Time Reversal Symmetry, Gyrotropy, and Topological Superconductors:

with:

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Also: Steve Kivelson, Sri Raghu, Pavan Hosur (Stanford) – Theory, coffee, etc. Z.-X. Shen's group – ARPES on Bi:2201 Marty Fejer (Stanford) – Sagnac design

and:

D. Bonn, W. Hardy R. Liang (UBC) - YBCO single crystals
G. Deutscher (TAU) - YBCO films
R. Hammond, G. Koster, W. Siemons (Stanford) - YBCO films
G. Gu, J. Tranquada, M. Hucker (BNL) - LBCO crystals
H. Eisaki (Tsukuba, Japan) - Pb-doped BSCO crystals
M. Greven, N. Barisic (U. Minnesota) - Hg:1201 crystals
C. Felser (MPI Dresden) - YPtBi crystals
E. Bauer (LANL) - URu₂Si₂ crystals
W. Halperin (Northwestern) - UPt3

Supported by DOE





Topological Superconductors

Insulators and Superconductors

There is a direct analogy between superconductors and insulators because the Bogoliubov-de Gennes (BdG) Hamiltonian for the quasiparticles of a superconductor is analogous to the Hamiltonian of a band insulator, with the superconducting gap corresponding to the band gap of the insulator.

Similar to a topological insulator (insulator with a gapless edge state), we can also find topological superconductors with two varieties:

- I. Time Reversal Symmetry Breaking topological superconductors (Chiral Superconductor)
- II. Time Reversal Symmetry Invariant topological superconductors (Helical Superconductor)

The band gap of the topological insulator is replaced by a superconducting gap in the bulk of the material.

I. Time Reversal Symmetry Breaking topological Insulators



II. Time Reversal Symmetry Invariant topological Insulators



I. Time Reversal Symmetry Breaking topological superconductors (Chiral Superconductors)



II. Time Reversal Symmetry Invariant topological superconductors (Helical Superconductors)



For the SC the edge states are replaced by Majorana states.

Proposals to realize Topological Superconductors

- I. Time Reversal Symmetry breaking topological superconductors
- 1. See e.g. N. Read, and D. Green, Phys. Rev. B 61, 10 267 (2000). p+ip superconductor such as Sr₂RuO₄
- 2. J.D. Sau, R. M. Lutchyn, S. Tewari, and S. Das Sarma, Phys. Rev. Lett. 104, 040502 (2010).

Proximity effect to a semiconductor where also inducing TRS breaking by using exchange coupling to a ferromagnetic insulating layer.

- II. Time Reversal Symmetry Invariant topological superconductors
- 1. L. Fu, and C. L. Kane, Phys. Rev. Lett. 100, 096407 (2008). Proximity effect to the surface states of **3D** topological insulators.
- X.-L. Qi, T. L. Hughes, and S.-C. Zhang, Phys. Rev. B 82,184516 (2010). Proximity effect to a 2D QAH insulator.

We will be interested in detecting some of the hallmark properties of unconventional, and topological superconductors.

in particular:

- Time Reversal Symmetry Breaking
- Chirality

Remember anyons.....

Remember anyons.....

Proposed Experiments to detect TRSB in anyon SC:

Muon Spin Rotation:

Measures Local magnetic field created by impurities or domain walls that reveal the underlying TRSB state.

Proposal: B. I. Halperin, J. March-Russell, and F. Wilczek, Phys. Rev. B40, 8726 (1989).

Spontaneous Hall Effect

Measures the existence of transverse voltage due to internal magnetic field. Equivalent also to spontaneous edge currents.

 $\frac{D_z}{M_z = 0}$ $\frac{M_z = 0}{B_z = 0}$

Proposal: H. Chen, B.I. Halperin, F. Wilczek and E. Witten, Int. J. Mod. Phys. B3, 1001 (1989).

Magneto-Optic Effects (Kerr, Faraday, Dichroism)

Measures off-diagonal terms in the optical conductivity as signatures

of TRSB.

VOLUME 62, NUMBER 24 PHYSICAL REVIEW LETTERS 12 JUNE 1989

Effective Theory of the T- and P-Breaking Superconducting State

X. G. Wen and A. Zee Institute for Theoretical Physics, University of California, Santa Barbara, California 93106 (Received 30 January 1989)

We propose an effective theory of superconductivity based on a microscopic theory of the *T*- and *P*-breaking spin-liquid state. There are two independent gauge invariances broken by two separate condensates. The theory may be useful for phenomenological calculations. In particular, we find that the H_{c1} are different for magnetic fields with opposite orientations. We also find that the polarization of an electromagnetic wave is rotated after reflection from these *T*- and *P*-breaking superconductors.

Proposal: X. G. Wen and A. Zee, Phys. Rev. Lett. **62**, 2873 1989; Phys. Rev. B **43**, 5595 1991.



Magneto-optics, Time Reversal Symmetry, and Gyrotropy



Because of the axial symmetry, the index of refraction for right (R) and left (L)circularly polarized light is related to the complex optical conductivity by:

$$\begin{split} \epsilon_{R,L} &= \tilde{n}_{R,L}^2 = (n_{R,L} + i\kappa_{R,L})^2 = 1 + i\frac{4\pi\sigma_{R,L}}{\omega}; \ (\sigma_{R,L} = \sigma_{xx} \pm i\sigma_{xy}) \\ & \text{and} \ \tilde{n}_L \neq \tilde{n}_R \end{split}$$

L

/



But, in a time-reversal invariant homogeneous medium:

$$\epsilon_{ab}(\omega, \mathbf{k}) = \epsilon_{ba}(\omega, -\mathbf{k})$$

In the limit of $\,k
ightarrow 0\,$ (i.e. local limit), it is a symmetric tensor, and thus $heta_K = 0$.

However, any odd contribution in k to ε must be antisymmetric!

$$\epsilon_{ab}(\omega, \mathbf{k}) = \epsilon_{ab}(\omega) + i\gamma_{abc}(\omega)k_c + \dots$$

$$\epsilon_{ab}(\omega) = \epsilon_{ba}(\omega) \equiv \epsilon_{ab}(\omega, \mathbf{0})$$
 and $\gamma_{abc}(\omega) = -\gamma_{bac}(\omega)$
 $\gamma_{abc}(\omega)$ is called the **gyrotropic** tensor.

For a gyrotropic medium:
$$\tilde{n}_L \neq \tilde{n}_R$$

[Note that for any crystal with inversion symmetry, or if there is any reflection symmetry about one of the in-plane axes (e.g. \hat{a}), $\gamma_{abc}=0$.]

Kerr effect will be finite if in addition, the medium is dissipative!

Initial estimates of signal

We need an apparatus that can measure TRSB, and/or gyrotropy (which can be a consequences of the material being a topological superconductor.)

Estimate of the effect for a TRS-breaking superconductor:

$$\begin{array}{l} \text{Recall: } \theta_K = -\mathcal{I}m\left[\frac{\tilde{n}_L - \tilde{n}_R}{\tilde{n}_L \tilde{n}_R - 1}\right] \\ \text{Jsually: } \theta_K \approx \frac{4\pi}{n(n^2 - 1)\omega} \sigma_{xy}''(\omega) \qquad \text{Estimate: } \sigma_{xy}(\omega) \approx \frac{e^2}{h} \left(\frac{\Delta_0}{\hbar\omega}\right)^2 \end{array} \end{array}$$

With $n\sim 5$, Optical frequency of $\hbar\omega\sim 10^{15}$ Hz (λ =1.55µm), and $T_c\sim 1{
m K}$:

We calculate: $\theta_K \sim 200$ nanorad

This is a very small signal!

Requirements from apparatus:

- 1. Reject reciprocal effects, especially linear birefringence.
- Measure an absolute value of the Kerr effect, rather than a result of a modulated signal*.
- **3. Effect needs to be measured with high sensitivity** since the effect is expected to be very small (< 300 nanorad).

A simple cross polarization method will not be enough!



* When Searching for TRSB in superconductors modulation, such as magnetic-field, is NOT possible!

Apparatus



We use an apparatus that is based on the Sagnac interferometer

A Sagnac interferometer with no sample is completely reciprocal

Samples that violate reciprocity because of:

Time reversal symmetry breaking
 gyrotropy + absorption

Will exhibit a phase shift: $\Delta \phi = 2\theta_{\rm K}$

A Sagnac loop:

(use an optical fiber realization)



When a Sagnac loop is rotated, time-reversal symmetry is broken.



When a Sagnac loop is rotated, time-reversal symmetry is broken.



Sagnac loop and Berry Phase

The Berry phase provides a natural geometrical formalism that describes variations of the light polarization along the propagation trajectory!



The nonrelativistic Sagnac phase shift is: $\Delta\phi=rac{2\pi}{\lambda}rac{4}{c}\Omega\cdot A=rac{4}{\hbar c}(\hbar k)\Omega\cdot A$

Suppose we have charged matter in the circuit instead of light. The correspondence $\vec{\Omega} \longleftrightarrow \vec{B}$ (the magnetic field), can be used to show that the **Sagnac** phase shift is the same as the **Aharonov-Bohm effect**, which is a manifestation of a **Berry Phase**!

In the absence of rotation (Ω =0), the phase shift (i.e. Berry Phase) measured at the detector is zero.

But,

if a Berry phase is added any other way into the Sagnac circuit, a finite phase shift will be measured at the detector!

Sagnac loop and Berry Phase



In the absence of rotation (Ω =0), the phase shift (i.e. Berry Phase) measured at the detector is zero.

But, if a Berry phase is added any other way into the Sagnac circuit, a finite phase shift will be measured at the detector!

- For TRSB it is "obvious"
- One way to make the connection to gyrotropy is by considering a Berry phase mechanism for optical gyrotropy:
 See: J. Orenstein and Joel E. Moore, Phys. Rev. B 87, 165110 (2013)



Basic Principle: A sagnac loop with two QWPs to select circular polarizations



Zero-area Sagnac magnto-optic interferometer



- Complete rejection of reciprocal effects
- Shot-noise limit resolution of 100 nanorad/Hz^{1/2}
- Diffraction-limited beam size

Jing Xia, Peter Beyersdorf, M. M. Fejer, and A. Kapitulnik, Appl. Phys. Lett. 89, 062508 (2006).





One of the first predicted chiral superconductor



Jing Xia, Yoshiteru Maeno, Peter Beyersdorf, M. M. Fejer, and A. Kapitulnik, Phys. Rev. Lett. 97, 167002 (2006)

Sr₂RuO₄

Sr₂RuO₄ is a quasi 2-dimensional, Strongly correlated Fermi liquid.

The low-temperatures metallic state shows T^2 behavior of the resistivity and quantum oscillations that reveal all 3 bands.



 Sr_2RuO_4 is a **layered** perovskite isostructural with $La_{2-x}Ba_xCuO_4$.

Y. Maeno, H. Hashimoto, K. Yoshida, S. Nishizaki, T. Fujita, J. G. Bednorz & F. Lichtenberg, Nature 372 (1994), 532.



Fermi Surface consists of **3** bands, one 2D orbital (d_{XY}) , and two 1D orbitals $(d_{XZ} \text{ and } d_{XZ})$ that hybridize to create the α and β bands.

Sr₂RuO₄

Sr_2RuO_4 is a quasi 2-dimensional, Strongly correlated Fermi liquid. Superconductor below $T_c = 1.5 \text{ K}$



Sr₂RuO₄ is a **layered** perovskite isostructural with $La_{2-x}Ba_xCuO_4$.

Y. Maeno, H. Hashimoto, K. Yoshida, S. Nishizaki, T. Fujita, J. G. Bednorz & F. Lichtenberg, Nature 372 (1994), 532.



Sensitivity to scattering: Destruction of superconductivity by nonmagnetic impurities



Spin triplet pairing: Knight-shift does not Change below T_c .

Time-Reversal-Symmetry-Breaking (TRSB) has to be tested independently, and in the bulk, to decide on possible assignments of order parameters!

Proposed symmetry for the order parameter of Sr₂RuO₄: $\vec{d} = \Delta_0 \hat{z} \left(p_x \pm i p_y \right)$

<u>Original proposal</u> – Superconductivity originates on the (2D orbital) γ band:

- T.M. Rice and M. Sigrist, J. Phys. Cond. Mat. 7, L643 (1995).
- G. Baskaran, Physica B 223&224, 490 (1996).

<u>Alternative proposal</u> – Superconductivity originates in the (hybridized 1D orbitals) β band: • S. Raghu, A. Kapitulnik, S. A. Kivelson, Phys. Rev. Lett. 105, 136401 (2010).



This is a chiral state with orbital magnetic moment and degeneracy = 2

Earlier conflicting evidence for TRSB:

Muon spin rotation

ntern



Search for edge currents





Observation of a spontaneous <u>extra relaxation</u> of the spin-polarization function below the superconducting transition temperature.

G. M. Luke, Y. Fudamoto, K. M. Kojima, M. I. Larkin, J. Merrin, B. Nachumi, Y. J. Uemura, Y. Maeno, Z. Q. Mao, Y. Mori, et al., Nature 394, 558 (1998).

No edge currents were detected using scanning Hall probe and scanning SQUID.

J. R. Kirtley, C. Kallin, C. W. Hicks, E. A. Kim, Y. Liu, K. A. Moler, Y. Maeno, and K. D. Nelson, Phys. Rev. B 76, 014526 (2007).

Sagnac Data:



Jing Xia, Yoshiteru Maeno, Peter Beyersdorf, M. M. Fejer, and A. Kapitulnik, Phys. Rev. Lett. 97, 167002 (2006)

Training a Kerr signal with a field for a TRSB case

What do we expect in zero-field cool, and in training experiments?

Example: The itinerant ferromagnet SrRuO₃: T_c~150 K





What do we expect in zero-field cool, and in training experiments?

Example: The itinerant ferromagnet SrRuO₃: T_c~150 K

Field-cooled (oriented)





Back to Sr₂RuO₄


Summary of observations on Sr₂RuO₄:

- Maximum signal is _65 ÷ 100* nanorad
- Signal onsets at T_c
- Temperature dependence of signal can be fitted with a quadratic dependence on the gap $\theta_{K} \sim (T_{c}-T)$.
- Chirality can be trained with a magnetic field.
 A minimum field is needed.
- Domain size is large, of order beam size >20 µm Zero-field cool show some fluctuations
- Signal cannot be explained by trapped flux max. zero-field cool signal equals field cool
- There is no Light-power dependence on the size of the signal (no heating effect).

* Effect and its size can be explained theoretically for pure p+ip by taking into account impurity scattering. [Jun Goryo, Phys. Rev. B 78, 060501(R) (2008); R. M. Lutchyn, P. Nagornykh, and V. M. Yakovenko, Phys. Rev. B 80, 104508 (2009).], or if it is a **multi-band system: Edward Taylor and Catherine Kallin,** Phys. Rev. Lett. 108, 157001 (2012).

Current understanding of Sr₂RuO₄

An ideal (one-band) chiral p-wave superconductor will not give a non-zero polar Kerr effect. In that case the Kerr angle will originate from impurity (skew) scattering. Jun Goryo, Phys. Rev. B 78, 060501(R) (2008); R. M. Lutchyn, P. Nagornykh, and V. M. Yakovenko, Phys. Rev. B 80, 104508 (2009).

A multi-band chiral p-wave superconductor can give rise to a nonzero Kerr effect, even in the absence of disorder.

S. Raghu, A. Kapitulnik and S.A. Kivelson, Phys. Rev. Lett. 105, 136401 (2010); E. Taylor and C. Kallin, Phys. Rev. Lett. 108, 157001 (2012); K.I. Wysokinski, J. F. Annett, and B. L. Gyorffy, Phys. Rev. Lett. 108, 077004 (2012).

New evidence in favor of 2-components triplet superconductivity in Sr_2RuO_4 comes from evidence in favor of half quantum vortices.

J. Jang, D.G. Ferguson, V. Vakaryuk, R. Budakian, S.B. Chung, P.M. Goldbart, Y. Maeno, Science 331, 186 (2011).

Absence of edge currents can be attributed to rough surfaces:

i) More significant changes in the currents in the case of multiband superconductivity.

S. Raghu, A. Kapitulnik and S.A. Kivelson, Phys. Rev. Lett. 105, 136401 (2010);

C. Kallin, Rep. Prog. Phys. 75, 042501 (2012).

ii) Nonspecular scattering can dramatically alter the surface spectrum, reducing or even eliminating the edge currents.

J.A. Sauls, Phys. Rev. B 84, 214509 (2011); B. Spivak, unpublished (2012).

Understanding of µSR results is not complete. Spontaneous currents generated at domain walls and defects which are used to explain µSr results are absent in edge current experiments. C. Kallin, Rep. Prog. Phys. 75, 042501 (2012).

Heavy Fermion Superconductors

Heavy Fermions in one slide

100

- At high temperatures $(T > \sim T^*)$, It is a metal, with local moments from f-electrons exhibiting a Curie –Weiss-type magnetic susceptibility.
- At low temperatures ($T < \sim T^*$), compensation of the *f*-moments occurs through hybridization between an antiferromagnetic exchange interaction which produces a virtual bound state between the *f*-moments and the conduction electrons. This strong exchange coupling leads among others to a large effective mass for the conduction electrons $m^* >> m_e$. Nevertheless, this strongly correlated state is a Fermi liquid.
- 100 (The hybridization is reminiscent of the Kondo effect observed for a single localized magnetic impurity in a non magnetic normal host.)
- HF compounds may exhibit novel electronic phases as they are cooled towards T=0

200

Some HF compounds can become superconductors.
 ★ Usually superconductivity in such systems is found to be unconventional as a result of spin fluctuations.

UPt₃

Maybe the first "official" unconventional superconductor



Early proposals predicted a "p+ip" order parameter - chiral superconductor



E. R. Schemm, W. J. Gannon, K. Avers, W. P. Halperin, and Aharon Kapitulnik, preprint (2013).

UPt₃

UPt₃ is a heavy-fermion compound with $m^* \approx 50 m_e$

Fermi liquid at low temperatures; Weak antiferromagnetism below $T_N = 5K$



The **uranium** atoms form a closed-packed hexagonal structure. The **platinum** atoms bisecting the planar bonds. Space group: P6₃ /mmc Point group: D_{6h} The lattice parameters: a=5.764 Å, c=4.899 Å

e.g. R. Joynt and L. Taillefer, Rev. Mod. Phys. 74, 235 (2002).



Three-dimensional Fermi surfaces calculated under the assumption that the 5f electrons are included in the Fermi volume.

S. R. Julian, et al., "The Fermi Surface of UPt_3 " (University of Cambridge, 2000, Cambridge).

UPt₃

UPt₃ is a heavy-fermion compound with $m^* \approx 50 m_e$

Superconductivity was discovered to be unconventional through multiple superconducting phases



The **uranium** atoms form a closed-packed hexagonal structure. The **platinum** atoms bisecting the planar bonds. Space group: $P6_3$ /mmc Point group: D_{6h} The lattice parameters:

a=5.764 Å, *c*= 4.899 Å

e.g. R. Joynt and L. Taillefer, Rev. Mod. Phys. 74, 235 (2002).



Double-peak in specific heat

J.P. Brison, *et al*., J. Low Temp. Phys. 95, 145 (1994).



Three phases in ultrasonic attenuation

S. Adenwalla, *et al.*, Phys. Rev. Lett. 65, 2298 (1990).

Proposed symmetry for the order parameter of UPt₃: Preferred symmetry is E_{2u} which is a f-wave superconductor (spin triplet)

Matthias J. Graf, S.-K. Yip, and J. A. Sauls, Phys. Rev. B 62, 14393 (2000).



4-fold anisotropy of JJ-critical current prefers $E_{2\mu}$

J. D. Strand, D. J. Bahr, D. J. Van Harlingen, J. P. Davis, W. J. Gannon, W. P. Halperin, Science 328, 1368 (2010).



Fig. 1. A two-dimensional representation of the superconducting order parameter, with the c axis out of the page. Each line represents the gap magniude at a different temperature, with the innermost two lines above T_{c-} and the rest of the lines below T_{c-} . The nodes in the high-temperature phase gradually fill in as the low-temperature component of the gap grows. Not shown is a line node in the basal plane dividing the positive and negative c axis.



Preferred symmetry is E_{2u} , yielding a phase diagram:

A. Huxley, P. Rodiere, D. M. Paul, N. van Dijk, R. Cubitt, and J. Flouquet: Nature 406, 160 (2000).

2-D order parameter: $\eta = (\eta_1, \eta_2)$

$$\Delta(\vec{k}_F) = \hat{z} \left[\eta_1(T) k_z (k_x^2 + k_y^2) + 2\eta_2(T) k_z k_x k_y \right]$$

A – phase:
$$\eta = (1, 0)$$

B – phase: $\eta = (1, \pm i)$
C – phase: $\eta = (0, 1)$



However Recent analysis of data challenges the E_{2u} scenario, proposing a

 E_{1u} scenario which is one dimensional, and does not break TRS.

Y. Machida, A. Itoh, Y. So, K. Izawa, Y. Haga, E. Yamamoto, N. Kimura, Y. Onuki, Y. Tsutsumi, and K. Machida, Phys. Rev. Lett. 108, 157002 (2012).

- 2-fold symmetry from thermal conductivity
- No time-reversal-symmetry breaking from µ-Sr



Sagnac Data:

Zero-field cool/Zero-field warmup Measure when warming up



Sagnac Data:

Zero-field cool/Zero-field warmup Measure when warming up



Sagnac Data:

Zero-field cool/Zero-field warmup Measure when warming up





0.6

Field-training data:

Observations/implications:

- 1. θ_{κ} can be trained with a small symmetry-breaking field
- 2. No additional signal for FC measurements
 - Single domain formation
 - \succ θ_{κ} not a vortex effect



Summary of observations on UPt₃:

- Maximum signal is ~400 nanorad (extrapolated to ~700 nanorad at T=0)
- Signal onsets at $T_{C_-} \approx 480 \text{ mK}$ (**B-phase)**, while superconductivity onsets at $T_{C_+} \approx 550 \text{ mK}$
- Temperature dependence of signal can be fitted with a quadratic dependence on the gap $\theta_{K} \sim (T_{c}-T)$.
- Chirality can be trained with a magnetic field.
- It seems like a single domain for the whole sample! (beam size ~10µm)
- Signal cannot be explained by trapped flux zero-field cool signal equals field cool
- There is no Light-power dependence on the size of the signal (no heating effect, power was changed x20 times!)

B-phase breaks time reversal symmetry

(E_{1u} proposal of Machida et al. cannot work)

Chirality in the pseudogap phase of the cuprates

Possible case for Kerr effect from Gyrotropy

Chirality in the pseudogap phase of the cuprates

Reminder: YBaCuO*

*Jing Xia, E. Schemm, G. Deutscher, S. A. Kivelson, D. A. Bonn, W. N. Hardy, R. Liang, W. Siemons, G. Koster, M. M. Fejer, and A. Kapitulnik, Phys. Rev. Lett. 100, 127002 (2008).

Anatomy of a data set: YBa₂Cu₃O_{6.67} (ortho-VIII), cooled in high field:



We note three distinct regimes:

- At high temperatures, flat (zero) Kerr rotation
- Below T_c, a signal dominated by trapped vortices



Anatomy of a data set: $YBa_2Cu_3O_{6.67}$ (ortho-VIII), cooled in high field:

We note three distinct regimes:

- At high temperatures, flat (zero) Kerr rotation
- Below T_c, a signal dominated by trapped vortices
- In some intermediate temperature range T_c<T<T_K, a small but nonzero Kerr signal



5 T

т

Bext

Anatomy of a data set: $YBa_2Cu_3O_{6.67}$ (ortho-VIII), cooled in zero field:



- Zero field: < 3 mOe
- No contribution from trapped vortices
- What remains is now pure signal



YBa₂Cu₃O_{6.5} (ortho-II):

Cool in high field (5 T), warm up in ZF:

- trapped vortex signal seen below T_c
- \bullet Kerr signal does not fall to zero until some higher $\rm T_s$





Summary for YBa₂Cu₃O_{6+x}

- A (very small) time reversal symmetry-breaking signal appears below a temperature T* >> Tc for all underdoped YBCO samples measured.
- A (very small) time reversal symmetry breaking signal appears below a temperature T* < Tc for near optimally doped samples.
- Kerr rotation measurements on films show TRSB signals comparable in magnitude and onset temperature to single crystals with similar doping.
- There is an unusual hysteretic memory effect in the magnetic response.

240 Single Crystals 220 Thin Films 200 180 160 TN Temperature (K 140 120 100 80 60 40 20 0.0 0.02 0.04 0.06 0.08 0.10 0.12 0.14 0.16 0.18 0.20 Hole doping (p)

Will be discussed further later!

Comparison with other results:

- Kerr effect seems to be Insensitive to disorder.
- There is an unusual hysteretic memory effect in the magnetic response. Will be discussed further later!
- Kerr Transition seems to coincide with subsequently observed CDW transitions! (RIX, HE-Xray).



Kerr effect onset was shown to coincide with charge order in other HTSC compounds!



Early Measurements of Pseudogap in LSCO/LBCO

Hall effect and resistivity

H. Y. Hwang, et al., PRL 72, 2636 (1994).



Magnetic susceptibility and resistivity T Nakano et al. Phys Rev B 49, 16000 (1994)

Identifying the structural phase transitions using birefringence: Second-order



And the Kerr effect...



Hovnatan Karapetyan, M. Hucker, G. D. Gu, J. M. Tranquada, M. M. Fejer, Jing Xia, A. Kapitulnik, Phys. Rev. Lett. 109, 147001(2012).

Training the Kerr signal with a field

Training the Kerr Signal in LBCO



Is Time reversal symmetry already broken at room temperature?

Possible explanation of the training effect:

Hall effect and resistivity

H. Y. Hwang, et al., PRL 72, 2636 (1994).



Х

Could it be that Time-reversal Symmetry is Broken for x=1/8 at ~550K. By 54K, TRS is already broken!

However: "problems" with opposite surface effect:

If the Kerr effect has to do with (any component of) ferromagnetism, and for a single domain, we expect the opposite surface to show the opposite sign of the Kerr effect: E(x)



Test opposite side signal:

However: "problems" with opposite surface effect:

If the Kerr effect has to do with (any component of) ferromagnetism, and for a single domain, we expect the opposite surface to show the opposite sign of the Kerr effect: E(x)



However: "problems" with opposite surface effect:

If the Kerr effect has to do with (any component of) ferromagnetism, and for a single domain, we expect the opposite surface to show the opposite sign of the Kerr effect: E(x)



Go back to test other HTSC for opposite surface:

If the Kerr effect has to do with (any component of) ferromagnetism, and for a single domain, we expect the opposite surface to show the opposite sign of the Kerr effect:










$$\epsilon_{xy} = -\epsilon_{yx}$$

Kerr signal response to strain in (110) direction suggests a **chiral** behavior since it is not minimum around zero strain.



Kerr effect can change by ~40% below T_{CO} =54K due to strain.



Observations:

- Kerr effect onsets at the charge-order transition (size of signal may vary).
- Same sample will retain the same sign of Kerr effect, irrespective of history of cooling, field, etc.
- If at all, TRS is broken at much higher temperatures (above room temperature).
- "opposite side" measurements give same sign.
- Strain effects suggest a chiral response (at least in LBCO).

Some possible explanations:

Observations:

- Kerr effect onsets at the charge-order transition (size of signal may vary).
- Same sample will retain the same sign of Kerr effect, irrespective of history of cooling, field, etc.
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- Strain effects suggest a chiral response (at least in LBCO).

Some possible explanations:

1) pre-existing magnetic state that changes its coupling to the off-diagonal conductivity at the light frequency at the T*- transition!

....and is modified at T* due to change in crystal symmetry/Fermi surface.

- 2) High-Tc materials are magnetoelectrics below T* Free energy acquires a term: $\Delta F_{ME} = -\alpha_{ij}E_iH_j$... and below T_{CO}, the symmetry is further lowered as acquiring anomalous Hall (and Nernst) effect and a finite Kerr effect.
- 3) High-Tc materials posses gyrotropic order below T* (without TRSB) Charge-ordering in the material gives rise to electron cholesteric order with inversion and all mirror symmetries which in a dissipative medium gives rise to a finite Kerr effect.

Possible Gyrotropic Effect*:

Charge order is arranged in a chiral way

Example: A 4-plane chiral stripe ordered state, but with period 3 mirrorplane breaking stripe order in each plane.

- For each individual crystal the chirality is predetermined. Possibly by structural effects.
- Unify the observations of coincidence of Kerr effect with charge order in the cuprates.



*P. Hosur, A. Kapitulnik, S.A. Kivelson, J. Orenstein, S. Raghu, Phys. Rev. B 87, 115116 (2013).

About the sign of the chirality:

- For each individual crystal the chirality is predetermined.
- →Each cooldown produces the same chirality (same sign of Kerr effect).
- Different crystals and different types of high-Tc materials may exhibit different sign.





Chirality of charge-order maybe linked to some intrinsic structural effects in the material (some recent evidence).

Other recent observations of chirality:

Nicola Poccia, Gaetano Campi, Michela Fratini, Alessandro Ricci, Naurang L. Saini, and Antonio Bianconi, Phys. Rev. B 84, 100504(R) (2011).

Use scanning micro-x-ray diffraction they study the spatial heterogeneity of the lattice incommensurate supermodulation in a single crystal of $Bi_2Sr_2CaCu_2O_{8+y}$ (Tc =84 K).

They find:

- ~50% variation in the amplitude distribution of the supermodulation
- The angular distribution of the supermodulation amplitude in the *a-b* plane shows a lattice chiral symmetry, forming a left-handed oriented striped pattern.
- Long-range 3D order and short-range 2D order.

Such results are strong evidence for pre-determined chirality that we find in our Kerr effect measurements!

Conclusions for HTSC:

There is mounting evidence that:

- Kerr effect onsets at the charge-order transition.
- Time-Reversal Symmetry is already broken at higher temperatures.

Some possible explanations:

High-Tc materials are magnetoelectrics below T* Free energy acquires a term: $\Delta F_{ME} = -\alpha_{ij}E_iH_j$... and below T_{CO}, the symmetry is further lowered as acquiring anomalous Hall (and Nernst) effect and a finite Kerr effect.

or

High-Tc materials posses gyrotropic order below T* (without TRSB) Charge-ordering in the material gives rise to electron cholesteric order with inversion and all mirror symmetries which in a dissipative medium gives rise to a finite Kerr effect.

