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H_{C2} Limiting and the Superconducting Double Transitions in Sr_2RuO_4

Solving the remaining puzzles

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Collaborators on this issue:

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Symmetry of the superconducting state

Experimental identification:

1. Const. inplane spin susceptibility
   (inplane equal-spin pairing: *d//z*)
   There should be no Pauli limiting
   for in-plane field.

2. Intrinsic magnetism (T-violation)
   (out-of-plane orbital moment)

$$\vec{d} = \hat{z} \quad (k_x \pm i k_y)$$

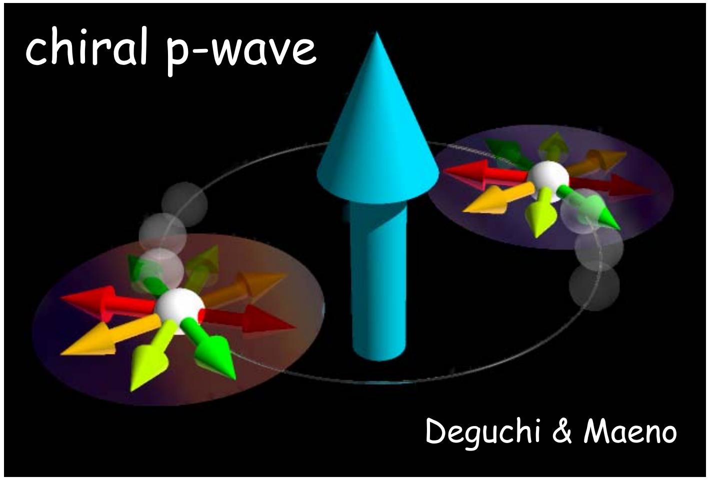
$\hat{z}$ → $\frac{1}{\sqrt{2}}[|\uparrow\downarrow\rangle + |\downarrow\uparrow\rangle]$

$(k_x \pm i k_y)$ → $L_z = +1, -1$

- chiral: orbital magnetic moment
- degeneracy: 2

Chiral p-wave state

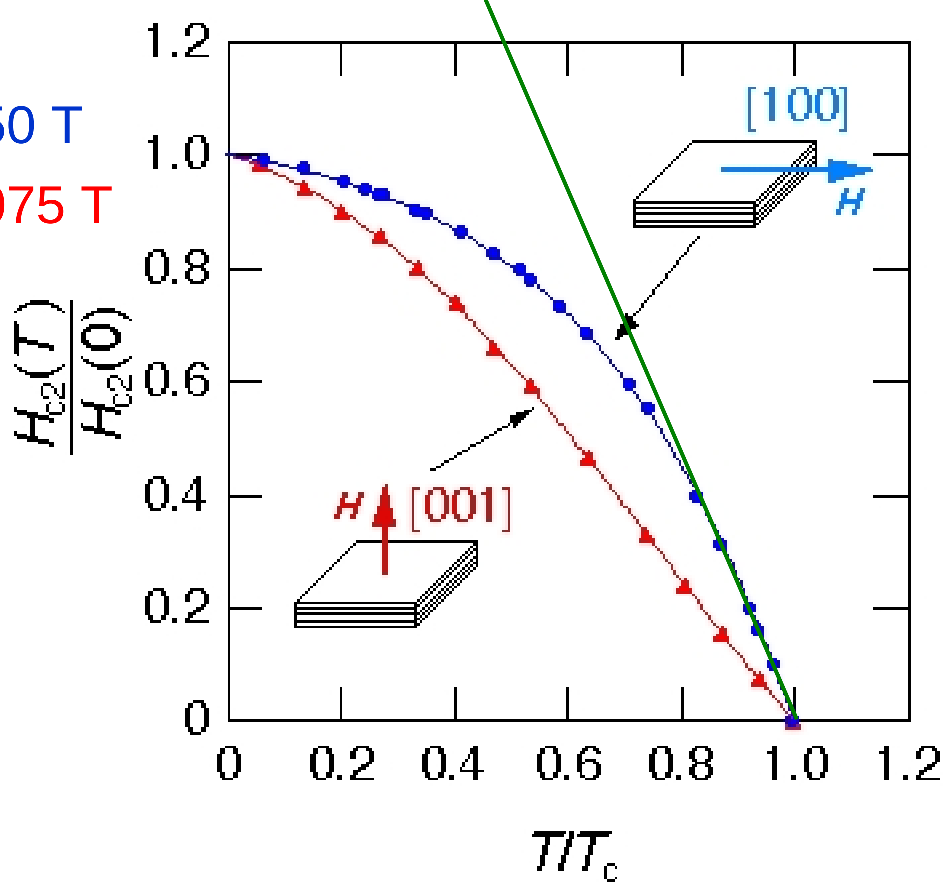
Γ	$\vec{d}$	
A_{1u}	$\vec{d} = \hat{x}k_x + \hat{y}k_y$	B-phase
A_{2u}	$\vec{d} = \hat{x}k_y - \hat{y}k_x$	B-phase
B_{1u}	$\vec{d} = \hat{x}k_x - \hat{y}k_y$	B-phase
B_{2u}	$\vec{d} = \hat{x}k_y + \hat{y}k_x$	B-phase
E_u	$\vec{d} = \hat{z}(k_x \pm ik_y)$	A-phase



Experimental Fact 1:
H_{c2} Limiting Behavior for H//ab

WHH curve would predict
much larger H_{c2}//ab
(Kittaka's presentation)

1.50 T
0.075 T



***H* // c**:
ordinary behavior
(conventional orbital limiting only)

***H* // ab: unusual H_{c2} suppression at low T**

⇕ ?

Pauli limiting should be irrelevant for
***H* // ab.**
(NMR Knight shift shows no change.)

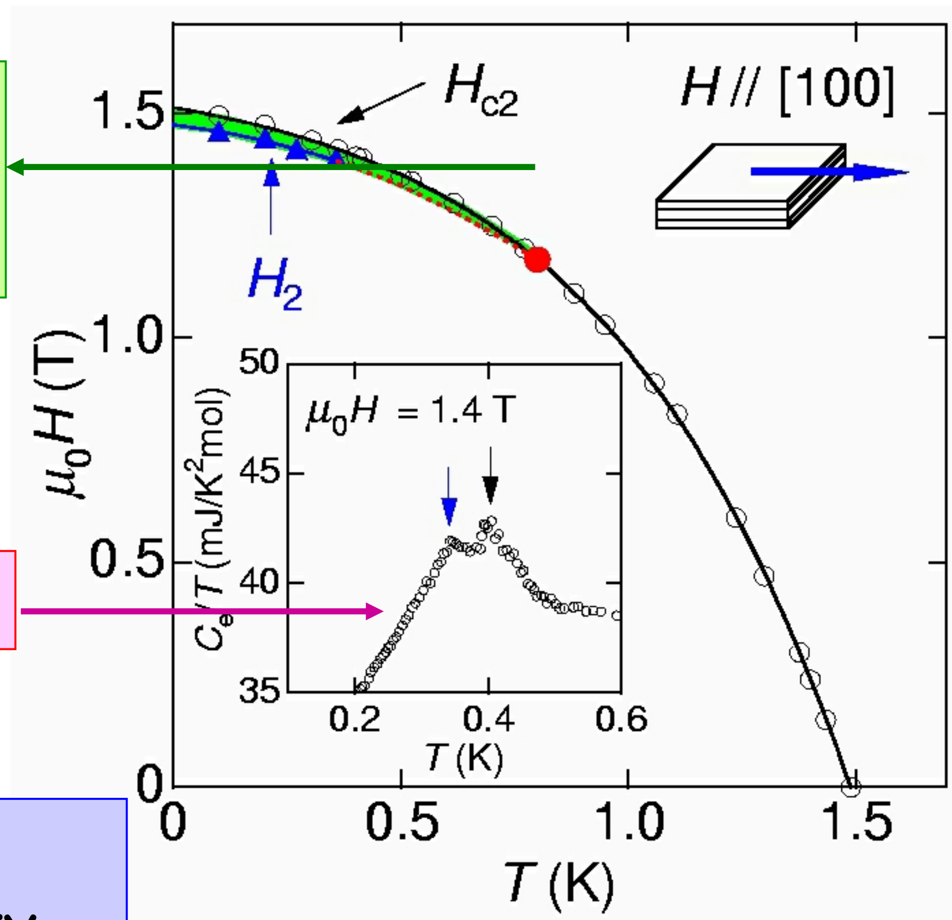
$$\frac{1}{2}\chi H_p^2 = \frac{1}{8\pi} H_c^2 \qquad \mu_0 H_p = 1.6\,\mathrm{T}$$

Experimental Fact 2:
Emergence of a Second Transition: The "Deguchi Phase"

Ru-NMR Knight does not change.

Ishida et al. (2007).

Specific Heat



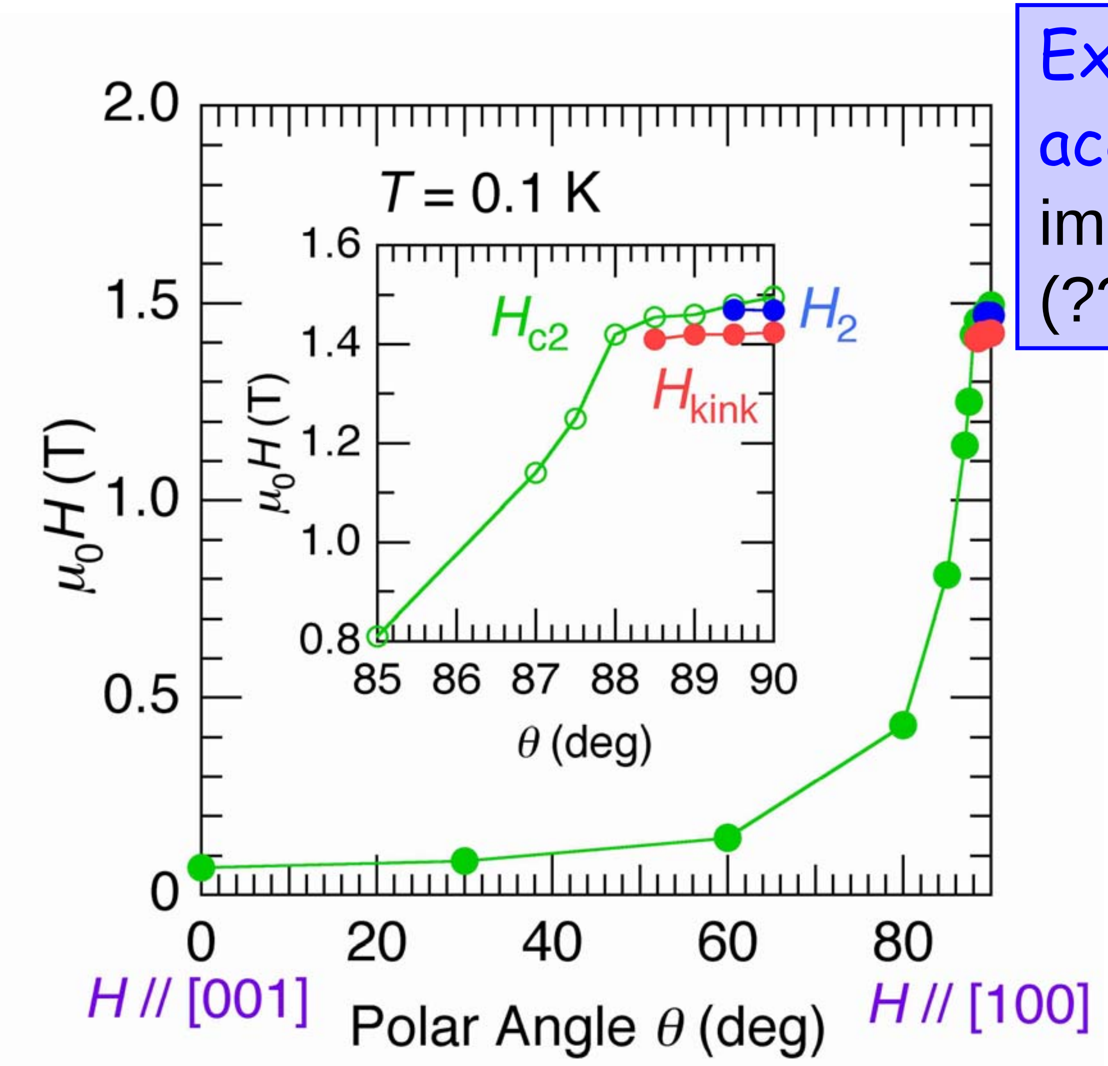
Observed also in thermal conductivity and *AC* susceptibility.

Double transitions

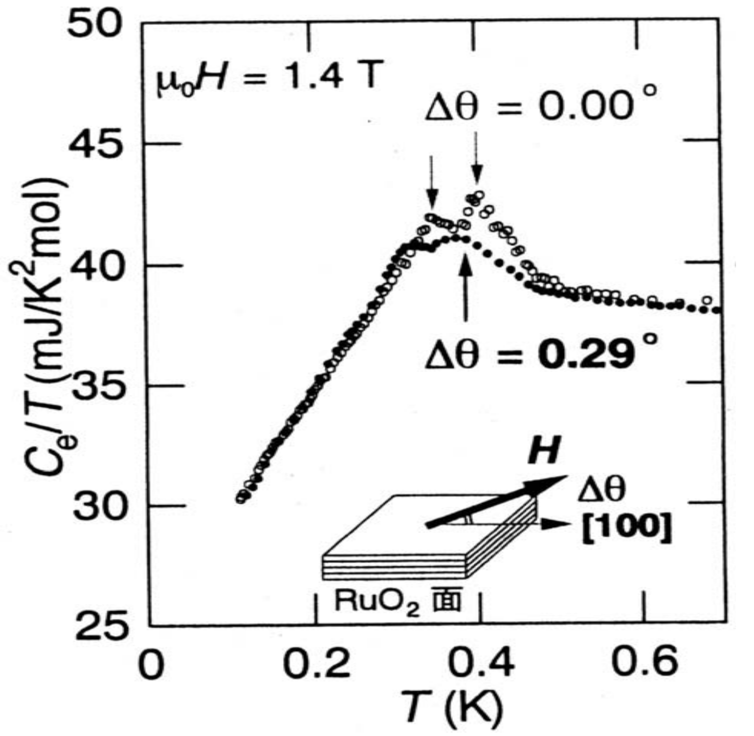
Deguchi *et al.*

Facts 1 and 2:

H_{c2} Suppression and Double Transitions are Linked

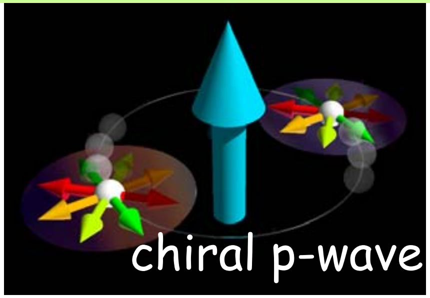


Extreme sensitivity to the accurate field alignment implies orbital mechanism (??).



Proposed models for the second phase

State at zero H: $d = z(k_x + ik_y)$

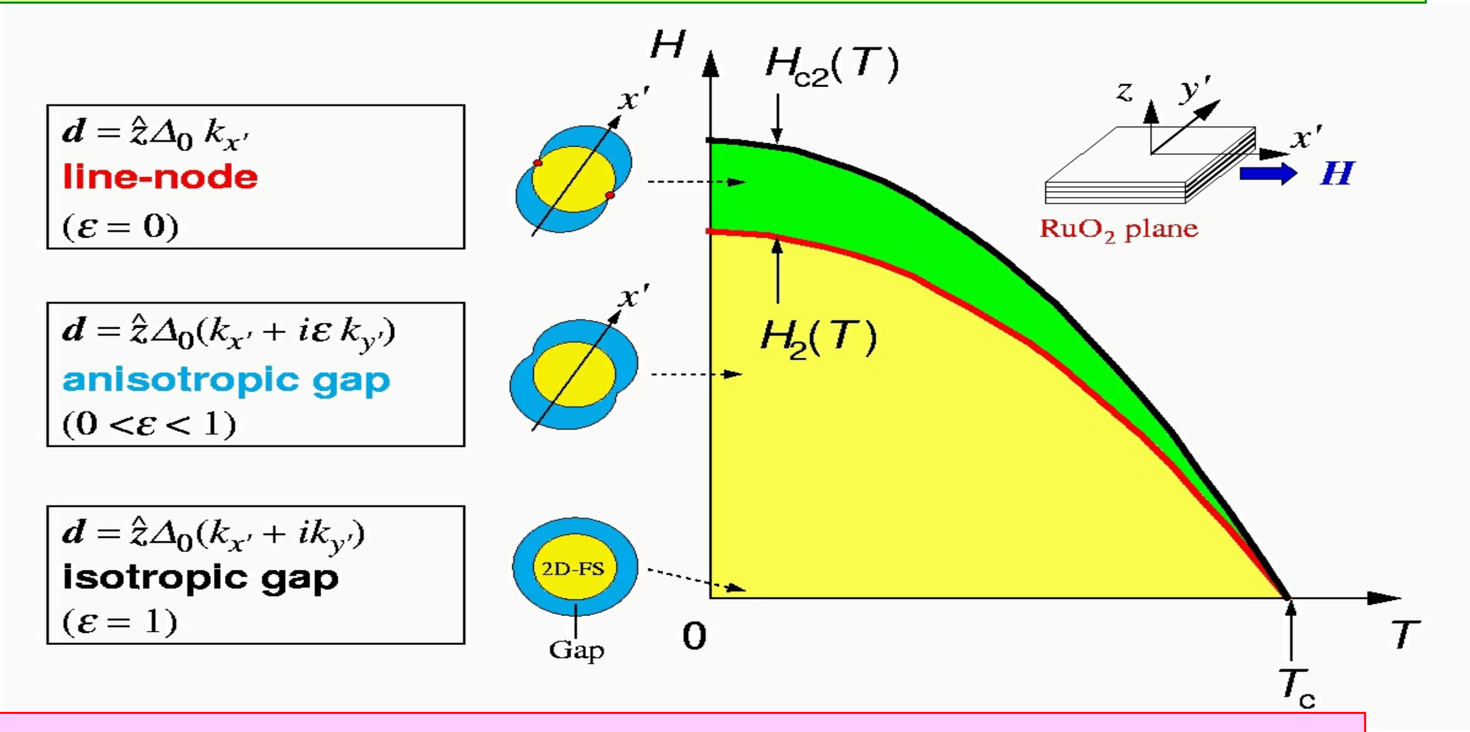


States under $H // x$:

Model	Spin	orb. (low H_x)	orb. (high H_x)	boundary	H_{c2} limiting?
Agterberg et al.	z	$k_x + i\varepsilon k_y$	k_x	2nd-order	No
Udagawa et al.	$z - i\alpha y$	$k_x + i\varepsilon k_y$	k_x	Crossover (Orb. 2nd-order transition at lower H)	No
^{3}He-A1	$z - i y$	$k_z - ik_y$ $\ell // d$ by dipole int.		2nd-order	No

Double Transitions: Theoretical Expectation

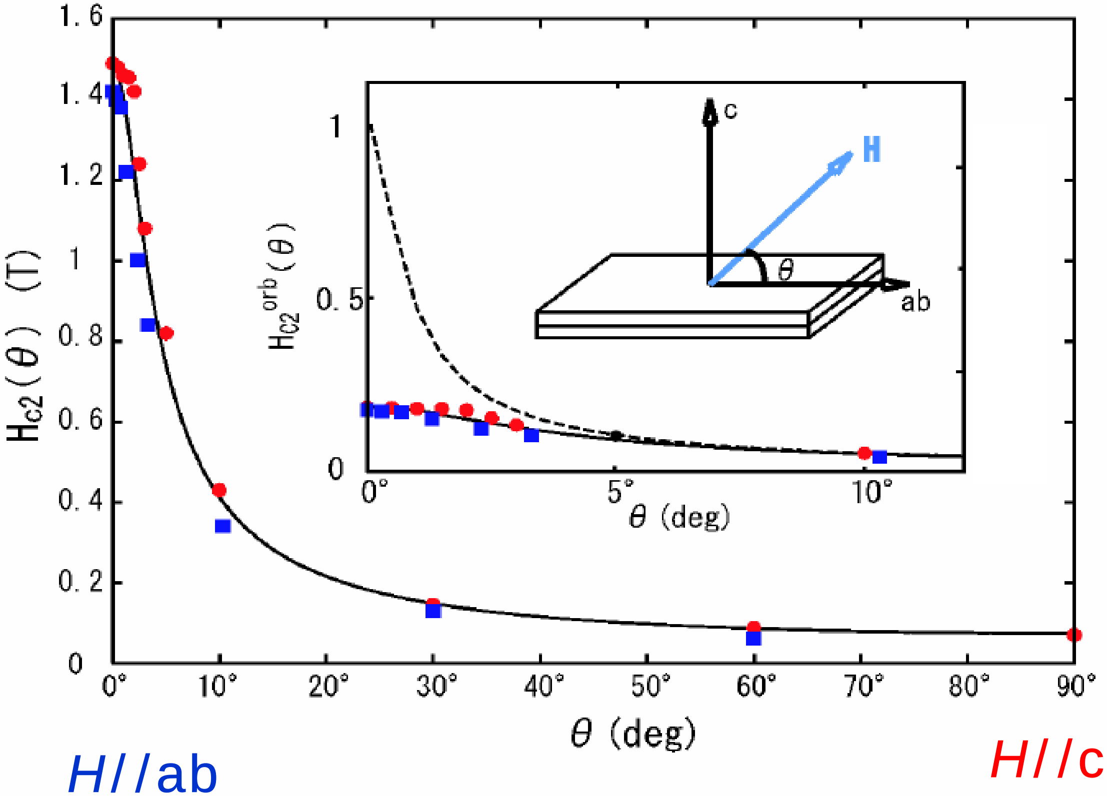
Orbital Scenario: D. Agterberg, PRL **80**, 5184 (1998);
Kaur, Agterberg, and Kusunose, PR B**72**, 144528 (2005).
Some extension to simulate the experimental results



Spin + orbital scenario: M. Udagawa *et al.*, JPSJ **74**, 2905 (2005).
considers a non-unitary state $(z - i\alpha y)\ k_x$ just below H_{c2}.
i.e., $|\uparrow\uparrow\rangle_x$ component.

In both scenarios, k_z **is ignored** because of Q2D.

The H_{c2} Suppression:
Can it be explained by Pauli limiting?



Machida and Ichioka (2007)

$$\frac{H_{c2}(\theta)}{H_{c2}^{orb}(\theta=0)} = \frac{1}{\sqrt{\Gamma^2 \sin^2\theta + \cos^2\theta + 2.4\mu_0^2}}$$

Need to use

Γ (anisotropy of ξ) = 107

Γ may be estimated from the H_{c2} ratio near T_c.

Experimentally,

Γ ($T \to T_c$) *is not so large.* (Kittaka's presentation).

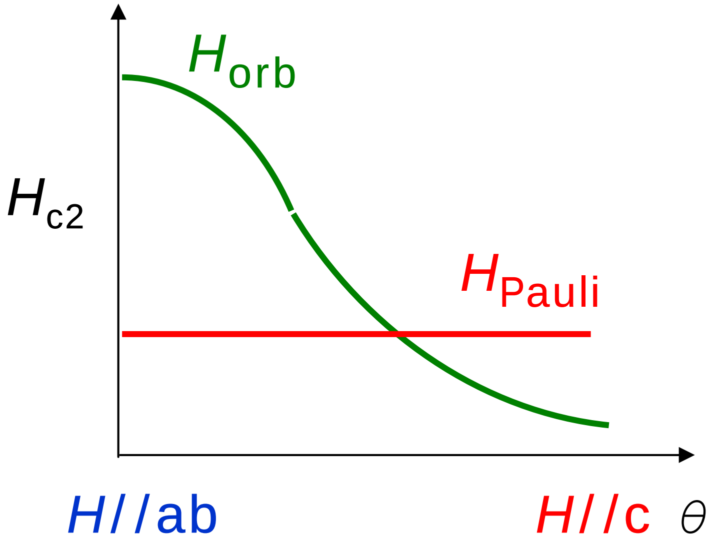
A single-band model is not appropriate, either.

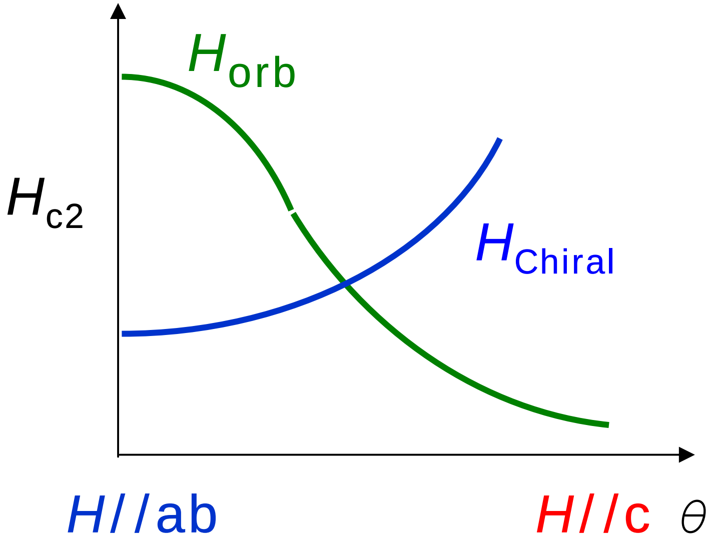
Origin of H_{c2} (//ab) Limiting in Sr_2RuO_4

1. Pauli Limiting theory is interesting.

   But it is NOT consistent with thermodynamic and other observations.

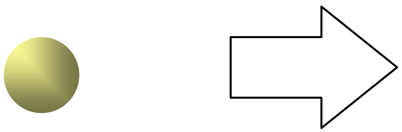
2. Novel *ORBITAL* limiting mechanism specific to the chiral triplet pairs seems to be operative for *H//ab*.

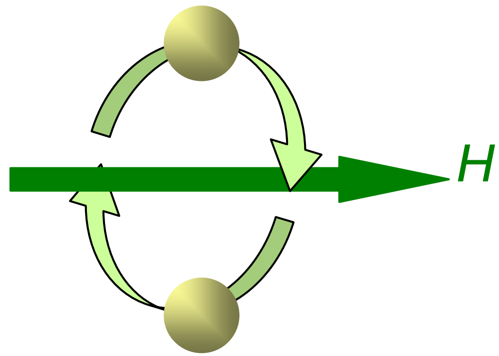




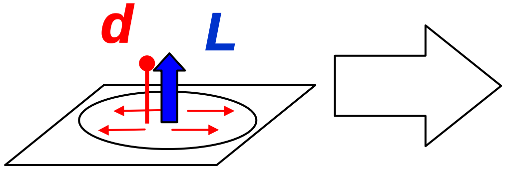
Additional Orbital Depairing Mechanism?

Spin singlet

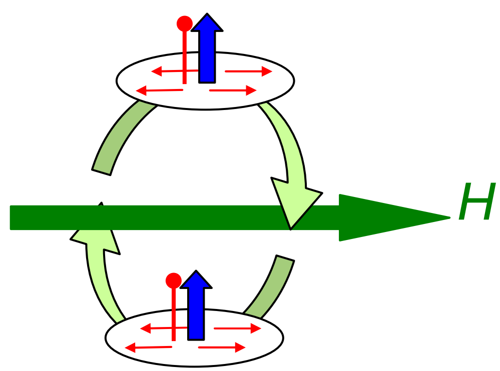




Chiral spin triplet



$d = z\,(k_x + ik_y)$

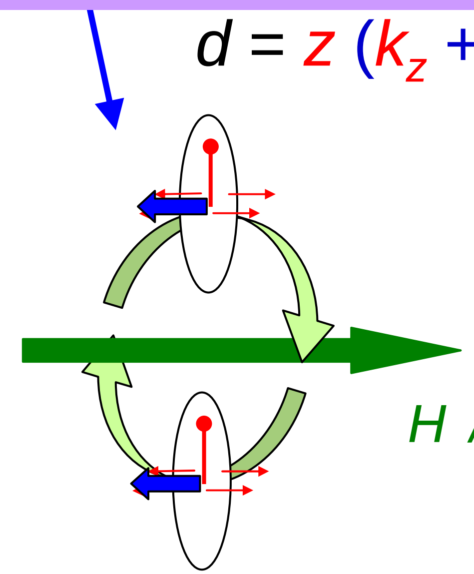


Conventional orb. limiting.

This state must

This effect should be too small and negligible.
I.A.Luk'yanchuk and V.P.Mineev, JETP **66**, 1168 (1987).

$d = z\,(k_z + ik_y)$



Additional effect due to the L-vector of a Cooper pair.

Proposed models for the second phase

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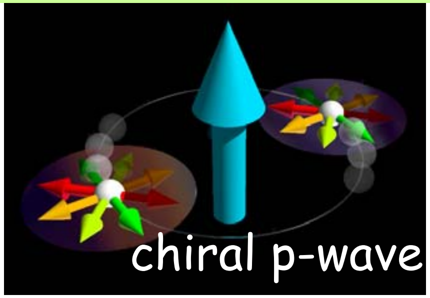

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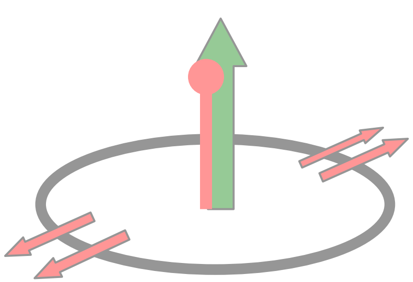
New	$z - i\alpha y$	$k_x + i\varepsilon k_y$ $\ell // z$	$k_z - ik_y$ $\ell // x$	?	Yes? negligible
^{3}He-A1	$z - iy$	$k_z - ik_y$		2nd-order	No

Alternative Interpretation

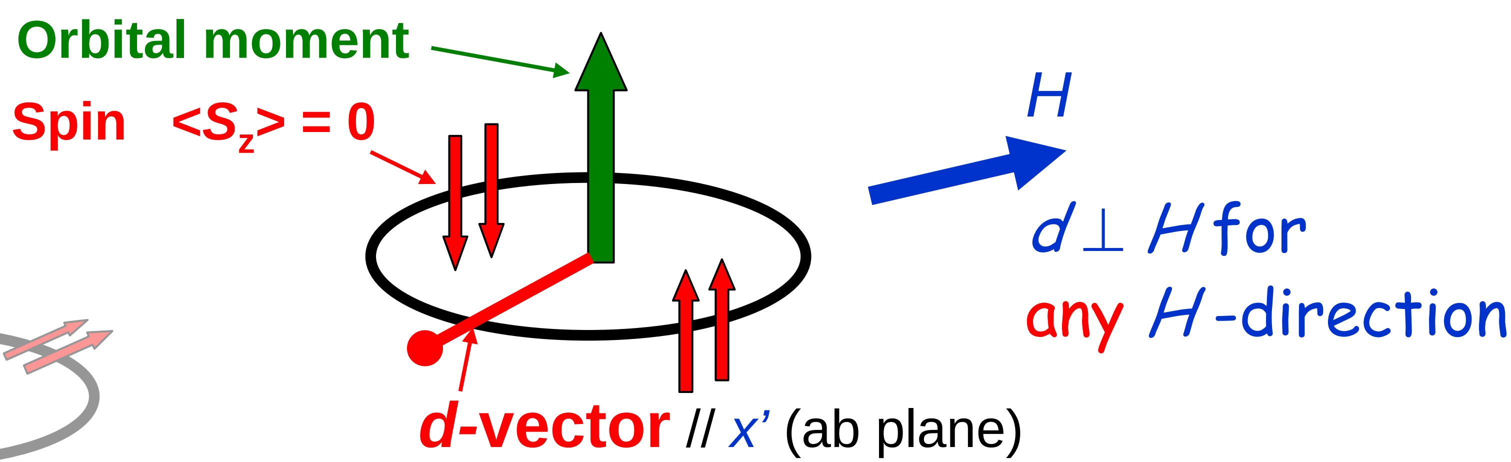
At $H=0$, $d = x'(k_x + ik_y)$:
The spin component pointing
in any direction within the *ab* plane.

Yoshioka, Hoshihara, Miyake

d-p model with Upp (O-2p on-site Coulomb) suggests *d* // ab.



$d = z\,(k_x + ik_y)$



$d = x'\,(k_x + ik_y)$

END