ULTRASONIC VELOCITY VARIATIONS IN $La_{2-x}Sr_xCuO_4$ SINGLE CRYSTALS.

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Abstract

We present the results of ultrasonic velocity measurements in two $La_{2-x}SrxCuO_4$ samples down to the 50 mK temperature range. Doing so we experimentally demonstrate that ultrasonic waves are coupled to three different kinds of excitation.

Introduction

Ultrasonic measurements has been determinant in the study of conventional superconductors. Very few experiments of that kind have been carried out in high Tc superconductors, probably because it is very difficult to get good single-crystals of convenient size for such technique. However in the case of $La_{2-x}Sr_xCuO_4$ some experiments has been realized. Migliori et al.[1] reported the measurement of all the elastic constants in compounds with x=0 and 0.14. They noticed a giant softening of the c_{66} coefficient at the tetragonal to orthorhombic transition. Hanaguri et al. [2], by using appropriate configurations of wave vector, polarization and magnetic field direction, detected the influence of the flux line lattice on sound velocity. Nohara et al. [3] explored the low temperature range in three crystals with x= 0.09, 0.14 and 0.19.. They reported an unconventional variation of the elastic constant c_{11}-c_{12}/2 for the compound with x=0.14 which almost disappears for the two others. Suzuki et al. [4] observed an analogous anomaly for the complex elastic constant of a longitudinal wave propagating along the [110] direction (tetragonal notation). Sakita et al. [5] tentatively explain the anomalous variations by the interplay between the superconducting gap formation and a structural transition of Peierls type. It seemed worth to us to reproduce the measurements and to extend their temperature range down to 50 mK. By doing so we have brought new insights into those variations.

Experimental Technique

We have used two samples with nominal x of 0.1 and 0.14. The single-crystals were grown in the Laboratoire de Chimie du Solide at the University Paris-Sud, in an optical image furnace by the A. Revcolevschi's team. Two surfaces perpendicular to the tetragonal [110] axis were polished on each sample and the [001] axis was materialized. The transducers were made from ZnO layer. Microwave frequencies in the 100 - 400 MHz range could be used to excite the transducers. Sound velocity variations were determined by monitoring the phase of the detected electromagnetic field on the output transducer. The samples have been mounted in a magnetic field with maximum intensity of 3 Tesla and apply along the [001] axis. The temperature could be varied between 0.05 K and 80 K. The superconducting transition (Tc) was determined by measuring the resistivity of the sample along the c-axis or by susceptibility measurement at a frequency of 100 kHz. The Tc of the x=0.14 sample is 34.9 K. The width of the transition curve was less than 1 degree. For the x=0.1, Tc is 29 K with a width of 2 degrees. For this sample we monitored the transition temperature with the magnetic field. We found the same strong depression, which has been reported in ref [5]. Transverse waves with polarization in the CuO plane $(c_{11}$-$c_{12})/2$ or along c-axis (c_{44}) has been used for the x=0.14 sample and longitudinal waves for the x=0.1 one.

Results

In figure 1 the velocity variations with temperature and without magnetic field, for the x=0.14 sample, are shown using a logarithmic temperature scale in order to emphasize the variations in the lowest temperature range (.01-10 K).

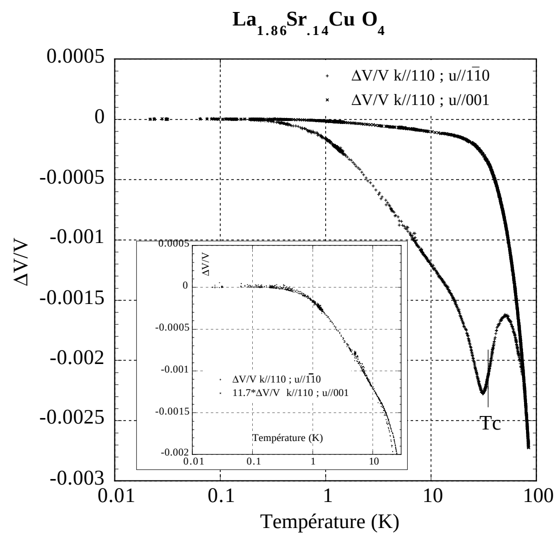

Fig. 1: Sound velocity variations with the temperature for the transverse waves propagating along the [110] axis and polarized either along the c-axis or in the CuO_2 plane. Insert: Same variations for the lowest temperature range, but the variations for the c-axis polarized wave has been multiplied by a factor 11.7. That emphasizes the similarity of the temperature variations for the two transverse polarizations.

The variations are very much alike those reported in ref [3-5] for similar Sr concentrations. Going from high temperature down to low temperature, we first see a hardening for both polarizations which becomes a softening for the wave polarized in the plane but stays a monotonous increase for the other. Around 30 K the hardening slow down for the wave polarized along the c-axis and restarts very strongly for the other. Then the velocity increase appears logarithmic for both polarizations down to 1.5 K before slowing down. At the lowest temperatures, the increase is not completely stopped but the variations are linear in temperature with a very small slope. In the inset of the figure, we have plotted again the lower temperature range of the measurements after multiplying by a factor 11.7 the variations of the wave polarized along the c-axis. As it can be seen both variations are now superimposed. This finding is certainly the most important result of this paper. It allowed to describe qualitatively the variations in the following way. The first hardening with decreasing temperature corresponds to the standard hardening, which appears in insulator crystals due to the interaction of the ultrasonic waves with the thermal phonons. The variation law is given by:

$$\Delta V / V = -\gamma^2 TC(T)/\rho V^2.$$

Where V is the sound velocity, γ the Gruneisen constant, C the phonon specific heat and ρ the specific gravity. For the wave with polarization along the c-axis, the lowest temperature part of the hardening is a relaxation-like variation due to the coupling between ultrasonic wave and the spin magnetization, as the magnetic field experiment will show. Finally for the in plane polarization, in the intermediate temperature range, a third interaction shows up which is very much like a phase transition. This phase transition is not coupled with the deformations of symmetry B_{2g}, but coupled with those with symmetry A_g or B_{1g}.

In figure 2, the temperature variations, with and without a 3 Tesla c-axis magnetic field applied, are compared for the in-plane polarization and for the same sample with x = 0.14. The relative variations has been brought in coincidence at high temperature since at those temperature, when monitoring the sound velocity during the magnetic field increase, no variations were observed. Again we measured analogous variations to those reported in ref [3,5]. It is clearly shown too that the magnetic field enhanced widely the low temperature relaxation-like variations. To our opinion it demonstrates that they are due to a spin-ultrasonic interaction. In the inset of the figure, the variations associated with the wave polarized along the c-axis are plotted.

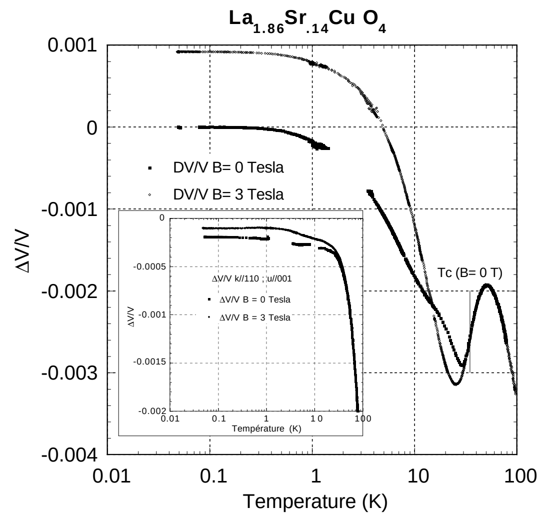

Fig.2: Sound velocity variations with the temperature, with and without a magnetic field, for the transverse wave polarized in the CuO_2 plane. Insert: the same but for the wave polarized along the c-axis.

It can be seen that the relaxation-like variations start already around 30 K for this polarization.

In figure 3, the variations with and without a magnetic field are shown for a longitudinal wave propagating along the tetragonal [110] axis in the sample with x = 0.1.

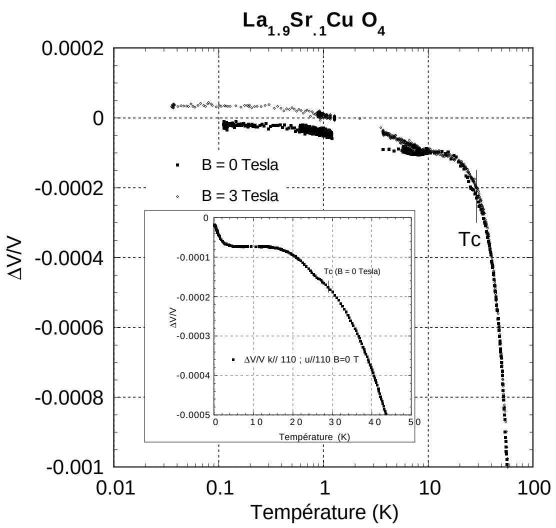

Fig. 3: Longitudinal wave velocity variations with the temperature in the sample with x=0.1 with and without a magnetic field apply along the c-axis. Insert: Variations whithout a magnetic field with a linear temperature scale to emphasize the small dip around 25 K.

The relaxation-like coupling is clearly observed but it does show up only for temperature lower than 10 K. Magnetic field increases too the strength of the effect.

In the insert, the variations without a magnetic field are displayed with a linear temperature scale to emphasize the small dip around 25 K which is probably what is left from the signature of the phase transition for that strontium concentration.

Discussion

Since $La_{2-x}Sr_xCuO_4$ is a metallic-like conductor for temperatures higher than 35 K and becomes a superconductor for lower temperatures, it is conceivable that a part of the acoustic properties are due to that conductivity. However, an order of magnitude of this effect can be obtained by using the Pippard formula for the sound attenuation in a metal: $\alpha = 10\omega^2\sigma h^2 N^{2/3}/2\pi\rho V^3 e^2$, where α is the sound attenuation coefficient, ω the sound pulsation, σ the conductivity, h the Planck's constant, N the number of carriers by unit volume, e the electronic charge. Using the values of these parameters for x=0.14 ($\sigma = 10^6$ Mho.m-1, N = 10^{27} m^{-3}, $\rho = 7.10^3$ $kg.m^{-3}$, V = $3.8.10^3$ m sec^{-1}) we find $\alpha = 10^{-2}$ m^{-1} = 4.10^{-2} dB m^{-1}. This value is too small to expect to be able to measure any contribution to the sound parameters due to the electrical conductivity of the material. Indeed, we do not see any.

In the introduction, we mention that Hanaguri et al. [2] did observe the influence of the vortex lattice (FLL) on the acoustic velocity. But with the polarization of the waves used in the x= 0.14 sample and, as it was emphasized in ref 2, we are either not coupled with the FLL (case of the c-axis polarization) or coupled with the very small c_{66} component of the FLL (case of the in-plane polarization). Therefore we cannot see any contribution of the FLL to the elastic constants.

Then the only possibilities of interaction for the ultrasonic waves are either with the crystal lattice or with the magnetic properties of the compounds. We have limited our analysis to the variations measured in the x= 0.14 sample and without a magnetic field. First of all, we concentrated on the measured variations for the c-axis-polarized wave since only two effects are visible. The contribution of the ultrasonic-phonon interactions to the variations of the sound velocity has been determined by adjustment of the above-cited law to the 40-100 K temperature range. We use as parameters The γ Gruneisen constant and the Θ_d Debye temperature. The best adjustment was obtained for Θ_d = 350 K and γ = 1.355.A calculation, using the elastic constant measured by Migliori [1], and the method proposed by Alers in ref 7 gives 330 K for Θ_d. Both value agree. Then we subtracted the theoretical phonon-phonon (ph-ph) contribution to the experimental variations in order to obtain the low temperature relaxation-like contribution to the velocity variations. That decomposition is shown in the insert of figure 4.

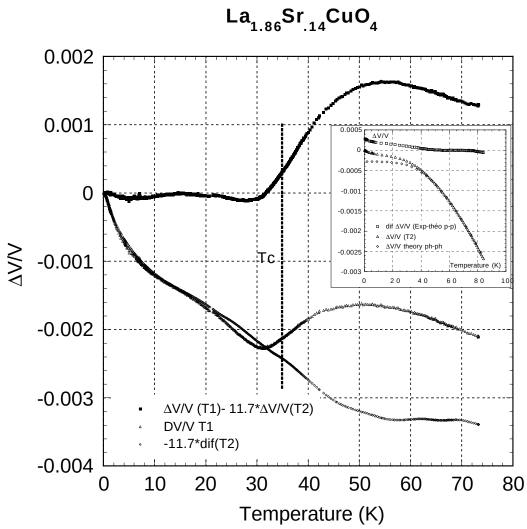

Fig. 4: Decomposition of the velocity variations for the in plane polarized wave. The relaxation-like contribution (-11.7*dif(T2)) was obtained, as explained in the text, from the decomposition, shown in the insert, of the variations measured for the c-axis polarized wave.

Once we have obtained that relaxation –like part of the variations for the c-axis polarized wave, we can multiply those variations by a factor 11.7, as already mentioned, and subtract the results from the measured variations for the in-plane polarized wave, as shown in the main part of figure 4. The result of the subtraction reveals fully the transition phase-like variations in the middle temperature range of the data. It is interesting to note that the evolution of the order parameter seems to stop just below the superconducting transition, as already noted in ref. 3 and 5. The limited extent of data for the upper-temperature range does not allow to further decompose the in-plane measurements and to separate for this polarization the ph-ph contribution from the transition-like variations.

Conclusion

The extension, down to the 10 mili-Kelvin temperature range, of the measurement of the sound velocity variations gave a new insight to those variations. It allows to decompose the variations in three main contributions: a relaxation-like one in the lowest temperature range, phase transition-like in the intermediate temperature range and, finally, a phonon-phonon like one in the upper temperature range. It is interesting to note that le relaxation-like variations mimic the evolution with temperature of the ordered spin moment squared, as measured by B. Lake et al. [6] in a x= 0.1 sample by elastic neutron scattering. This suggest that component of the velocity variations is the result of the coupling of the ultrasonic wave with this squared moment.

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