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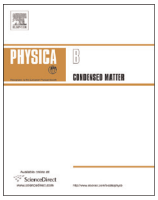

Tilted loop currents in cuprate superconductors

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ABSTRACT

The paper briefly surveys theoretical models for the polar Kerr effect (PKE) and time-reversal symmetry breaking in the pseudogap phase of cuprate superconductors. By elimination, the most promising candidate is the tilted loop-current model, obtained from the Simon–Varma model by tilting one triangular loop up and another one down toward the apical oxygens. The model is consistent with the PKE, spin-polarized neutron scattering, and optical anisotropy measurements. Spontaneous currents in this model flow between the in-plane and apical oxygens in such a manner that each oxygen belongs to one current loop. This loop-current pattern is similar to the spin order in the magnetoelectric antiferromagnet Cr_2O_3, where the PKE is observed experimentally. By analogy, it should be possible to train the PKE sign in the cuprates magnetoelectrically. Several experiments are proposed to confirm the loop-current order: the magnetic-field-induced polarity, the nonlinear anomalous Hall effect, and the second-harmonic generation.

1. Introduction

Experiments indicate that various symmetries are broken in the pseudogap phase of cuprate superconductors and several phase transitions separate it from the high-temperature metallic phase (see, e.g., Fig. 1 in [1]). One of these broken symmetries is the time-reversal symmetry (TRS). Spontaneous time-reversal symmetry breaking (TRSB) in cuprates was first proposed in the anyon superconductivity model [2–4]. However, this model was discarded after negative experimental results for the Faraday effect in transmission [5] and the polar Kerr effect (PKE) in reflection [6] of light. Eventually, the PKE was observed in the pseudogap phase with improved sensitivity of the specially designed Sagnac interferometer [7–11]. The PKE in the cuprates appears well above the superconducting transition temperature and, apparently, is unrelated to superconductivity, unlike in the low-temperature superconductors Sr_2RuO_4 [12] and UPt_3 [13].

The PKE is routinely observed in ferromagnets, so its observation in the pseudogap phase of the cuprates was initially interpreted as evidence for a ferromagnetic-like order parameter, which breaks macroscopic TRS. However, this interpretation faces difficulties, particularly in the view of the most recent measurements [11]. The PKE is expected to have *opposite* signs for light reflection from the opposite surfaces of a sample, because the ferromagnetic vector points into the sample for one surface and out of the sample for another surface. However, the *same* sign of the PKE was observed in [11]. Moreover, it should be possible to control the PKE sign by going through the TRSB phase transition in the presence of an external magnetic field, as demonstrated in other materials [12,13]. However, it was found that such “training” is extremely difficult [7] or impossible [10,11] to achieve in the cuprates.

These observations argue against macroscopic, ferromagnetic-like TRSB. But the Sagnac interferometer is specifically designed to detect non-reciprocity in the normal reflection from a sample, which, according to Onsager's principle, is possible only if the TRS is broken. These statements can be reconciled within antiferromagnetic-like models, where the TRS is broken microscopically, but not macroscopically. In these models, local magnetic moments have opposite signs in two sublattices or within a unit cell, so the net ferromagnetic order parameter vanishes in the bulk, and the Faraday effect is absent in transmission of light. Nevertheless, the PKE in reflection is generally non-zero, because it is primarily determined by magnetic moments in the first surface layer, as pointed out in [4]. Magnetic moments of the opposite signs can be exposed at the opposite surfaces of a crystal, resulting in the PKE the *same* sign upon reflections from these surfaces, in agreement with [11]. Moreover, since the antiferromagnetic order parameter does not couple directly to an external magnetic field, training would be impossible or very difficult.

A symmetry analysis of whether the PKE is zero or non-zero in various antiferromagnetic models was presented by Orenstein [14]. Since antiferromagnetic ordering of atomic magnetic

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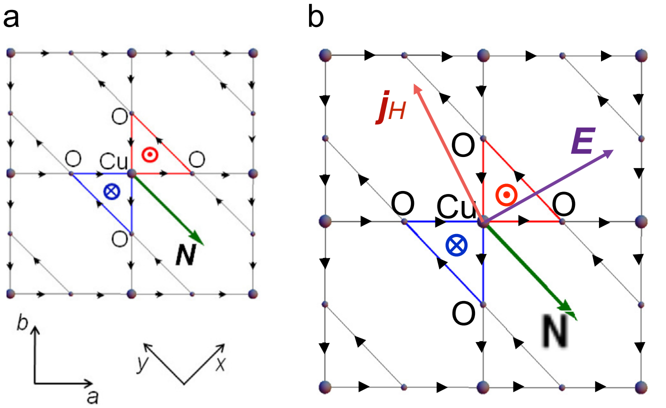

Fig. 1. (a) Loop-current order in a CuO_2 plane [15]. Black arrows show directions of microscopic persistent currents between copper and oxygen atoms. Green arrow shows the anapole moment $\boldsymbol{N}$. (b) The nonlinear anomalous Hall effect, where the in-plane Hall current $\boldsymbol{j}^H \propto \boldsymbol{E}\times[\boldsymbol{E}\times\boldsymbol{N}]$ is perpendicular to the applied in-plane electric field $\boldsymbol{E}$, but is proportional to the second power of $\boldsymbol{E}$. (For interpretation of the references to color in this figure caption, the reader is referred to the web version of this article.)

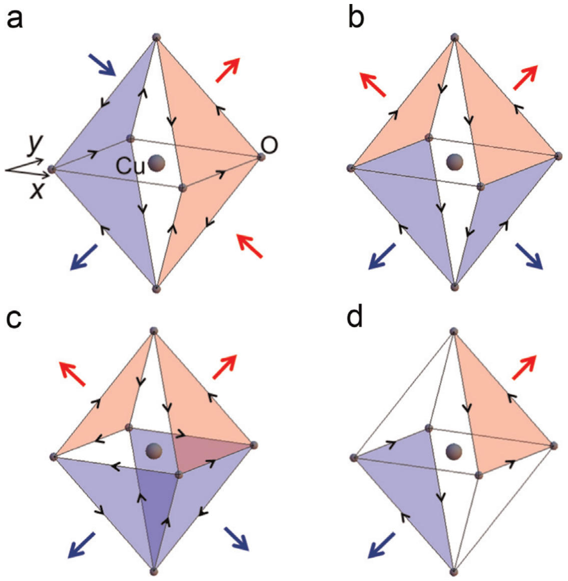

Fig. 2. Out-of-plane loop-currents models: (a) the model proposed in [21]; (b) the model proposed in [14] and shown in (a) there; (c) the model proposed in [14], but not shown there; (d) the titled loop-current (TLC) model proposed in Fig. 4) of [24]. The red and blue arrows represent orbital magnetic moments with positive and negative z components, respectively. (For interpretation of the references to color in this figure caption, the reader is referred to the web version of this article.)

moments in the undoped phase is destroyed in the pseudogap phase, we focus on spontaneous orbital electric currents. A much-discussed model of such loop currents was proposed by Simon and Varma [15]. This model is illustrated in Fig. 1(a), where the currents flow between the copper and oxygen atoms in the CuO_2 plane along triangular loops. The orbital magnetic moments of the two loops have opposite directions along the z ($\boldsymbol{c}$) axis perpendicular to the plane, so this is an orbital antiferromagnet with intra-unit-cell magnetic moments. Substantial experimental support for this model was found in spin-polarized neutron scattering [16–20]. These experiments also indicate that the net magnetic moment is zero, thus arguing against a ferromagnetic-like order parameter. However, it was shown in [14] by symmetry analysis that the model [15] gives zero PKE. Moreover, while the neutron scattering experiments do observe opposite magnetic moments inside the unit cell, these magnetic moments are not perpendicular to the CuO_2 plane, but are tilted by a substantial angle of the order of 45°.

In order to explain the tilt of the magnetic moments, a modified model with out-of-plane loop currents was proposed in [21] and also discussed in [17] in the context of $HgBa_2CuO_{4+\delta}$. This monolayer tetragonal material, where copper is surrounded by a octahedron of six oxygens, is conceptually the simplest and, thus, the most instructive to study [18]. In the model of [21], shown in Fig. 2(a), the currents flow between the in-plane and the out-of-plane apical oxygen atoms located above and below the copper atom. This structure can be obtained by duplicating the pattern shown in Fig. 1(a) and then buckling one copy up and another copy down. In Fig. 2, the shading color, red or blue, of the triangular loops represents positive or negative projections of their magnetic moments onto the z axis. However, it was shown in [14] by symmetry analysis that Fig. 2(a) also gives zero PKE. It is also the case for an alternative proposal [22] to explain the tilt of magnetic moments by a quantum superposition of the states in Fig. 1(a) with four different orientations.

In order to obtain a non-zero PKE, two other out-of-plane loop structures were proposed in [14] and are shown in Fig. 2(b) and (c). Fig. 2(b) can be obtained from Fig. 2(a) by reversing the upper-left and lower-right loop currents, so that all magnetic moments point out of the octahedron formed by oxygen atoms. Fig. 2(c) can be obtained from Fig. 2(b) by rotating the bottom loop currents by 90° around the vertical z axis. It was argued in [14] that both Figs. 2(b) and (c) give non-zero PKE. However, they do not agree with the neutron scattering data [23]. When Fig. 2(c) is viewed along the z axis, i.e. projected onto the CuO_2 plane, the z components of the magnetic moments form a d-wave pattern with alternating signs $\begin{smallmatrix}+&-\\-&+\end{smallmatrix}$ in the four quadrants of the ($\boldsymbol{a}$, $\boldsymbol{b}$) plane [15], which does not agree with the neutron scattering. When Fig. 2(b) is viewed along the z axis, the z components of magnetic moments cancel out, and only in-plane components remain, in disagreement with the neutron scattering.

Yet another model, shown in Fig. 2(d), was discussed in [24]. This structure can be obtained from Fig. 1(a) by tilting one triangular loop up and another triangular loop down. Thus, I refer to this structure as the tilted loop-current (TLC) model. Each oxygen atom belongs to only one current loop in Fig. 2(d), whereas the apical oxygens are shared between two current loops in the other panels of Fig. 2. Fig. 2(d) can be thought of as a superposition of Figs. 2(a) and (b), where the upper-left and lower-right magnetic moments cancel out. Since Figs. 2(a) and (b) produce zero and non-zero PKE respectively, their superposition in Fig. 2(d) produces non-zero PKE. Fig. 2(d) is reasonably consistent with neutron scattering [23,24].

Moreover, Fig. 2(d) agrees with the observation in [25] that the in-plane principal optical axes are slightly rotated away from the crystallographic axes $\boldsymbol{a}$ and $\boldsymbol{b}$. For a tetragonal crystal where the $\boldsymbol{a}$ and $\boldsymbol{b}$ axes are equivalent, the loop currents produce anisotropy between the x and y directions indicated in Fig. 1(a), so the principal optical axes are along the $\boldsymbol{a}+\boldsymbol{b}$ and $\boldsymbol{a}-\boldsymbol{b}$ directions. This was shown in [26] by calculating the renormalized dielectric susceptibility to the second order in the loop-current order parameter $\boldsymbol{N}$. In addition, many cuprate materials have anisotropy between the $\boldsymbol{a}$ and $\boldsymbol{b}$ axes, either because of nematicity [1,27] or the crystal structure of YBCO. A combination of the $\boldsymbol{a}$ vs. $\boldsymbol{b}$ and $\boldsymbol{a}+\boldsymbol{b}$ vs. $\boldsymbol{a}-\boldsymbol{b}$ anisotropies results in an intermediate orientation of principal axes away from the crystal axes.

In conclusion, among the loop-current models discussed above, only the TLC model shown in Fig. 2(d) is simultaneously consistent with the PKE, neutron, and optical anisotropy experiments. However, all loop-current models are expected to produce non-zero magnetic fields at barium and oxygen sites [28], whereas NMR measurements [29–31] find no such fields. This discrepancy