In search of topological states with half quantum vortices.

Eun-Ah Kim

Cornell University

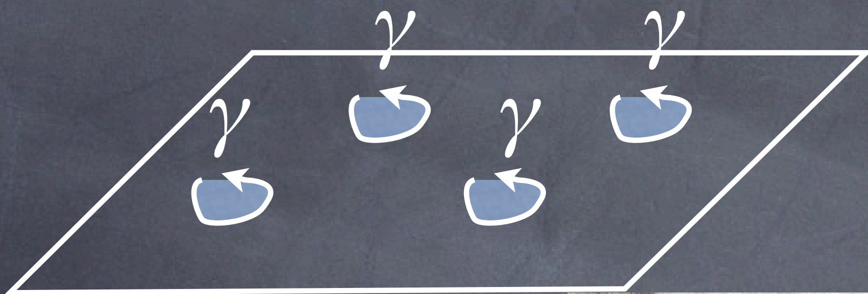
Suk-Bum Chung (Stanford)

Hendrik Bluhm (Harvard)

Subroto Mukerjee (Berkeley)

Daniel Agterberg (UWM)


TIMEO
ETIC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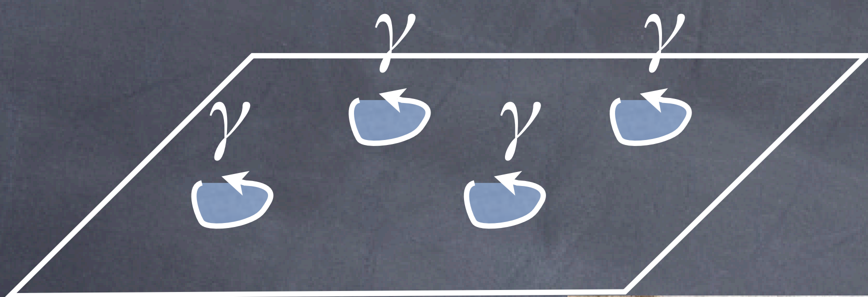
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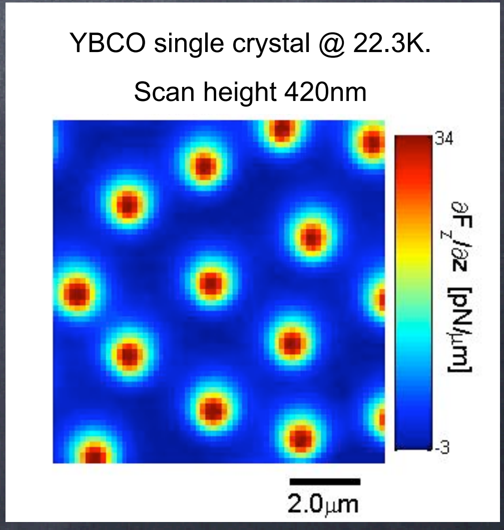
YBCO single crystal @ 22.3K.
Scan height 420nm
34
-3
$\partial F_z/\partial z$ [pN/μm]
2.0μm

In search of topological states with half quantum vortices

- Topological order and fractionalization
- 1/2 QV's
- Stability of 1/2-QV's in SrRuO
- 1/2 QV lattices

Ground state degeneracy

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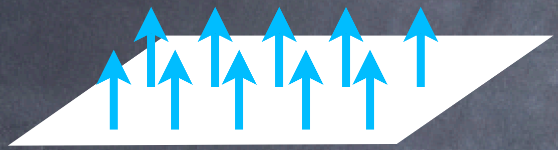
Conventional order

Ground state degeneracy

Conventional order



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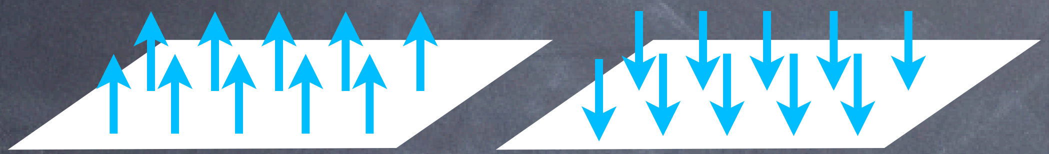

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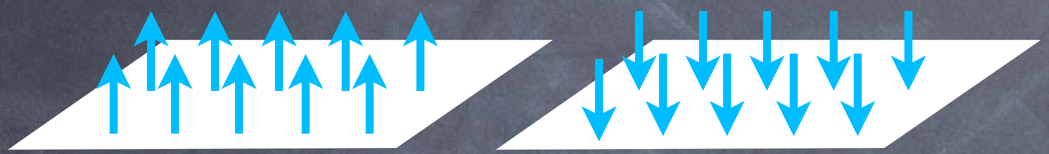

- Symmetry of the underlying Hamiltonian.

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⟺ reduced symmetry

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- Gapped spectrum

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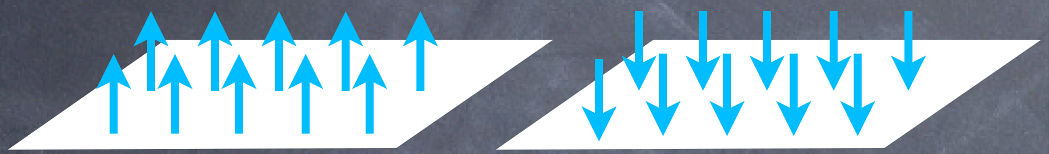

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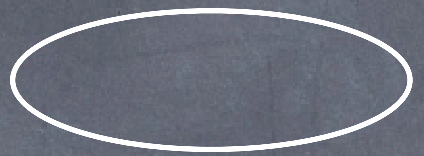

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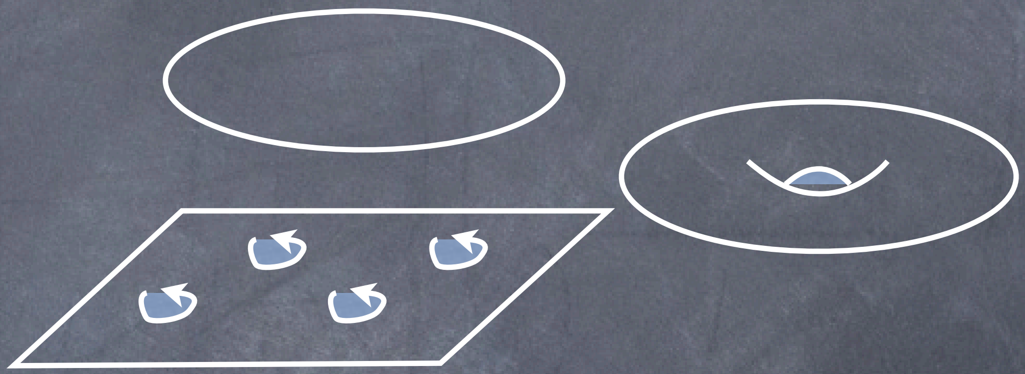

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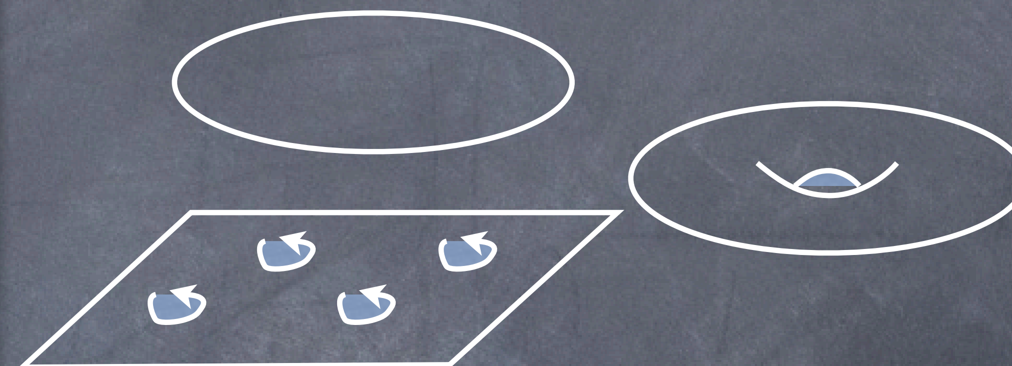

- Gapped spectrum
- Topological invariance

⟺ emergent symmetry

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Sweet Topology

Sweet Topology

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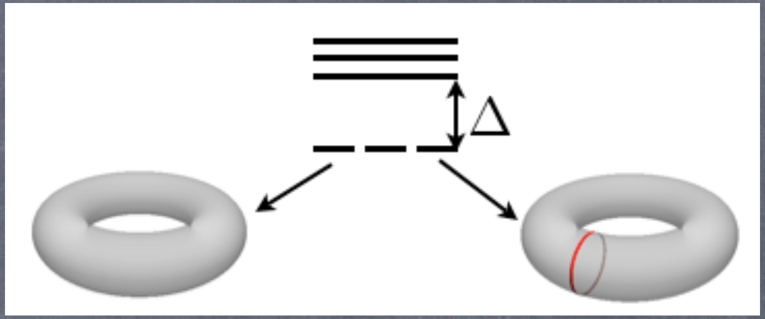
N_g & fractionalization

- Fractional charge $e^*=e/q$

  $N_g=q^g$ e.g., $N_1=3$



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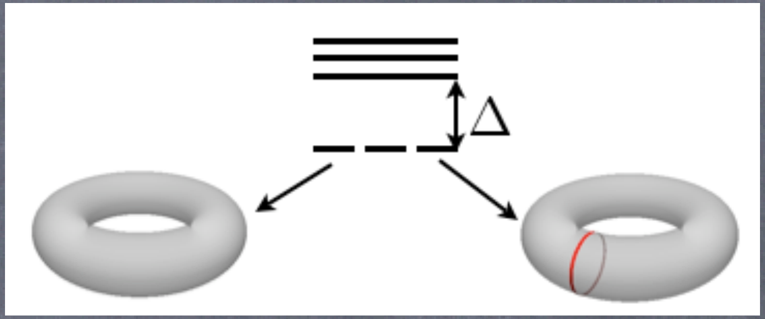

- 2n Non-abelian vortices

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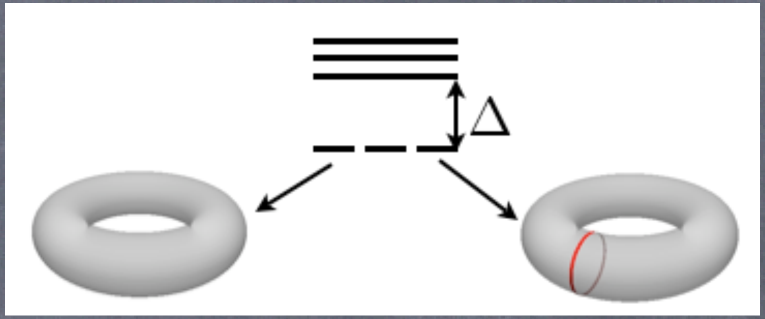

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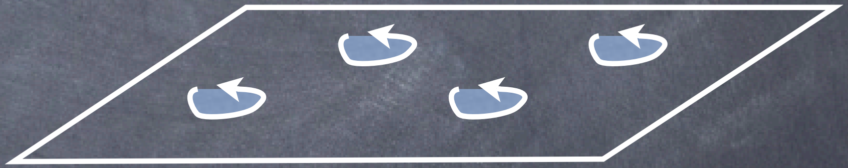

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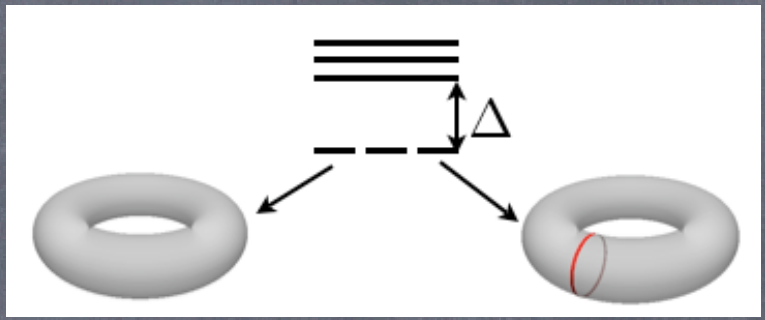

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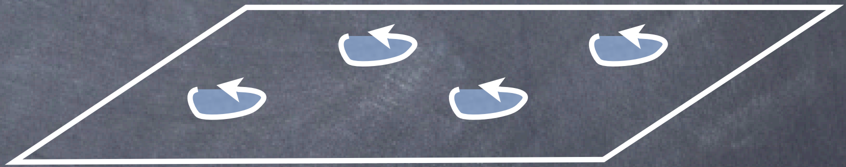

$N_{2n}=2^{n-1}$ for MR state or p+ip SF

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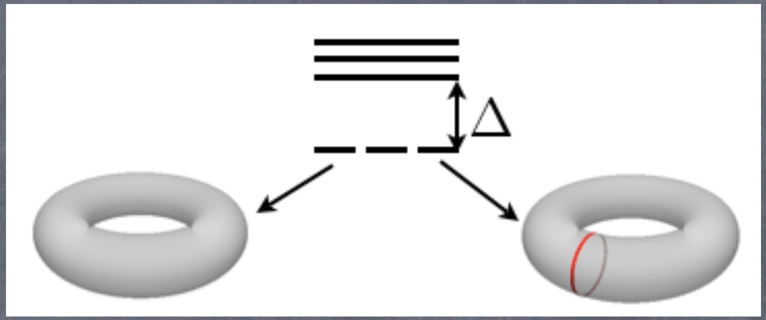

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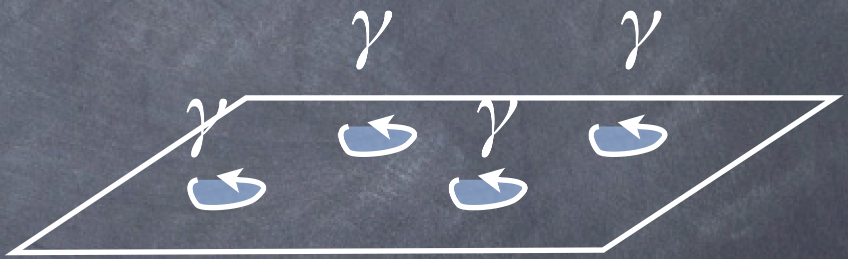

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exchange of qp's:
→ phase multiplication to a complex number

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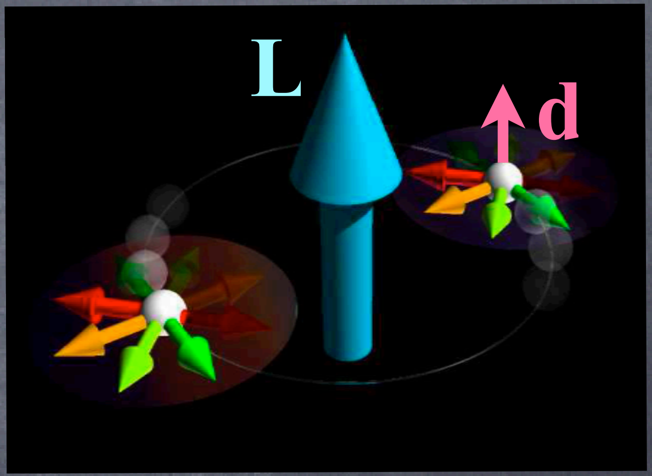
- Triplet gap matrix $$\begin{aligned}\hat{\Delta}(\mathbf{k}) &= i(\mathbf{d}(\mathbf{k})\cdot\hat{\boldsymbol{\sigma}})\hat{\sigma}_y \\ &= \begin{bmatrix} -d_x(\mathbf{k})+id_y(\mathbf{k}) & d_z(\mathbf{k}) \\ d_z(\mathbf{k}) & d_x(\mathbf{k})+id_y(\mathbf{k}) \end{bmatrix}\end{aligned}$$

p+ip SC

- T-breaking (ABM)

$$\Delta(\hat{\mathbf{k}}) = \Delta_0(T)(p_x \pm ip_y)\begin{pmatrix} -d_x + id_y & d_z \\ d_z & d_x + id_y \end{pmatrix}$$

where $\hat{\mathbf{d}}$ is a real unit vector



- In plane $\hat{\mathbf{d}}$

d_z=0 i.e., $\mathbf{d}$ = (cosα , sinα, 0)

$$\Delta(\hat{\mathbf{k}}) = \Delta_0(T)(p_x \pm ip_y)\begin{pmatrix} -e^{-i\alpha} & 0 \\ 0 & e^{i\alpha} \end{pmatrix}$$

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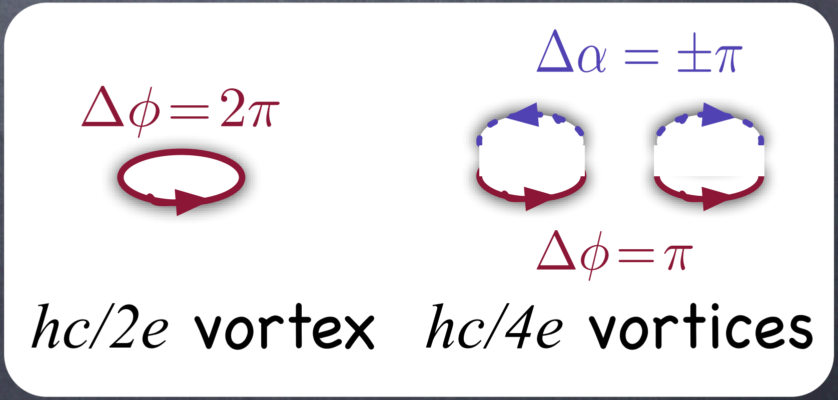
$\Leftrightarrow$ π winding of order parameter phase ϕ

$+\ \pi$ rotation of $\mathbf{d}$ vector



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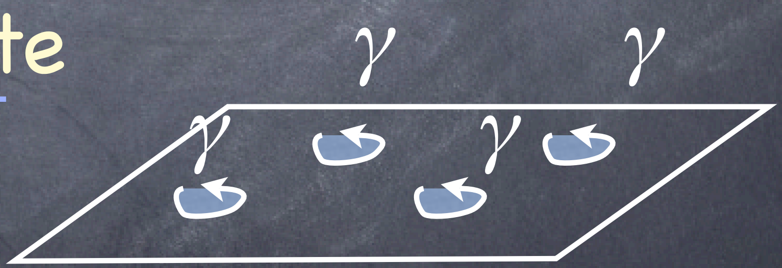

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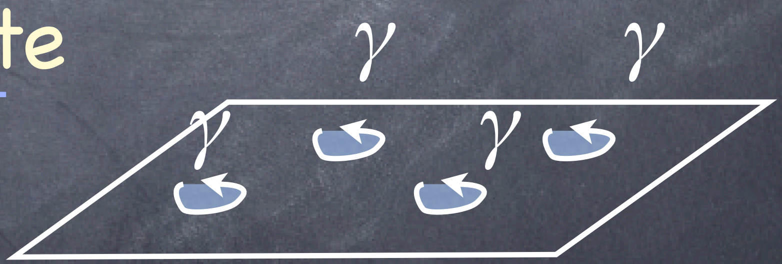

Das Sarma, Tewari, Nayak (06) Stone & Chung(06) Ivanov(01)

1/2 QV's: single Majorana zero mode

5/2 state described as p+ip paired stated of composite fermion

Pfaffian is real space many body BCS wave function of p+ip SF

HQV is equivalent to 1/4 qp

Moore & Read (91)   Read & Green (00)

Schriffer, p 48

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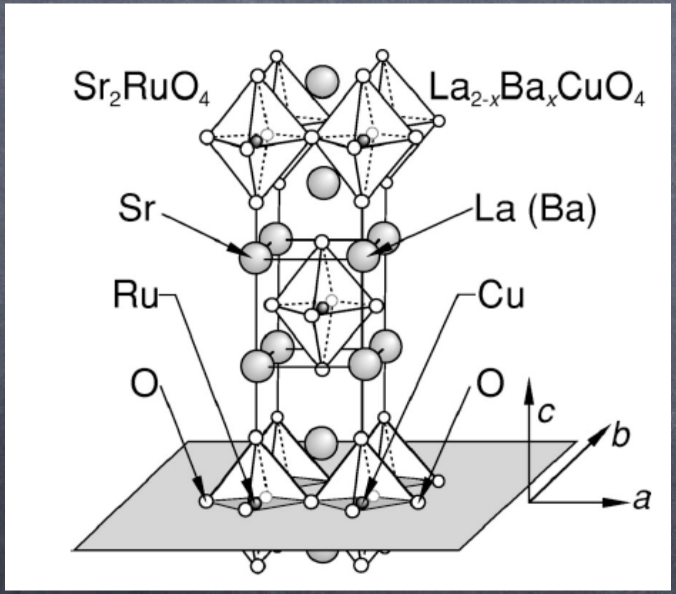
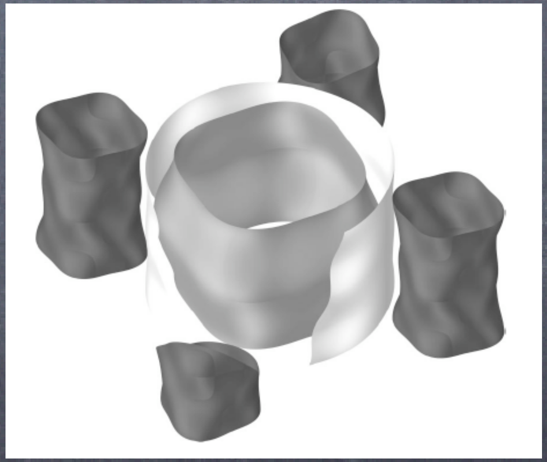
K. Ishida et al, Nature (1998)

Spin-triplet superconductivity in Sr_2RuO_4 identified by ^{17}O Knight shift





Experiments?

- NMR on ^{3}He-A thin films: X Hakonen et al. Physica (89)
- Small angle neutron scattering: X Riseman et al. Nature (98)
- Scanning SQUID imaging: X
  Dolocan et al, PRL (05), Bjorsson et al, PRB (05)
- NMR in the presence of $\mathbf{H} \perp ab$
  - $\mathbf{d}\, //\, ab$: for $H_\perp \gtrsim 200$ G , Murakawa et al, PRL (04)

Energetics

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- Gradient free energy when $\mathbf{d} \perp \mathbf{L}$ (London limit)

$$f_{\rm grad}^{\rm 2D} = \frac{1}{2}\left(\frac{\hbar}{2m}\right)^2 \left[\rho_{\rm s}\left(\nabla_\perp \phi - \frac{2e}{\hbar c}\mathbf{A}\right)^2 + \rho_{\rm sp}\left(\nabla_\perp \alpha\right)^2\right] + \frac{1}{8\pi}(\nabla \times \mathbf{A})^2$$

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- Spin current energy diverges logarithmically!

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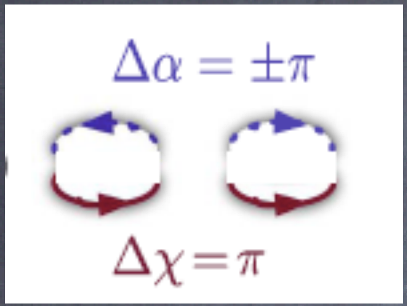
- Energy competition between full-QV and 1/2-QV
  - Reducing vorticity saves magnetic energy
  - d-vector bending costs energy
- Gradient free energy when $\mathbf{d} \perp \mathbf{L}$ (London limit)

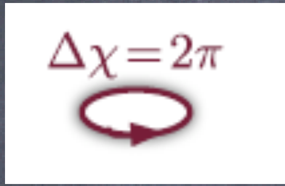
$$f_{\rm grad}^{\rm 2D} = \frac{1}{2}\left(\frac{\hbar}{2m}\right)^2 \left[\rho_{\rm s}\left(\nabla_\perp \phi - \frac{2e}{\hbar c}\mathbf{A}\right)^2 + \rho_{\rm sp}\left(\nabla_\perp \alpha\right)^2\right] + \frac{1}{8\pi}(\nabla \times \mathbf{A})^2$$

- Spin current energy diverges logarithmically!

$$\epsilon_{\rm sp} = \frac{\pi}{4}\left(\frac{\hbar}{2m}\right)^2 \rho_{\rm sp} \ln\left(\frac{R}{\xi}\right)$$

stability of 1/2 QV



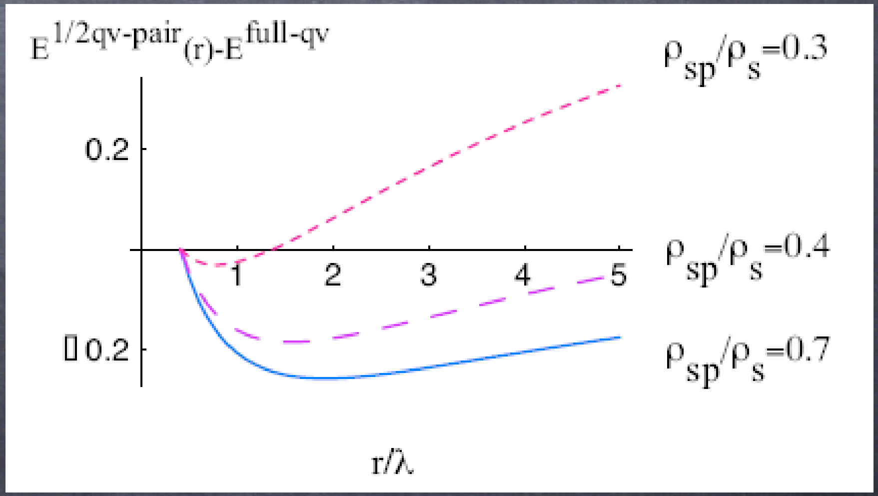


$$E^{\text{half}}_{\text{pair}}(r_{12}) = \frac{1}{2}\,\frac{\Phi_0^2}{16\pi^2\lambda^2}\left[\ln\left(\frac{\lambda}{\xi}\right) + K_0\left(\frac{r_{12}}{\lambda}\right) + \frac{\rho_{\text{sp}}}{\rho_{\text{s}}}\ln\left(\frac{r_{12}}{\xi}\right)\right]$$

$$E^{\text{full}} = \pi\left(\frac{\hbar}{2m}\right)^2 \rho_{\text{s}} \ln\left(\frac{\lambda}{\xi}\right) = \frac{\Phi_0^2}{16\pi^2\lambda^2}\ln\left(\frac{\lambda}{\xi}\right)$$

- Competition between screened magnetic repulsion and unscreened spin attraction

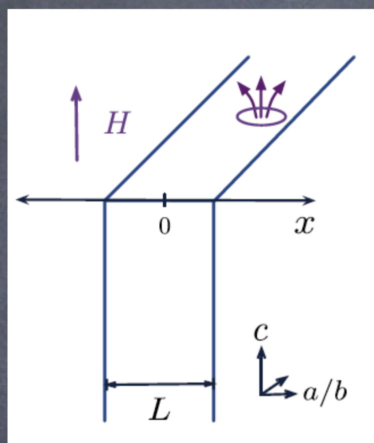
- Finite equilibrium size for small ρ_{sp}/ρ_s



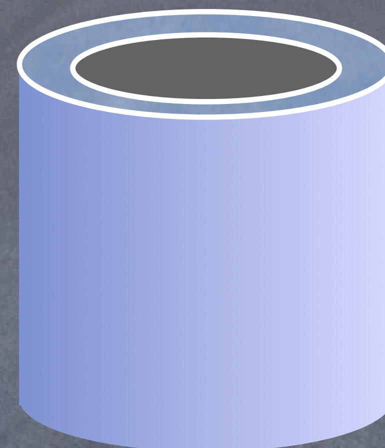
Leggett RMP 75

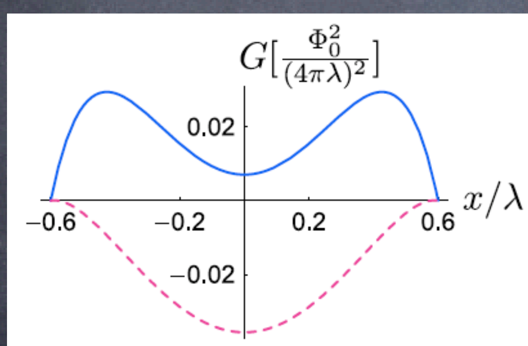
Mesoscopic sample

- Sample of size ~ λ a few micron



$$L = 2\lambda$$





Underway in Budakian lab

- Sample of size ~ λ a few micron

In search of topological states with fractionalized excitations.

- Topological order and fractionalization
- 1/2QV's
- Stability of 1/2-QV's in SrRuO
- 1/2 QV lattices

1/2 QV Lattice?

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- Natural way to stabilize 1/2 QV

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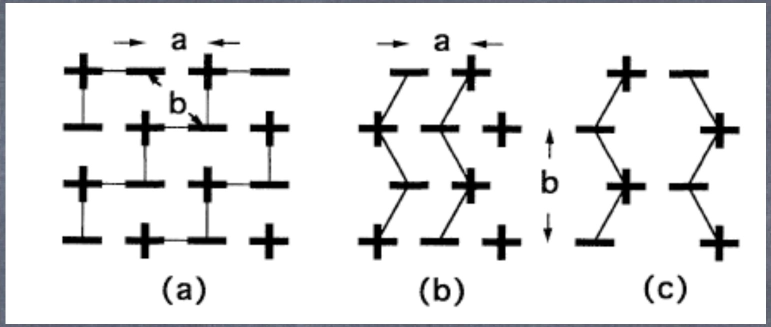
- Good track record for full QV lattice
  - Agterberg, PRB (98) predicted square lattice
  - T. Riseman at el , Nature (98) confirmed square lattice

1/2 QV Lattice?

- Natural way to stabilize 1/2 QV
- Good track record for full QV lattice
  - –Agterberg, PRB (98) predicted square lattice
  - –T. Riseman at el , Nature (98) confirmed square lattice
- Potential of tuning ρ_{sp}/ρ_s
  - –Knowledge exist for ρ_{sp}/ρ_s as a function of Fermi liquid parameters
  - –p-wave Feshbach resonance

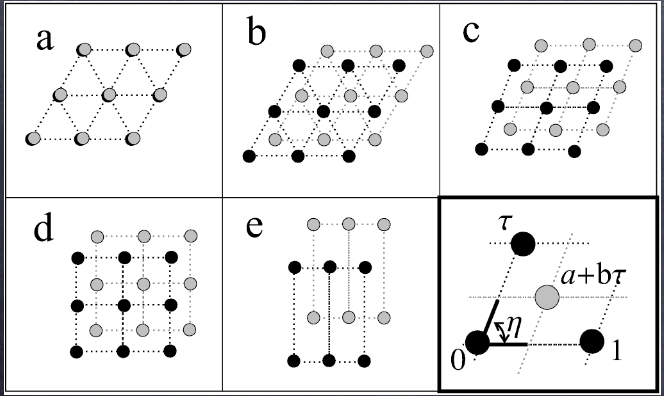
1/2 QV Lattice?

- SC (SF) with additional U(1) symmetry due to $\hat{d}$ rotation
- Interlacing lattices of two types of vortices



–Different geometry depending on density and LL mixing

- Similar case arise in spinor condensate

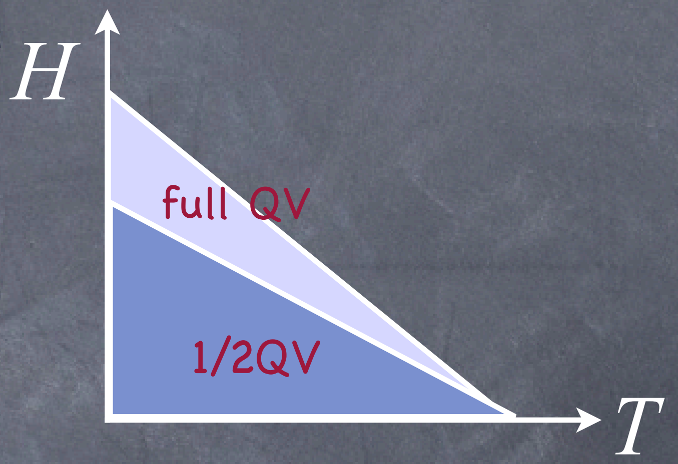


Muller & Ho(02)

Barnett, Mukergee & Moore(08)

Prediction

- Minimze GL free energy to determine the VL structure
- Quartic terms in the free energy determine the structure



Field distribution as can be measured by neutron

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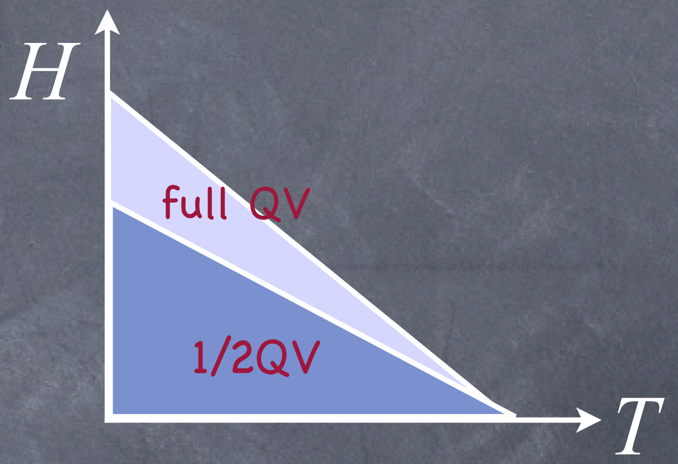

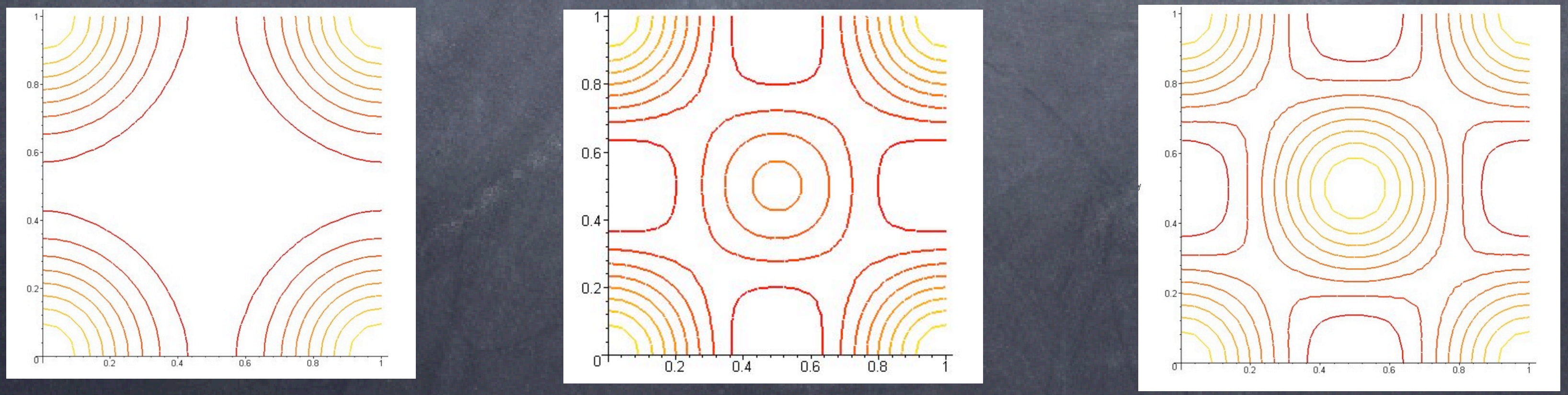

Field distribution as can be measured by neutron

Stiffness engineering?

- p-wave Feshbach resonance can allow for tuning for Fermi liquid parameters

$$H = \sum_{\mathbf{p}} \epsilon(\mathbf{p}) a^\dagger_{\mathbf{p}} a_{\mathbf{p}} + \sum_{\mathbf{p},\alpha} \left[\epsilon_\alpha + \frac{\epsilon(\mathbf{p})}{2} \right] b^\dagger_{\mathbf{p}\alpha} b_{\mathbf{p}\alpha} + \frac{1}{\sqrt{V}} \sum_{\mathbf{p},\mathbf{q},\alpha} g_{\mathbf{p}} p_\alpha \left(b_{\mathbf{q}\alpha} a^\dagger_{\mathbf{p}+\frac{\mathbf{q}}{2}} a^\dagger_{-\mathbf{p}+\frac{\mathbf{q}}{2}} + \mathrm{h.c.} \right)$$

Gurarie, L. Radzihovsky, & A. V. Andreev (05)

- Hope to arrive at a PD where ρ_{sp}/ρ_s can be tuned as a function of microscopic parameter

In search of topological states with half quantum vortices

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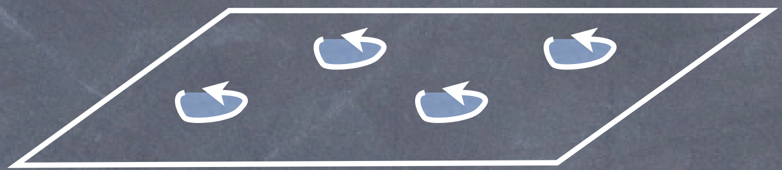
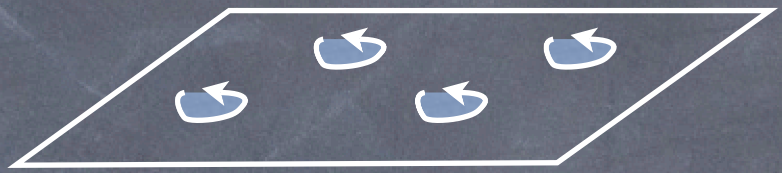
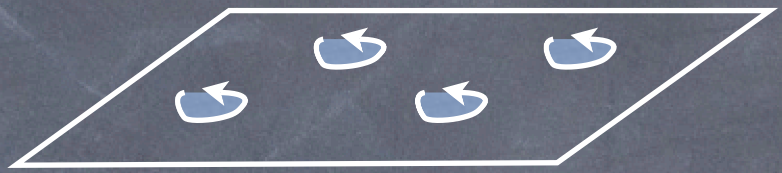


In search of topological states with half quantum vortices



- 1/2 QV's are not stable in bulk systems

In search of topological states with half quantum vortices



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- Mesoscopic samples could favor 1/2 QV's

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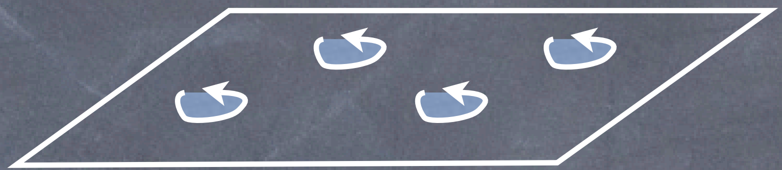

- 1/2 QV's are not stable in bulk systems
- Mesoscopic samples could favor 1/2 QV's
- 1/2 QV Vortex Lattice can be pursued and detected