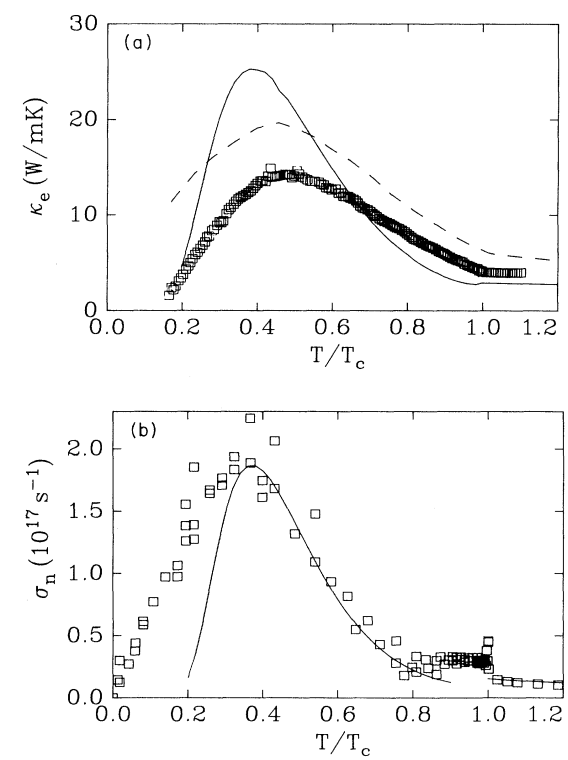

FIG. 1. (a) Temperature dependence of κ_e. The solid line is the calculated value, and the squares are the data from Ref. 1. The dashed line represents the experimental values extracted using the procedure discussed in the text. (b) Temperature dependence of σ_n. The solid line is the calculated value, and the squares are the data of Ref. 7.

fest themselves in a small temperature region just below T_c. Hence they cannot be responsible for the low-temperature peak in σ_n or κ_e. As well, the coherence factor for κ_e is $N^2(\omega)-M^2(\omega)\simeq 1$, which would not cause a coherence peak in any case.

Some of the discrepancy between the experimental value of $\kappa(T)$ at the peak and the calculated value can be attributed to the method Yu *et al.* have used to subtract out the phonon contribution $\kappa_{\rm ph}(T)$. They have chosen to use an approximate expression for umklapp phonon-phonon scattering, which is inversely proportional to temperature. A better approach might be to use the experimental thermal conductivity measured for the insulating phase of $YBa_2Cu_3O_{7-\delta}$.[6] These data will not contain an electronic contribution, but should have a similar phonon contribution. The main difference between this procedure and that used by Yu *et al.* occurs at low temperatures where the experimentally observed thermal conductivity decreases with temperature. Using our procedure yields the dashed line in Fig. 1(a). We note that the peak height is in better agreement with the calculation and that the low-temperature trend is no longer toward zero thermal conductivity at finite temperature. Our procedure should work well if the phonon lifetime is due to phonon-phonon scattering, but not necessarily as well as for impurity scattering. In this light it is clear that to extract the electronic thermal conductivity in an unambiguous fashion one will need data on both the superconducting and insulating phase of the same crystal. This is a suggestion for future work.

Our calculations[2] of the quasiparticle width $\Gamma(\omega)$ can clearly be improved when more information is available about $\chi(\mathbf{q},\omega)$. Our approach is easily extended to a *d*-wave gap, but only the very-low-temperature results would be altered significantly. At higher temperatures, all portions of $\Delta(\mathbf{k})$ are sampled, leading to results not too different from those expected for an isotropic gap. The assumption that the antiparamagnon spectrum is unchanged from the normal state for $\omega>2\Delta$ is overly simplistic but still physically very reasonable. Once one is above the pair-breaking gap at 2Δ, the particle-hole spin excitations in a superconductor are expected to be increasingly similar to those of a normal metal. We also note that the dominant contribution to κ_e and σ_n is from excitations with energy close to the quasiparticle energy gap Δ.

In summary, our work strengthens the conjecture of Yu *et al.*[1] that the same scattering mechanism is involved in $\kappa_e(T)$ and $\sigma_n(T)$. Moreover, we note that there is now strong consistent evidence for the suppression of antiparamagnon fluctuations below T_c in the electronic thermal conductivity,[1] microwave conductivity,[7] nuclear spin-lattice relaxation,[4] inelastic neutron scattering,[5] and infrared conductivity.[8,9] This suppression of the low-frequency antiparamagnon spectrum ($\omega<2\Delta$) means that these modes cannot be important as a mechanism for high-temperature superconductivity. On the other hand, we cannot rule out the possiblity that high-frequency antiparamagnons ($\omega\gg 2\Delta$) contribute to the pairing mechanism.

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