Response of Acoustic Phonons to Charge and Orbital Order in the 50% Doped Bilayer Manganite LaSr$_2$Mn$_2$O$_7$


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Response of acoustic phonons to charge and orbital order in the 50% doped bilayer manganite LaSr$_2$Mn$_2$O$_7$

F. Weber, 1, 2, * S. Rosenkranz, 1 J.-P. Castellan, 1 R. Osborn, 1 H. Zheng, 1 J. F. Mitchell, 1 Y. Chen, 3, 4 Songxue Chi, 3, 4 J. W. Lynn, 3 and D. Reznik 2, 5

1 Materials Science Division, Argonne National Laboratory, Argonne, Illinois, 60439, USA
2 Karlsruher Institut für Technologie, Institut für Festkörperfysik, P.O.B. 3640, D-76021 Karlsruhe, Germany
3 NIST Center for Neutron Research, National Institute of Standards and Technology, Gaithersburg, Maryland, 20899, USA
4 Department of Materials Science and Engineering, University of Maryland, College Park, Maryland, 20742, USA
5 Department of Physics, University of Colorado at Boulder, Boulder, Colorado, 80309, USA

We report an inelastic neutron scattering study of acoustic phonons in the charge and orbitally ordered bilayer manganite LaSr$_2$Mn$_2$O$_7$. For excitation energies less than 15 meV, we observe an abrupt increase (decrease) of the phonon energies (linewidths) of a transverse acoustic phonon branch at $q = (h, h, 0)$, $h \leq 0.3$, upon entering the low temperature charge and orbital ordered state ($T_{COO} = 225$ K). This indicates a reduced electron-phonon coupling due to a decrease of electronic states at the Fermi level leading to a partial removal of the Fermi surface below $T_{COO}$, and provides direct experimental evidence for a link between electron-phonon coupling and charge order in manganites.

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The complex phase diagrams of many transition metal oxides highlight the strong interplay and competition between lattice, spin and charge degrees of freedom [1-4]. Among the various different ground states, the so-called CE-type [5] charge and orbital order (COO) has particularly attracted scientific interest. Long range COO is the ground state of half-doped manganites [4-6], and short-range CE-type COO is believed to play a crucial role for colossal magnetoresistance at lower doping [7, 8]. The origin of the charge modulation is typically attributed to the ordering of Mn$^{3+}$ and Mn$^{4+}$ ions [6] producing Jahn-Teller type distortions of the oxygen octahedra around the Mn$^{3+}$ sites. Although these lattice distortions have been verified experimentally, the charge disproportionation has been argued to be much smaller than one [9-12]. More recently, it has been shown that the doping dependence of the ordering wavevector for pseudo-cubic manganites near half doping can be described in a charge-density-wave picture [13] and, indeed, experimental evidence for such a scenario was found in La$_{0.5}$Ca$_{0.5}$MnO$_3$ [14] and Pr$_{0.48}$Ca$_{0.52}$MnO$_3$ [15].

Although the importance of electron-lattice interaction for manganites and, in particular, the CE-type ordered state is based on theoretical considerations [7, 8] as well as experimental observations [16], detailed experimental information on phonon dispersions and electron-phonon coupling in manganites is scarce [19-22]. Here, we present results of an investigation of acoustic phonons in the CE-type COO bilayer manganite La$_{2-x}$Sr$_x$Mn$_2$O$_7$ ($x = 0.5$). We found that phonons are clearly sensitive to the onset of COO at $T_{COO} = 225$ K, but in a way not expected from the standard CDW picture [17, 18].

We chose the double layer manganite despite the large crystallographic unit cell because it lacks structural complications of its pseudo-cubic counterparts such as twinning and tilted MnO$_6$ octahedra [21]. As phonon softening is often observed as a precursor to a structural phase transition at the ordering wavevector, our focus was on acoustic phonon dispersions along directions that include wavevectors where superstructure peaks were reported [10, 23, 24]. To this end, we measured the ab-plane polarized transverse acoustic (TA) phonon branch in the crystallographic (110) direction, which includes the COO wavevector $q_{COO} = (0.25, 0.25, 0)$, and the longitudinal acoustic (LA) branch in the (100) direction. In the latter we looked for anomalous behavior associated with the presence of short-range polaron correlations with a wavevector $q = (0.3, 0, 1)$ [25, 26] by comparing data from $Q = (2.3, 0, 0)$ and $(2.3, 0, 1)$.

The neutron scattering experiments were performed on the BT-7 thermal triple-axis spectrometer at the NIST Center for Neutron Research. Pyrolytic graphite was used both as monochromator (vertically focused) and analyzer (horizontally focused). We used a final energy of $E_f = 14.7$ meV and a graphite filter in the scattered beam in order to suppress higher order scattering. The resolution was calculated based on the Cooper-Nathans formalism [27] and a force-constant model for the 3-dimensional phonon dispersion developed in an earlier investigation of La$_{1.2}$Sr$_{1.8}$Mn$_2$O$_7$ [28].

Our single crystal sample of LaSr$_2$Mn$_2$O$_7$ was melt grown in an optical image furnace [29] having the shape of a cylinder of 0.4 cm in diameter and 2 cm length. The crystal was mounted in a standard closed-cycle refrigerator allowing measurements down to $T = 5$ K and up to room temperature. Measurements were carried out in the $h00$ and $h0l$ scattering planes. The com-
samples show a strong competition with an A-type antiferromagnetic state at low temperatures with a similarly large hysteresis in the same temperature range. More recently, it was shown that the CE-type orbital ordering as we observe it for $T \leq 225$ K is susceptible to both CE-type and A-type antiferromagnetism [30]. The reduced integrated intensity of the COO superlattice peak at low temperatures can then be attributed to ferromagnetic fluctuations in the $ab$ plane of an A-type antiferromagnet, which favor double-exchange and, therefore, slowly melt the Mn$^{3+}$-Mn$^{4+}$ charge-order, which persists in the CE-type antiferromagnetic regions.

We also checked for the presence of short-range polaron correlations with a wavevector $\mathbf{q} \approx (0.3, 0, 1)$. In Fig. 1c we plot elastic scans taken at $\mathbf{Q} = (2 + h, 0, 1)$, $h = 0.2 - 0.4$, and $T = 100$ K and $200$ K. We clearly observe the presence of this type of superstructure in the partially reentrant state at low temperatures, but with a finite correlation length $\xi \approx 40$ Å and an amplitude that is an order of magnitude smaller than the one observed for the COO peak. The temperature dependence of the polaron peak at $\mathbf{q} \approx (0.3, 0, 1)$ as observed in a heating cycle is roughly opposite to that of the COO peak at $\mathbf{q}_{\text{COO}}$, i.e. the polaron peak is barely present when the COO peak reaches its maximum intensity.

From the measurements presented in Fig. 1 it is evident that CE-type COO is reduced at low temperatures. However, the measured phonons (see below) only react to the onset of COO at $T_{\text{COO}} = 225$ K and show no response to the reduction of COO at lower temperatures. Thus, we believe that CE-type COO is representative of the ground state of our specimen as far as phonons are concerned. This view is corroborated by the fact that the competing A-type antiferromagnetic phase in principle supports and only slowly melts the orbital order via an increased double-exchange rate [30].

We investigated the acoustic and low lying optic phonons along the transverse $(110)$ direction, i.e. $\mathbf{q} = (+h, -h, 0)$, where $h = 0.25$ corresponds to the symmetry and wavevector positions of the COO superlattice peak. Raw data of constant $\mathbf{Q}$ scans at $T = 5$ K for the TA phonon mode at $\mathbf{Q} = (2 + h, 2 - h, 0)$ are shown in Fig. 2. For $h \leq 0.3$, a single well-defined excitation is observed. For larger wave vectors additional phonon peaks start to develop and finally three peaks can be distinguished at the zone boundary, i.e. $h = 0.5$. The fitted energies agree well with previous measurements on La$_2$Sr$_{1.5}$Mn$_2$O$_7$ [28]. Near the zone boundary, our measurements show additional peaks due to optic phonon branches, which come close in energy to the acoustic dispersion. This is corroborated by measurements in a different Brillouin zone adjacent to the zone center wavevector $\mathbf{\tau} = (3, 3, 0)$, where the structure factors of the optic phonons are much stronger and acoustic phonons have practically zero intensity (see inset of Fig. 2). In a second inset of Fig. 2 we show the observed linewidths (Full Width at Half Maxi-
both the energy and linewidth at entering the COO state. As a function of temperature, phonon energy increases and the linewidth decreases on an absolute scale for phonons with de-T jumps at ≤ T. T have a significant intrinsic linewidth. The effect is not localized at the ordering wavevector, and changes of less than 0.2 meV in the phonon energy could not determined. We note that no temperature dependence was detected for the investigated optic q superstructure at q = (0.3, 0.25, 0) that have been discussed elsewhere[22]. We did not observe any particular temperature or wavevector dependence at this q position. We note, however, that the statistical uncertainty here is larger than for the TA phonon data and changes of less than 0.2 meV in the phonon energy could not determined.

FIG. 2. (Color online) Constant Q scans of the transverse acoustic (TA) phonon at Q = (2 + h, 2 − h, 0), h = 0.1 − 0.5, at T = 5 K. Solid lines are Lorentzian fits convoluted with the instrumental resolution on an experimental background. Dashed horizontal lines indicate the respective scan base line. The insets show energies measured at Q = (2 + h, 2 − h, 0) (squares) and (3 − h, 3 + h, 0) (circles) (upper panel) and phonon linewidths (FWHM) at T = 300 K (squares) and T = 5 K (triangles) of the TA phonon (lower panel). The black line is the calculated resolution.

FIG. 3. (Color online) Temperature dependent (a) background subtracted data, (b) energy and (d) Lorentzian linewidth (full-width at half maximum) of the transverse acoustic phonon at Q = (2 + h, 2 − h, 0), h = 0.25. Energies and linewidths were extracted from Lorentzian fits (solid lines) to the data convoluted with a Gaussian energy resolution (∼ 2 meV). The dashed vertical lines in (b), (d) mark the onset of orbital order at T_{COO} = 225 K. (c) Energy shift of TA phonons at Q = (2 + h, 2 − h, 0), 0.1 ≤ h ≤ 0.35, between T = 5 K and 300 K plotted versus phonon energy at T = 5 K.

creasing energies, i.e. decreasing h. On the other side, the energy shift between low and high temperatures vanishes (within experimental error) for a phonon energy of roughly 15 meV or h > 0.3. We note that no temperature dependence was detected for the investigated optic branch between T = 5 K and 300 K, which further indicates that the observed effect is restricted to low energy acoustic phonons.

Measurements of the LA phonon at wavevectors corresponding to the wavevector of the short-range superstructure at q = (0.3, 0.1) agreed well with shell model calculations developed for the compound with x = 0.4 that have been discussed elsewhere[22]. We did not observe any particular temperature or wavevector dependence at this q position. We note, however, that the statistical uncertainty here is larger than for the TA phonon data and changes of less than 0.2 meV in the phonon energy could not determined.

Summarizing our experimental results, we observe a jump in the TA phonon energy and linewidth at T_{COO}. The effect is not localized at the ordering wavevector, i.e. q_{COO} = (0.25, 0.25, 0), but occurs over an extended range in momentum transfer, as long as the energy is lower than 15 meV or q ≤ (0.3, 0.3, 0).

The phonon linewidth can be roughly divided into an anharmonic part and the electronic contribution to the phonon linewidth, i.e. electron-phonon coupling (EPC). Anharmonic interactions typically result in a gradual increase of the phonon linewidth with increasing temper-
ature. In principle, this can happen in a more abrupt manner, when a rigid order suddenly relaxes into an unordered state. However, this effect should not be limited to a certain range of phonon wavevectors or energies. Therefore, the observed abrupt changes in the phonon linewidths and energies in LaSr₂Mn₂O₇ cannot be explained by a sudden increase of anharmonic contributions.

EPC for a particular phonon mode requires the existence of electronic states close to the Fermi energy $E_F$, which can be excited by the phonon to unoccupied states above $E_F$. If these decay channels are frozen out, the phonon lifetime increases and the linewidth is reduced. This is a well known effect in, e.g., conventional superconductors for phonon energies below the superconducting gap value $2\Delta_{SC}$ [31-33]. Further, the participating electronic states have to be connected by the phonon wavevector $q$. Unfortunately, information about the Fermi surface in the half-doped bilayer manganite is scarce. Angle resolved photoemission spectroscopy (ARPES) only reported experiments in the COO state [34]. Here, the Fermi surface is such that phonon vectors with $q < (0.25, 0.25, 0)$ cannot connect different states at $E_F$. On the other hand, calculations of the electronic band structure via density-functional-theory [35] in not charge-ordered LaSr₂Mn₂O₇ show the presence of a small electron pocket around the center of the Brillouin zone ($\Gamma$ point) in addition to the Fermi surface spanning wavevectors with 2∆ < 15 meV at $T = 5$ K. So far, however, there is no microscopic evidence from electronic probes for the existence of such an energy gap in LaSr₂Mn₂O₇ [40]. Further, CDW compounds typically exhibit phonon softening at the ordering wavevector as predicted by standard weak-coupling theory. Some known CDW compounds do not follow this phenomenology exactly. For example, in NbSe₂ phonons soften over a relatively large range of wavevectors around the ordering wavevector [38], NbSe₃, which is believed to be in the strong-coupling regime, shows not softening but line broadening at the CDW wavevector on approach to the transition [39]. But all CDW compounds exhibit some anomalous phonon behavior tied to the ordering wavevector. In contrast, acoustic phonons in LaSr₂Mn₂O₇, do not show a Kohn anomaly nor an enhanced linewidth at the ordering wavevector, which rules out the conventional CDW picture.

In conclusion we investigated acoustic phonons in the presence of long- and short-range charge correlations in CE-type COO ordered LaSr₂Mn₂O₇ via inelastic neutron scattering. We found a clear response to the onset of COO at $T_{COO} = 225$ K in the TA branch of the (110) direction. For this branch, the phonon linewidths are significantly reduced for phonon modes with excitation energies smaller than 15 meV ($q \leq (0.3, 0.3, 0)$). This is direct evidence for a link between charge order and electron-phonon coupling in this compound. The observed wavevector dependence of the effect at the phase transition is not consistent with a conventional CDW mechanism of the charge ordering.

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* frank.weber@kit.edu

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