Time-reversal symmetry breaking and Polar Kerr effect from charge order in cuprates

Yuxuan Wang[1], Andrey Chubukov[1,2], and Rahul Nandkishore[3]

[1] Department of Physics, University of Wisconsin-Madison

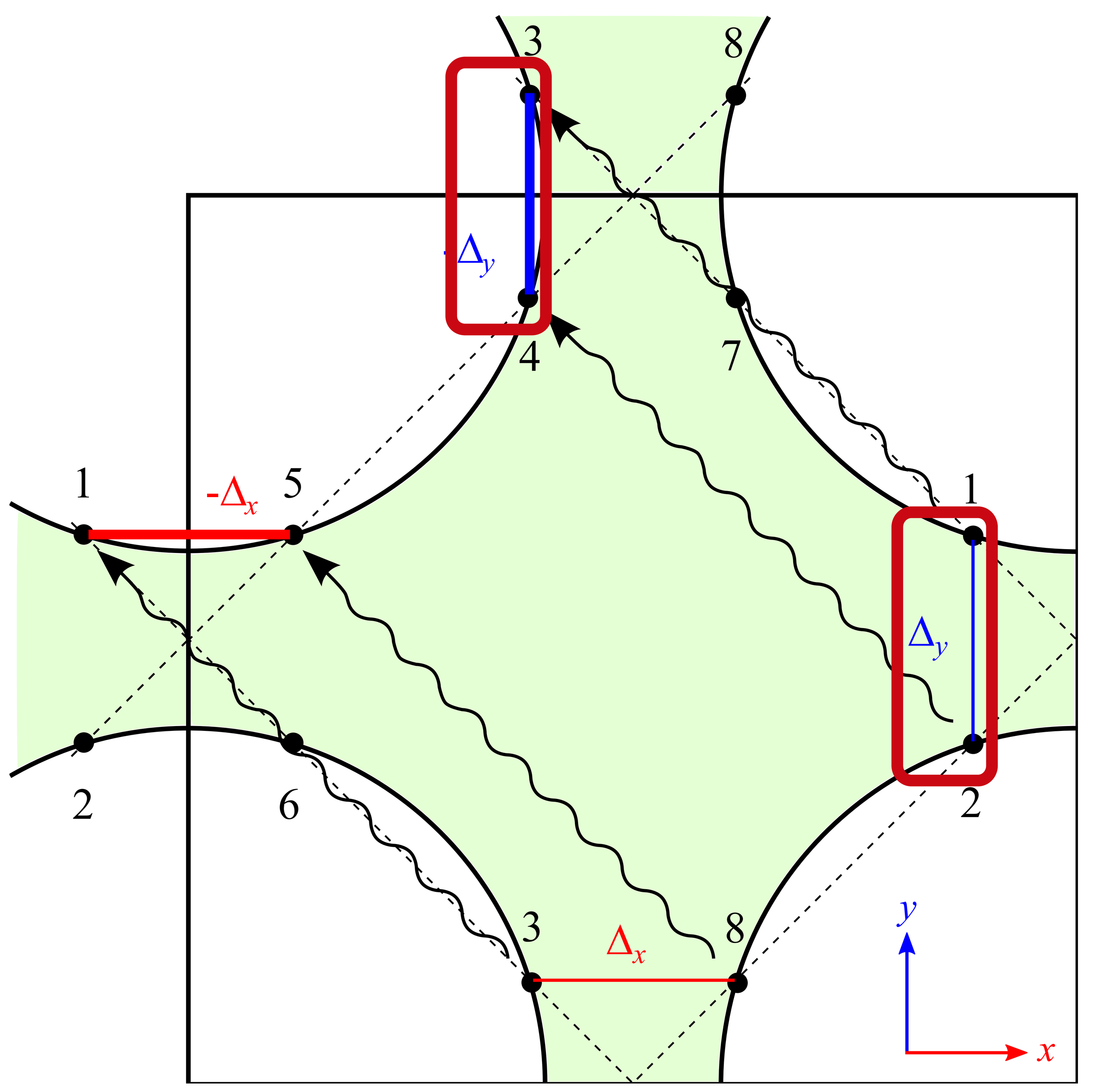
[2] William Fine Institute of Theoretical Physics and Department of Physics and Astronomy, University of Minnesota

[3] Princeton Center for Theoretical Science, Princeton University

Motivation

- Charge order has been ubiquitously found in hole doped cuprates.
- Polar Kerr effect has been observed in hole-doped cuprates. The most natural explanation is time-reversal symmetry breaking.
- Intra-unit-cell magnetic order has been observed in polarized neutron scattering, which indicates time-reversal symmetry is broken.

Model



Spin-fermion interaction (represented by wavy lines in the figure above)

$$\mathcal{S} = -\int_k^\Lambda G_0^{-1}(k)\,\psi^\dagger_{k,\alpha}\psi_{k,\alpha} + \frac{1}{2}\int_q^\Lambda \chi_0^{-1}(q)\ \mathbf{S}_q\cdot\mathbf{S}_{-q}$$
$$+g\int_{k,q}^\Lambda \psi^\dagger_{k+q,\alpha}\sigma_{\alpha\beta}\psi_{k,\beta}\cdot\mathbf{S}_{-q}.$$

$$\Delta^Q_{k_0}(\Omega_m) = \frac{3\bar{g}T}{4\pi^2}\sum_{m',k} G_1(\omega_m,k)G_2(\omega_m,k)\frac{\Delta^Q_{k_\pi}(\Omega_{m'})}{k_x^2+k_y^2+\gamma|\Omega_m-\Omega_{m'}|}$$

$$\Delta^Q_{k_\pi}(\Omega_m) = \frac{3\bar{g}T}{4\pi^2}\sum_{m',k} G_1(\omega_m,k)G_2(\omega_m,k)\frac{\Delta^Q_{k_0}(\Omega_{m'})}{k_x^2+k_y^2+\gamma|\Omega_m-\Omega_{m'}|}$$

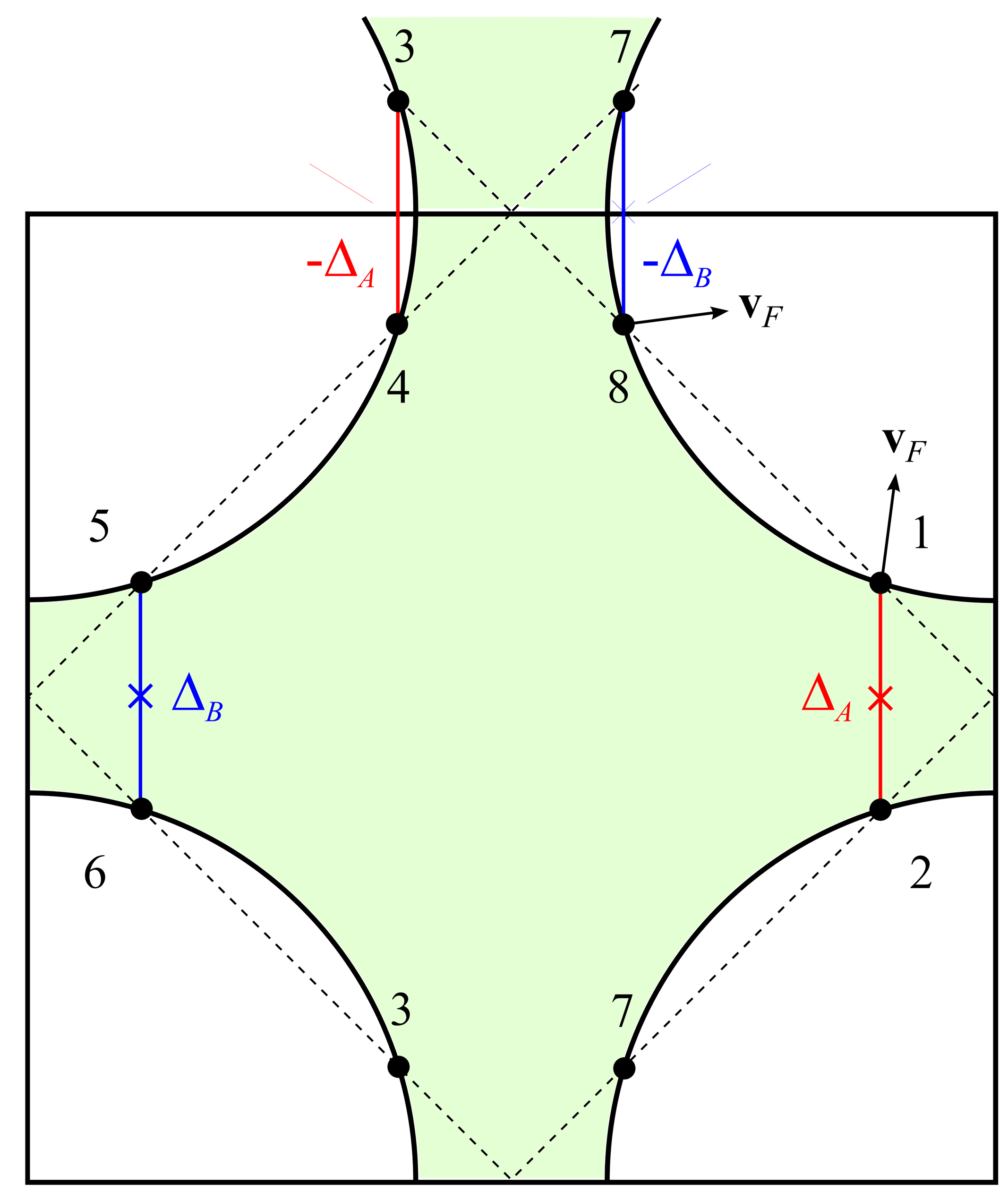
Instability comes from bosonic propagator — Landau damping term. Moving away from QCP the CDW will ultimately vanish.

Nematic transition

$$\mathcal{S}_{\text{eff}} = \alpha(|\Delta_x|^2+|\Delta_y|^2)$$
$$+\beta_1(|\Delta_x|^4+|\Delta_y|^4)+2\beta_2|\Delta_x|^2|\Delta_y|^2$$

- $\beta_2>\beta_1$, so charge order develops in either x or y direction, but not in both (stripes).

TRSB transition



Δ_A and Δ_B are related by time reversal.
Going beyond hot-spot analysis we find a coupling term between them

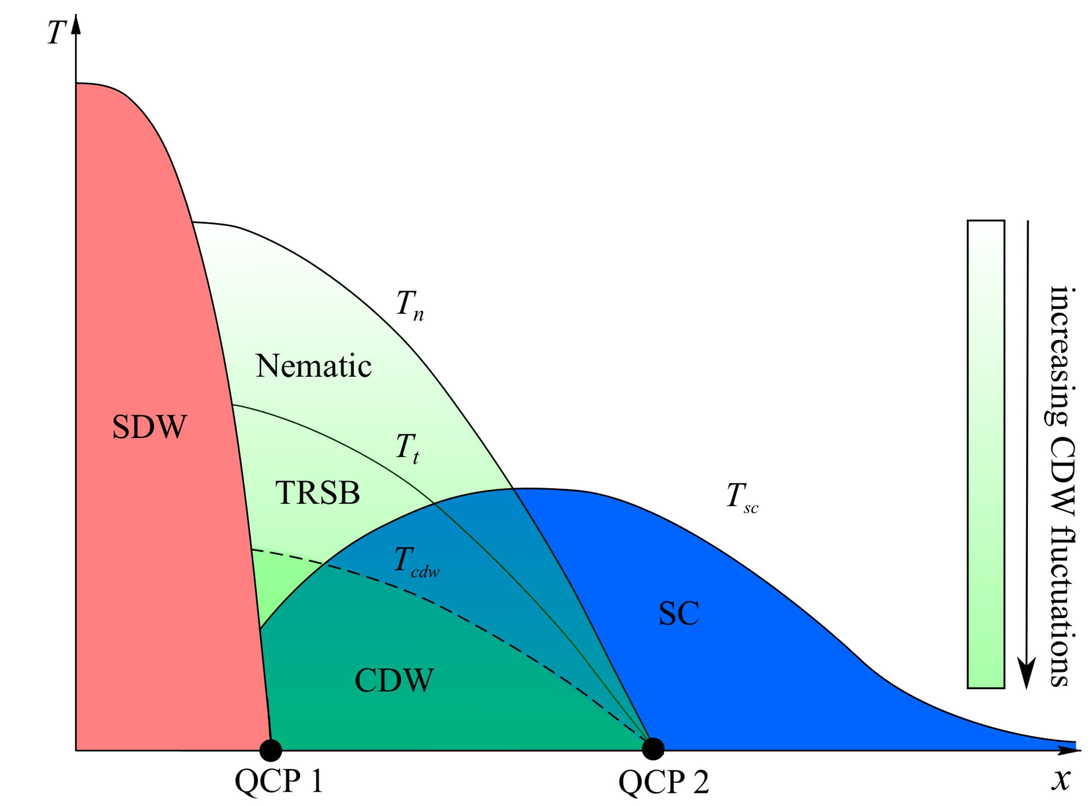
$$\mathcal{S}_{\text{eff}} = \alpha(|\Delta_A|^2+|\Delta_B|^2)+\beta_1(|\Delta_A|^4+|\Delta_B|^4)$$
$$+\beta'[i(\Delta_A\Delta_B^*-\Delta_A^*\Delta_B)]^2$$

$\beta'>0$, Δ_A and Δ_B develop with a relative $\pi/2$ phase difference. Time-reversal symmetry is broken. $\langle\Delta_A\Delta_B^*-\Delta_A^*\Delta_B\rangle \equiv \pm i\Upsilon$

Preemptive orders

Going beyond mean-field analysis we find that nematic transition and TRSB transition occurs at a higher temperature then the primary CDW transition.
Even before CDW develops, C_4 rotation symmetry and time-reversal symmetry is already broken.

Phase diagram

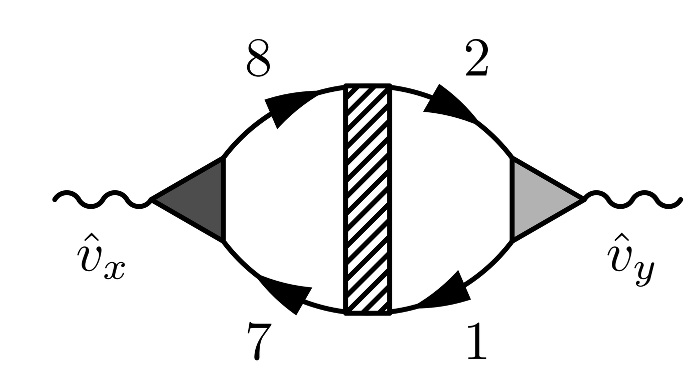


- The charge order terminates at a finite SDW correlation length (controlled by doping).
- Two preemptive orders, one nematic and one time-reversal symmetry breaking, set in prior to the primary charge density wave order.
- The charge-density-wave order is enhanced by preemptive orders, while SC is suppressed.

Polar Kerr effect from composite order

- Polar Kerr effect requires time-reversal symmetry and both mirror symmetries to be broken. ⟶ Satisfied!

	$\mathcal{M}_x$	$\mathcal{M}_y$	$\mathcal{T}$
Δ_A	Δ_A^*	Δ_B	Δ_B
Δ_B	Δ_B^*	Δ_A	Δ_A
$\Upsilon=-i(\Delta_A\Delta_B^*-\Delta_B\Delta_A^*)$	$-\Upsilon$	$-\Upsilon$	$-\Upsilon$

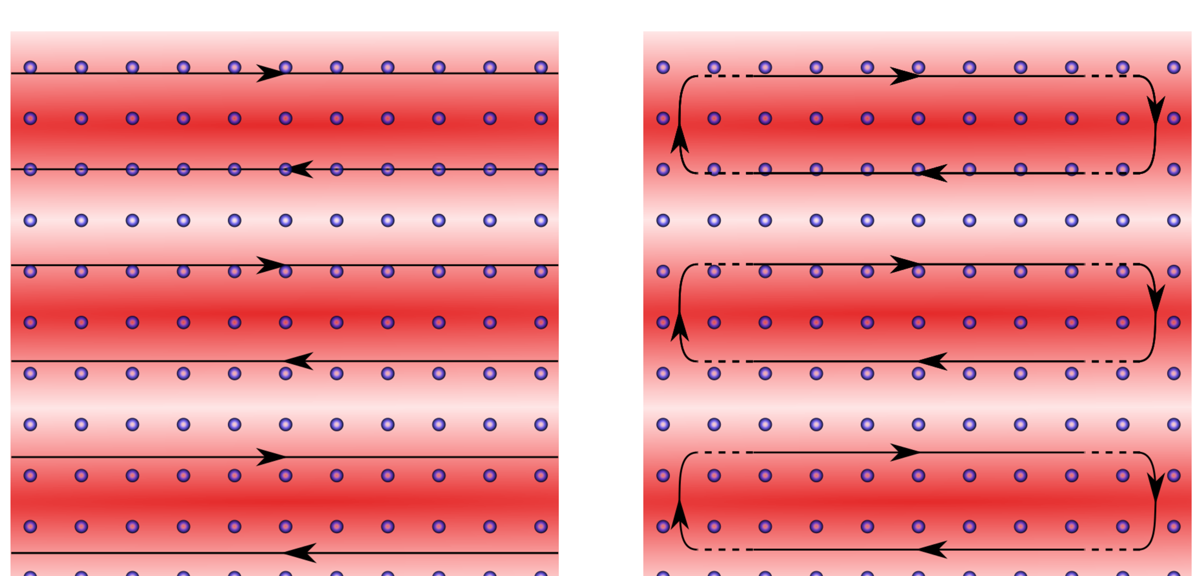


For a general system that is not rotationally invariant, the Kerr angle can be expressed by the antisymmetric component of the Hall conductivity.

$$\theta_K = \frac{\lambda}{c}\mathrm{Im}\left[\frac{\sigma_{xy}-\sigma_{yx}}{n(n^2-1)}\right]$$

- If one uses linear dispersion for fermions then the interaction can be fulfilled by skew scattering by disorder, which is odd in frequency.
- Gaussian-type disorder and spin fluctuations can also give nonzero result, but one has to invoke particle-hole asymmetry (nonlinear dispersion).

The bulk current $\langle\Delta_A-\Delta_B\rangle$ has a finite momentum and does not couple to a uniform magnetic field. Symmetry-wise, the composite order Υ can couple to a uniform magnetic field. However, we argue this coupling is via a surface current, which vanishes in thermodynamical limit.



References

- YW and AC, Phys Rev B **90** 035149 (2014)
- YW, AC and RN, arXiv:1409.5441 (2014)