Peculiar roles of spins in the thermal conductivity of pure and doped La_2CuO_4: Comparison with $CuGeO_3$

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Abstract

In-plane and out-of-plane thermal conductivities (κ_{ab} and κ_c) are measured on single crystals of pure, 1%-hole-doped, and 1%-Zn-doped La_2CuO_4. The roles of magnons and the spin stripes in the heat transport in these samples are discussed. Comparison with the heat transport in $CuGeO_3$, which shows similar $\kappa(T)$ behavior as that of La_2CuO_4, gives us a lesson of how the heat transport can probe the difference in the spin ground state.

Key words: thermal conductivity; spin excitation; stripe; phonon

Thermal conductivity is a basic transport property that usually bears information on charge carriers and phonons, as well as their scattering processes. In materials where spins are playing a major role, the behavior of the thermal conductivity is largely governed by the spins, because the spin excitations can carry heat current themselves and also scatter electrons and phonons. Although the heat transport due to spin excitations in magnetic materials has been known for a long time [1], recent studies of the heat transport in strongly-correlated low-dimensional cuprate systems (such as high-T_c cuprates [2], spin-Peierls material $CuGeO_3$ [3,4], *etc.*) have found the spin-related heat transport to be useful for extracting information on the peculiar spin systems in these compounds. In this paper, we present some new data on the thermal conductivity κ of lightly Sr- or Zn-doped La_2CuO_4 (LCO), where we find unusual difference between Sr- and Zn-doping. Comparison of the data of lightly-doped LCO with those of $CuGeO_3$ demonstrates how the behavior of $\kappa(T)$ reflects the difference in the spin ground states.

The single crystals of LCO, $La_{2-x}Sr_xCuO_4$ (LSCO), and $La_2Cu_{1-y}Zn_yO_4$ (LCZO) are grown by the traveling-solvent floating-zone technique [5]. The thermal conductivity is measured with a steady-state technique below 150 K, and with a modified steady-state technique, which minimizes the radiation loss, above 150 K. Details of the $CuGeO_3$ experiments are described in Refs. [3] and [4].

Figure 1 shows $\kappa_{ab}(T)$ and $\kappa_c(T)$ for LCO, LSCO (x=0.01), and LCZO (y=0.01); here, we concentrate on comparing the effect of hole doping and Zn doping of the same amount, 1%. The LCO sample has the Néel temperature T_N of 307 K. It has already been known [2] that the high-temperature peak in $\kappa_{ab}(T)$ is due to magnons, while the low-temperature peak is due to phonons. It is useful to note that T_N is still relatively high for both LSCO with x=0.01 (T_N=242 K) and LCZO with y=0.01 (T_N=295 K); nevertheless, the high-temperature magnon peak already disappears in LSCO, while it remains significant in LCZO. This suggests that the magnetic frustrations caused by the hole doping are detrimental to the magnon heat transport. On the other hand, the low-temperature phonon peak in $\kappa_{ab}(T)$ is more strongly suppressed in LCZO than in LSCO. This is rather surprising, because the atomic mass difference between Cu and Zn is much smaller than that between La and Sr, and thus one would expect a smaller impurity-scattering cross section for phonons in LCZO. Most likely, the enhanced damping of the phonon peak in LCZO is due to the magnon scattering of phonons.

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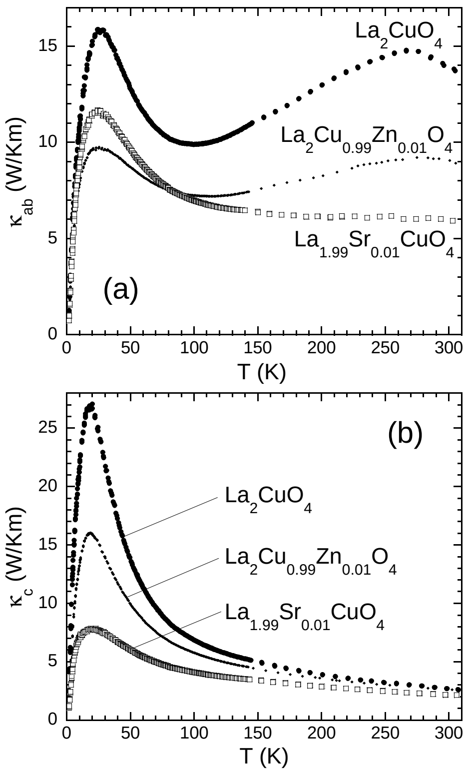

Fig. 1. (a) $\kappa_{ab}(T)$ and (b) $\kappa_c(T)$ data of LCO, LSCO (x=0.01), and LCZO (y=0.01).

When one looks at the $\kappa_c(T)$ behaviors in Fig. 1(b), one notices that the difference between Sr- and Zn-doping is more pronounced in this direction, and the trend is opposite to that in $\kappa_{ab}(T)$; namely, along the c-axis the Sr doping causes much stronger damping of the phonon peak. Although the exact mechanism of this strong damping is to be scrutinized by future research, we tentatively ascribe this effect to the spin stripes observed by neutrons [6] in this lightly Sr-doped region: Since there is a strong spin-lattice coupling in LSCO [7], formation of the spin stripes is expected to induce local lattice distortions; such lattice distortions do not scatter phonons if they are periodic (in fact, we do not see strong scattering of phonons in the in-plane direction, for which the stripes are well ordered), but the stripes are known to be very disordered along the c-axis [6]. Thus, we have a good reason to expect that the anomalous damping of the phonon peak in κ_c(T) with only 1% of hole doping is due to the existence of peculiar spin texturing and strong spin-lattice coupling.

Comparison of the data in Fig. 1(a) to the $\kappa(T)$ behavior of $CuGeO_3$ [3] measured along the spin chain direction (Fig. 2) is quite illuminating. The 0-T data in Fig. 2 look quite similar to the $\kappa_{ab}(T)$ data of LCO, which is natural because in both systems the high-temperature peak is caused by the heat conduction

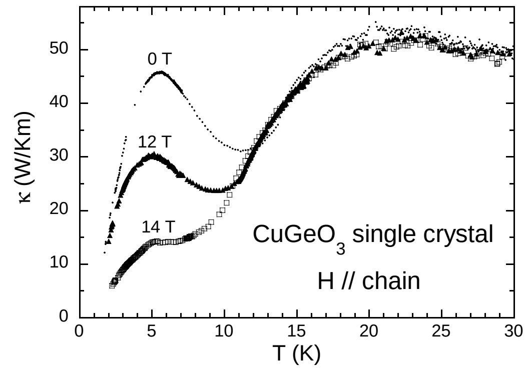

Fig. 2. $\kappa(T)$ data of $CuGeO_3$, taken from Ref. [3], along the chain direction. The magnetic field is applied along the chains.

due to spin excitations and the low-temperature peak is due to phonons. The spin heat transport (high-temperature peak) is quickly suppressed upon doping Mg to $CuGeO_3$ [4], as is the case with doped LCO. The difference between the two systems becomes evident when one compares the magnetic-field dependences. In $CuGeO_3$, as is shown in Fig. 2, application of magnetic field along the chain direction causes a damping of the phonon peak, and the 14-T field, which closes the spin gap of the spin-Peierls state, completely suppresses the phonon peak; we discussed [3] that this is because more and more spin excitations (which scatter phonons) are allowed as the spin gap is suppressed with the magnetic field. On the other hand, for LCO, we observed that the $\kappa(T)$ behavior is essentially unchanged with magnetic field; this is understandable, because the characteristic magnetic energy in LCO is given by the exchange interaction J, which is order of 2000 K. Therefore, the behavior of the thermal conductivity clearly reflects the different nature of the spin ground state in the two systems.

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