Theory of the magnetoelectric effect in a lightly doped high-Tc cuprate
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Fields 1, 2 Among the materials discovered with such physical order than a bilinear coupling between electric and magnetic effect, i.e., the dominant magnetoelectric coupling is of higher driven by the discovery of the nonlinear magnetoelectric theoretical and experimental progress in recent years, mainly orthorhombic phase (LTO).11 Though this allows a small Moriya (DM) interaction existing in the low-temperature field effect. polarization and magnetization naturally lead to the observed explained. Here, we focus on the magnetoelectric effect in antiferromagnetic Mott insulators need to be theoretically experimental results about the nature of doped charge carriers low-temperature effects, including a feedback enhancement of the magnetization within the ferroelectric phase, and a predicted magnetocapacitive effect.

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The field of magnetoelectrics has witnessed intense theoretical and experimental progress in recent years, mainly driven by the discovery of the nonlinear magnetoelectric effect, i.e., the dominant magnetoelectric coupling is of higher order than a bilinear coupling between electric and magnetic fields.12 Among the materials discovered with such physical properties are the so-called birelaxors.3,4 These systems show both relaxor ferroelectric and relaxor magnetic properties and are associated with spin–charge coupling at a mesoscopic scale. Focusing on the parent high-$T_c$ superconductor La$_2$CuO$_4$$_{+x}$ (LCO) with an exceptionally low carrier concentration $n = 10^{17}$ cm$^{-3}$, we have recently found that this material is in fact a ferroelectric at low temperatures.5 More specifically, LCO has been shown to be a relaxor ferroelectric where the dielectric mode behavior is caused by freezing of randomly oriented polarized regions.6,7 In addition, LCO exhibits a distinct magnetoelectric effect with a pronounced dependence of the polarization on an externally applied magnetic field. These experimental results about the nature of doped charge carriers in antiferromagnetic Mott insulators need to be theoretically explained. Here, we focus on the magnetoelectric effect discovered in Ref. 5, and show how nonlinear terms coupling polarization and magnetization naturally lead to the observed field effect.

Parent cuprate superconductors are two-dimensional (2D) antiferromagnets with weak interplanar exchange coupling giving rise to three-dimensional (3D) long-range Néel order.8–10 In the case of LCO, the Cu spins are slightly canted out of the CuO$_2$ planes because of a finite Dzyaloshinskii-Moriya (DM) interaction existing in the low-temperature orthorhombic phase (LTO).11 Though this allows a small ferromagnetic moment to build up on each CuO$_2$ plane, the net magnetic moment is zero since the moments in consecutive layers are oriented in opposite directions. On application of an external magnetic field a first-order spin–flop transition is observed at a critical magnetic field $H_{sf} \sim 5 T$.11,12 Clear evidence for coupled spin and charge degrees of freedom in these systems comes from the observation of pronounced discontinuities in resistivity and dielectric constant at a magnetic field corresponding to $H_{sf}$.5,13 Further evidence of such coupling is found in LCO by the possibility to detwin these crystals, e.g., by the application of an in-plane magnetic field.14

In the following we use a symmetry-based analysis to identify the particular magnetoelectric interaction terms that are responsible for spin–charge coupling in underdoped LCO. We further construct a Landau theory, and show how this model reproduces all the qualitative features of the magnetic field dependence of the polarization curves reported in Ref. 5.

Below approximately 530 K the crystal structure of LCO is LTO with space group $Cmca$ ($D_{2h}^8$).15 If $(\hat{x}, \hat{y}, \hat{z})$ denote unit vectors along the crystal axes, then we define fractional translations by

$$\tau = \frac{1}{4}(a\hat{x} + c\hat{z})\tau' = \frac{1}{4}(a\hat{x} + b\hat{y}),$$

where $a, b, c$ are the lattice constants. The symmetry elements of this crystal structure are then written as $G = G_0 + \tau G_0$, where $G_0$ contains the eight elements

$$E, I, \sigma_a, \sigma_{a}'', \sigma_c, C_{2a}, C'_{2a}, C_{2c}. \quad (2)$$

Here $E$ denotes the identity, $I$ inversion about a Cu site, $\sigma_a, \sigma_{a}'', \sigma_c$ reflections about the planes $x = a/2, y = b/2, z = c/2$, and $C_{2a}, C'_{2a}, C_{2c}$ are 180° rotations about the axes that emanate from the center of the unit cell. Primed elements must be complemented by translation $\tau'$ that is itself not a symmetry operation.

Taking into account the above-mentioned symmetry properties of the $Cmca$ space group, the free energy can be expressed as a sum of three contributions

$$F = F_M + F_{MP} + F_P. \quad (3)$$

Here, $F_M$ is the purely magnetic free energy, $F_{MP}$ is the magnetoelectric contribution, and $F_P$ is the polarization free energy. The magnetic free energy that accounts for the crystal structure of the LTO phase has been studied previously by,
e.g., Thio et al., and is given by

\[
F_M = \frac{1}{2} \sum_{i=1}^{4} \left[ \frac{\chi_{2D} L_1^2}{2} + \frac{1}{4} A L_1^4 + \frac{1}{6} B L_1^6 - C L_i M_i \right] + \frac{\chi_{3D}}{2} M_2^2 - H_M M_i - H_{ab} L_i \right] + \frac{1}{2} J_{2} L_1 L_2. \tag{4}
\]

Here, the out-of-plane (κ direction) [in-plane (a-b plane)] applied magnetic field is represented by \( H_{k} \) [\( H_{ab} \)]. The coefficients \( A, B, \) and \( C \) would in general be temperature dependent.

The order parameter \( L_i = (S_{ki} + S_{bi})/2 \) is the ferromagnetic moment per spin with \( S_{ki}, S_{bi} \) being the sublattice spins in the ith plane, and \( L_i = (S_{ki} - S_{bi})/2 \) is the antiferromagnetic order parameter \( (L_i || a) \). The spins are slightly canted due to the DM interaction term \(-CM_i L_i\), which causes them to lie in the a-c plane of the magnetic unit cell. The coupling between the different planes is included by the \( J_2 \) term.

The presence of an inversion symmetry in the space group of the crystal forbids any linear magnetoelectric effect and the physics is dominated by nonlinear coupling terms. We can obtain stable solutions, and therefore, we are interested in higher-order terms. However, since we are interested in the magnetoelectric effect close to the ferroelectric transition, it is reasonable to restrict our analysis to the above terms.

In terms of the following rescaled quantities \( l_+ = \chi_0 C(L_1 + L_2)/2, \quad l_- = \chi_0 C(L_1 - L_2)/2, \quad M = (M_1 + M_2)/2, \quad \gamma_{1a} = 2\gamma_{2a}(\chi_0 C)^{-1}, \quad \gamma_{3a} = 2\gamma_{2a}(\chi_0 C)^{-1} \), the polarization dependence on the applied magnetic field can be expressed as

\[
P_a(H_{ab})/P_a(0) = \left\{ 1 + \frac{s_a}{l_-^2(0)}[l_-^2(H_{ab}) - l_-^2(0) + l_+^2(H_{ab})]\right\}^{1/2}. \tag{12}
\]

\[
P_a(H_c)/P_a(0) = \left\{ 1 + \frac{s_a}{l_+^2(0)}[l_+^2(H_c) - l_-^2(0) + g_a M(H_c)^2]ight\}^{1/2} + (1 - g_a - q_a)l_+^2(H_c) + q_a M(H_c)[l_+(H_c)]\right\}^{1/2}, \tag{13}
\]

where \( s_a = \lambda_c l_+^2(0)/[\chi_{2D} + \lambda_c l_+^2(0)], \quad g_a = \gamma_{3a}/\lambda_a, \) and \( q_a = \gamma_{3a}/\lambda_a, \) with \( \lambda_a = \gamma_{1a} + \gamma_{2a} + \gamma_{3a}. \) In general, all three...
parameters $s_α$, $g_α$, and $q_α$ will be temperature dependent. The temperature dependence of $s_α$ primarily results from its relation to the electric susceptibility; hence an estimation of the amplitude of $s_α$ can reveal the magnitude of anisotropy in the electric polarization.

In the case of an out-of-plane magnetic field $H_c$, the measured $P_α(H_c)$ increases with field and exhibits a pronounced hump at the spin-flop transition at $Hsf$, as seen from Fig. 2(a). By contrast, $P_{ab}(H_c)$ decreases with increasing $H_c$ but also exhibits a hump feature at $Hsf$, as seen from Fig. 2(c). This behavior indicates a scenario where the coupling between the magnetic order and out-of-plane polarization $P_α$ is attractive whereas the coupling with $P_{ab}$ is repulsive. However, we find that the theoretical picture is more complex due to the presence of two competing magnetic orders $L$ and $M$ coupling to the electric polarization. For the out-of-plane magnetic field, we calculate the $P_α(H_c)$ response using the magnetization data shown in Fig. 1(a). As seen from Figs. 2(b) and 2(d), we obtain qualitative agreement with both experimental polarization curves including the hump feature at $Hsf$. Note that for the coupling to the magnetization we have set $g_α = g_β = g_γ = −0.2$. Therefore, the source of anisotropy between $P_α(H_c)$ and $P_{ab}(H_c)$ is the DM-induced coupling term $q_α P_α^3 M_1 L_1$ with $q_α = q_β = 0$ and $q_γ = −6.58$.

In the case of an in-plane magnetic field $H_{ab}$, $P_α(H_{ab})$ depends on only a single fitting parameter $s_α$ that controls the magnitude of the polarization ratio, whereas the shapes of the theoretical curves are governed by the magnetic order parameter of the system. Further, we can deduce from Eq. (12) that the polarization primarily couples to the 2D antiferromagnetic order through a magnetoelectric interaction term $P_{ML} \sim \lambda_{ab} P_α^2 L_1^2$. The anisotropy in polarization through the parameter $\lambda_{ab}$ for in-plane magnetic fields is primarily controlled by the DM-induced magnetoelectric coupling term $q_α P_α^3 M_1 L_1$, since $q_α$ undergoes the largest variation between in-plane and out-of-plane directions. The DM physics therefore plays an important role in generating an anisotropy between $P_α(H)$ and $P_{ab}(H)$ in La$_2$CuO$_{4+x}$.

Using the magnetization curve from Fig. 1(b), the solutions of $P_α(H_{ab})$ are presented in Figs. 3(b) and 3(d). Though the theoretical curves have similar shapes, the scales are different in the two figures due to the difference in $s_α$ values. Note that all theoretical curves have been plotted using magnetization data available at $T = 5$ K while the experimental curves correspond to $T = 2.5$ K, which accounts for the smaller scale of the theoretical curves. As seen from the plots, we find again qualitative agreement with the experimental data shown in Figs. 3(a) and 3(c), though the experimental plot in Fig. 3(a) has a steeper slope than theory. This steeper curve in the experimental curve could be the result of some history effect in these relaxor systems, a feature that has not been taken into account in our analysis. As in Fig. 2, the plots correspond to $s_α = 0.1$, $s_β = 0.074$, which leads to a small anisotropy in the electric susceptibilities $\chi_{αα}$ and therefore between the zero magnetic field values of in-plane polarization $P_{ab}$ and the out-of-plane component $P_α$. This small anisotropy has been observed in experiments$^5$ and implies a much weaker anisotropy of the electric polarization compared to the magnetic order. This result lends support to a scenario where the nonstoichiometric oxygen dopants (charge carrier doping) play an important role in generating the relaxor ferroelectricity in La$_2$CuO$_{4+x}$.$^5$

We have observed experimentally that the magnetization shows a small enhancement below the temperatures where the ferroelectric order sets in.\textsuperscript{26} This effect is in addition to the typical upturn in magnetization near the spin-glass freezing temperature.\textsuperscript{27,28} We can study such a feedback effect of a finite polarization on the magnetization by minimizing $F$.

FIG. 2. (Color online) Polarization $P_α$ vs out-of-plane magnetic field $H_c$. (a), (c) Experimentally measured values at $T = 2.5$ K. (b), (d) Theoretically calculated $P_α(H_c)/P_α(0)$ for $s_α = 0.1$, $s_β = 0.074$, $g_α = g_β = g_γ = −0.2$, $q_α = −6.58$, and $q_β = 0$ using available experimental magnetization values at $T = 5$ K.

FIG. 3. (Color online) Polarization $P_α$ vs in-plane magnetic field $H_{ab}$. (a), (c) Experimentally measured values at $T = 2.5$ K. (b), (d) Theoretically calculated $P_α(H_{ab})/P_α(0)$ for $s_α = 0.1$ and $s_β = 0.074$ using available experimental magnetization values at $T = 5$ K.
FIG. 4. (Color online) Real-space illustration of polar nanoregions with randomly oriented electric polarizations (large black arrows) at high $T$ within the antiferromagnet (small red/grey arrows). Also shown are the distorted magnetic moments within a correlation arrow. The length of the polar nanoregions (light yellow regions).

within the ferroelectric phase. This gives to lowest order

$$M_e = \frac{\chi_0 H_e + \left[ 1 - \chi_0 \sum_\alpha \gamma_{\alpha} \partial_\alpha^2 P_\alpha^2(H_e) \right] l_e(H_e)}{1 + \chi_0 \sum_\alpha \gamma_{\alpha}^2 P_\alpha^2(H_e)}, \quad (14)$$

$$M_{ab} = \frac{\left[ 1 - \chi_0 \sum_\alpha \gamma_{\alpha} \partial_\alpha^2 P_{\alpha}^2(H_{ab}) \right] l_{ab}(H_{ab})}{1 + \chi_0 \sum_\alpha \gamma_{\alpha}^2 P_\alpha^2(H_{ab})}. \quad (15)$$

Note that in this expression the relative sign of the coefficients can be determined from the relations $\gamma_{\alpha}^2 / \gamma_{\alpha}^{\prime 2} = q_\alpha / g_\alpha > 0$. This also implies that since $\gamma_{\alpha}^{\prime 2} < 0$ in our model, it naturally causes an enhancement of magnetization due to the presence of a ferroelectric state. Additionally, we also find that this enhancement is present both in the in-plane and out-of-plane magnetization, with the relative size of the enhancement depending on the amplitude of polarization change with magnetic field.

A biquadratic coupling has been used to explain the observation of magnetocapacitive effects in materials such as doped SrTiO$_3$. It is defined by the relation $\epsilon_{\alpha} = -\tilde{\alpha} F / \partial_\alpha P_\alpha^2$ and hence requires at least quadratic terms in the polarization. For LCO the relative change in dielectric constant is given by

$$\Delta \epsilon_{\alpha} = [\epsilon_{\alpha}(H) - \epsilon_{\alpha}(0)] / \epsilon_{\alpha}(0) = \Delta P_{\alpha}^2(H). \quad (16)$$

A weak magnetocapacitive effect is therefore predicted in experiments at low temperatures. Note that in the above expression we would expect a small suppression in the permittivity for magnetic fields in the $a$-$b$ plane.

The observation of relaxor ferroelectricity in underdoped LCO has been argued to originate from the formation of polar nanoregions (PNRs) around the nonstoichiometric oxygen dopants. The formation of PNRs and the mechanism by which they condense into a ferroelectric phase is a well studied topic. Though the relaxor physics in LCO naturally relates to the presence of dopants, the extremely low concentration of excess oxygen in the samples used in Ref. 5 may imply the presence of additional mechanisms for the PNRs to couple and undergo a spontaneous transition to long-range ferroelectric order. One may speculate that such mechanisms include subtle noncentrosymmetric structural distortions in the host lattice and/or a tendency for the dopants to cluster and thereby reduce the inter-PNR distance. As shown in Fig. 4, in magnetic materials such as LCO the PNRs may also cause a distorted spin structure that could lead to a magnetoelastic effect through, e.g., geometric frustrations in the presence of a DM interaction and/or indirectly through coupling to strains. This physics has similarities to the observation of magnetoelastic behavior in a number of other relaxor ferroelectrics.

In summary, we have shown that the magnetoelastic effect in extremely underdoped La$_2$CuO$_{4-\delta}$ can be explained by biquadratic terms in the free energy. It is proposed that the microscopic origin of the ferroelectricity is caused by polar nanoregions generated by dopant ions. The discovery of ferroelectricity and a magnetoelastic effect in the cuprate materials due to charge carrier doping has sparked many questions for future studies. In particular, what happens at higher doping levels and what is the fate of the PNRs in the regime where the pseudogap and superconducting phases emerge?

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The coefficients in $F_M$ are $\chi_0 = 5.625 \times 10^{-4}$ cm$^3$/mol, $C\chi_0 = 1.88 \times 10^{-3}$, $C_2\chi_0 - J_z = -4.4 \mu$eV, $a = 2.4 \times 10^{-3}/(C\chi_0)^2$ eV/(emu)$^2$, $b = 10^{-3}/(C\chi_0)^4$ eV/(emu)$^2$.


