Re-examining evidence for time-reversal symmetry breaking (TRSB) in cuprates

TRSB or not TRSB?
That is the question!

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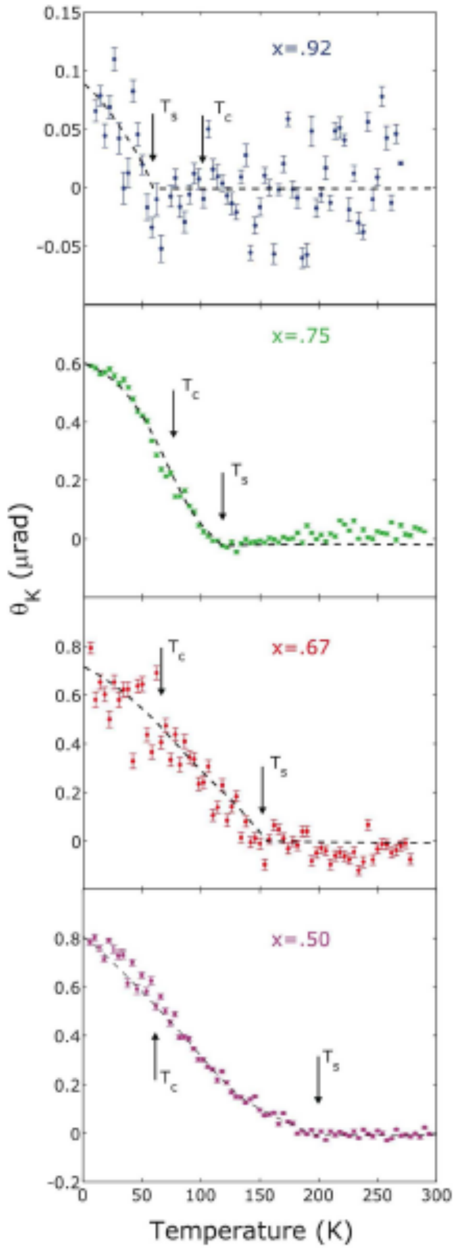
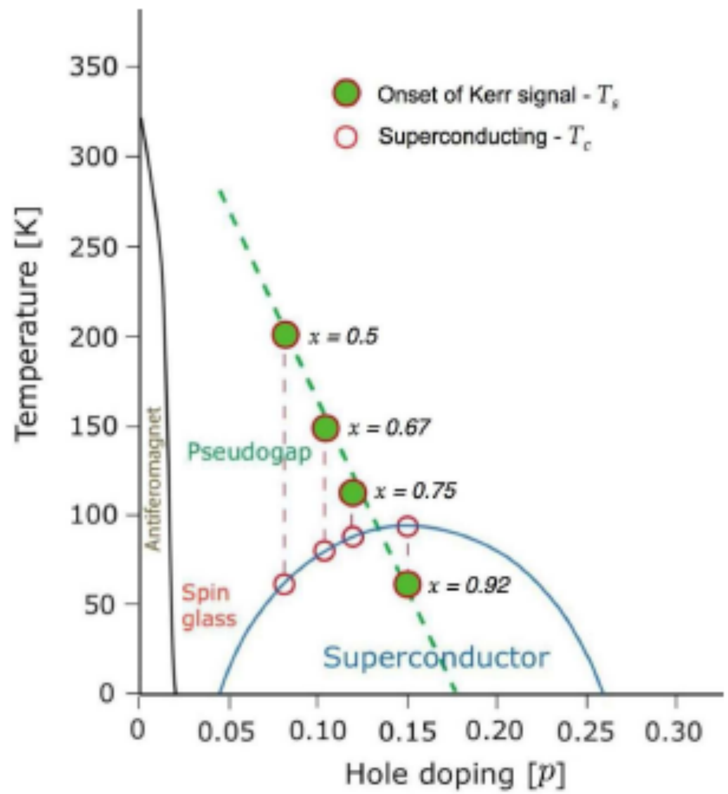
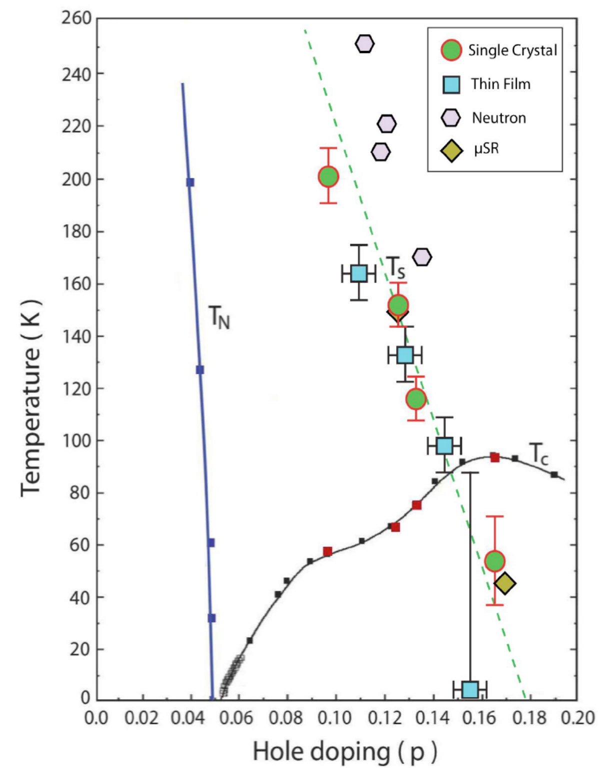
Experimental observation of the polar Kerr effect in underdoped cuprates $YBa_2Cu_3O_{6+x}$





Xia at al., *PRL* **100**, 127002 (2008)



Kapitulnik *et al.*, *New J Phys* **11**, 055060 (2009)

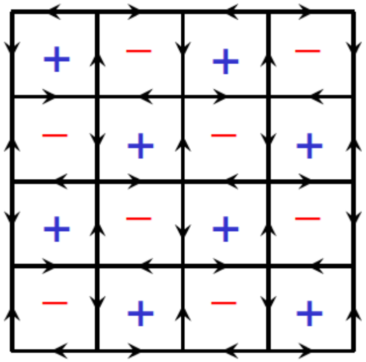
Kerr effect indicates spontaneous symmetry breaking and a phase transition in underdoped cuprates, unrelated to superconductivity, but related to pseudogap.

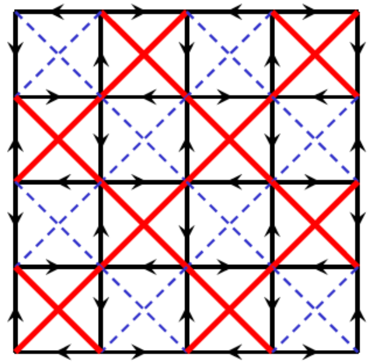
Initial interpretation:
Kerr effect = macroscopic TRSB

Theoretical scenario by Tewari, Zhang, Yakovenko, & Das Sarma, *PRL* **100**, 217004 (2008), based on Yakovenko, *PRL* **65**, 251 (1990):

$d_{xy}+id_{x^2-y^2}$ density wave with $\boldsymbol{Q}$=(1/2,1/2)

$id_{x^2-y^2}$ density wave: staggered currents along bonds





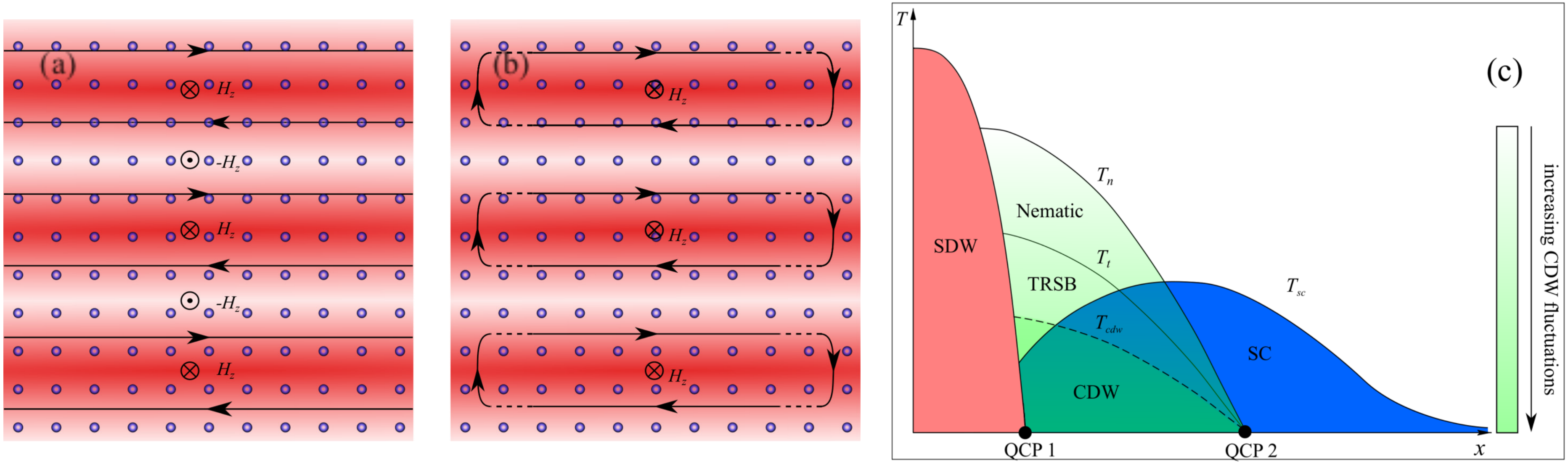
$d_{xy}+id_{x^2-y^2}$ density wave: modulation of plaquettes

The $d_{xy}+id_{x^2-y^2}$ density wave model

- breaks macroscopic time-reversal symmetry
- has non-zero Berry curvature
- exhibits anomalous (sponaneous) Hall effect with $\sigma_{xy}\neq0$
- shows polar Kerr effect with $\theta_K\neq0$

Charge-density wave with staggered currents

Wang and Chubukov, *PRB* **90,** 035149 (2014)



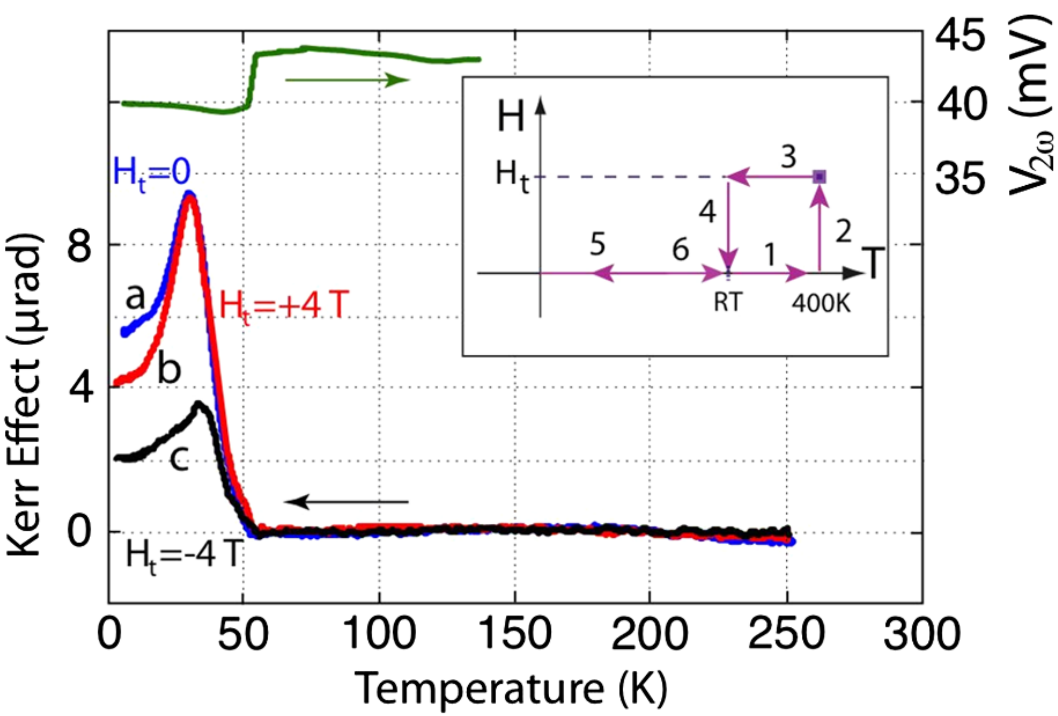
Anomalous Hall conductivity and Kerr effect due to

- Impurities: Wang, Chubukov, Nandkishore, *PRB* **90**, 205130 (2014)
- Berry curvature: Gradhand, Eremin, Knolle, *PRB* **91**, 060512 (2015)

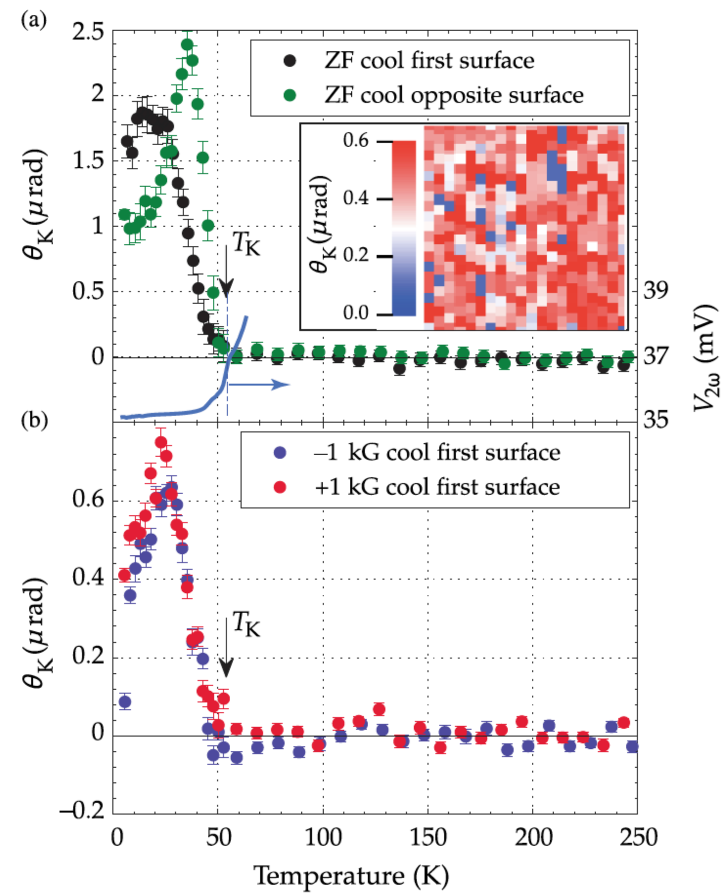
New developments: Karapetyan *et al.* *PRL* **109**, 147001 (2012), *PRL* **112**, 047003 (2014)

- Sign of θ_K cannot be trained by a magnetic field
- Sign of θ_K is the same on the opposite surfaces
- θ_K changes linearly with applied uniaxial strain

Conclusion: not TRSB!



$La_{1.875}Ba_{0.125}CuO_4$



Circular dichroism due to spatial dispersion if inversion and mirror symmetries are broken (chirality or natural optical activity)

$$\varepsilon_{\alpha\beta}(\omega,\mathbf{k}) = \varepsilon_{\alpha\beta}(\omega,0) + \gamma(\omega)\varepsilon_{\alpha\beta\delta}k_\delta + O(k^2),$$ $\gamma(\omega)$ is a pseudoscalar

Proposals for Kerr effect due to chiral order without TRSB:

- Arfi & Gor'kov, *PRB* **46**, 9163 (1992):
  Broken inversion symmetry
- Hosur, Kapitulnik, Kivelson, Orenstein, Raghu, *PRB* **87**, 115116 (2013):
  Various density-wave chiral structures
- Orenstein & Moore, *PRB* **87**, 165110 (2013):
  Berry curvature
- Mineev, *PRB* **88**, 134514 (2013):
  Noncentrosymmetric media with spin-orbit
- Pershoguba, Kechedzhi, & Yakovenko, *PRL* **111**, 047005 (2013): Helical texture of loop currents

By Onsager's reciprocity principle, reflection matrix is symmetric for a time-reversal system, so the Kerr effect must vanish and cannot be obtained due to chiral order

- Bert Halperin, *High-T_c Proceedings* (1992)
- Peter Armitage, *PRB* **90**, 035135 (2014)
- Alex Fried, *PRB* **90**, 121112 (2014)

Retractions of claims for Kerr effect due to chiral order

- Mineev and Yoshioka, *PRB* **89**, 139902 (2014)
- Hosur, Kapitulnik, Kivelson, Orenstein, Raghu, Cho, Fried, *PRB* **91**, 039908 (2015)
- Pershoguba, Kechedzhi, and Yakovenko, *PRL* **113**, 129901 (2014)

Different forms of constituent relations with surface terms:

$4\pi \boldsymbol{P} = \gamma \boldsymbol{\nabla} \times \boldsymbol{E}$ - incorrect

$4\pi \boldsymbol{P} = \boldsymbol{\nabla} \times (\gamma \boldsymbol{E}) = \gamma \boldsymbol{\nabla} \times \boldsymbol{E} + (\boldsymbol{\nabla}_z \gamma) \times \boldsymbol{E}$ - incorrect

$4\pi \boldsymbol{P} = \gamma \boldsymbol{\nabla} \times \boldsymbol{E} + (1/2)(\boldsymbol{\nabla}_z \gamma) \times \boldsymbol{E}$ - correct, zero Kerr effect

“Multipole Theory in Electromagnetism”

by R. E. Raab and O. L. de Lange
(Oxford University Press, 2005)

Electric dipole density

$$P_\alpha = (\kappa_{\alpha\beta} - \cancel{i\kappa'_{\alpha\beta}})E_\beta + \frac{1}{2}(\cancel{a_{\alpha\beta\gamma}} - ia'_{\alpha\beta\gamma})\nabla_\gamma E_\beta + (G_{\alpha\beta} - \cancel{iG'_{\alpha\beta}})B_\beta$$

Magnetic dipole density

$$M_\alpha = (G_{\beta\alpha} + \cancel{iG'_{\beta\alpha}})E_\beta$$

Electric quadrupole density

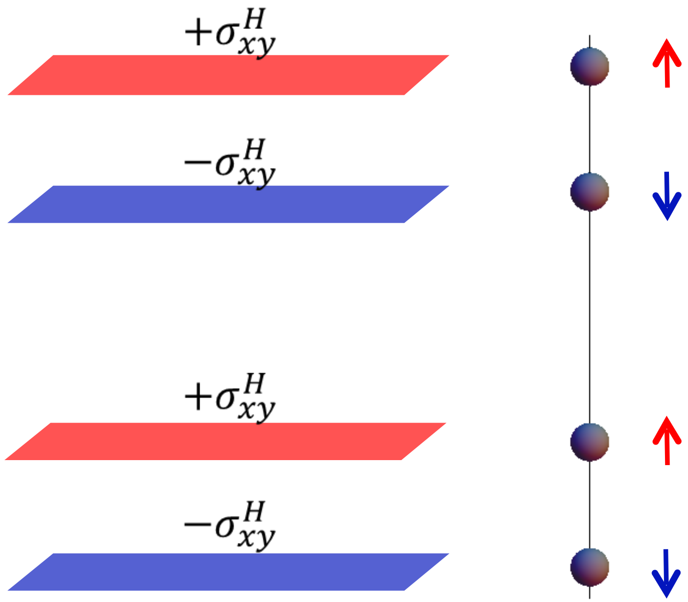
$$Q_{\alpha\beta} = (\cancel{a_{\gamma\alpha\beta}} + ia'_{\gamma\alpha\beta})E_\gamma$$

The primed functions are odd with respect to time reversal

Electric current density

$$J_\alpha = \dot{P}_\alpha - \frac{1}{2}\nabla_\beta \dot{Q}_{\alpha\beta} + \epsilon_{\alpha\beta\gamma}\nabla_\beta M_\gamma$$

Microscopic TRSB & Kerr effect in antiferromagnets



Dzyaloshinskii *Phys Lett A* **155**, 62 (1991)

Cr_2O_3

Magnetoelectric effect in Cr_2O_3

$$F = c_1 E_z B_z + c_2 (E_x B_x + E_y B_y)$$

predicted by Dzyaloshinskii *Sov. Phys. JETP* **10**, 628 (1960)
observed by Astrov *Sov. Phys. JETP* **11**, 708 (1960)

Kerr effect in Cr_2O_3

predicted by Hornreich and Shtrikman, *PR* **171**, 1065 (1968)
observed by Krichevtsov et al. *J Phys Cond Mat* **5**, 8233 (1993)

- Same sign of the Kerr effect on the opposite surfaces
- Magnetoelectric training by applying ***E*** and ***B***

Measurements of the Kerr effect in Cr_2O_3

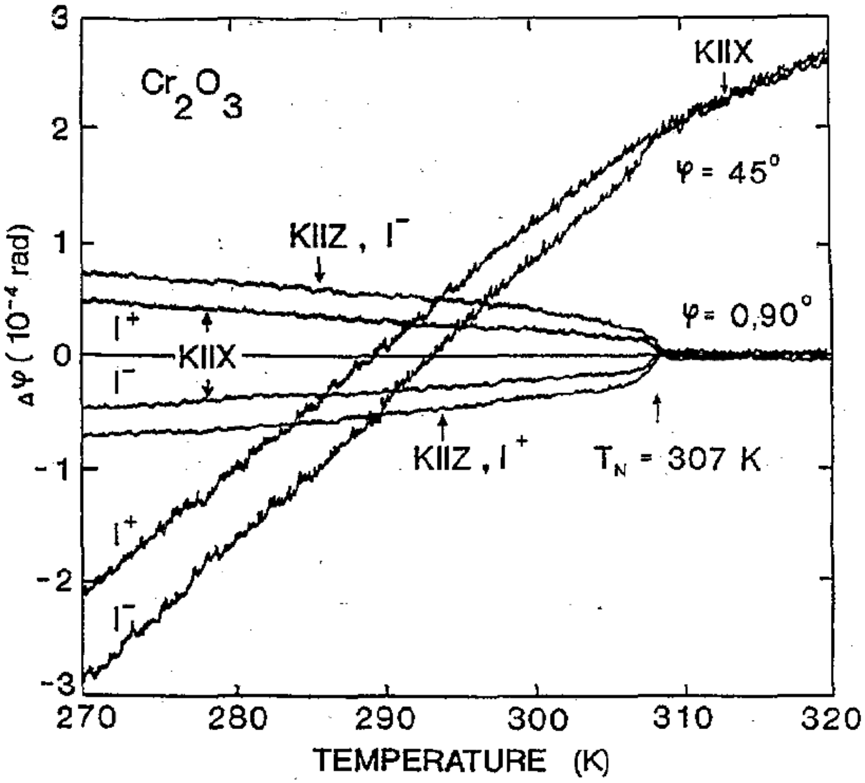
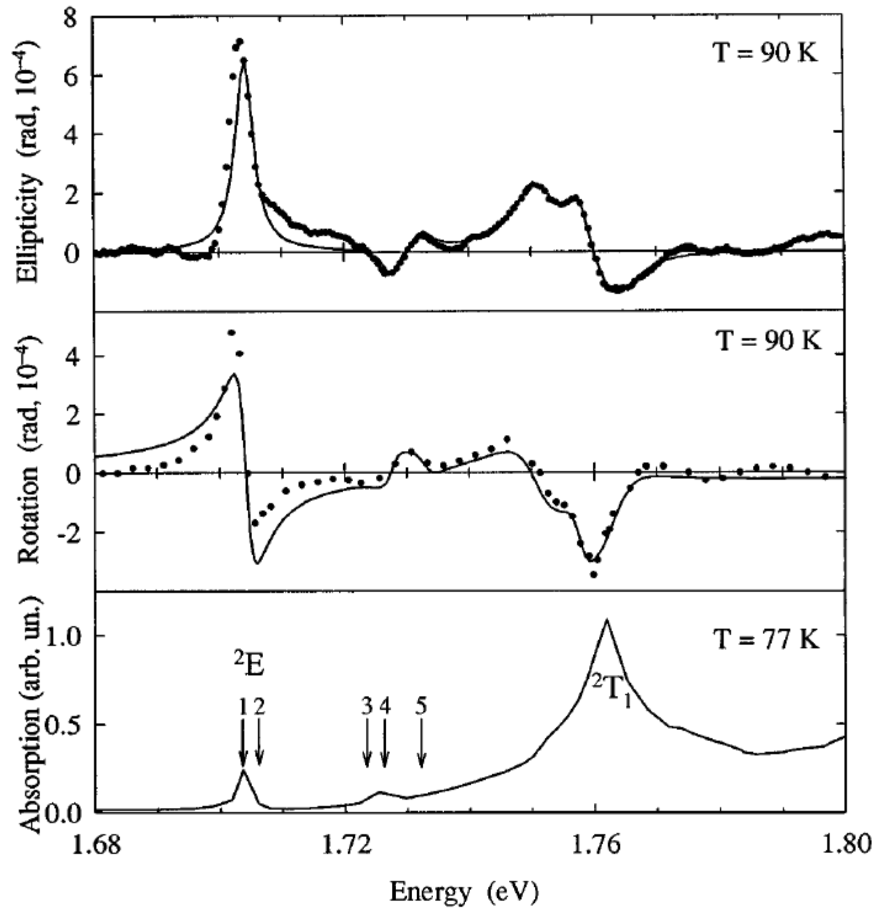


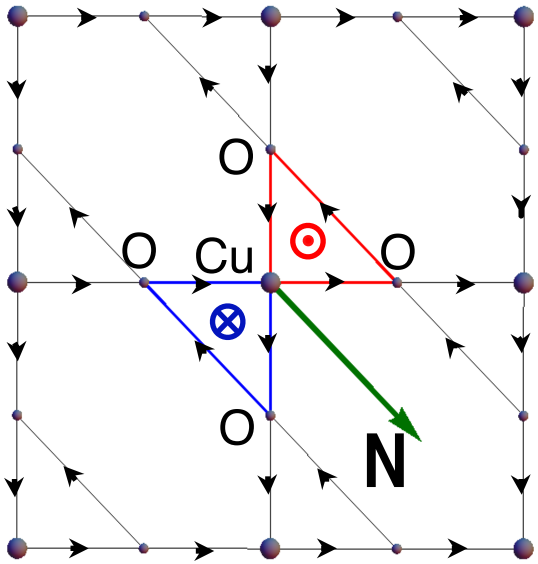
Figure 1. The NR rotation $\Delta\varphi$ versus temperature in two antiferromagnetic states l^+ and l^- and for two principal orientations of the wavevector k of the incident–reflected light wave.

Krichevtsov *et al.*
J Phys Cond Mat
5, 8233 (1993)



Krichevtsov *et al.*
PRL **76**, 4628 (1996)

Varma's loop currents



Anapole moment

$$\mathbf{N} = \int [\mathbf{r} \times \mathbf{m}(\mathbf{r})] d^2 r$$

Symmetries:

Time-reversal odd

Inversion odd

Magneto-electric effect

$$S[\mathbf{E},\mathbf{B}] = \int \beta(\omega)\, \mathbf{N}[\mathbf{E} \times \mathbf{B}]$$

Electric polarization

$$\mathbf{P} = \frac{\delta S}{\delta \mathbf{E}} = \beta[\mathbf{B} \times \mathbf{N}]$$

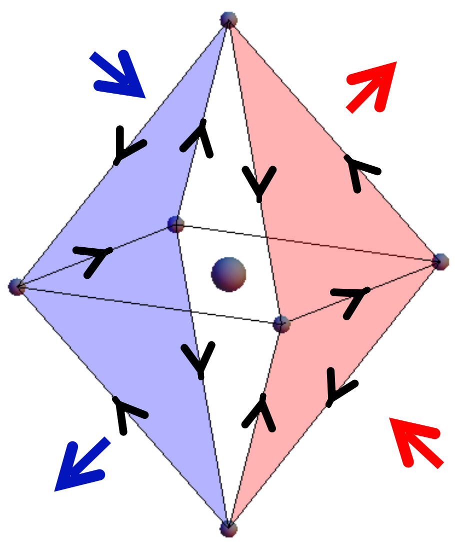
Magnetization

$$\mathbf{M} = \frac{\delta S}{\delta \mathbf{B}} = \beta[\mathbf{N} \times \mathbf{E}]$$

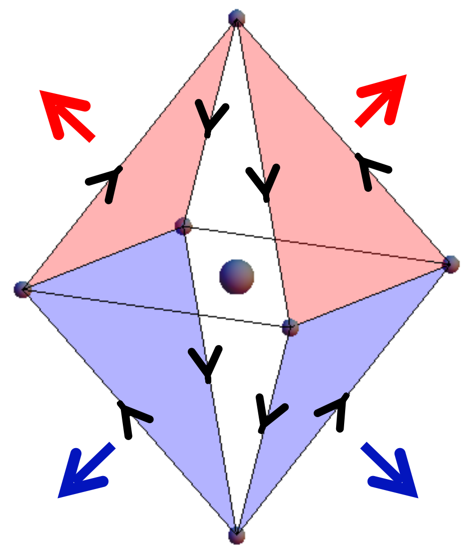
In-plane electric field → Out-of-plane magnetization

Out-of-plane magnetic field → In-plane polarization

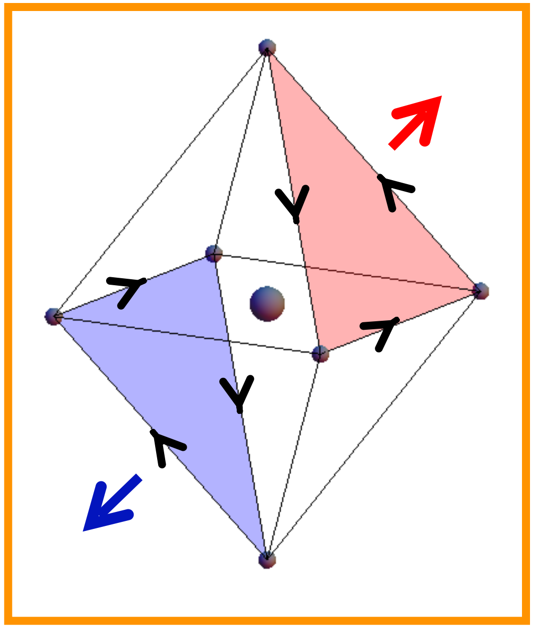
Tilted loop current models for cuprates



Weber et al. *PRL* **102,** 017005 (2009) gives $\theta_K=0$, no Kerr effect



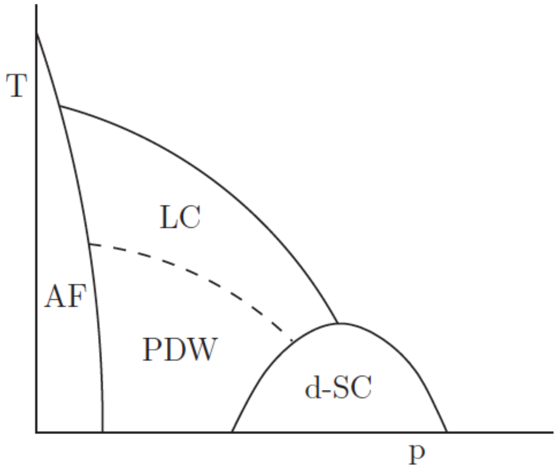
Orenstein, *PRL* **107**, 067002 (2011) $\theta_K\neq0$ but disagrees with neutrons

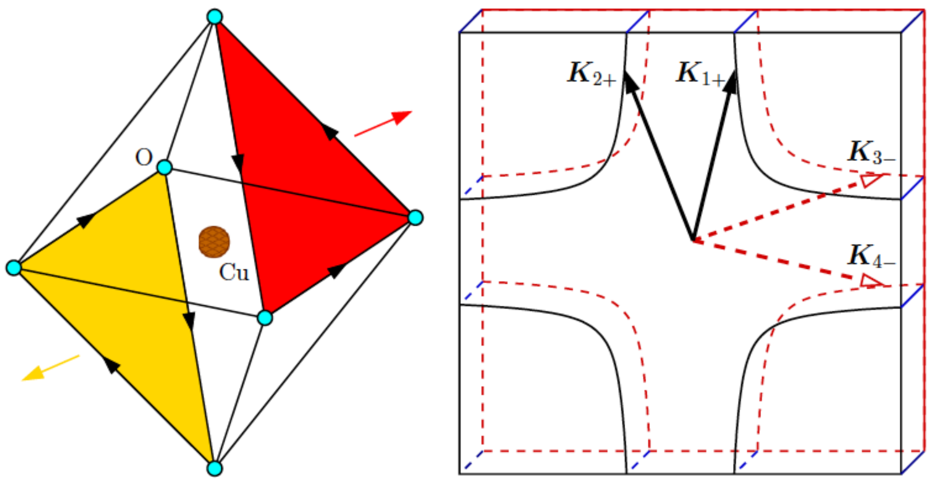


Yakovenko *Physica B* (2015) Yuan Li, *PhD thesis* 2010 $\theta_K\neq0$, agrees with neutrons

Emergent loop current (LC) order from pair density wave (PDW) superconductivity

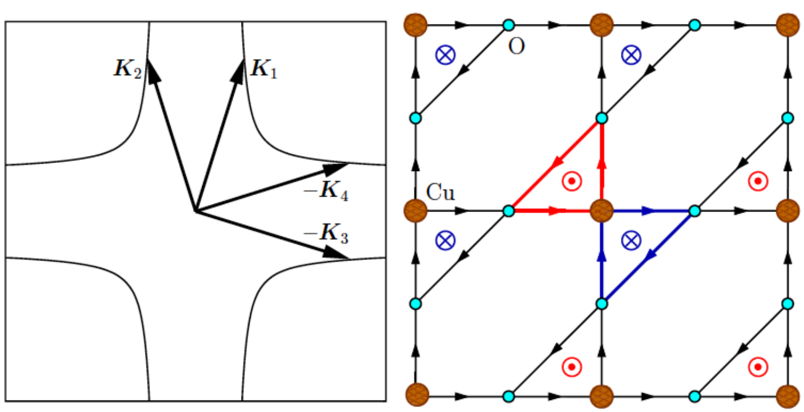
Agterberg *et al.* *PRB* **91**, 054502 (2015)





(a) (b)

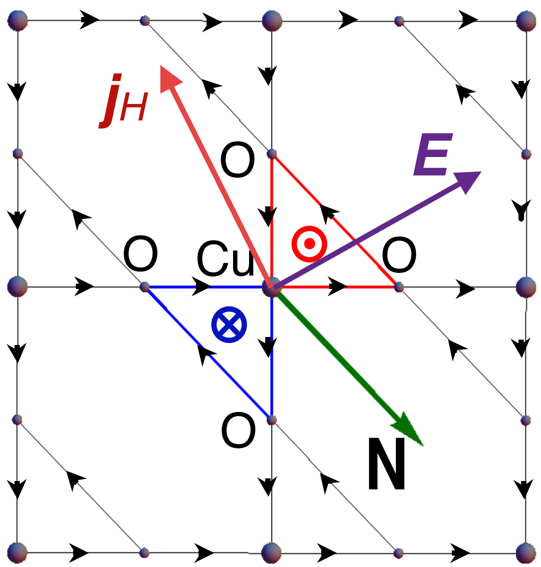
FIG. 5. (Color online) (a) Tilted loop current state proposed by Yakovenko [26]. The arrows on the bonds depict the direction of the current, the longer arrows depict the associated magnetic moments. (b) PDW state with the same symmetry properties as the tilted loop current state. The arrows $\boldsymbol{K}_i$ depict the nonzero components of the PDW order parameter. Wave vectors labeled "+" are above the x-y plane and those labeled "−" are below the x-y plane.



Experimental proposals

Magnetic-field-induced polarity to be observed by STM

Nonlinear Hall effect [Gao, Yang, Niu, *PRL* **112**, 166601 (2014)]



In Varma's model, an in-plane electric field $\boldsymbol{E}$ induces an out-of-plane magnetic field

$$\boldsymbol{B}_{\rm eff} \propto \beta[\boldsymbol{E} \times \boldsymbol{N}]$$

E and $B_{\rm eff}$ produce an in-plane Hall current

$$\boldsymbol{j}_H \propto [\boldsymbol{E} \times \boldsymbol{B}_{\rm eff}] \propto \beta \boldsymbol{E} \times [\boldsymbol{E} \times \boldsymbol{N}]$$

Possible experimental manifestations:

(1) dc Hall current proportional to the intensity of ac radiation:

$$\boldsymbol{j}_H(\mathrm{dc}) \propto \boldsymbol{E}(\omega) \times [\boldsymbol{E}(-\omega) \times \boldsymbol{N}]$$

(2) Second harmonic generation: $\boldsymbol{j}_H(2\omega) \propto \boldsymbol{E}(\omega) \times [\boldsymbol{E}(\omega) \times \boldsymbol{N}]$

Permitted because Varma's model breaks inversion and time reversal

Second harmonic generation and visualization of AFM domains in Cr_2O_3

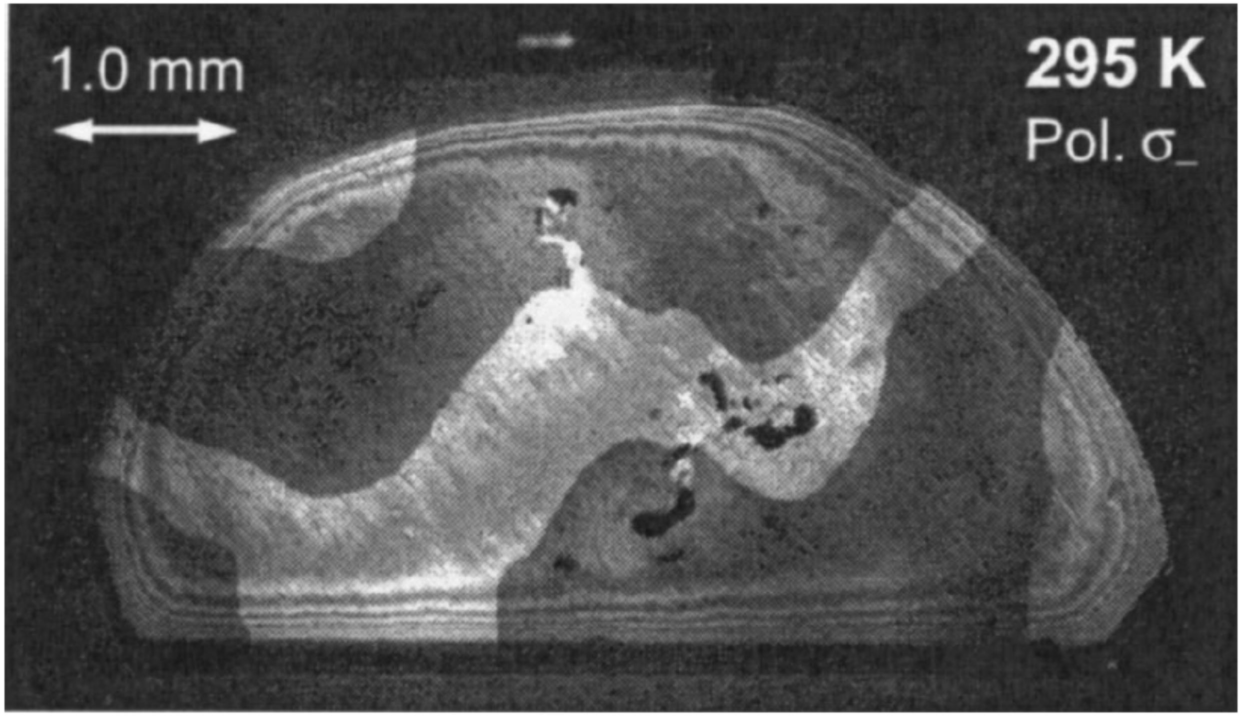


Fig. 6. Antiferromagnetic 180° domains in Cr_2O_3 exposed to circularly polarized light for SHG at 2.1 eV. Exposure time was 35 min but was reduced to 1–5 min in subsequent experiments.

Fiebig et al. *J Opt Soc Am. B* **22**, 96 (2005)

Summary: Yakovenko, *Physica B* **460**, 159 (2015)

The tilted loop current model for cuprates explains

- Kerr effect of the same sign on the opposite surfaces
- No magnetic-field training, but proposes magneto-electric one
- Tilted intra-unit-cell magnetic moments observed by neutrons
- Optical axes rotation away from ***a*** and ***b***,
  Lubashevsky et al. *PRL* **112**, 147001 (2014)

Proposed experiments for inversion and time reversal breaking

- Magnetic-field-induced polarity in STM
- Nonlinear Hall effect:
  - Second-harmonic generation
  - Photogalvanic effect, dc current proportional to ac intensity

Surprising connection with experiments in Sr_2IrO_4 by D. Hsieh

Not explained

- The absence of local magnetic field on apical oxygen in NMR