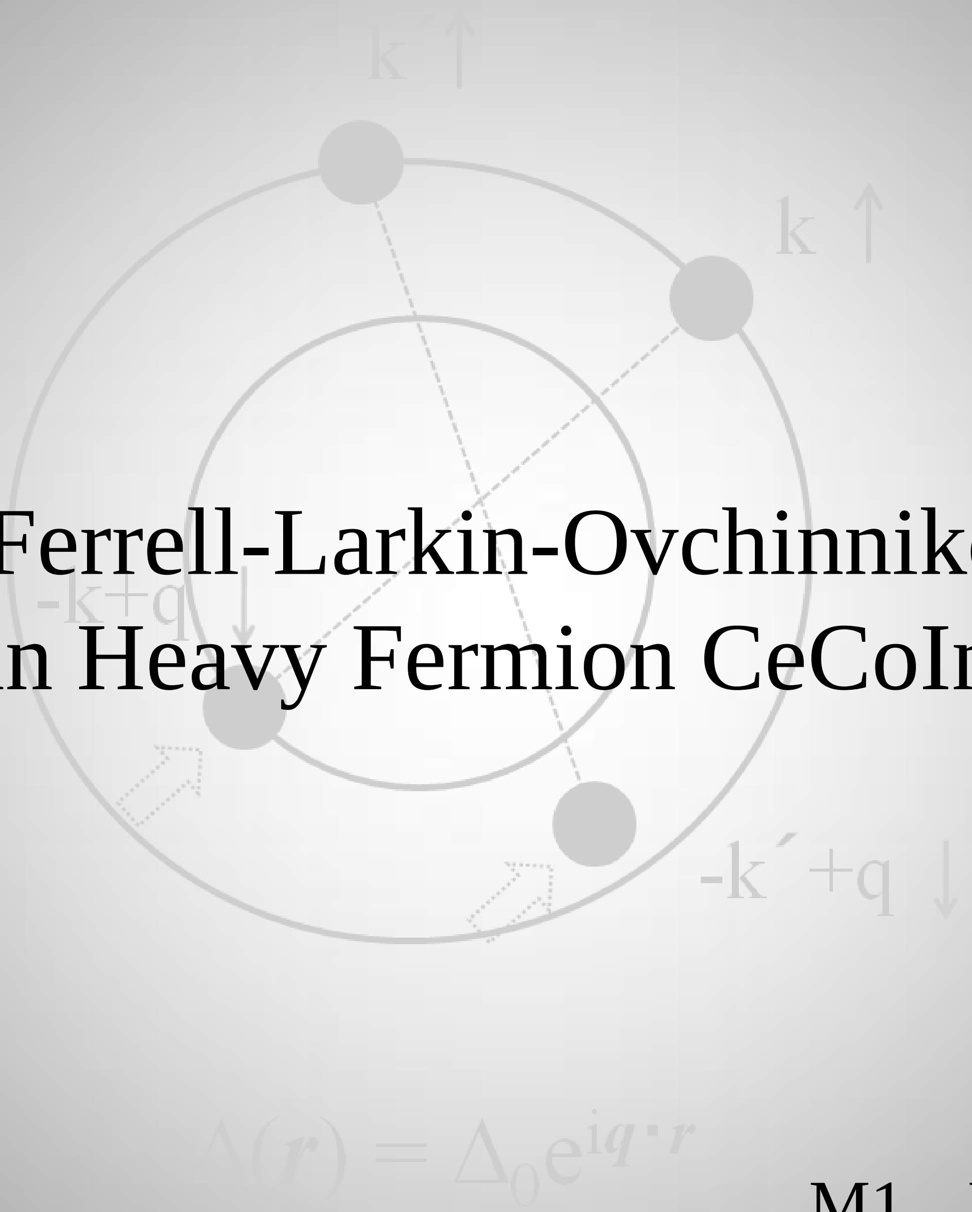
Fulde-Ferrell-Larkin-Ovchinnikov State in Heavy Fermion $CeCoIn_5$



M1　Mizukami Yuta

Introduction

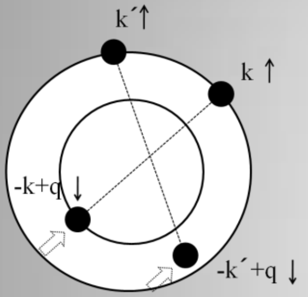
FFLO state : Unconventional state(SC) predicted by
Fulde, Ferrell, Ovchinnikov, and Larkinin in 1964

Cooper pair with finite center-of-mass momentum *q* in high field *H*

Pairing in FFLO state

(*k*↑、-*k*+*q*↓)

$$q = \frac{2\mu_B H}{\hbar v_F}$$



$$\Delta(\boldsymbol{r}) = \Delta_0 e^{i\boldsymbol{q}\cdot\boldsymbol{r}}$$

Order parameter : oscillatory

- More realistic state than BCS state under a certain condition
- Order parameters of the two degenerate states

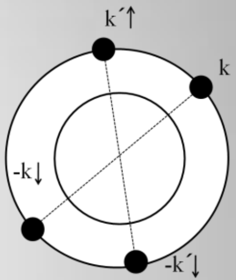
$\Delta(\boldsymbol{r}) = \Delta_0 e^{i\boldsymbol{q}\cdot\boldsymbol{r}}$
$\Delta(\boldsymbol{r}) = \Delta_0 e^{-i\boldsymbol{q}\cdot\boldsymbol{r}}$:FF state

→linear combination

$\Delta(\boldsymbol{r}) = 2\Delta_0\cos(q\cdot r)$: LO state

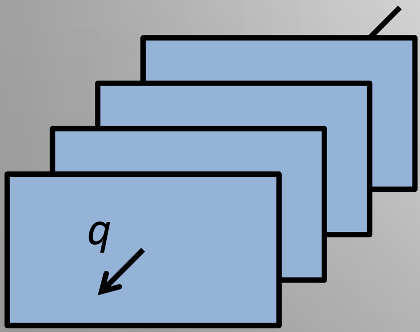
Pairing in BCS state

(*k*↑、-*k*↓)



$$\Delta(\boldsymbol{r}) = \Delta_0$$

Order parameter : constant



$\Delta(\boldsymbol{r}) = 0$

LO state:
Planar nodes
perpendicular to
wave vector *q*

The condition in which the FFLO state realizes
- orbital limit > Pauli limit
- clean limit
- 2-dimentional Fermi surface

Introduction

Orbital limit and Pauli limit in type Ⅱ superconductor

- orbital limit

Linearized GL eq. $-\frac{\hbar^2}{2m^*}[\nabla-\frac{ie^*}{\hbar}A]^2\Psi(r)+\alpha\Psi(r)+\cancel{\beta}\Psi^3(r)=0$ (near the transition point)

$\rightarrow H_{\mathrm{c2}}^{\mathrm{orb}}(T)=\frac{\phi_0}{2\pi\xi^2(T)}$: Condensed state is destroyed by vortexes.

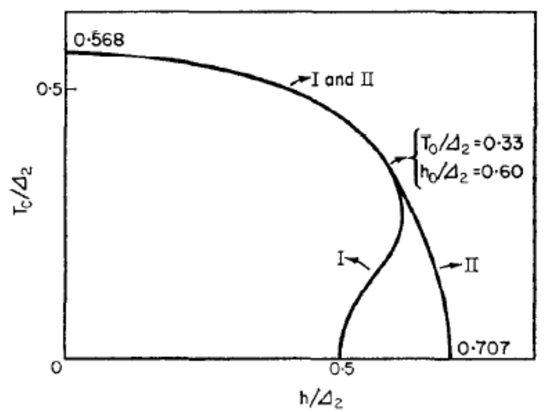
- Pauli limit

$E_{\mathrm{c}}=\frac{1}{2}N(0)\Delta^2$:condensation energy

$E_{\mathrm{p}}=\frac{1}{2}\chi_{\mathrm{n}}H^2$:Zeeman energy ($\chi_{\mathrm{n}}=\frac{1}{2}(g\mu_{\mathrm{B}})^2N(0)$)

$E_{\mathrm{c}}=E_{\mathrm{p}}\ \rightarrow\ H_{\mathrm{c2}}^{\mathrm{P}}=\frac{\sqrt{2}\Delta}{g\mu_{\mathrm{B}}}$: Condensed state is destroyed by Pauli paramagnetic effect.

Phase transition can be first order below a certain temperature.



G. Sarma, J. Phys. Chem. Solids. **24**, 1029 (1963).

※Maki parameter

$\alpha=\frac{\sqrt{2}H_{\mathrm{c2}}^{\mathrm{orb}}}{H_{\mathrm{c2}}^{\mathrm{P}}}\propto\frac{\Delta}{\varepsilon_{\mathrm{F}}}$ (<< 1 conventional superconductor)

Introduction

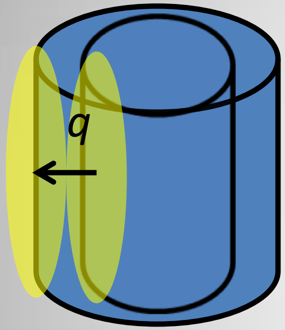
Clean limit

Nonmagnetic impurity is very harmful to the FFLO state.

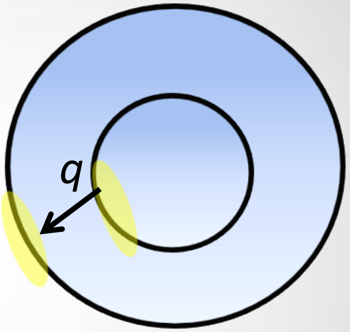
2-dimenstional Fermi surface

Fermi surfaces split by Zeeman effect should be fit by translation.

→2-D more favorable than 3-D



2-dimentional Fermi surface

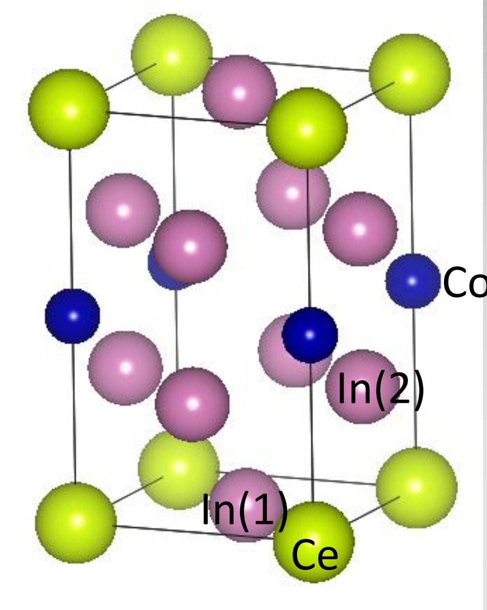


3-dimentional Fermi surface

Candidate systems for the FFLO state which meet the upper conditions

- organic SC
- cold atoms
- astrophysics
- nuclear physics

Heavy fermion $CeCoIn_5$

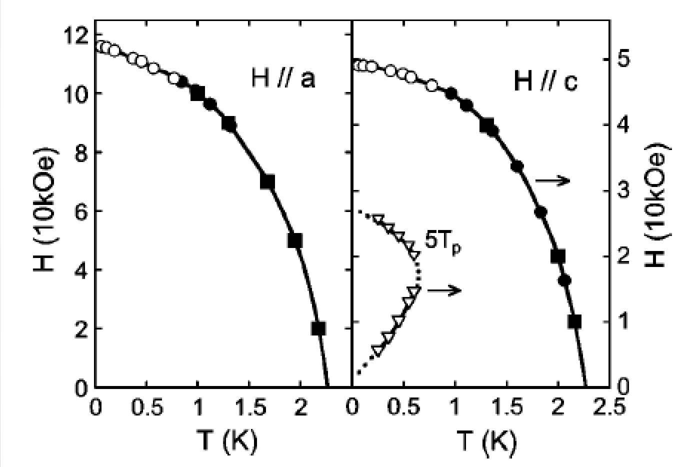


$CeCoIn_5$

Tetragonal structure T_c = 2.3 K

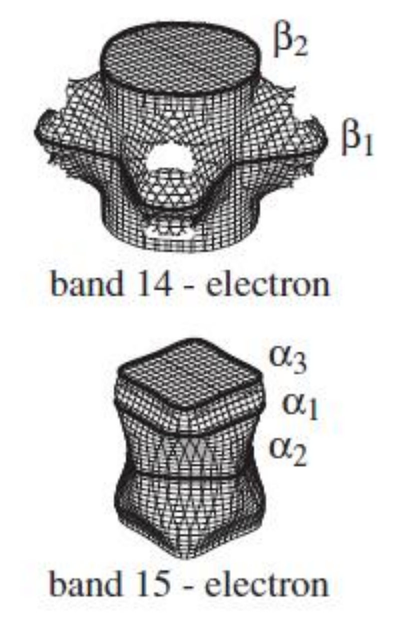
$\gamma \sim$ 1000 mJ/K^2mol($\sim$1-10 for normal metal)

- first order phase transition *at* H_{c2} → indicating Pauli limit
- $CeIn_3$-$CoIn_2$ layered-structure → 2-dimensional



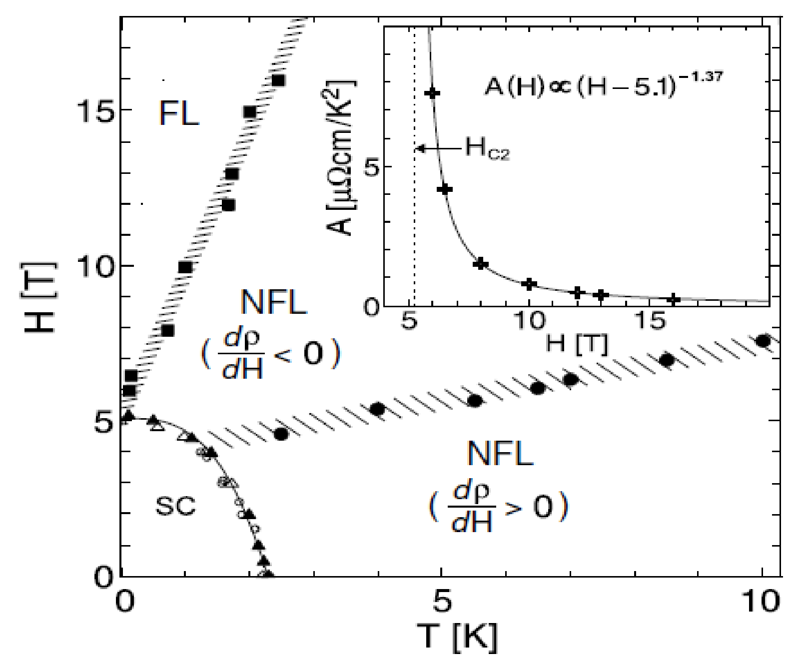
T. Tayama *et al*., Phys. Rev. B. **65**, 180504 (2002).

✔Maki parameter : α = 4.6(*H // a*), 5.0(*H//c*)
✔mean free path : *l* ∼ 3000 nm (∼10 nm for free electron)
✔2-dimentional Fermi surface →

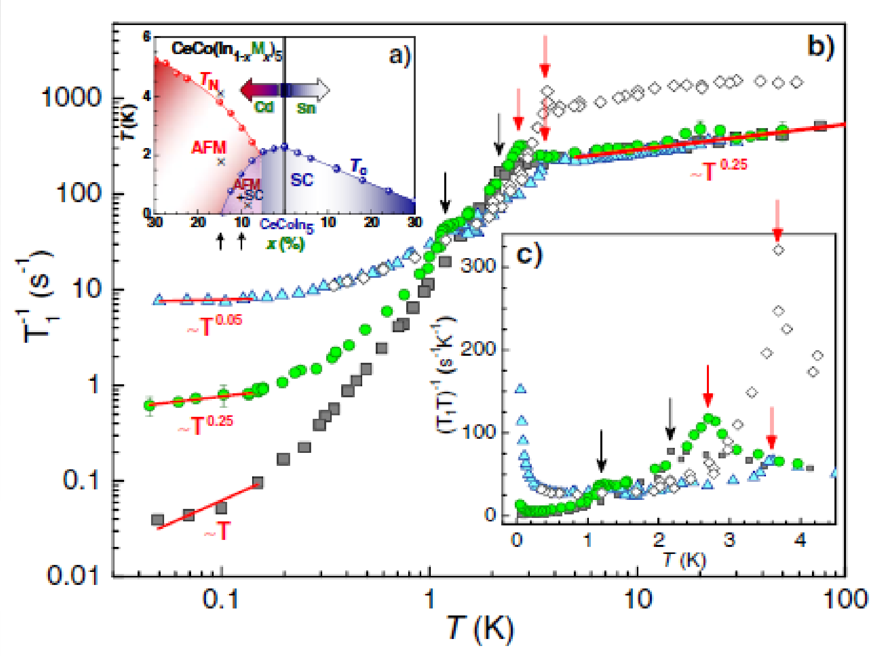


H. Shishido *et al*., J. Phys. Soc. Jpn. **74**, 1103 (2005).

Heavy fermion CeCoIn_5



J. Paglione *et al.*, Phys. Rev. Lett. **91**, 246405 (2003).



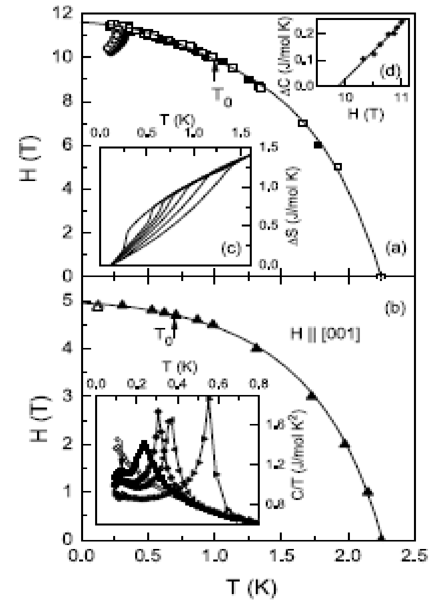
R. R. Urbano *et al.*, Phys. Rev. Lett. **99**, 146402 (2007).

- $\rho - \rho_0 \propto T$: Non-FL
- Divergence of A value near the $H_{c2}(T = 0)$

→ Quantum critical point near the $H_{c2}(T = 0)$

- AFM induced by Cd dope(hole)

Heavy fermion CeCoIn$_5$



A. Bianchi *et al*., Phys. Rev. Lett. **91**, 187004 (2003).

New phase in high-field and low-temperature(HFLT) region

- Specific heat measurement :
  branch of the 2-order
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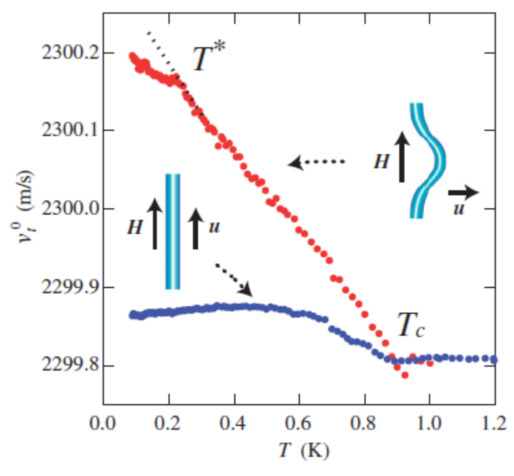
- Ultrasound measurement :
  Lorentz mode (red line)
  with a cusp at *T**
  →'softening' of vortexes
  because of planar nodes



Y. Matsuda *et al*., J. Phys. Soc. Jpn. **76**, 051005 (2007).

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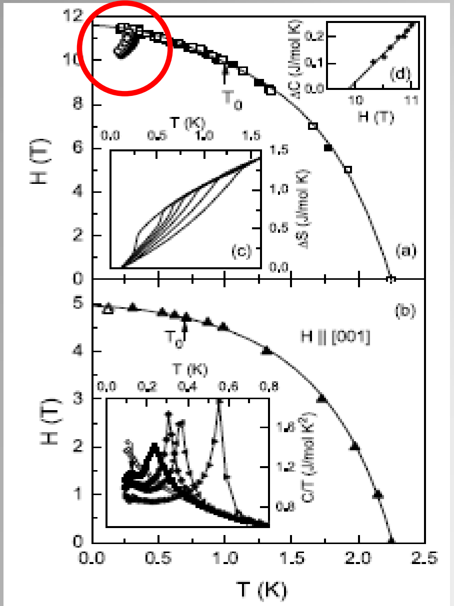

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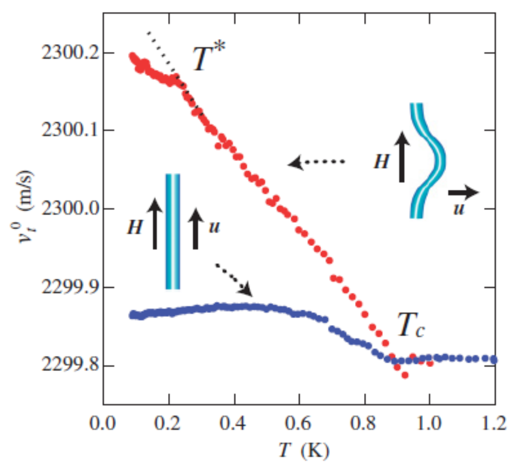

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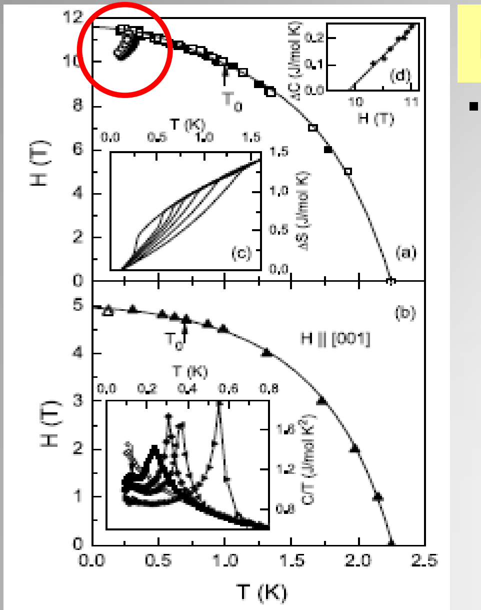

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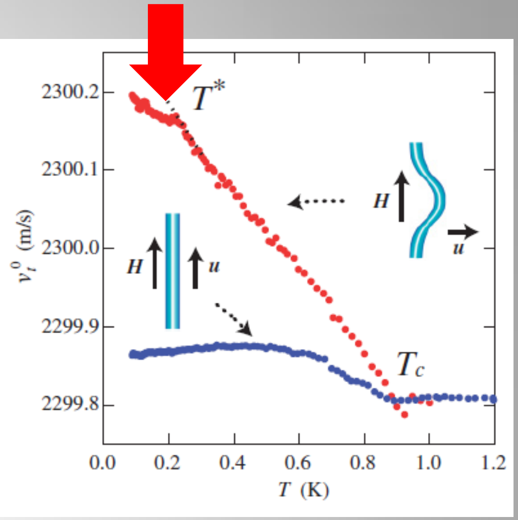

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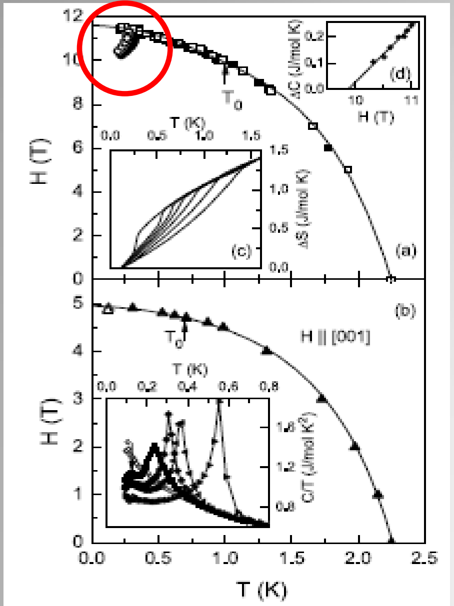

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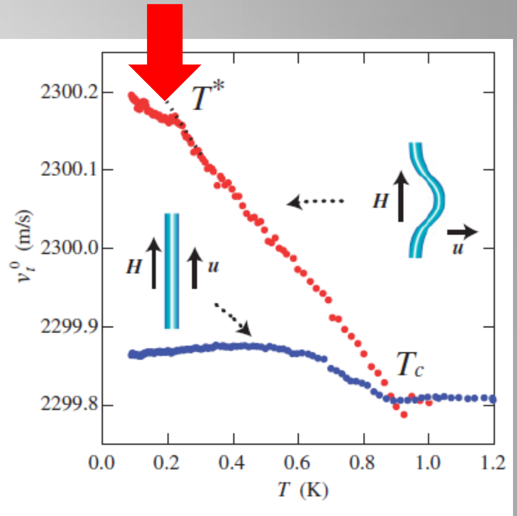

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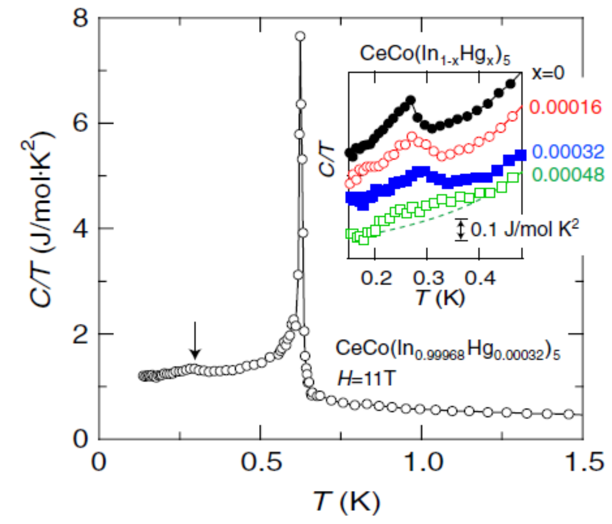

Y. Tokiwa *et al*., Phys. Rev. Lett. **101**, 037001 (2008).

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Heavy fermion $CeCoIn_5$

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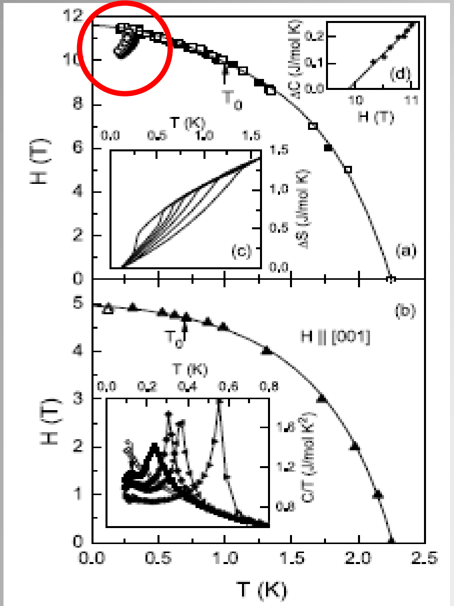

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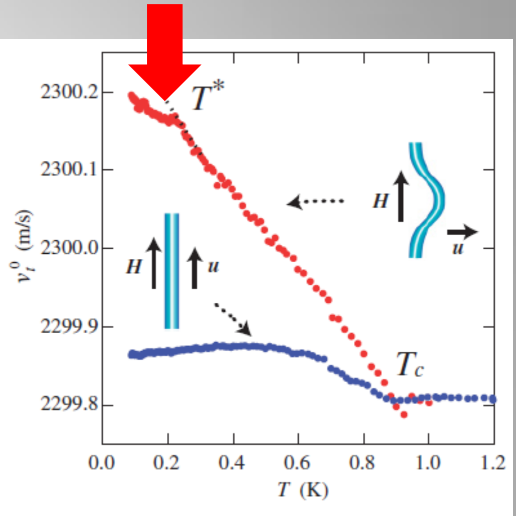

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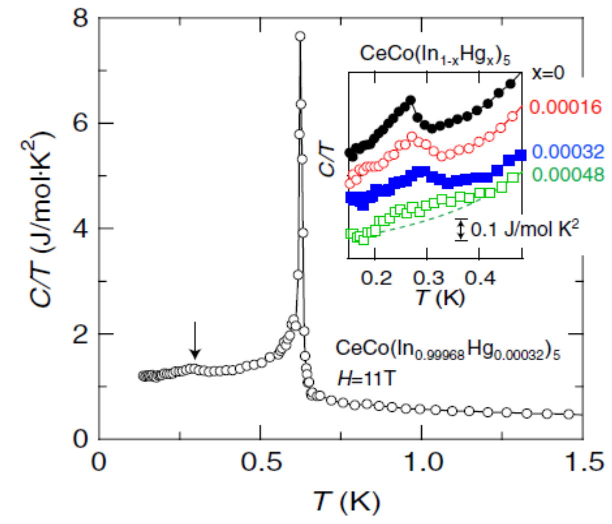

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- stability against suppression of
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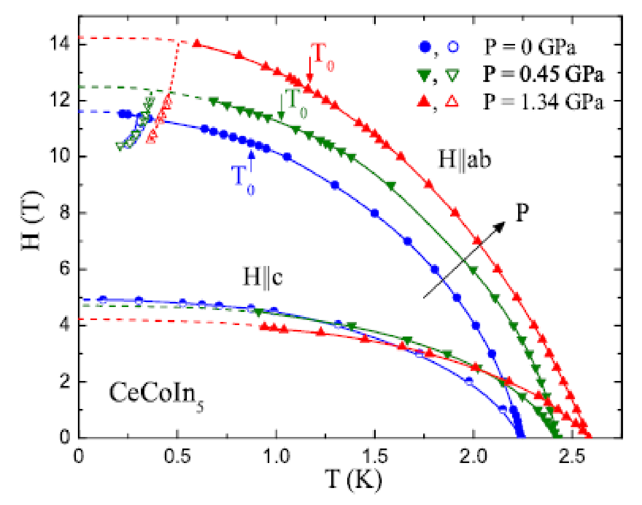
  →irrelevant to AFM

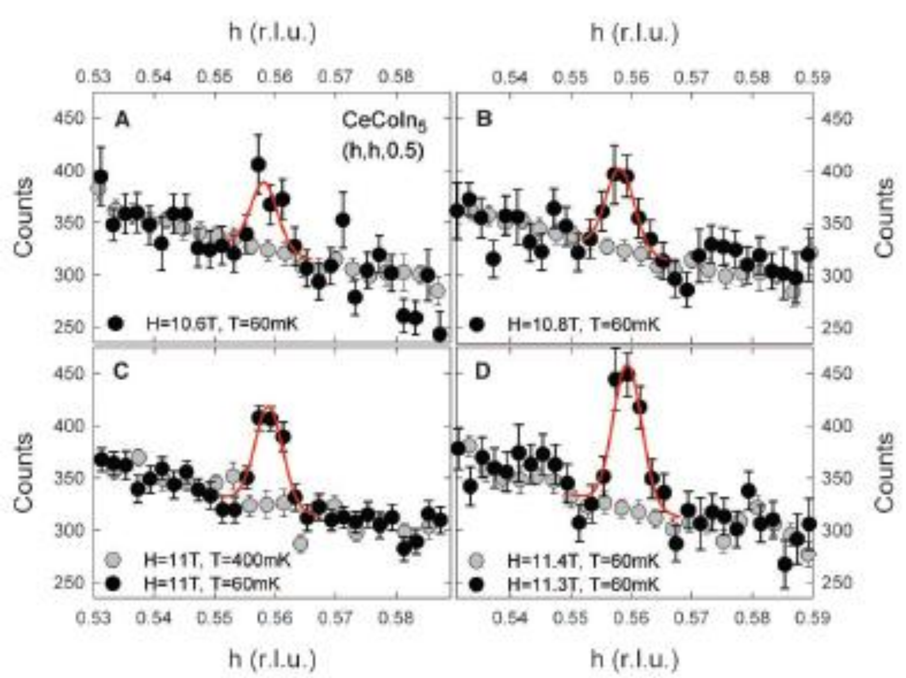


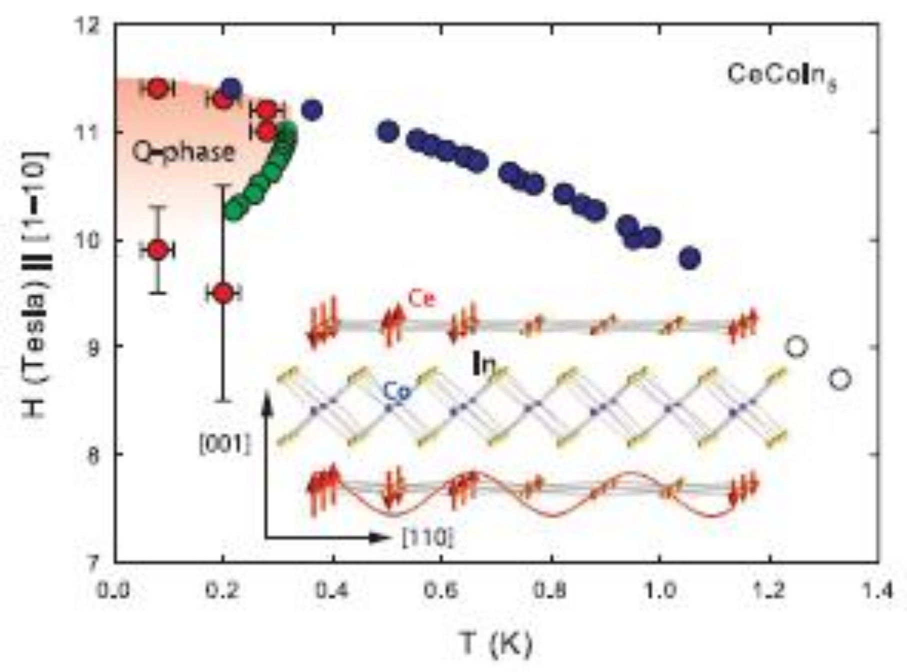
C. F. Miclea *et al*., Phys. Rev. Lett. **96**, 117001 (2006).

Neutron diffraction measurement

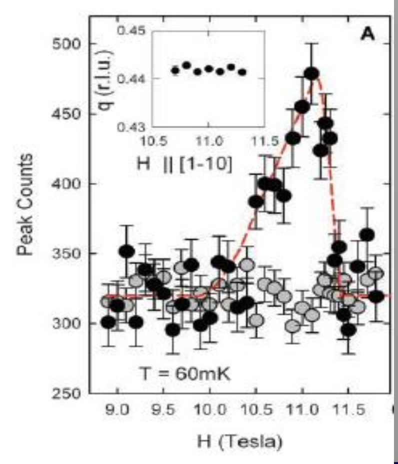
M. Kenzelmann *et al*., Science **321**, 1652 (2008).

H // [1-10] (*h*,*h*,0.5)





- magnetic order scale: 60 nm >> vortex core scale:∼10 nm
- magnetic structure $\mathbf{Q}=(\frac{1}{2}+q,\frac{1}{2}+q,\frac{1}{2})$ q = 0.06 $\mathbf{S}\perp\mathbf{H}\perp\mathbf{q}$ $\mu_0=0.15\mu_B$
- q : H - independent In FFLO state $q=\frac{2\mu_B H}{h v_F}$ →inconsistent with FFLO



Incommensurate(IC) magnetic order
→ SC gap function that carries finite momentum

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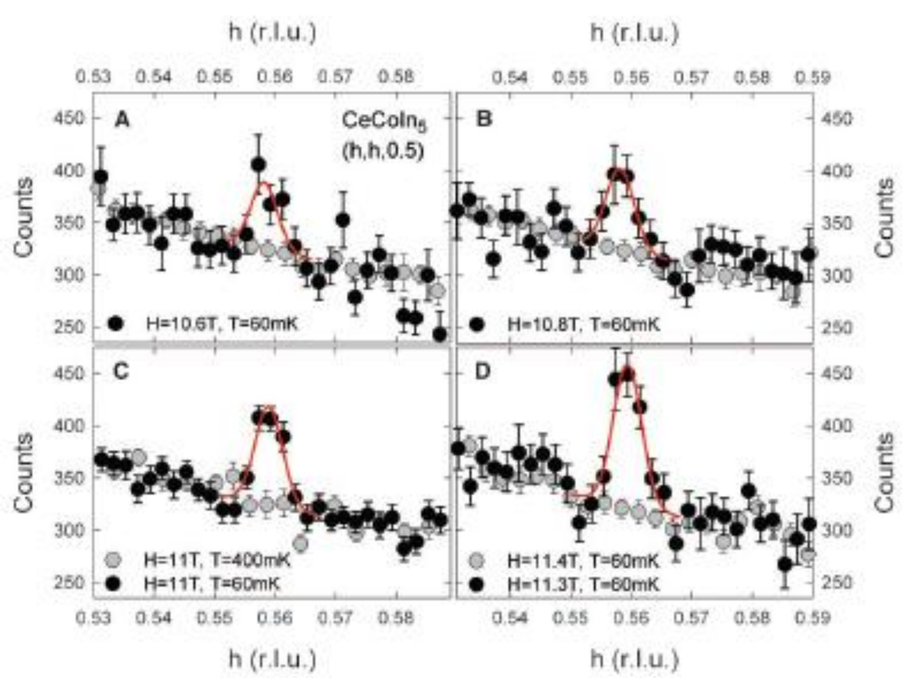

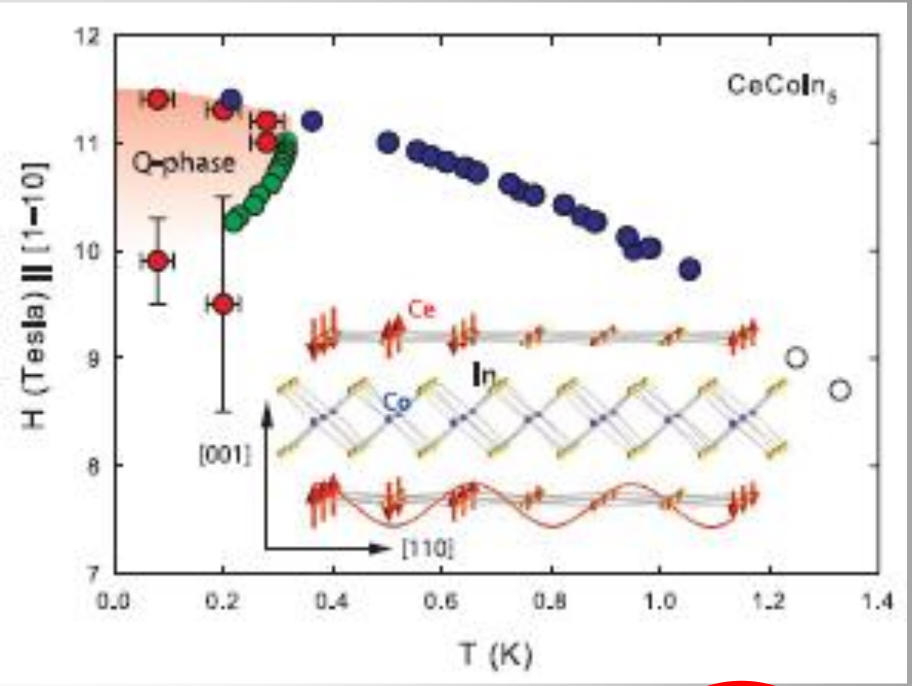

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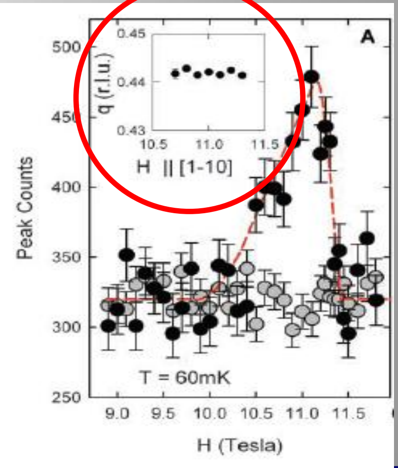

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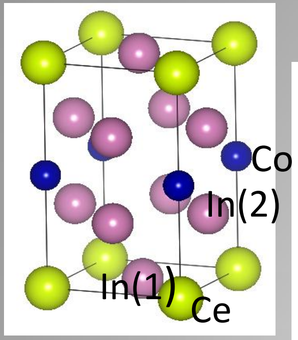
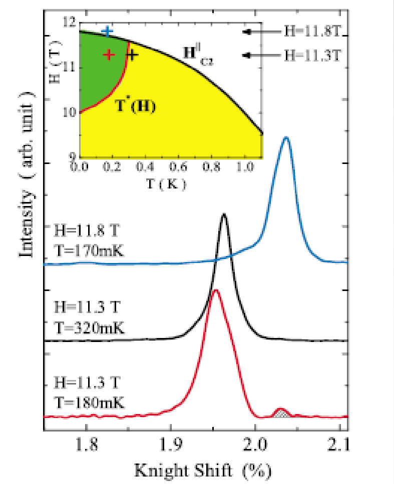
NMR measurement

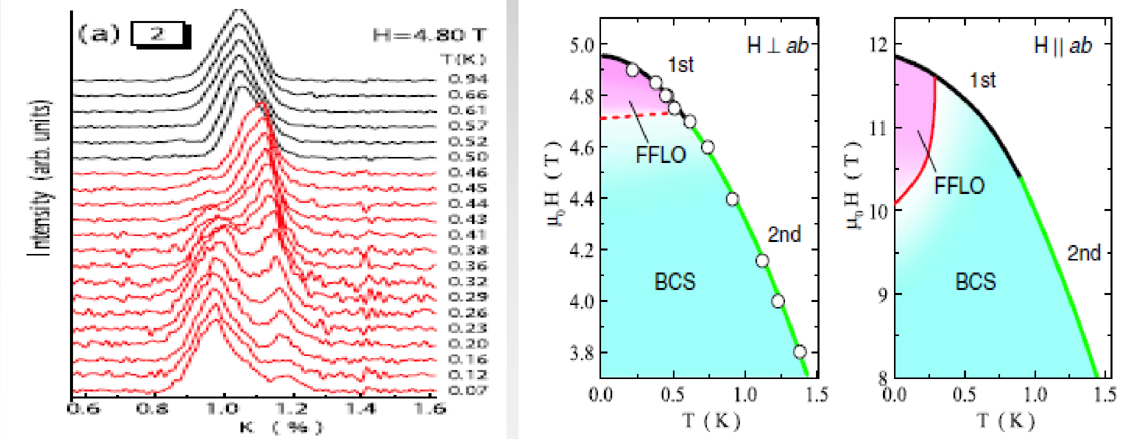


In(1) site *H* // [100]



K. Kakuyanagi *et al*., Phys. Rev. Lett. **94**, 047602 (2005).

In(1) site *H* // [001]

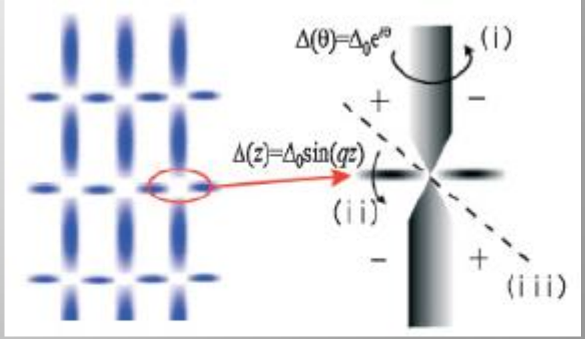


K. Kumagai *et al*., Phys. Rev. Lett. **97**, 227002 (2006).

- double peaks in HFLT region →coexistence of SC and normal state
  inhomogeneous FFLO state

- well-separated peaks No quasiparticle excitation at the point where vortex intersects with node
  The sign of order parameter is same across the dot line in the picture.

  →No Andreev bound state



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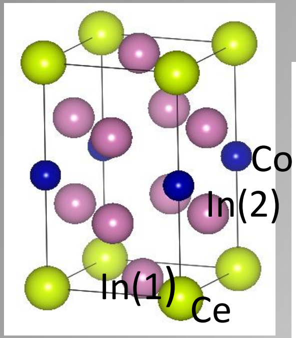
NMR measurement



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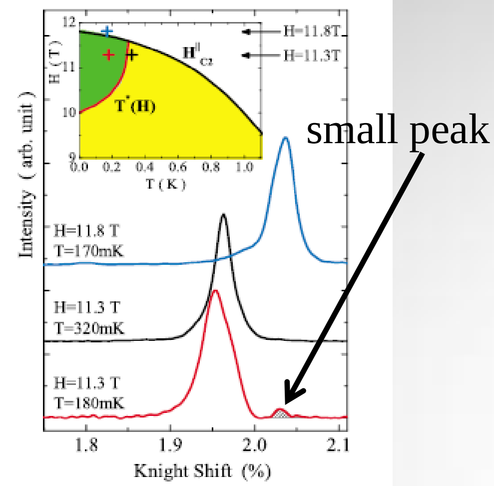

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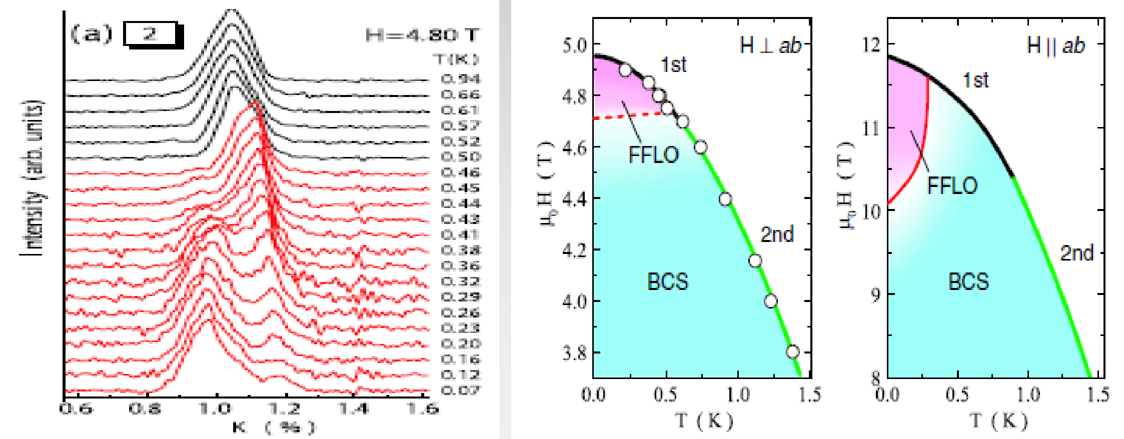

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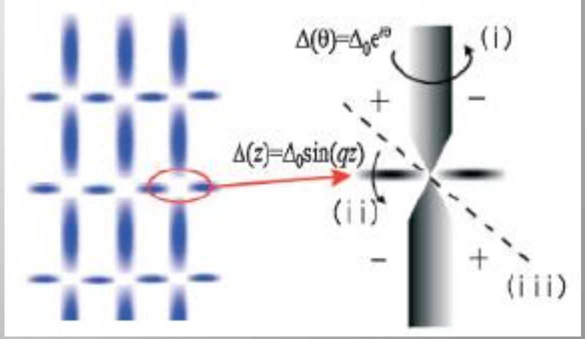

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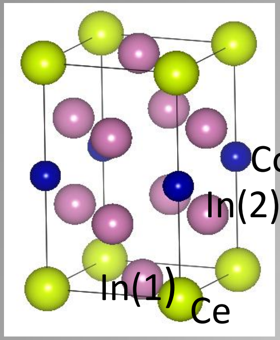
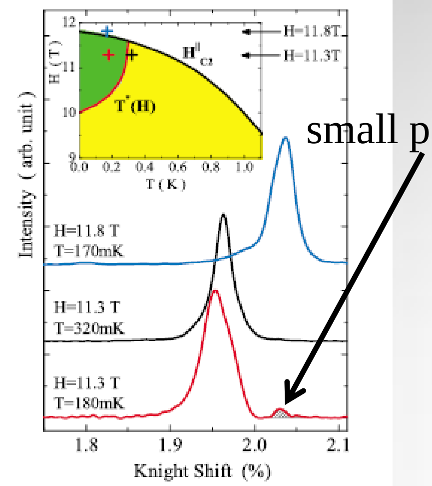
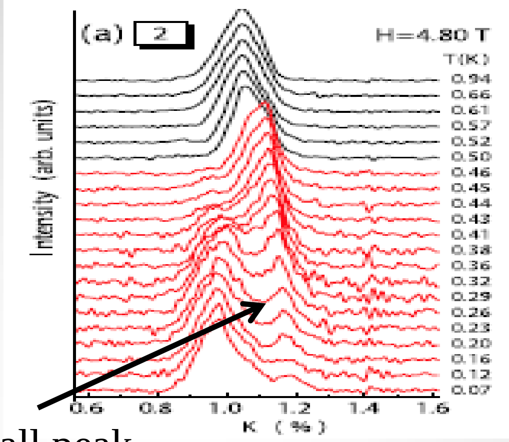


In(1) site *H* // [100]

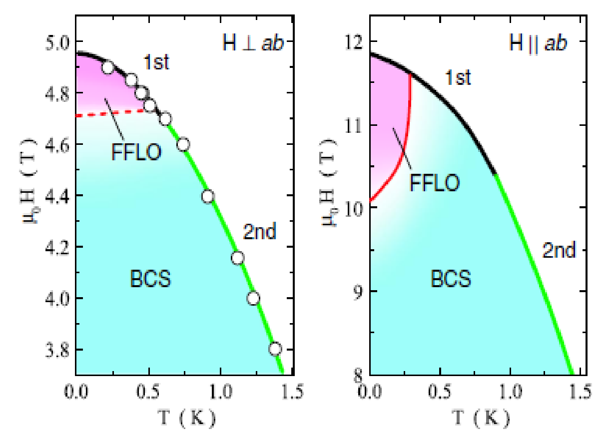


small peak

In(1) site *H* // [001]



small peak



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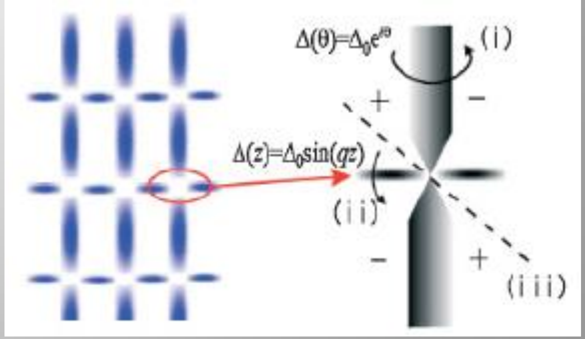

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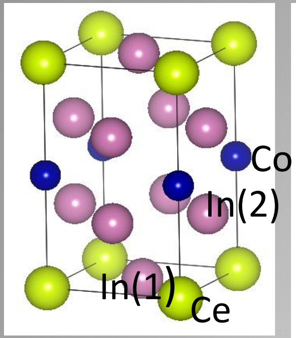
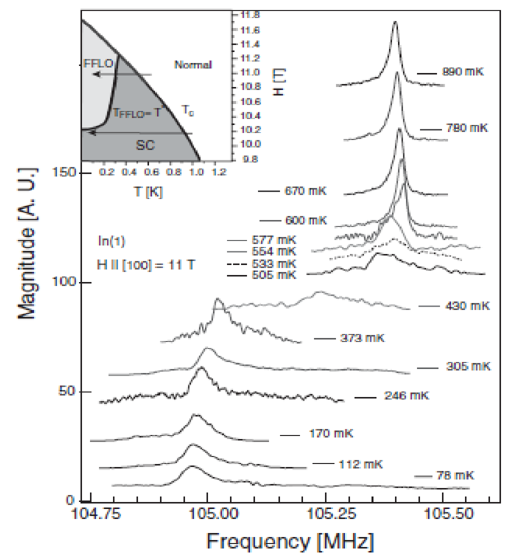
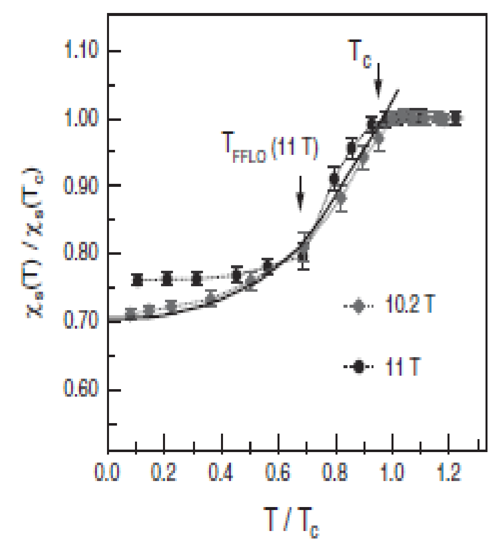






In(1) site *H* // [100]

In HFLT region

- no other peaks
- χ enhanced
  T-independent

←DOS at E_F in FFLO

$\chi \propto \mathrm{DOS}(E_F)$

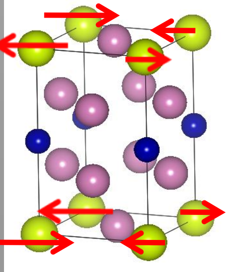
V. F. Mitrovic *et al*., Phys. Rev. Lett. **97**, 117002 (2006).

In(1),In(2),Co site *H* // [100]

- In(2) site : double broadening peaks
- Broadening depends on sites.

→Not from FFLO or vortexes but from magnetic order in the vortex core

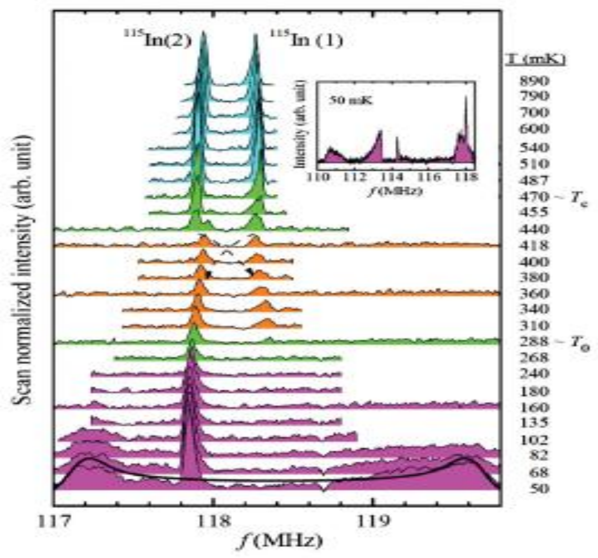
magnetic structure consistent with data

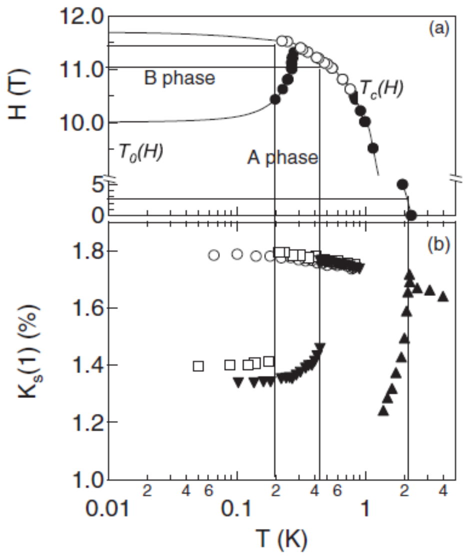


$$\mathbf{Q} = (\frac{1}{2}+q, \frac{1}{2}, \frac{1}{2})$$

q : undetermined

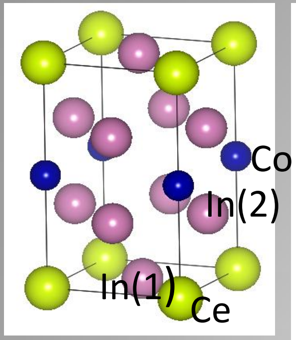
spin : $\mathbf{S} // \mathbf{H} //[100]$

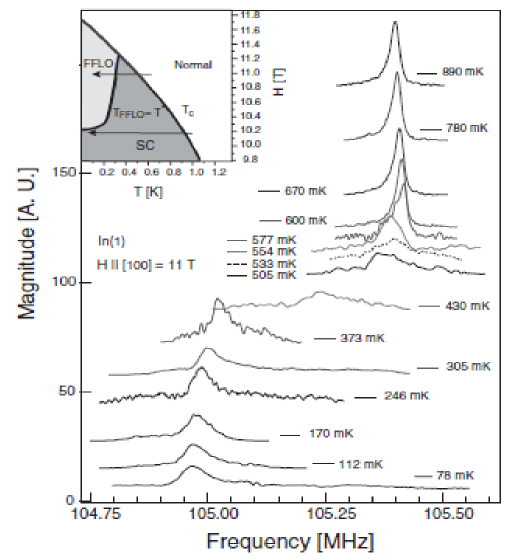


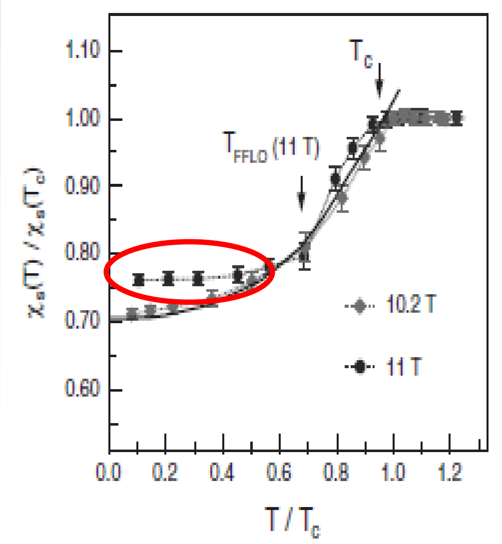


B. L. Young *et al*., Phys. Rev. Lett. **98**, 036402 (2007).

NMR measurement







In(1) site H // [100]

In HFLT region

- no other peaks
- χ enhanced
  T-independent

←DOS at E_F in FFLO

$\chi \propto$ DOS(E_F)

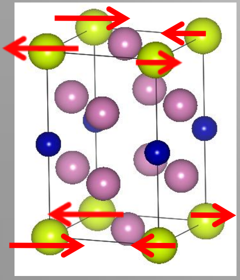
V. F. Mitrovic *et al.*, Phys. Rev. Lett. **97**, 117002 (2006).

In(1),In(2),Co site H // [100]

- In(2) site : double broadening peaks
- Broadening depends on sites.

→Not from FFLO or vortexes but from magnetic order in the vortex core

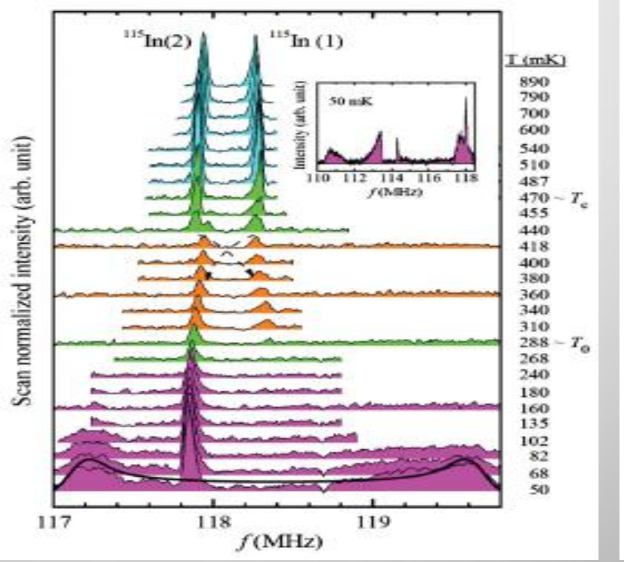
magnetic structure consistent with data

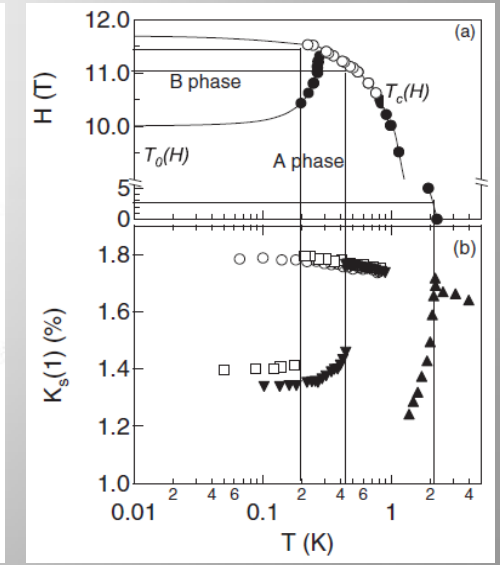


$$\mathbf{Q} = (\frac{1}{2} + q, \frac{1}{2}, \frac{1}{2})$$

q : undetermined

spin : **S** // **H** //[100]





B. L. Young *et al.*, Phys. Rev. Lett. **98**, 036402 (2007).

Magnetic Structure

N. J. Curro *et al.*, J. Low. Temp. Phys. **158**, 635 (2010).

NMR

$\mathbf{S} \perp \mathbf{H} \perp \mathbf{q}$ (neutron diffraction measurement) : dipolar hyperfine coupling

$\mathbf{S} // \mathbf{H} //[100]$ (NMR measurement) : isotropic hyperfine coupling

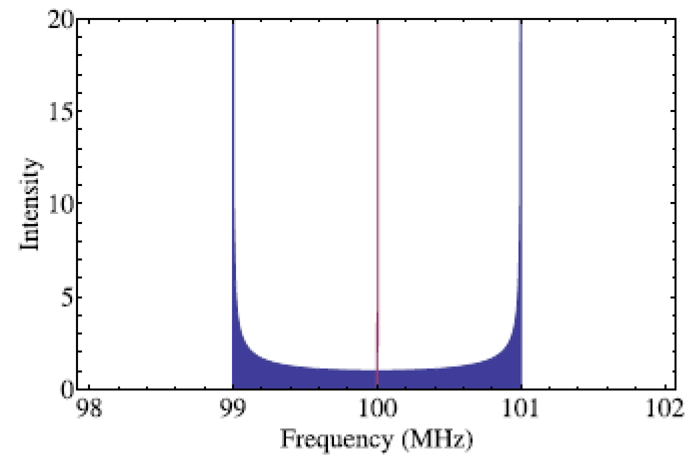
Resonance frequency: $f = \gamma |\mathbf{H}_0 + \mathbf{H}_{hf}| + f_Q$

f_Q : quadrupolar interaction

γ : gyromagnetic ratio

Electric field gradient is unaffected by the onset of SC or magnetism.

In(2a) : double broad peaks In(1),In(2b),Co : no dramatic change requirement from data



N. J. Curro *et al.*, J. Low. Temp. Phys. **158**, 635 (2010).

$\mathbf{H} // \mathbf{H}_{hf}$: blue line

$\mathbf{H}_0 \perp \mathbf{H}_{hf}$: red line

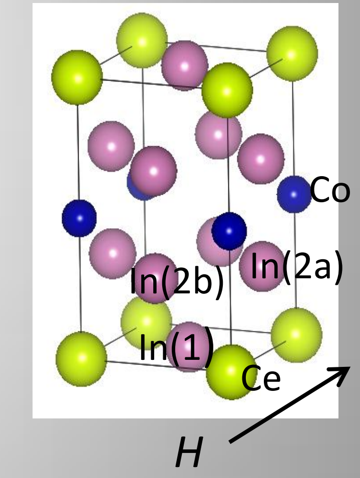
$$\mathbf{H}_{hf}(\mathbf{r}) = \sum_{i=1}^{4} \frac{\mathbf{B}_i \cdot \mathbf{S}(\mathbf{r}+\mathbf{r}_i)}{\gamma\hbar}$$ at In(1)

$$\mathbf{H}_{hf}(\mathbf{r}) = \sum_{j=1}^{2} \frac{\mathbf{B}_i \cdot \mathbf{S}(\mathbf{r}+\mathbf{r}_j)}{\gamma\hbar}$$ at Co

$$\mathbf{H}_{hf}(\mathbf{r}) = \sum_{k=1}^{2} \frac{\mathbf{B}_i \cdot \mathbf{S}(\mathbf{r}+\mathbf{r}_k)}{\gamma\hbar}$$ at In(2a)

$$\mathbf{H}_{hf}(\mathbf{r}) = \sum_{l=1}^{2} \frac{\mathbf{B}_i \cdot \mathbf{S}(\mathbf{r}+\mathbf{r}_l)}{\gamma\hbar}$$ at In(2b)

$$\mathbf{B}_i = \mathbf{B}_{iso} + \mathbf{B}_{dip} \qquad \mathbf{Q} = \mathbf{Q}_0 + \mathbf{q}$$

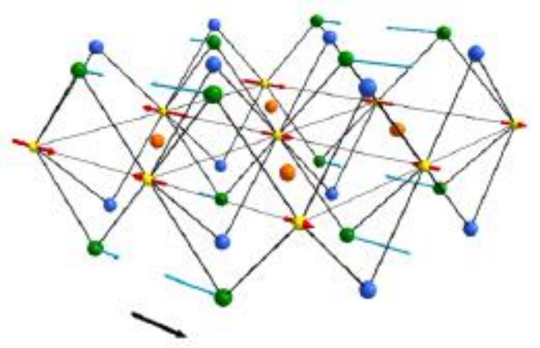


Magnetic Structure

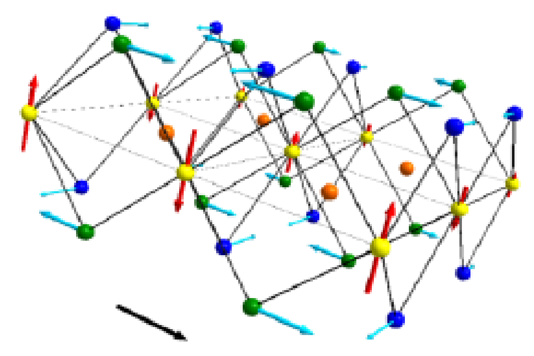
N. J. Curro *et al.*, J. Low. Temp. Phys. **158**, 635 (2010).

$$\mathbf{B}_{iso} = B_{iso}\begin{pmatrix}1 & 0 & 0\\ 0 & 1 & 0\\ 0 & 0 & 1\end{pmatrix} \quad \mathbf{B}_{dip} = \frac{B_{dip}}{r^2}\begin{pmatrix} 2x^2-y^2-z^2 & 3xy & 3xz\\ 3xy & -x^2+2y^2-z^2 & 3yz\\ 3xz & 3yz & -x^2-y^2+2z^2\end{pmatrix}$$

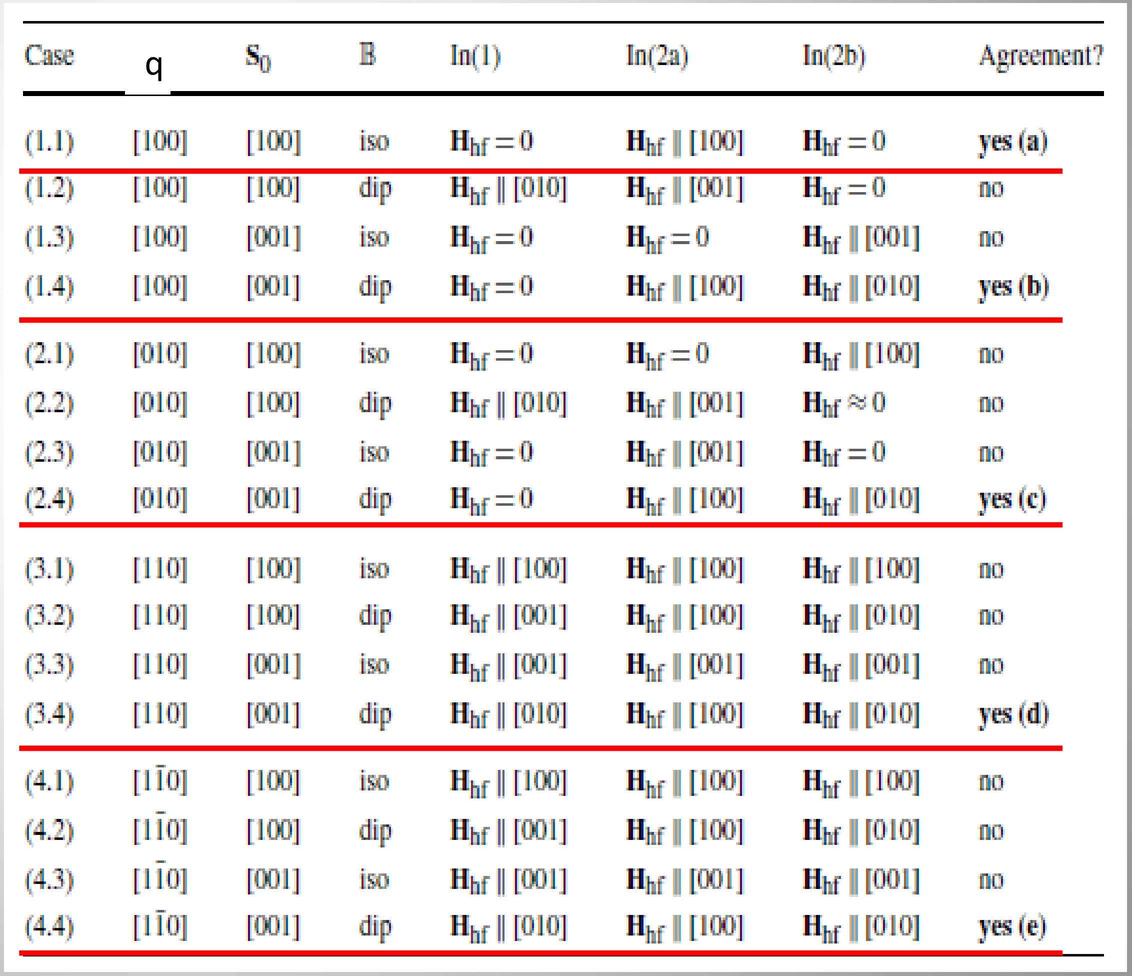
Calculate $\mathbf{H}_{hf}$, assuming various $\mathbf{S}, \mathbf{q}, \mathbf{B}_i$ under the condition of *H* // [100]



Case(1.1)



Case(2.4)



Case	q	S_0	B	In(1)	In(2a)	In(2b)	Agreement?
(1.1)	[100]	[100]	iso	$\mathbf{H}_{hf} = 0$	$\mathbf{H}_{hf} \parallel [100]$	$\mathbf{H}_{hf} = 0$	yes (a)
(1.2)	[100]	[100]	dip	$\mathbf{H}_{hf} \parallel [010]$	$\mathbf{H}_{hf} \parallel [001]$	$\mathbf{H}_{hf} = 0$	no
(1.3)	[100]	[001]	iso	$\mathbf{H}_{hf} = 0$	$\mathbf{H}_{hf} = 0$	$\mathbf{H}_{hf} \parallel [001]$	no
(1.4)	[100]	[001]	dip	$\mathbf{H}_{hf} = 0$	$\mathbf{H}_{hf} \parallel [100]$	$\mathbf{H}_{hf} \parallel [010]$	yes (b)
(2.1)	[010]	[100]	iso	$\mathbf{H}_{hf} = 0$	$\mathbf{H}_{hf} = 0$	$\mathbf{H}_{hf} \parallel [100]$	no
(2.2)	[010]	[100]	dip	$\mathbf{H}_{hf} \parallel [010]$	$\mathbf{H}_{hf} \parallel [001]$	$\mathbf{H}_{hf} \approx 0$	no
(2.3)	[010]	[001]	iso	$\mathbf{H}_{hf} = 0$	$\mathbf{H}_{hf} \parallel [001]$	$\mathbf{H}_{hf} = 0$	no
(2.4)	[010]	[001]	dip	$\mathbf{H}_{hf} = 0$	$\mathbf{H}_{hf} \parallel [100]$	$\mathbf{H}_{hf} \parallel [010]$	yes (c)
(3.1)	[110]	[100]	iso	$\mathbf{H}_{hf} \parallel [100]$	$\mathbf{H}_{hf} \parallel [100]$	$\mathbf{H}_{hf} \parallel [100]$	no
(3.2)	[110]	[100]	dip	$\mathbf{H}_{hf} \parallel [001]$	$\mathbf{H}_{hf} \parallel [100]$	$\mathbf{H}_{hf} \parallel [010]$	no
(3.3)	[110]	[001]	iso	$\mathbf{H}_{hf} \parallel [001]$	$\mathbf{H}_{hf} \parallel [001]$	$\mathbf{H}_{hf} \parallel [001]$	no
(3.4)	[110]	[001]	dip	$\mathbf{H}_{hf} \parallel [010]$	$\mathbf{H}_{hf} \parallel [100]$	$\mathbf{H}_{hf} \parallel [010]$	yes (d)
(4.1)	$[1\bar{1}0]$	[100]	iso	$\mathbf{H}_{hf} \parallel [100]$	$\mathbf{H}_{hf} \parallel [100]$	$\mathbf{H}_{hf} \parallel [100]$	no
(4.2)	$[1\bar{1}0]$	[100]	dip	$\mathbf{H}_{hf} \parallel [001]$	$\mathbf{H}_{hf} \parallel [100]$	$\mathbf{H}_{hf} \parallel [010]$	no
(4.3)	$[1\bar{1}0]$	[001]	iso	$\mathbf{H}_{hf} \parallel [001]$	$\mathbf{H}_{hf} \parallel [001]$	$\mathbf{H}_{hf} \parallel [001]$	no
(4.4)	$[1\bar{1}0]$	[001]	dip	$\mathbf{H}_{hf} \parallel [010]$	$\mathbf{H}_{hf} \parallel [100]$	$\mathbf{H}_{hf} \parallel [010]$	yes (e)

Theory

K. Miyake, J. Phys. Soc. Jpn. **77**, 123703 (2008).

G.L. free energy(mode coupling)

$$F = F_0 + \frac{a_M}{2}M^2 + \frac{b_M}{4}M^4 + \frac{a_\Psi}{2}\Psi^2 + \frac{b_\Psi}{4}\Psi^4 + \underline{C\Delta M\Psi}$$

M, Ψ, Δ : order parameter of SDW, π-pairing SC , d-wave SC (a_M,b_M,a_Ψ,$b_\Psi > 0$)

↔assuming that d-wave SC (not FFLO state) is necessary for SDW and π-pairing SC.

Minimize with respect to M, Ψ

$$\left[\begin{array}{l} \Psi = -\dfrac{C\Delta}{a_\Psi}M \\ M^2 = \dfrac{1}{b_M}\left[\dfrac{(C\Delta)^2}{a_\Psi} - a_M\right] \end{array}\right.$$

Approximation : $\Psi^3 << \Psi$ (considering CeCoIn$_5$ is near the QCP)

$(C\Delta)^2 > a_\Psi a_M$

→*M* exists only in FFLO phase.

Wave vector *q* (Estimation of *q* and comparison with the data)

$$\mathbf{Q} = \mathbf{Q}_0 + \mathbf{q}$$

- Estimation : $q = \dfrac{2\mu_B H}{\hbar v_F} \cong 2.4\times10^8\,\mathrm{m}^{-1}$ $\dfrac{q}{Q_0} \cong 3.3\times10^{-2}$
- Data (Kenzelmann *et al.*) : $\dfrac{q}{Q_0} \cong 1.2\times10^{-2}$

$\Delta Q = 2.1\times10^{-3}$: comparable to the error

- the possibility of *H*-dependence of V_F

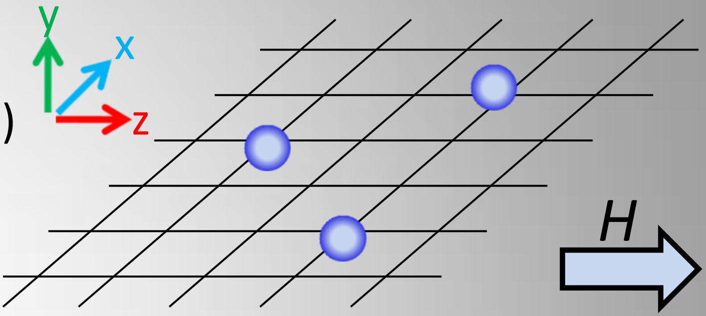
→The robustness of *Q* against *H* is understood.

Theory

Y. Yanase *et al.*, J. Phys. Soc. Jpn. **78**, 114715 (2009).

model $$H = -t \sum_{\langle i,j\rangle,\sigma} c^{\dagger}_{i,\sigma} c_{j,\sigma} + t' \sum_{\langle\langle i,j\rangle\rangle,\sigma} c^{\dagger}_{i,\sigma} c_{j,\sigma} + U \sum_{i} n_{i\uparrow} n_{i\downarrow} + V \sum_{\langle i,j\rangle} n_i n_j + J \sum_{\langle i,j\rangle} S_i S_j - g_{\mathrm{B}} H \sum_{i} S_i$$

- *<i,j>*(*<<i,j>>*) : summation over nearest(next nearest) site
- assuming square lattice (for quasi-two-dimensional CeCoIn$_5$)
- *H // z*



Approach 1 : BdG eq. (neglecting AFM fluctuation)
Approach 2 : FLEX approximation (considering AFM fluctuation)

Approach 1

Define mean field: $\langle S_i \rangle, \langle n_i \rangle, \Delta^{\sigma,\sigma'}_{i,j} = \langle c_{i\sigma} c_{j\sigma'} \rangle$

Staggered moment : $M_{\mathrm{AF}}(i) = (-1)^{m+n} \langle S_i \rangle$

d-wave order parameter : $\Delta^{\mathrm{d}}(i) = \Delta^{\uparrow\downarrow}_{i,i+a} + \Delta^{\uparrow\downarrow}_{i,i-a} - \Delta^{\uparrow\downarrow}_{i,i+b} - \Delta^{\uparrow\downarrow}_{i,i-b}$ (*a*, *b* : unit vectors along the z, x-axes)

π-triplet order parameter : $d_{a,b}(i)$

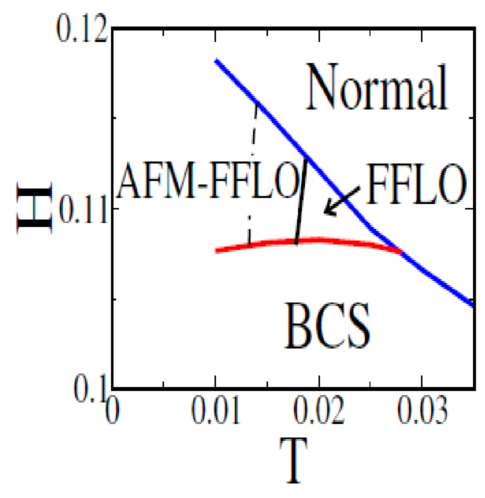
$$\Delta^{\sigma\sigma}_{i,i\pm a} = \pm(-1)^{m+n} \frac{1}{2}\left[-\sigma d^{x}_{a}(i) + i d^{y}_{a}(i)\right]$$

$$\Delta^{\sigma\sigma}_{i,i\pm b} = \pm(-1)^{m+n} \frac{1}{2}\left[-\sigma d^{x}_{b}(i) + i d^{y}_{b}(i)\right]$$

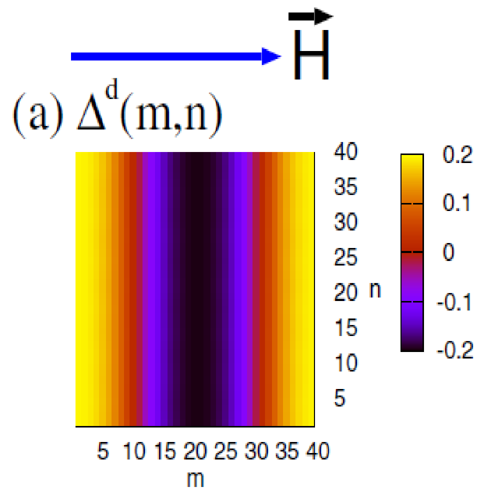
Theory

Y. Yanase *et al.*, J. Phys. Soc. Jpn. **78**, 114715 (2009).

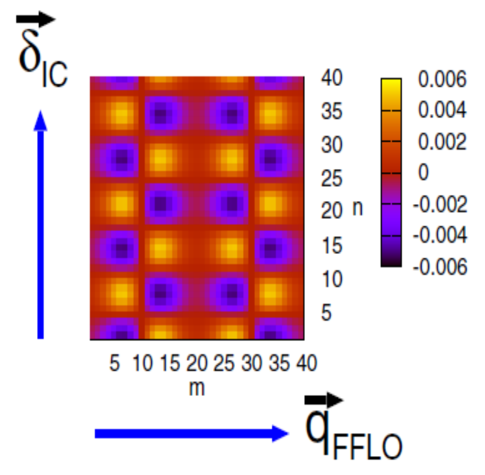
Then the thermodynamic average <･･･> (mean field Hamiltonian)
→self-consistent eq. for $\langle S_i \rangle, \langle n_i \rangle$, and $\Delta^{\sigma,\sigma'}_{i,\delta}$ for each *i* : BdG eq.



- AFM only in FFLO
  Andreev bound state
- Normal state to SC is first order in high field.
  ↑*U* and *J* are required.
- $T_c(H = 0) = 0.096$
- dashed line :
  π-triplet is neglected
  →important for AFM

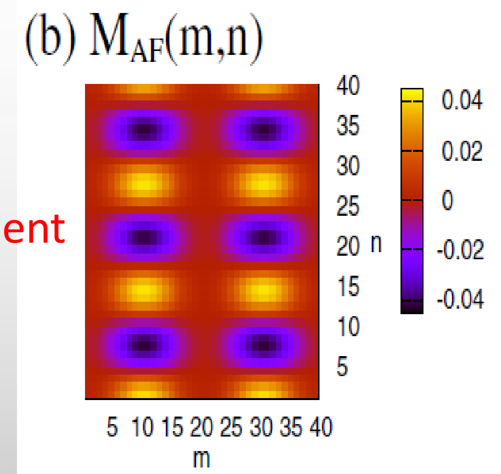


- Modulated order parameter
- large DOS around the nodes



- $\delta_{\mathrm{IC}} \perp q_{\mathrm{FFLO}} // H$
- $|\delta_{\mathrm{IC}}|$: independent of nodal planes

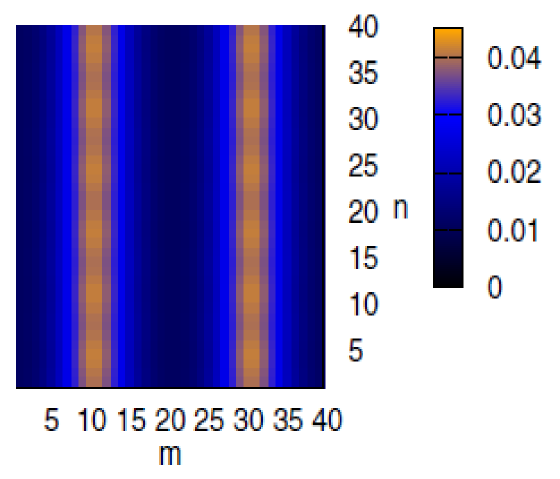
consistent with experiment



- AFM order occurs with nucleation of the planar nodes
- localized around the nodes
- $q_{\mathrm{FFLO}} // H$ (assumption)
  → $\delta \perp H$, $M \perp H$

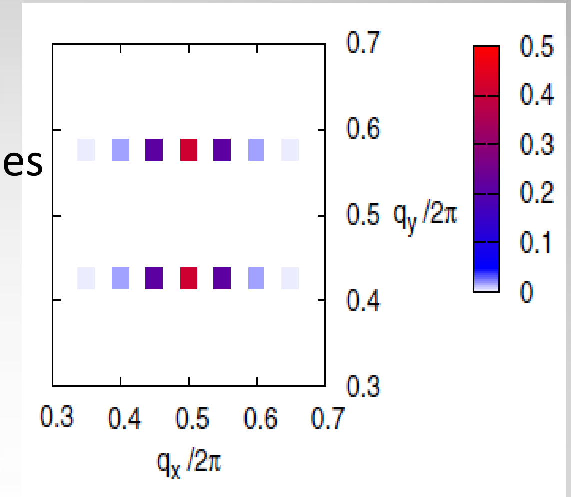
Theory

Y. Yanase *et al.*, J. Phys. Soc. Jpn. **78**, 114715 (2009).



$<S_i>$

- weak modulation along the nodal lines IC-AFM order



Fourier transformation of $<S_i>$

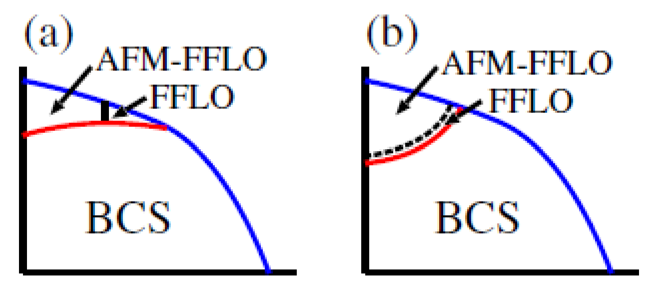
- Peaks at

$$\mathbf{Q} = \mathbf{Q}_0 \pm \boldsymbol{\delta}_{\mathrm{IC}}$$

<u>※Remark</u>

Satellite peaks

<u>Approach 2</u>



- AFM order : from three to quasi-2-dimentions near the BCS-FFLO transition line
→enhanced spin fluctuation

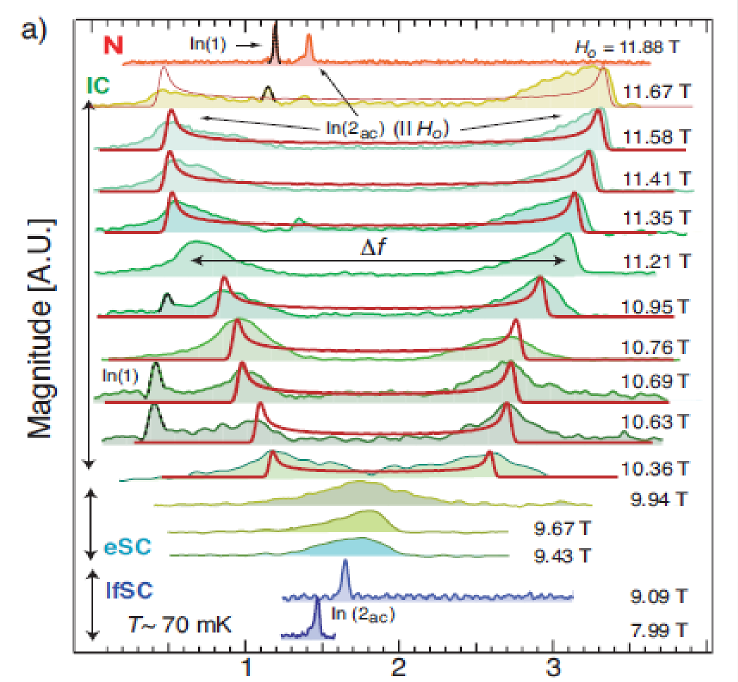
Pure FFLO state without AFM order

Findings : Inhomogeneous FFLO state → Andreev bound state → stabilized AFM
(π-triplet SC)

New phase near the AFM-FFLO state, where strong spin fluctuation exists

NMR measurement

G. Koutroulakis *et al*., arXiv:0912.3548v1.



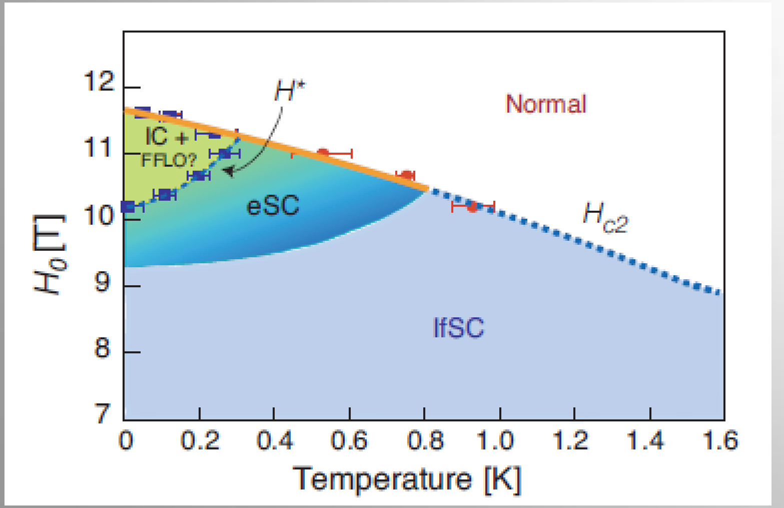
<u>In(1),In(2_{ac}),In(2_{bc}) site   *H* // [100]</u>

- In(2_{ac}) : broadening, double peaks
- In(1),In(2_{bc}) : not broadening

$\boldsymbol{\mu}_i \,//\, \mathbf{c} \perp \mathbf{H}$ $\mu_0 = 0.15\mu_{\mathrm{B}}$

$\boldsymbol{\delta} \,//\, \mathbf{b} \perp \mathbf{H}$ $\delta = 0.085$ →consistent with data

Direction of δ : *H*-independent



- In(2ac) : weak signal, disappearance of the double peak

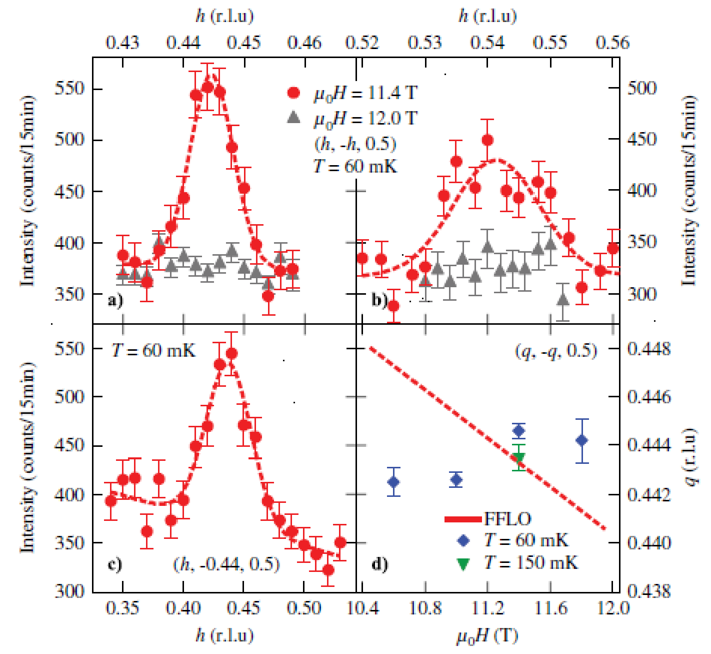
New phase under the IC+FFLO phase

Very strong AFM fluctuation

Neutron diffraction measurement

M. Kenzelmann *et al.*, Phys. Rev. Lett. **104**, 127001 (2010).

H // [100] (*h*,*h*,0.5)



- correlation length > 25 nm > 10 nm (vortex core scale)
- magnetic structure

$$\mathbf{Q} = (q, -q, \frac{1}{2}) \quad q = 0.45 \quad \mathbf{S} \perp \mathbf{H} // [100] \quad \mu_0 = 0.16\mu_B$$

q : *H*-independent → inconsistent with FFLO

Direction of *Q* : parallel to the direction of node?

$$d_{x^2-y^2}$$

[11*l*] electron nesting →SDW

SDW originates from local magnetism in vortex cores.

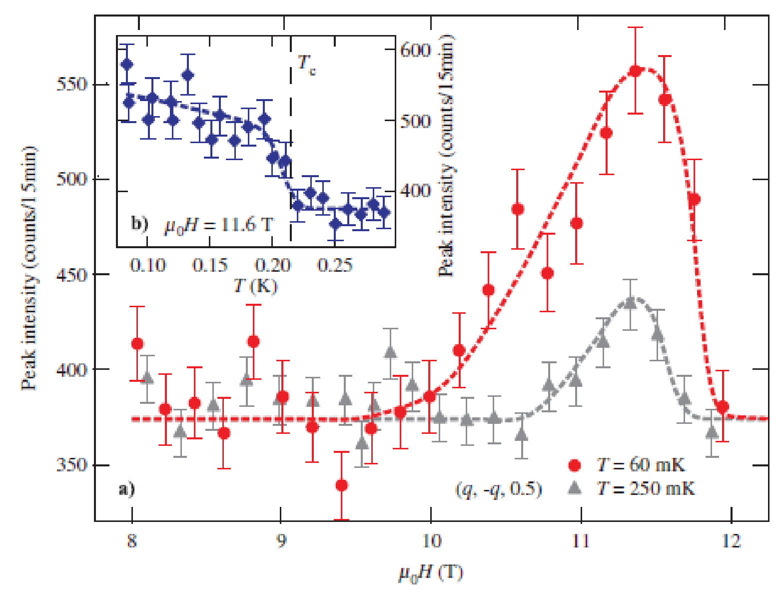
High DOS of low-energy excitation that induces magnetism

→Enhanced vortex magnetism

Vortexes (～13-15 nm) almost overlap in high field.

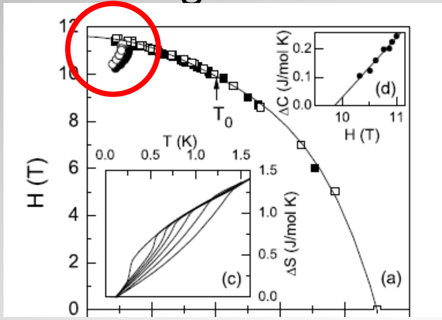
→long-range SDW

SC and SDW vanish at the same time, H_{c2}. : consistent

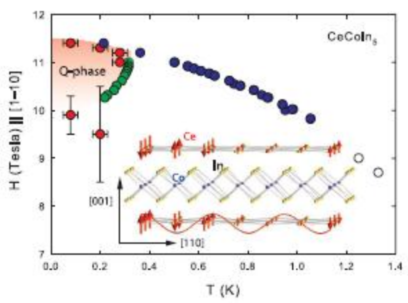


Summary

- New phase was found in HFLT region in $CeCoIn_5$, and AFM coexists with SC in that region.

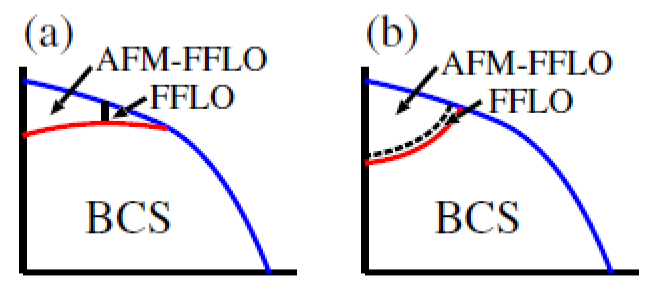


A. Bianchi *et al.*, Phys. Rev. Lett. **91**, 187004 (2003).



M. Kenzelmann *et al.*, Science **321**, 1652 (2008).

- Theories predict that FFLO state (inhomogeneous) and AFM can coexist and moreover, the phase is FFLO state-driven.



Y. Yanase *et al.*, J. Phys. Soc. Jpn. **78**, 114715 (2009).

- Neutron scattering experiment indicates that the phase is magnetic-driven and the data is inconsistent with theories above.