Phonon thermal conductivity in doped La$_2$CuO$_4$: relevant scattering mechanisms

C. Hess, B. Büchner, U. Ammerahl, and A. Revcolevschi

1 Département de Physique de la Matière Condensée, Université de Genève, Genève, Switzerland
2 Physikalisches Institut, RWTH-Aachen, 52056 Aachen, Germany
3 Laboratoire de Physico-Chimie, Université Paris-Sud, 91405 Orsay, France

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Results of in-plane and out-of-plane thermal conductivity measurements on La$_{1.8-x}$Eu$_x$Sr$_x$CuO$_4$ (0 ≤ x ≤ 0.2) single crystals are presented. The most characteristic features of the temperature dependence are a pronounced phonon peak at low temperatures and a steplike anomaly at T_{LT}, i.e., at the transition to the low temperature tetragonal phase (LTT-phase), which gradually decreases with increasing Sr-content. Comparison of these findings with the thermal conductivity of La$_{2-x}$Sr$_x$CuO$_4$ and La$_2$NiO$_4$ clearly reveals that in La$_{2-x}$Sr$_x$CuO$_4$ the most effective mechanism for phonon scattering is impurity-scattering (dopants), as well as scattering by soft phonons that are associated with the lattice instability in the low temperature orthorhombic phase (LTO-phase).

There is no evidence that stripe correlations play a major role in suppressing the phonon peak in the thermal conductivity of La$_{2-x}$Sr$_x$CuO$_4$.

I. INTRODUCTION

The segregation of spins and holes into stripelike arrangements appears to be a common feature of doped Mott insulators. These so-called stripe correlations seem to be of particular importance in understanding the electronic phase diagram of high-temperature superconductors, where a competition between a static stripe phase and the superconducting phase is widely discussed. Such a competition is expected to be reflected by the dynamics of stripes, i.e., static stripes should reduce the superconducting order parameter while stripes should be fluctuating in the presence of fully developed superconductivity. Indeed, there is growing experimental evidence for such a scenario. While many experiments give evidence towards static stripes of holes and spins signatures of stripe fluctuations currently only comprise magnetic correlations. A direct observation of fluctuating charge stripes, however, is still missing. A promising alternative approach to study stripe dynamics involves the phonon heat transport which is an indirect probing method. Since charge stripes lead to lattice distortions, a sensitivity of the phonon heat transport to the dynamics as well as the degree of periodicity of stripes can be expected.

The thermal conductivity $\kappa$ of doped La$_2$CuO$_4$ has repeatedly been the subject of experimental research, yet no detailed understanding of the rather complicated and strong changes of the temperature dependence of $\kappa$ upon partial substituting Sr and/or small Rare Earths (RE) like Nd or Eu for La has been achieved. For example, in the antiferromagnetic insulators La$_{2-y}$RE$_y$CuO$_4$ a huge peak at room temperature which arises due to magnetic heat transport is found in the thermal conductivity parallel to the CuO$_2$-planes ($\kappa_{ab}$), while the thermal conductivity perpendicular to the CuO$_2$-planes ($\kappa_c$) is purely phononic without a high temperature peak. Similarly intriguing is a strong suppression of the phononic low temperature peak in both $\kappa_{ab}$ and $\kappa_c$, which is found in the superconducting doping levels of La$_{2-x}$Sr$_x$CuO$_4$. There is a seeming correlation between this suppression and superconductivity because a phononic low temperature peak reappears in overdoped, non-superconducting La$_{2-x}$Sr$_x$CuO$_4$ as well as in La$_{2-x-y}$RE$_y$Sr$_x$CuO$_4$, where superconductivity is suppressed in favor of static stripe order. Baberski et al. qualitatively explained these observations based on the idea that in superconducting compounds fluctuating stripes provide a new scattering channel for phonons. In recent studies by Sun et al., such a scattering channel plays an important role in the data interpretation.

There is clear-cut evidence that in isostructural stripe ordering La$_{2-x}$Sr$_x$NiO$_4$ the phonon thermal conductivity $\kappa_{ph}$ is closely correlated with both the dynamics and the periodicity of stripes: While $\kappa_{ph}$ is almost unaffected in the presence of static and long range ordered stripes, it is strongly suppressed as soon as the stripes become disordered or dynamic. Apparently, in these compounds the thermal conductivity is indeed a probe for stripe correlations. One might question, however, whether this is true also in the cuprates for two reasons: First, the electron-phonon coupling in the nickelates is much stronger than in the cuprates. Therefore, the effect of stripes on $\kappa_{ph}$ can be expected to be much smaller in the cuprates. Second, from a structural point of view the situation in the nickelates is much simpler than in the cuprates. In the latter a structural instability exists and as a consequence a number of structural phase transitions occur as a function of temperature as well as of Sr- and RE-content. Since the structural instability involves soft phonon modes enhanced scattering of the heat carrying phonons is likely.

In this article we reinvestigate the phonon thermal conductivity $\kappa_{ph}$ of doped La$_{2-x}$Sr$_x$CuO$_4$ and present new experimental results on Eu-doped single crystals. The single crystalline data allow us to investigate the anisotropy of the $\kappa$-tensor and provide more precise absolute values of $\kappa$. In previous measurements on polycrystals this information was not available. It
is, however, necessary in order to judge the strength and therefore the importance of various scattering mechanisms for phonons. The analysis of our data yields compelling arguments that both impurities (dopants) and soft phonons, which are associated with the lattice instability in these compounds, strongly scatter phonons and therefore must not be neglected in the data interpretation. Data on La$_{2}$NiO$_{4}$ corroborate this conclusion and allow us to qualitatively understand $\kappa_{ph}$ of La$_{2-x-y}$(RE)$_{y}$Sr$_{x}$CuO$_{4}$ in a wide doping range. In particular, it is not necessary to include a stripe induced scattering channel.

The structure of this paper is as follows: After a brief description of the experimental details in section II we review previous results on the thermal conductivity of doped La$_{2}$CuO$_{4}$ in section III before we proceed to the presentation of our new experimental results on La$_{1.8-x}$Eu$_{0.2}$Sr$_{x}$CuO$_{4}$ in section IV. Our main results will be discussed in section V.

II. EXPERIMENTAL

We have prepared single crystals of La$_{1.8-x}$Eu$_{0.2}$Sr$_{x}$CuO$_{4}$ ($x = 0, 0.08, 0.15, 0.2$) as well as of La$_{2}$NiO$_{4}$ utilizing the traveling solvent floating zone technique. $\kappa$ of these crystals was measured as a function of temperature $T$. We used a standard steady state method on pieces cut along the principal axes with a typical length of 2 mm along the measuring direction and of about 0.5 mm for the two other directions. The thermal gradient was determined by measuring the temperature difference $\Delta T$ between the junctions of a differential Au/Fe-Chromel thermocouple. The junctions of this thermocouple have been glued onto the sample using GE varnish. $\Delta T$ varied between 0.5% and 2% of the absolute temperature, which has been stabilized for each data point. Errors due to radiation loss, which could occur at higher temperatures, are avoided in our experimental setup. Stoichiometric oxygen contents in La$_{1.8-x}$Eu$_{0.2}$Sr$_{x}$CuO$_{4}$ and La$_{2}$NiO$_{4}$ were achieved by annealing in high vacuum and CO/CO$_{2}$-atmosphere, respectively.

III. PREVIOUS RESULTS

Prior to discussing our new experimental results, we review previous results on the striking doping dependence of the thermal conductivity of doped La$_{2}$CuO$_{4}$. At first, we concentrate on the low temperature phononic peak in the thermal conductivity of La$_{2-y}$Sr$_{y}$CuO$_{4}$. As is evident from the lower panel of Fig. II which reproduces $\kappa_{c}$ of La$_{2-y}$Sr$_{y}$CuO$_{4}$ ($x = 0, 0.1, 0.15, 0.2, 0.3$) as published by Nakamura et al. this peak evolves non-monotonically with increasing Sr-content: A well pronounced phononic low-$T$ peak in $\kappa_{c}$ is only present at $x = 0$ and $x = 0.3$, whereas at intermediate doping levels ($0.1 \leq x \leq 0.2$) a peak structure is hardly identifiable. Note that the material is a superconductor in this doping range whereas it is insulating and metallic at $x = 0$ and $x = 0.3$, respectively.

Baberski et al. have pointed out that the suppressed low-$T$ peak at intermediate Sr-doping reappears upon RE-doping, provided that this doping induces the so-called LTT-phase (Low Temperature Tetragonal) and thereby suppresses superconductivity. This is illustrated in the upper panel of Fig. III where $\kappa$ of polycrystalline Pr- and Nd- doped La$_{2-x-y}$(RE)$_{y}$Sr$_{x}$CuO$_{4}$ at the finite Sr-content $x = 0.12$ is shown. The Pr-doped compound does not undergo the transition to the LTT-phase. Like La$_{2-y}$Sr$_{y}$CuO$_{4}$, it remains in the so-called LTO-phase (Low Temperature Orthorhombic) and is a superconductor. Its thermal conductivity monotonically decreases with decreasing $T$ and hence is very similar to the aforementioned findings by Nakamura et al. for $\kappa$ of La$_{2-y}$Sr$_{y}$CuO$_{4}$ at $0.1 \leq x \leq 0.2$. The situation is completely different in the non superconducting,
Nd-doped compound, which is in the LTT-phase below $T_{LT} \approx 80$ K: Here, $\kappa_{ph}$ abruptly enhances at $T_{LT}$ and exhibits a well pronounced phononic peak around 25 K.

The doping dependence of $\kappa$ described above must be attributed to strong changes in the phonon thermal conductivity $\kappa_{ph}$ of this material: Non-phononic contributions to $\kappa$ can be excluded in the out-of-plane direction, since the electrical conductivity $\sigma_{ph}$ and the magnetic couplings along the c-axis are too small to allow significant electronic and magnetic thermal conduction. Concomitantly, the doping dependence of the low-$T$ peak is evident along all crystal directions (c.f. also the data below).

In crystalline materials, the low-$T$ peak in $\kappa_{ph}$ is very sensitive to scattering of phonons. Generally, the height of this peak reduces with increasing phonon scattering rates. One important mechanism in this regard is scattering of phonons by impurities. In alloyed compounds like doped La$_2$CuO$_4$ this phonon-impurity scattering is induced by non-uniform ions on one lattice site. Upon alloying, this should lead to a gradual reduction of the phonon peak. Even though phonon-defect scattering inevitably must be present in this material, it is not a scattering mechanism which solely dominates $\kappa_{ph}$, because the phonon peak evolves non-monotonically upon Sr-doping and even reappears at additional RE-doping.

Another scattering mechanism for phonons in this material is suggested by the abrupt change of $\kappa_{ph}$ at the structural phase transition, which occurs in the Nd-doped compound. It appears that phonons are scattered stronger in the LTO-phase. This interpretation is confirmed by neutron scattering studies on Nd-doped La$_{2-x}$Sr$_x$CuO$_4$ at $T_{LT}$: The acoustic phonon line width abruptly decreases at the transition from the LTO- into the LTT-phase, signaling a proportional decrease of scattering processes. Anomalous phonon thermal conductivity in the vicinity of structural phase transitions is well known from a number of perovskite oxides as, for example, SrTiO$_3$ and KTaO$_3$. There, a suppression of $\kappa_{ph}$ is caused by enhanced scattering of acoustic phonon modes due to their energetic degeneracy with soft optical phonon modes. Indeed, soft phonon branches do exist in the LTO-phase of doped La$_2$CuO$_4$ which could cause a suppression of $\kappa_{ph}$ (in the following this scattering mechanism will briefly be named 'soft-phonon scattering'). The change of $\kappa_{ph}$ at $T_{LT}$ then would follow from the discontinuous hardening of the soft phonon branch in the LTT-phase and an associated reduced scattering rate of acoustic phonons.

Since all compounds with a suppressed phonon peak are in the LTO-phase at low $T$, soft-phonon scattering could be important for understanding the suppression of the peak as well. There is, however, not a one to one correlation between the LTO-phase, i.e., the possible presence of soft phonon scattering, and the suppression of the peak. This is most obvious in La$_{2-x}$Sr$_x$CuO$_4$, because the soft phonon properties only slightly change for $x \leq 0.2$, whereas the phonon peak is maximum for La$_2$CuO$_4$.

Baberski et al. have noticed that both impurity scattering and soft-phonon scattering separately do not allow to understand the suppression of the phonon peak. Therefore, they suggested, that the suppression of the phononic peak could be correlated with the superconducting properties of the material, since the peak suppression occurs whenever the material is superconducting. In their model, they proposed that stripes couple to phonons and thereby cause an unconventional scattering mechanism for phonons depending on the dynamics of stripes: A suppression of the phonon peak then is the consequence of fluctuating stripes, which are present in the superconducting compounds, while $\kappa_{ph}$ exhibits a usual phonon peak when stripes are static or even absent in the non-superconducting cases. There, static stripes are present in the LTT-phase. Therefore, instead of being caused by an abrupt softening of optical phonon modes, the jump of $\kappa_{ph}$ at $T_{LT}$ could just as well originate from a change of the stripe dynamics from static (LTT) to fluctuating (LTO). Even though a consistent interpretation of the data discussed afore is possible within such a model, its validity is questionable because the actual role of impurity- and soft-phonon scattering remains unclear.

IV. NEW RESULTS

In order to elucidate the importance of this conventional scattering mechanisms we now turn to our measurements on single crystals, which provide profound information in this regard. In Fig. 2 we present the complete data set of $\kappa$ of La$_{1.8-x}$Eu$_{0.2}$Sr$_x$CuO$_4$ ($x = 0, 0.08, 0.15, 0.2$) measured along the $c$-axis ($\kappa_c$) and parallel to the $ab$-planes ($\kappa_{ab}$) in the temperature-range $7 \sim 300$ K. All compounds are in the LTT-phase at $T < T_{LT}$, with a variation of $T_{LT}$ between about 110 K and 130 K. For $T > T_{LT}$ and $x \leq 0.15$ the structure is LTO in the investigated temperature range. At $x = 0.2$ the compound undergoes a further structural phase transition from the LTO- into the so called HTT-phase (High-Temperature-Tetragonal) at $T_{HTT} \approx 220$ K.

$\kappa_c$ of La$_{1.8}$Eu$_{0.2}$CuO$_4$ [cf. panel (a) of Fig. 2] exhibits a low-temperature peak around 20 K with a falling edge that continuously extends to $T_{LT} \approx 130$ K. A jump-like decrease occurs at $T_{LT}$, followed by a constant $\kappa_c$ up to room temperature. The inset of Fig. 2 depicts a cooling- and heating curve of $\kappa_c$ in the area of the jump. A clear hysteresis being a characteristic feature of first-order phase transitions is evident.

For $T \lesssim 50$ K, the thermal conductivity along the CuO$_2$-planes, $\kappa_{ab}$, is comparable to $\kappa_c$. The peak centered around 20 K is slightly smaller; we find $\kappa_{max}^{\kappa_{max}} / \kappa_{max}^{\kappa_{max}} \approx 1.3$, which is similar to the findings in non-doped La$_2$CuO$_4$ and isostructural La$_{5/8}$Sr$_{1/8}$NiO$_3$. For $T \gtrsim 50$ K the temperature dependencies of $\kappa_{ab}$ and $\kappa_c$ differ completely: With rising temperature, $\kappa_{ab}$ strongly increases and evolves into a broad peak at room tempera-
κc is very similar to that of κc of La1.8Eu0.2CuO4 in the whole temperature range. As in the case at x = 0, κab deviates from the qualitative T-dependence of κc above ∼ 50 K and evolves into an increase with rising temperature. A step-like anomaly at TLT exists in each case, but no high temperature peak as in La1.8Eu0.2CuO4 is present.

A comparable anisotropy as in the previous compounds is also evident at x = 0.2 [cf. panel (d) of Fig. 2], but the low temperature peak in κc is almost completely suppressed and κc slightly increases for T ≳ 75 K with nearly constant positive slope. The low temperature peak is even absent in κab. Here, κab(T) monotonically increases upon heating in the entire temperature range. At TLT ≈ 110 K no anomaly is present, neither in κab nor in κc. Apparently, the transition at THT also causes no anomaly in the thermal conductivity.

V. DISCUSSION

A. Anisotropy

As mentioned before, κc is purely phononic, since electronic and magnetic contributions can be ruled out for heat transport along the c-axis. In order to understand the anisotropies of κ for T ≳ 50 K, it is reasonable to distinguish the cases x = 0 and x > 0. It has been shown in Ref. 18 that in insulating, antiferromagnetic La1.8Eu0.2CuO4 the high temperature peak of κab must be explained by magnetic contributions. Upon Sr-doping, the doped holes destroy the magnetic order which leads to a strong suppression of the high temperature peak [cf. Fig. 2]. Simultaneously, the material becomes electrically conducting within the ab-planes. Therefore, the much smaller, but apparently still existing anisotropy in the Sr-doped compounds is due to electronic, rather than magnetic, contributions to κab. Indeed, an estimation using the Wiedemann-Franz-law yields electronic contributions of the same order of magnitude as the observed anisotropy for κab and negligible electronic contributions for κc. The magnetic and electronic contributions to κab become important for T ≳ 50 K. Below this temperature, κab can be considered to be primarily phononic with a similar magnitude of κph as κc. This is nicely confirmed by the very similar temperature dependence of κab and κc in this temperature range, as shown in Fig. 3. It is remarkable that for all compounds the phonon peak of κc is slightly larger than that of κab as long as a peak is clearly resolved in both quantities. A possible explanation could be related to slightly different velocities of the acoustic phonons along the ab- and c-directions.
ever, we should note that the structural differences between the LTT and LTO-phases diminish with increasing Sr-content. Therefore, apart from phonon-impurity scattering, structural reasons play a role in the suppression of the jump at $T_{LT}$. This is consistent with the observation by Baberski et al., that the jump disappears, whenever the tilting angle of the CuO$_6$-octahedra becomes lower than a critical value.$^{22}$

It is now very instructive to consider $\kappa_{ph}$ of pure La$_{2-x}$Sr$_x$CuO$_4$ (cf. Fig. 1) for comparison. Apparently, doping Sr into La$_2$CuO$_4$ suppresses the phonon peak much more effectively than in the Eu-doped counterpart: On the one hand the phonon peak of non-doped La$_2$CuO$_4$ is by a factor of about two larger than in non-doped La$_{1.8}$Eu$_{0.2}$CuO$_4$. On the other hand the phonon peaks in La$_{1.8-x}$Eu$_{0.2}$Sr$_x$CuO$_4$ are clearly better developed for finite Sr-contents with higher maximum values as in La$_{2-x}$Sr$_x$CuO$_4$. One has therefore to conclude that a further scattering mechanism exists in La$_{2-x}$Sr$_x$CuO$_4$ which becomes more important upon doping and which is absent or at least much weaker in the Eu-doped compounds. In this case, this mechanism must cause a more effective scattering than the surely present phonon-impurity scattering induced by the Eu-ions. One plausible candidate (besides scattering due to dynamic stripes) for such a mechanism is soft-phonon scattering connected with the structural instability of the LTO-phase since the soft-phonon energies decrease further upon Sr-doping and hence enhance soft-phonon scattering.

In order to judge the relevance of soft-phonon scattering a measure for its strength with respect to phonon-impurity scattering is necessary. Such a measure could be achieved, for example, by comparison with a compound where neither a lattice instability nor doped impurities are present. Though being no cuprate, isostructural La$_2$NiO$_4$ is yet a well suited candidate perfectly fulfilling these requirements. The phonon spectra of La$_2$CuO$_4$ and La$_2$NiO$_4$ are almost identical$^{55,56}$ because the atomic masses of Ni and Cu are very similar. At low temperatures ($T \lesssim 73$ K) this compound is in the LTT-phase and hence a structural instability does not exist$^{22}$. Moreover, no phonon-impurity scattering is present in this non-doped compound.

Fig. 1 presents our result for phononic $\kappa_{ab}$ of electrically insulating La$_2$NiO$_4$ in comparison with $\kappa_{ab}$ of La$_2$CuO$_4$ as measured by Nakamura et al. and with $\kappa_{ab}$ of La$_{1.8}$Eu$_{0.2}$CuO$_4$. It is intriguing that the phonon peak of La$_2$NiO$_4$ is about one order of magnitude larger than the peak in both La$_2$CuO$_4$ and La$_{1.8}$Eu$_{0.2}$CuO$_4$. At $T_{LT} \approx 73$ K, the structure changes from LTT to LTO, which also in this material causes a jumplike decrease in the thermal conductivity. Compared to La$_{1.8}$Eu$_{0.2}$CuO$_4$ the jump size is larger by a factor of about 10. In the LTO-phase, $\kappa_{ab}$ is of the similar size as in La$_2$CuO$_4$.

It immediately follows from this observation that in La$_2$CuO$_4$ as well as in La$_{1.8}$Eu$_{0.2}$CuO$_4$ the heat carrying phonons are subject of severe scattering at low temperatures. In both cases this scattering obviously sup-

**B. Phononic peak and jump at $T_{LT}$**

The development of the low temperature peak of $\kappa_{ph}$ upon doping can be viewed in Fig. 3. Obviously, the peak size is gradually reduced as the Sr-content increases. A similar result is found for the size of the jump $\Delta \kappa_c$ at $T_{LT}$ which is shown as a function of doping in the inset of Fig. 3. While the gradual reduction of the peak size can straightforwardly be explained by phonon-impurity scattering, the reduction of the jump at $T_{LT}$ requires further comments. First of all, we stress the presence of a jump in insulating La$_{1.8}$Eu$_{0.2}$CuO$_4$. It clearly proofs that it is caused by soft-phonon scattering in the LTO-phase, which therefore has to be regarded as an important scattering channel for phonons indeed. When this scattering channel becomes active in the LTO-phase, the relative importance of phonon-impurity scattering is reduced. The gradual reduction of the jump size $\Delta \kappa_c$ with increasing Sr-content may therefore be attributed to doping induced phonon-impurity scattering as well.

**FIG. 3:** Doping dependence of low temperature peak in the thermal conductivity of La$_{1.8-x}$Eu$_{0.2}$Sr$_x$CuO$_4$ along the c-axis ($\kappa_c$, top) and parallel to the ab-planes ($\kappa_{ab}$, bottom). Inset: Doping dependence of the jump size $\Delta \kappa_c$ at $T_{LT}$.
presses the peak of $\kappa_{\text{ph}}$ by about one order of magnitude. Translated to the strength of the two discussed scattering mechanisms this means that referring to a non-impurity-doped LTT-phase both soft-phonon scattering and phonon-impurity scattering independently of each other reduce the peak of $\kappa_{\text{ph}}$ by almost the same amount.

This conclusion now allows us to understand the doping dependence of the phonon peak, when a combination of both, phonon-impurity- and soft-phonon scattering is consired: In La$_{1-x}$Eu$_{0.2}$CuO$_4$, where the thermal conductivity is already strongly influenced by the Eu-ions, Sr-doping simply further increases the phonon-impurity scattering rate. This consequently leads to a gradual reduction of the phonon peak with increasing Sr-content. Soft-phonon scattering is not relevant here. In La$_{2-x}$Sr$_x$CuO$_4$ with the same Sr-content than a Eu-doped counterpart, the phonon-impurity scattering rate is slightly reduced since no Eu-ions are present. Yet, the resulting phonon thermal conductivity is somewhat smaller. Hence, the effect of a slightly reduced phonon-impurity scattering rate must be overcompensated by soft-phonon scattering. This is indeed reasonable since it is a qualitatively different scattering mechanism whose importance upon Sr-doping grows since thereby the relevant soft modes soften further.

The reappearance of the phonon peak in La$_{2-x}$Sr$_x$CuO$_4$ at high Sr-concentrations as $x = 0.3$ can now be understood as a natural consequence of the doping dependence of $T_{\text{HT}}$. For $x \gtrsim 0.22$, the LTO-phase disappears in La$_{2-x}$Sr$_x$CuO$_4$ and the structure remains in the HTT-phase for all temperatures. Hence, for $x = 0.3$ soft-phonon scattering associated with the LTO-phase is not active for such overdoped compounds. The result of such decreased phonon scattering is the reappearance of the phonon peak.

It is necessary to mention that the growing density of holes as the Sr-content is increased in principle could be a further source of scattering and therefore contribute to the reduction of $\kappa_{\text{ph}}$ and in particular the phonon peak via phonon-electron scattering. However, since the transition to superconductivity in La$_{2-x}$Sr$_x$CuO$_4$ causes no significant anomaly in $\kappa_c$ at $T_c$ (cf. Fig. 4), this scattering mechanism is usually considered to be unimportant in this material and its (RE)-doped relatives. Yet if this scattering channel is active in this material no inconsistency to our interpretation arises because in this case the phonon-'impurity' scattering induced by Sr-ions can be regarded simply as slightly more effective than the phonon-impurity scattering induced by Eu-ions.

C. Stripes as a scattering mechanism for phonons?

The above discussion of $\kappa_{\text{ph}}$ of the insulating materials La$_2$CuO$_4$, La$_{1-x}$Eu$_{0.2}$CuO$_4$ and La$_2$NiO$_4$ provides unambiguous evidence that phonon-impurity and soft-phonon scattering are important scattering mechanisms for phonons in doped La$_2$CuO$_4$. Since the major doping dependencies of the low-$T$ peak can be explained based on these mechanisms without any problems, there is no compelling reason to incorporate a stripe induced scattering channel in the data interpretation. It is unlikely though that stripes in doped La$_2$CuO$_4$ have no effect at all on $\kappa_{\text{ph}}$ because the aforementioned stripe-induced phonon scattering in the nickelate is an unambiguous physical fact. However, it appears extremely difficult to prove the existence and to study the strength of purely stripe induced scattering in doped La$_2$CuO$_4$ via $\kappa_{\text{ph}}$. This is not only because phonon-impurity and soft-phonon scattering are already dominating $\kappa_{\text{ph}}$ in insulating La$_2$CuO$_4$; Due to the intimate relation of LTT-phase and stripe dynamics, scattering on fluctuating stripes in the Sr-doped compounds could be viewed as an altered but already existing soft-phonon scattering, i.e., from this point of view these two scattering mechanisms are conceptually indistinguishable.

D. High temperature increase of $\kappa_{\text{ph}}$

For completeness, we briefly mention the unusual temperature dependence of $\kappa_c$ which is evident at higher temperatures $T \gtrsim 100$ K. Instead of a decrease as $\sim T^{-1}$, which at elevated temperatures is usually expected for thermal conductivity by acoustic phonons, $\kappa_c$ is almost temperature independent or even increases with rising $T$. As has been shown in Ref. 60, this strong deviation from the usual behavior arises due to thermal conduction by dispersive optical phonons in addition to the usual contribution by acoustic phonons.

FIG. 4: Temperature dependence of $\kappa_{ab}$ of La$_2$NiO$_4$ in comparison with $\kappa_{ab}$ of La$_2$CuO$_4$ and La$_{1-x}$Eu$_{0.2}$CuO$_4$. The data for La$_2$CuO$_4$ are reproduced from Ref. 49.
VI. SUMMARY

In summary, we have presented experimental results on the thermal conductivity of La$_{1-x}$Eu$_x$Sr$_x$CuO$_4$ for a wide doping range of Sr. The analysis of our data suggests that in this material phonons are strongly scattered on the doped impurities, i.e., Sr and Eu, as well as on soft phonons that are present in the LTO-phase of this material. Comparison of our data with the thermal conductivity of La$_{2-x}$Sr$_x$CuO$_4$ and isostructural La$_2$NiO$_4$ leads to the conclusion that these scattering mechanisms are most relevant in La$_{2-x}$Sr$_x$CuO$_4$ as well. In particular, in contrast to other studies, there remains no direct evidence that the stripe correlations cause a relevant scattering channel in doped La$_2$CuO$_4$.

VII. ACKNOWLEDGMENTS

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