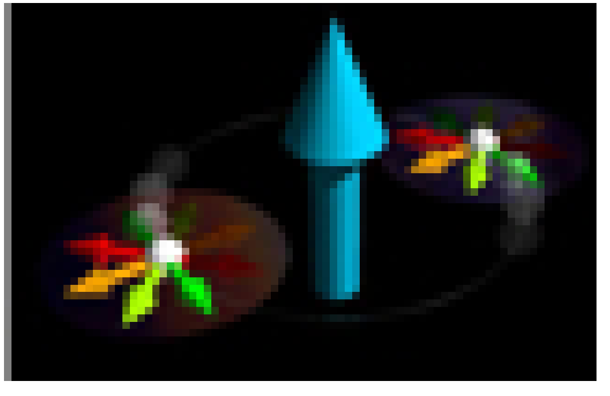
Role of magnetic fields in probing two component chiral p-wave order

Daniel F. Agterberg

University of Wisconsin - Milwaukee

R. Heeb (ETH) R.P. Kaur (UWM), H. Kusunose (Ehine University), M. Sigrist (ETH)



Properties of the E_u state

- $\mathbf{d}=\mathbf{z}(\eta_x f_x + \eta_y f_y)$.
- (η_x,η_y) can be found by minimizing the free energy.

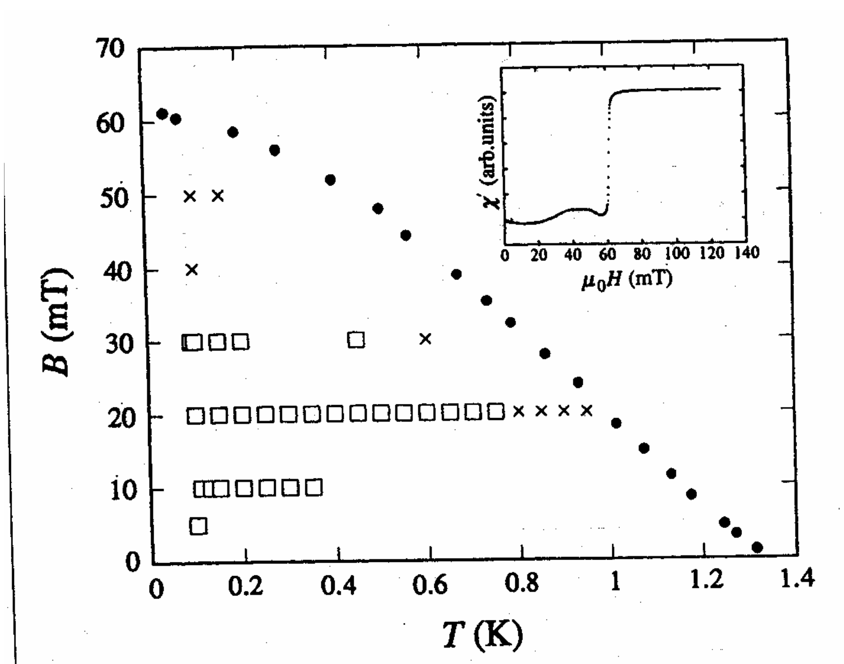
$$(\eta_1,\eta_2) \propto (1,0) \quad \text{Line nodes}$$

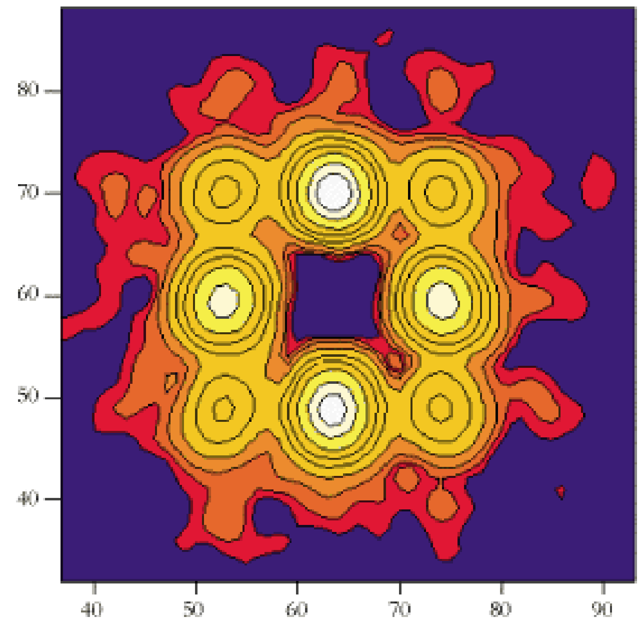
$$(\eta_1,\eta_2) \propto (1,1) \quad \text{Line nodes}$$

$$(\eta_1,\eta_2) \propto (1,i) \quad \text{Nodeless, chiral}$$

- Weak coupling theory wants to use the full density of states so favors the nodeless $\mathbf{d}=\mathbf{z}(f_x+if_y)$ chiral phase ($T_c/T_F=10^{-4}$ for Sr_2RuO_4).

c-axis fields: SANS measurements





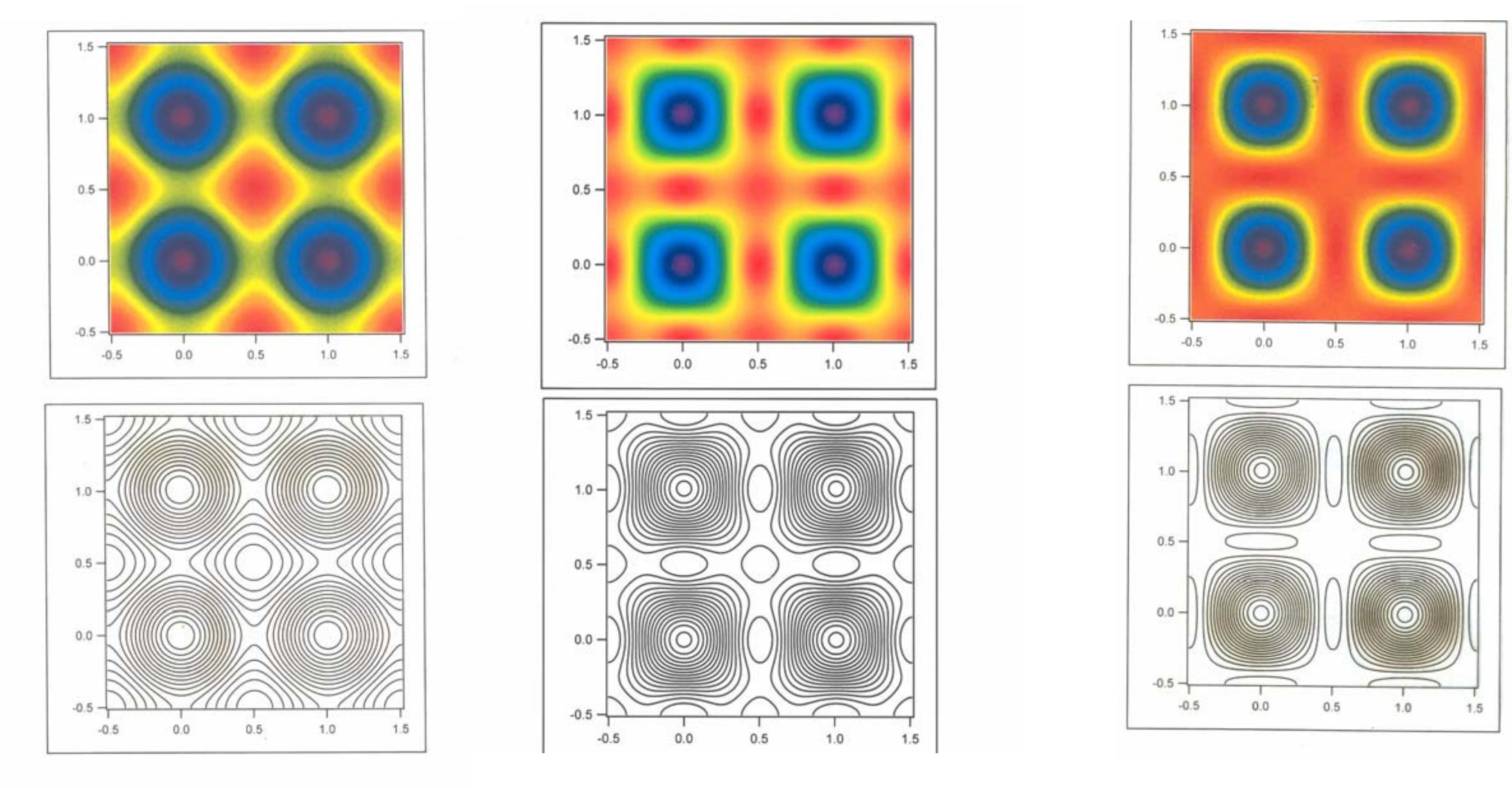
T.M. Riseman *et al*., Nature **396**, 242 (1998)

- From multiple Bragg peaks can determine the field distribution

SANS measurements

- Compare measured field distribution to theory

Abrikosov | E_u State | Measured

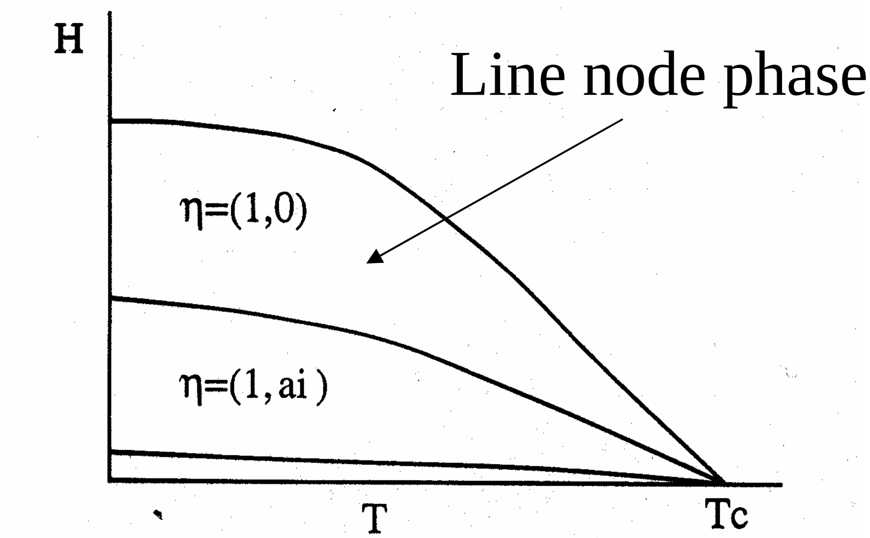


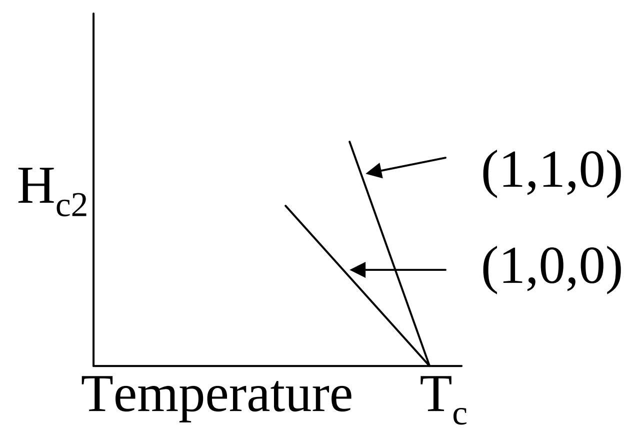
P.G. Kealey *et al.*, PRL **84**, 6094 (2000).

- Consistent with chiral p-wave state.

General Predictions for in-plane fields

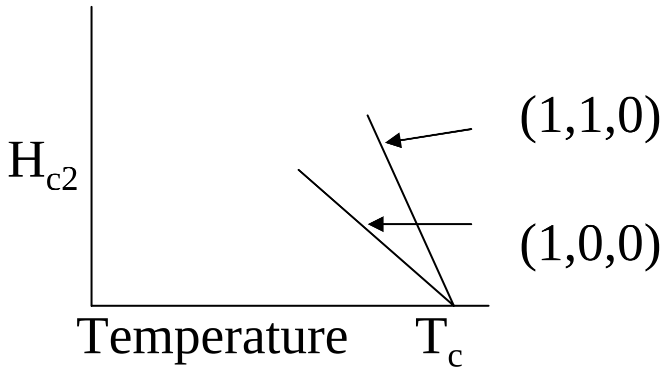
- 1- Multiple phases and phase transitions must exist due to a change in the structure of the order parameter.
- 2- There must exist an in-plane anisotropy in Hc_2 *near* T_c.





D.F. Agterberg, PRL **80**, 5184 (1998). L.P. Gor'kov, JEPT Lett. **40**, 1155 (1984).

H_{c2} anisotropy



Observed anisotropy is less than 1% (Deguchi) – but not zero.

$f_x(\mathbf{k})$	$f_y(\mathbf{k})$	Fermi Surface	$\frac{H_{c2}^{100}}{H_{c2}^{110}}$
v_x	v_y	γ	0.50
$(\cos k_x - \cos k_y)v_x$	$-(\cos k_x - \cos k_y)v_y$	γ	0.86
$\sin k_x \sin k_y v_y$	$\sin k_x \sin k_y v_x$	γ	0.31
$\sin k_x$	$\sin k_y$	γ	0.36
$\mathrm{os}\, k_x - \cos k_y) \sin k_x$	$(\cos k_x - \cos k_y) \sin k_y$	γ	0.51
$\sin^2 k_y \sin k_x$	$\sin^2 k_x \sin k_y$	γ	0.24
v_x	v_y	α	2.0
$(\cos k_x - \cos k_y)v_x$	$-(\cos k_x - \cos k_y)v_y$	α	3.9
$\sin k_x \sin k_y v_y$	$\sin k_x \sin k_y v_x$	α	1.2
v_x	v_y	β	2.5
$(\cos k_x - \cos k_y)v_x$	$-(\cos k_x - \cos k_y)v_y$	β	5.23
$\sin k_x \sin k_y v_y$	$\sin k_x \sin k_y v_x$	β	1.52

Multiple Phases for in-plane Fields

- Due to the breaking of tetragonal symmetry
- For H along x, σ_x is a symmetry for which η_x and η_y have different eigenvalues:

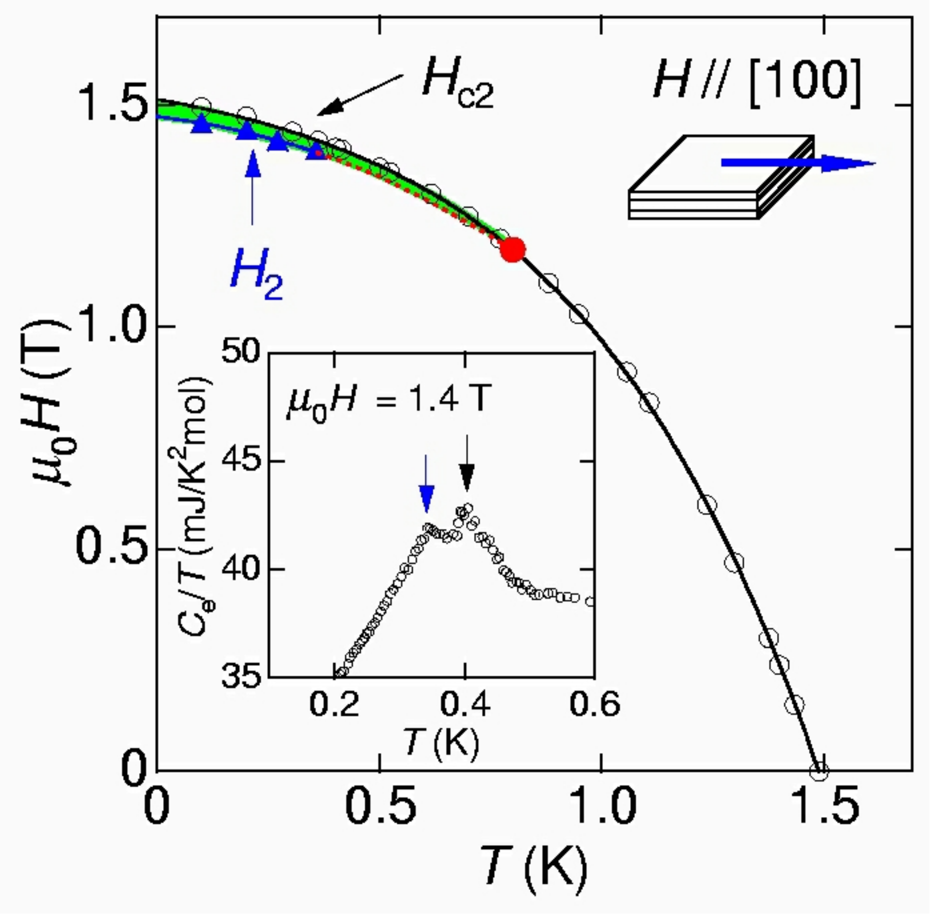
$$\boldsymbol{F} = \kappa_1 \,|\, \boldsymbol{D}_y \eta_y \,|^2 + \kappa_2 \,|\, \boldsymbol{D}_y \eta_x \,|^2$$

$$\kappa_1 \propto < \boldsymbol{v}_y^2 \boldsymbol{f}_y^{\,2} >; \kappa_2 \propto < \boldsymbol{v}_y^2 \boldsymbol{f}_x^{\,2} >; \kappa_1 \neq \kappa_2$$

Either η_x *or* η_y *orders at* Hc_2.

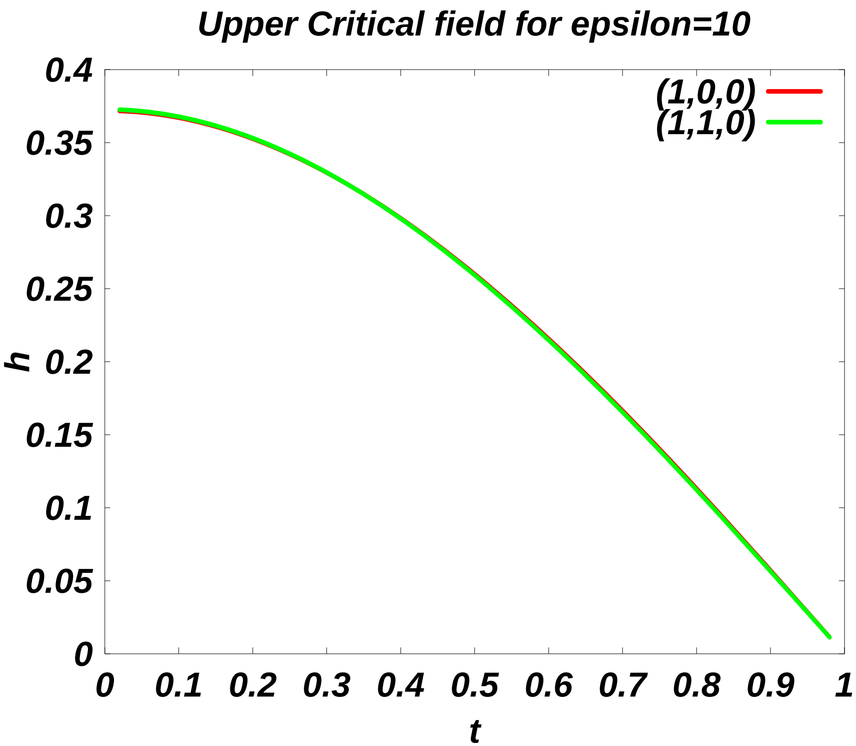
- The second component appears at a *second phase* transition for the chiral ground state when field is along (1,0,0), (0,1,0), (1,1,0), and (1,-1,0).
- For non-chiral ground state (1,1); a second phase transition occurs for fields along (1,0,0) and (0,1,0)

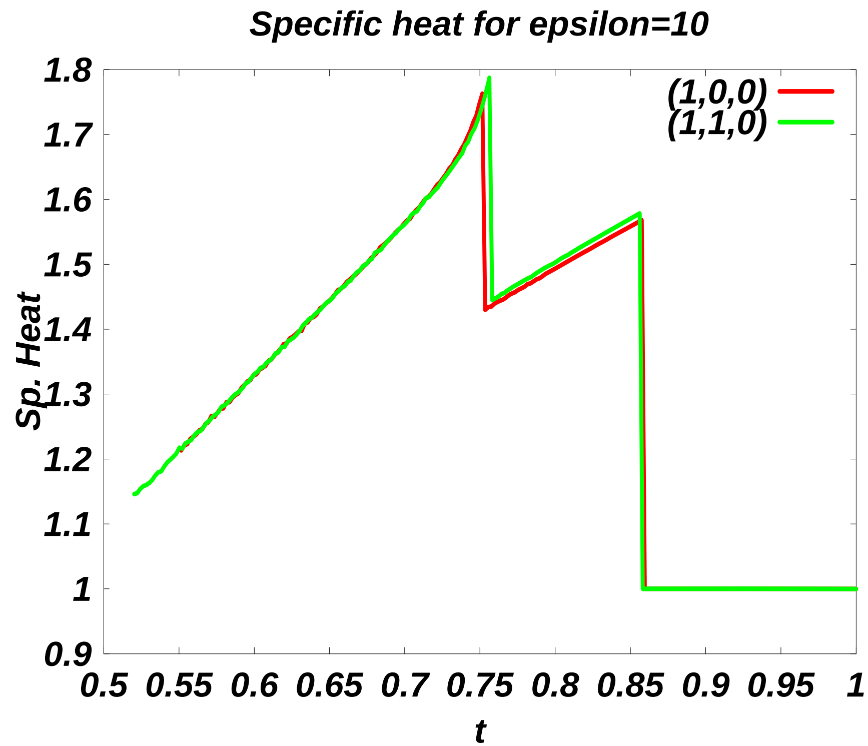
High Field Transitions



Theory predicts multiple transitions for all fields.

Can both vanish at once?





Generally not possible to explain absence of both anisotropy and second specific heat anomaly.

Possible Resolution?

1- Vortex fluctuations mask second transition?

2- In-plane d-vector?

$$\boldsymbol{d} = \hat{\boldsymbol{x}}[\eta_{xx} \boldsymbol{f}_x(\boldsymbol{k}) + \eta_{xy} \boldsymbol{f}_y(\boldsymbol{k})] + \hat{\boldsymbol{y}}[\eta_{yx} \boldsymbol{f}_x(\boldsymbol{k}) + \eta_{yy} \boldsymbol{f}_y(\boldsymbol{k})]$$

- Closely related to half-flux quanta with non-abelian core states (where $\eta_{xx}=i\eta_{xy}, \eta_{yy}=i\eta_{yx}$).
- Will discuss more carefully next week – including a discussion on the role of tetragonal (orbital and spin-orbit) symmetry on half-flux quanta vortices.

Conclusions

- Chiral p-wave is consistent with c-axis square vortex lattice.
- The lack of anisotropy in Hc_2 for in-plane fields can be accounted for within reasonable models.
- The resulting state predicts a phase diagram for in-plane fields with multiple phases which seems inconsistent with experimental results.