Pauli limited superconductivity in $CeCoIn_5$

Roman Movshovich

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- Pauli limiting in $CeCoIn_5$: phase diagram, first order SC transition, FFLO?
- Specific heat for H||[001] and H||[100]

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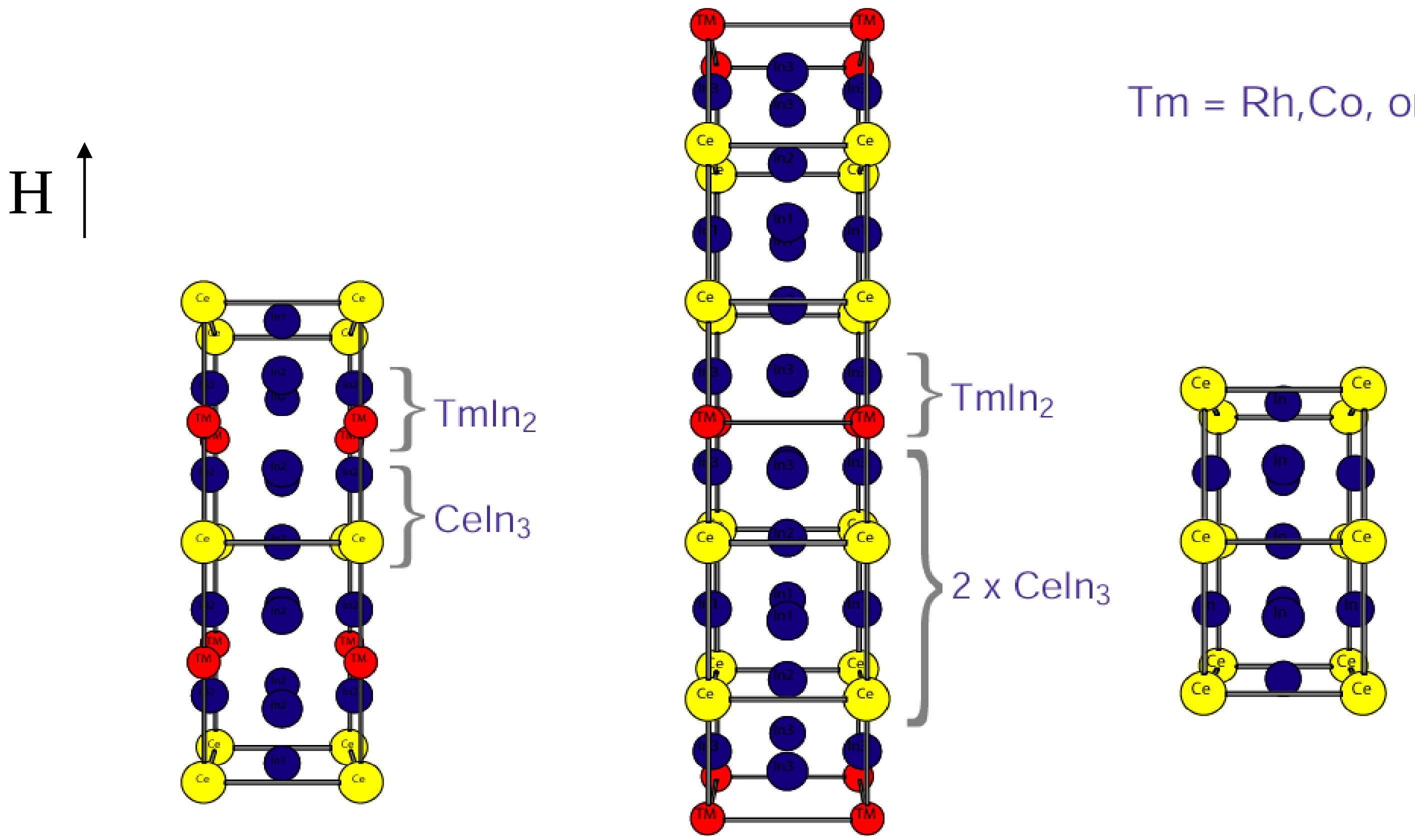
Crystal structures of the $Ce_nTm_mIn_{3n+2m}$ family

Tm = Rh,Co, or Ir

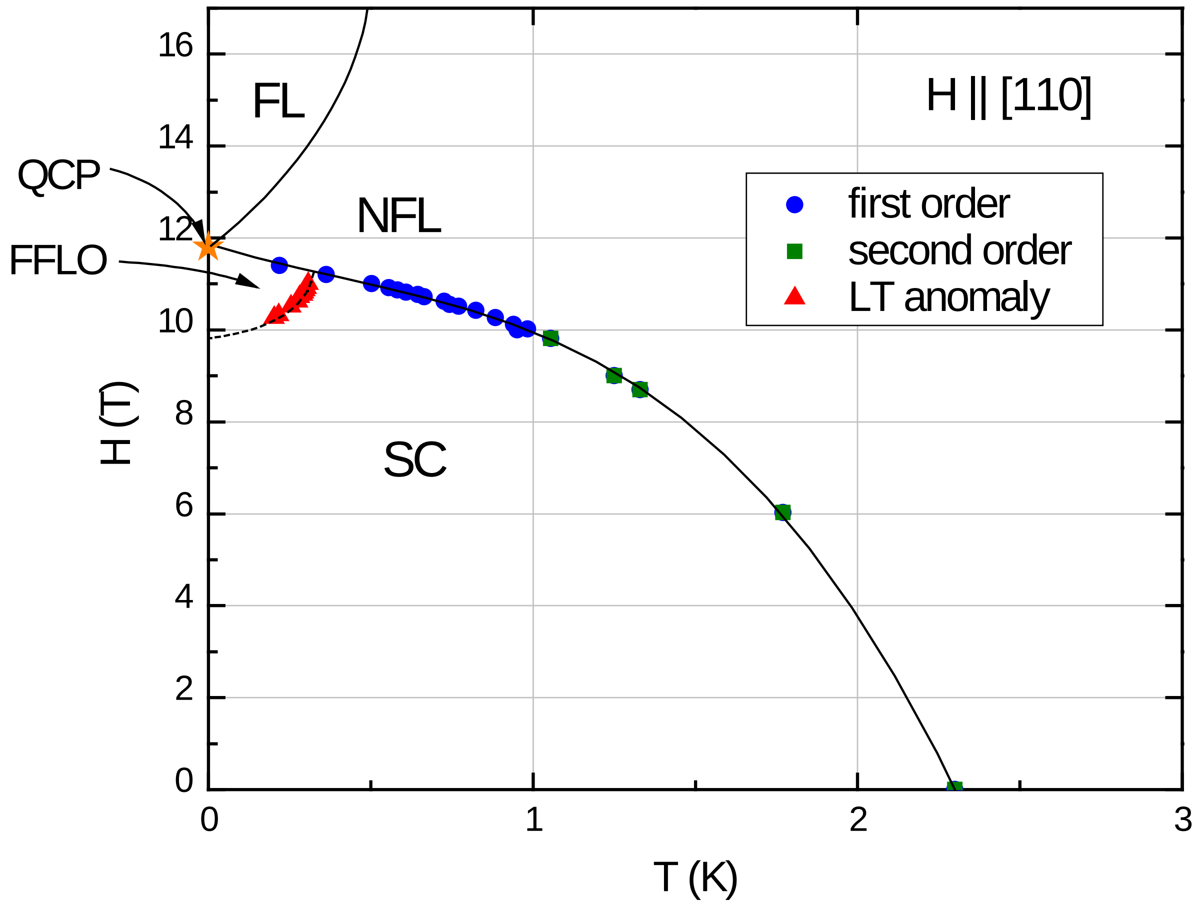


$CeTmIn_5$ Ce_2TmIn_8 $CeIn_3$

Superconductors,
T_c up to 2.3 K at
ambient pressure

T_c < 200 mK
P ~ 25 kbar

H-T phase diagram of $CeCoIn_5$



Complex phase diagram :

1. coinciding QCP and H_{c2}
2. superconducting transition itself changes from second to first order
3. a new phase in the High Field-Low Temperature HFLT corner of SC phase.

Q's:

- origin of QCP?
- HFLT - possibly FFLO?
- relation between HFLT and QCP and its underlying magnetism?

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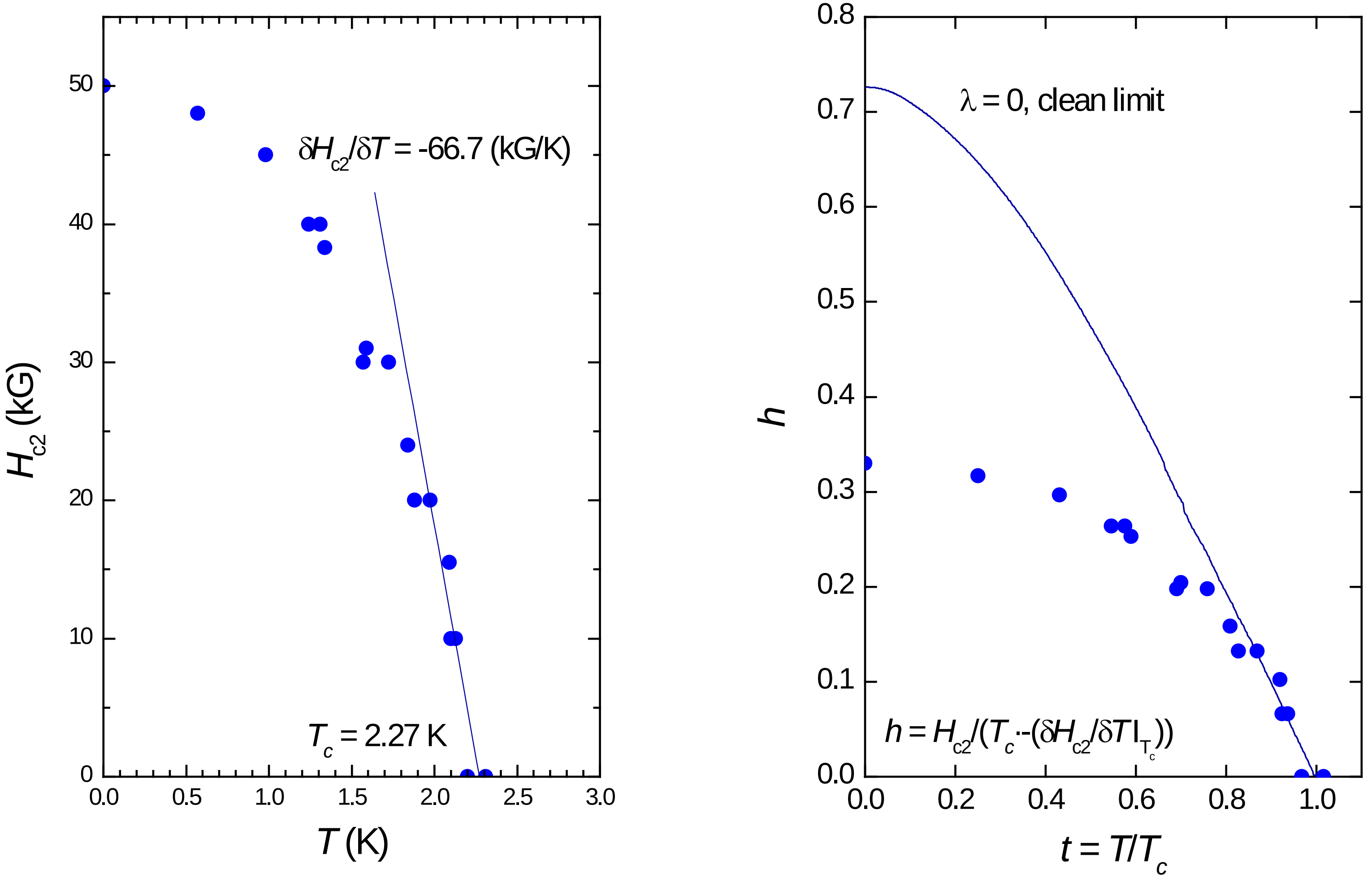
CeCoIn5 – upper critical field for *H* II c



E. Helfand and N.R. Werthamer Phys.Rev. **147** 313 (1967)

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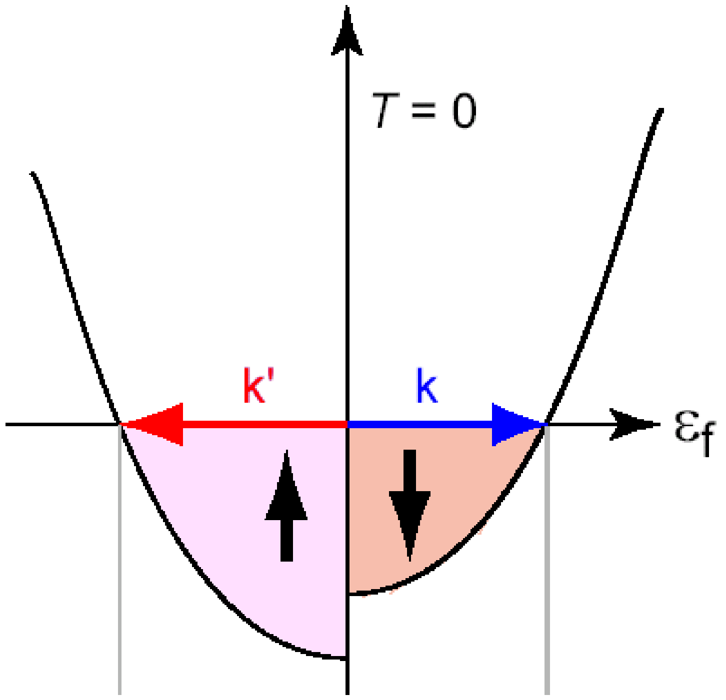
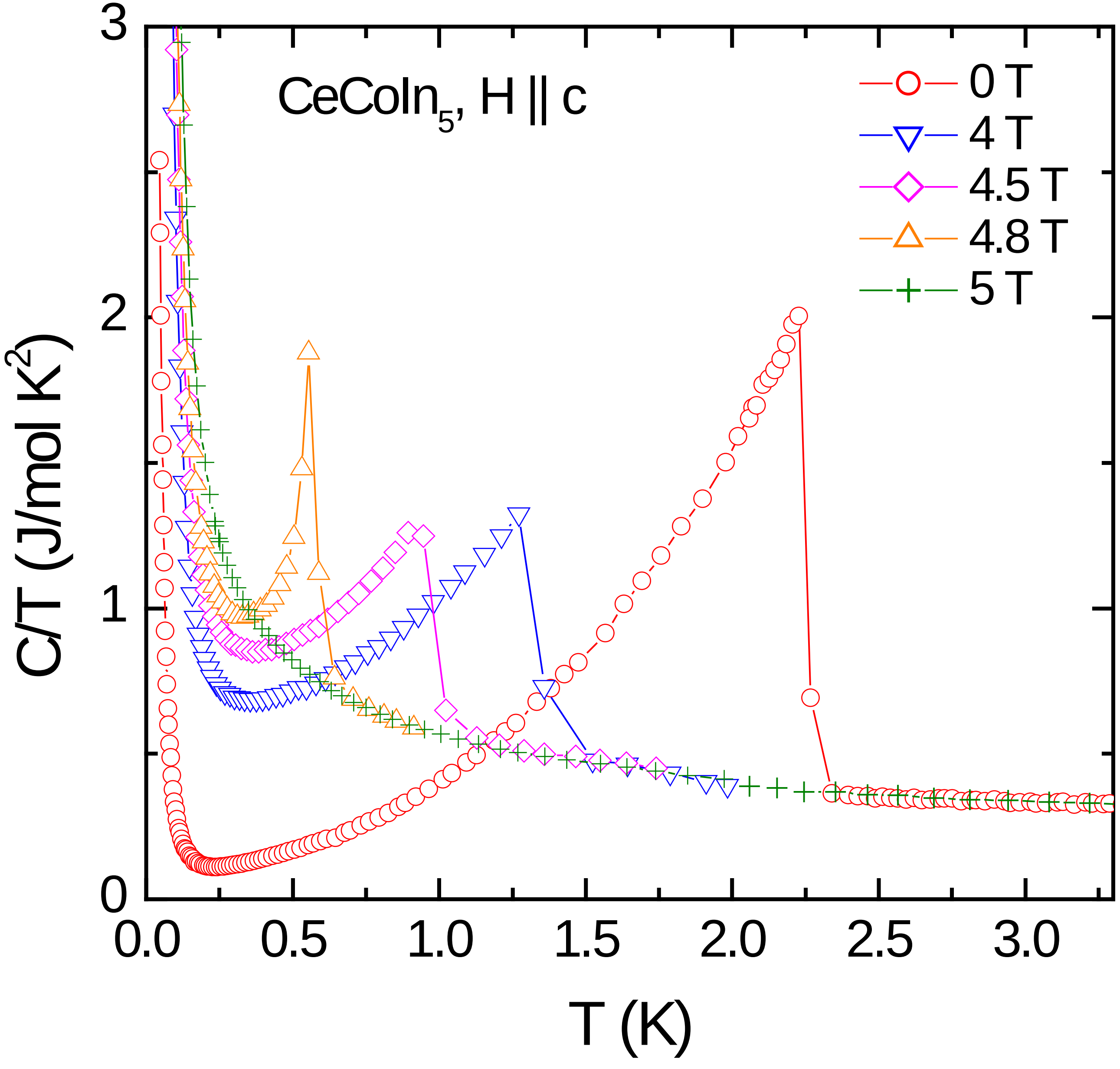
Pauli limiting



$$H_p = \Delta_0 \Big/ \sqrt{2}\,\frac{g}{2}\,\mu_B$$

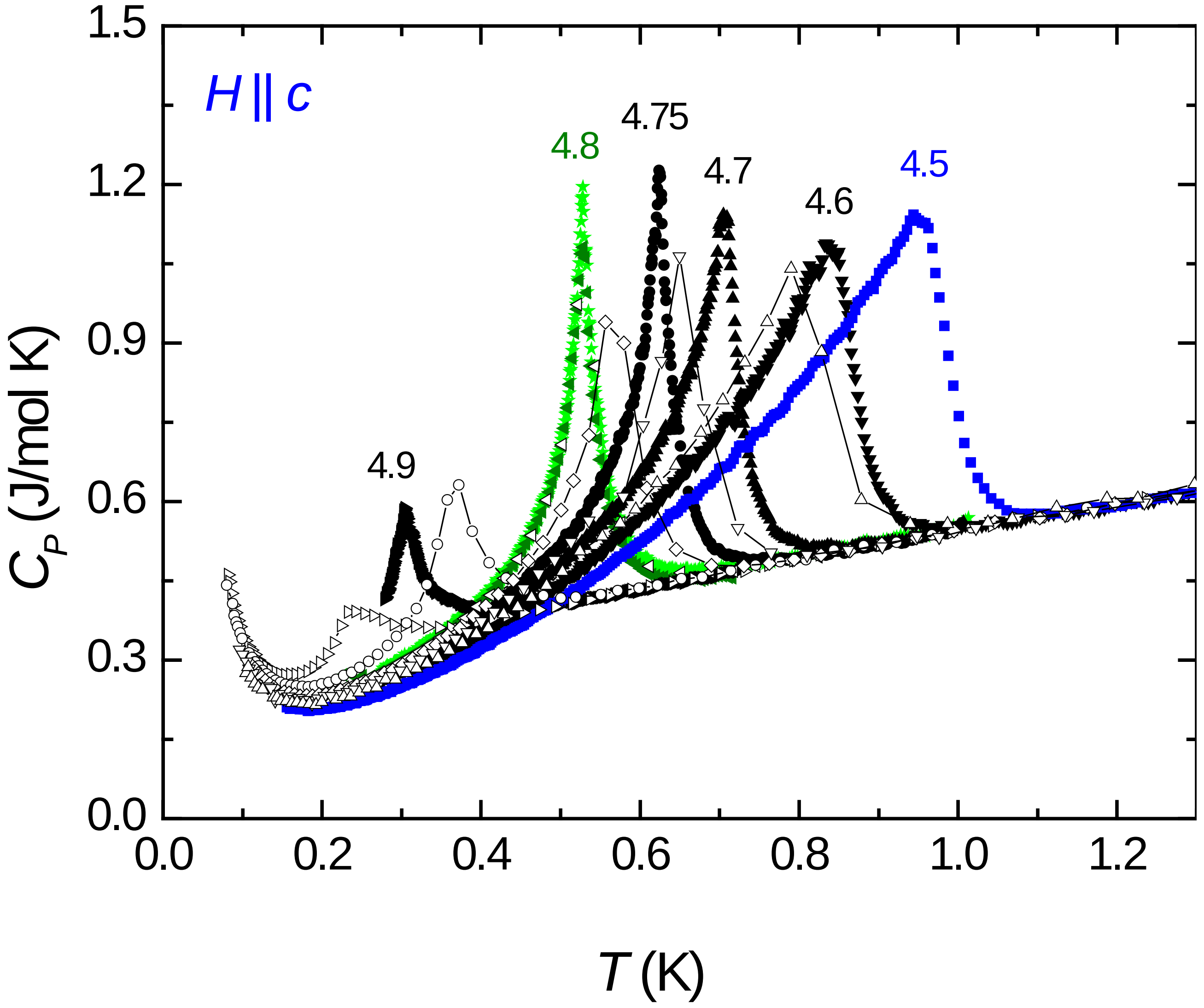
Zeeman splitting of the spin up and spin down bands in the normal state. If the superconducting Cooper pair forms a spin-singlet (orbital *s*-wave or *d*-wave), Zeeman energy can be taken advantage of in superconducting state. Pauli paramagnetism leads to an upper limit for the superconducting critical field, Pauli limiting field H_p, also called the Clogston paramagnetic limit.

A.M. Clogston, Phys. Rev. Lett. 2, 9 (1962).



CeCoIn5, H || c
0 T
4 T
4.5 T
4.8 T
5 T
C/T (J/mol K2)
T (K)
0
1
2
3
0.0
0.5
1.0
1.5
2.0
2.5
3.0

$CeCoIn_5$ – second order – first order



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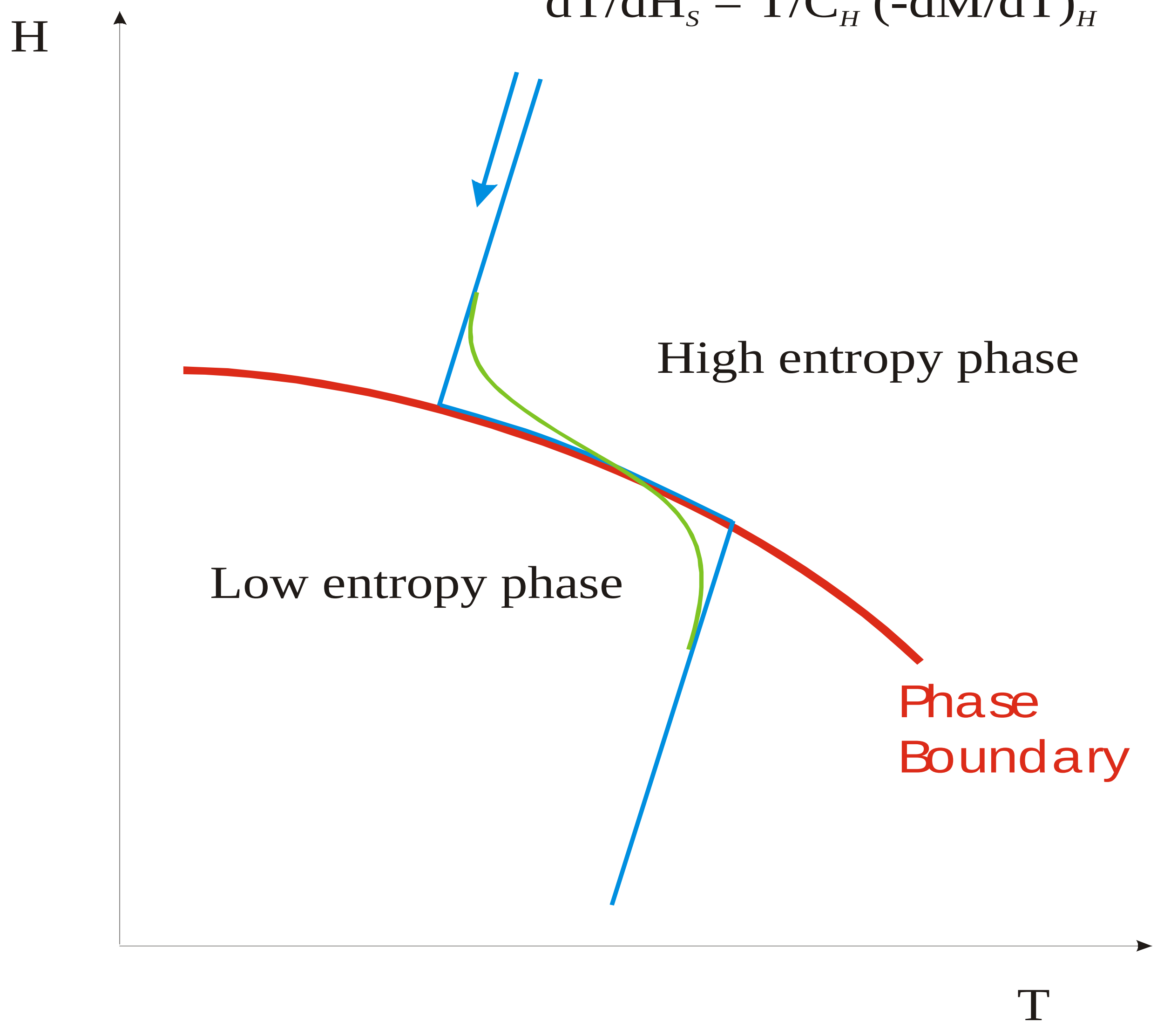
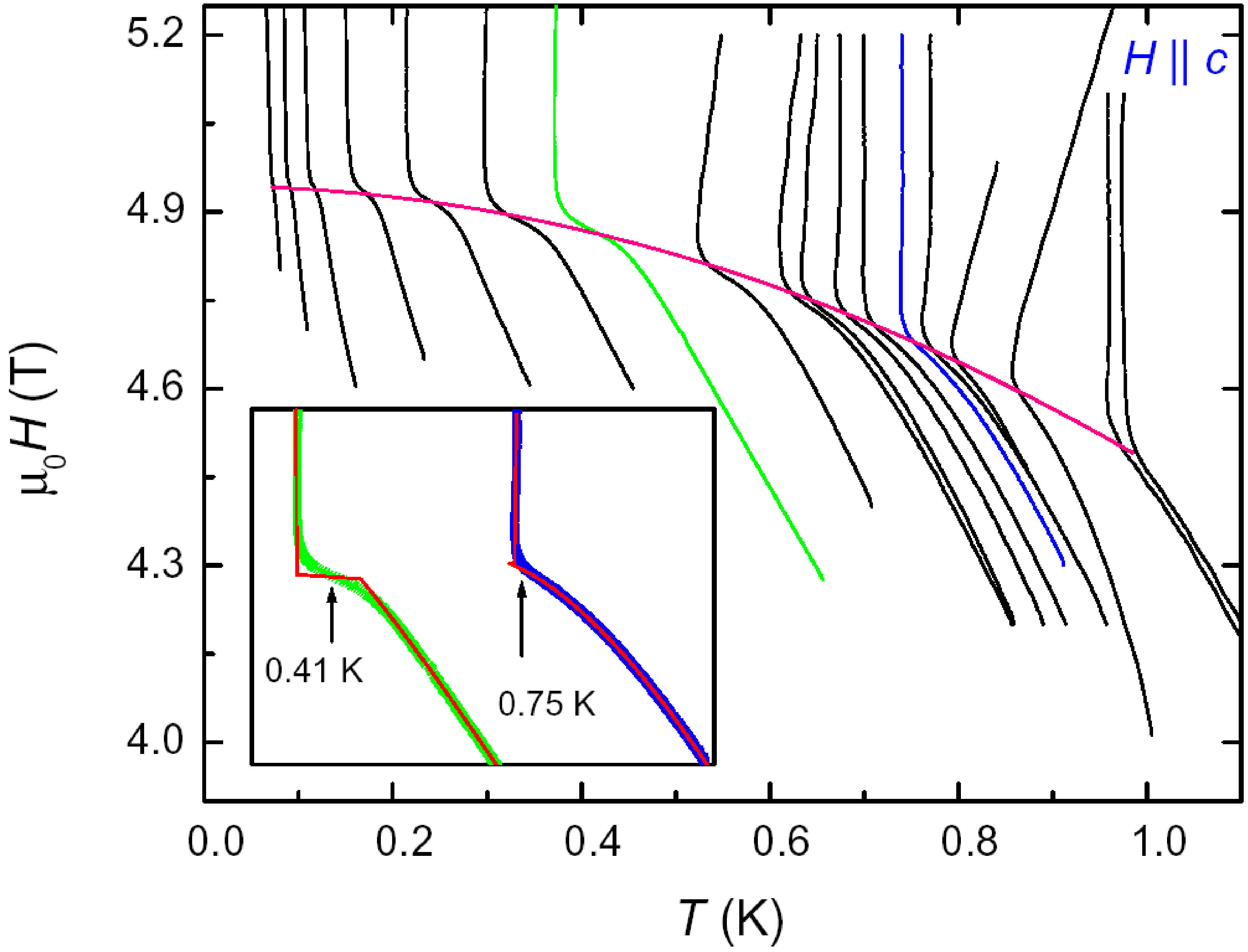
A. Bianchi *et al.*, Phys. Rev. Lett. **89**, 137002 (2002)

Magnetocaloric effect
for first order phase transition

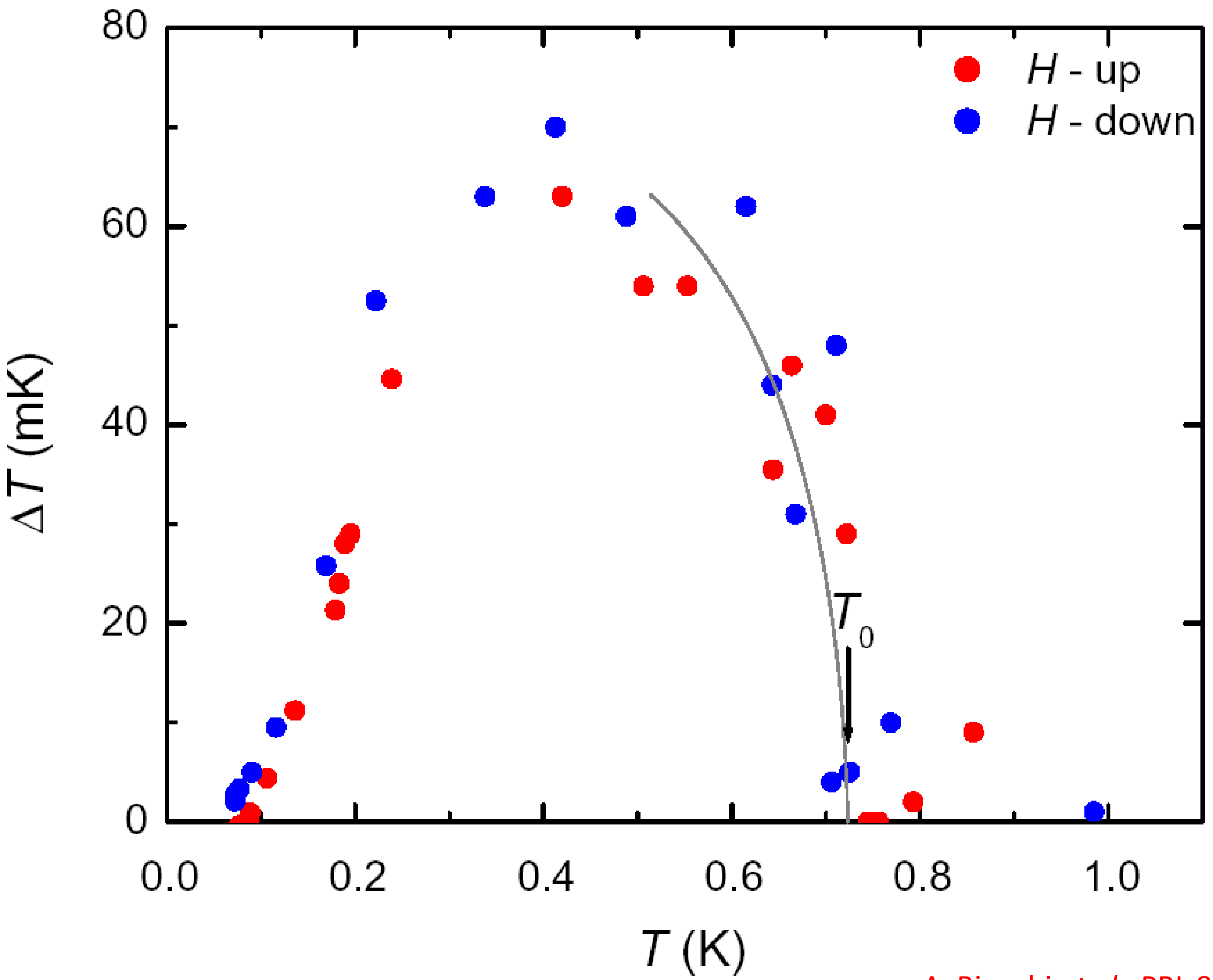
$$dT/dH_S = T/C_H \, (-dM/dT)_H$$





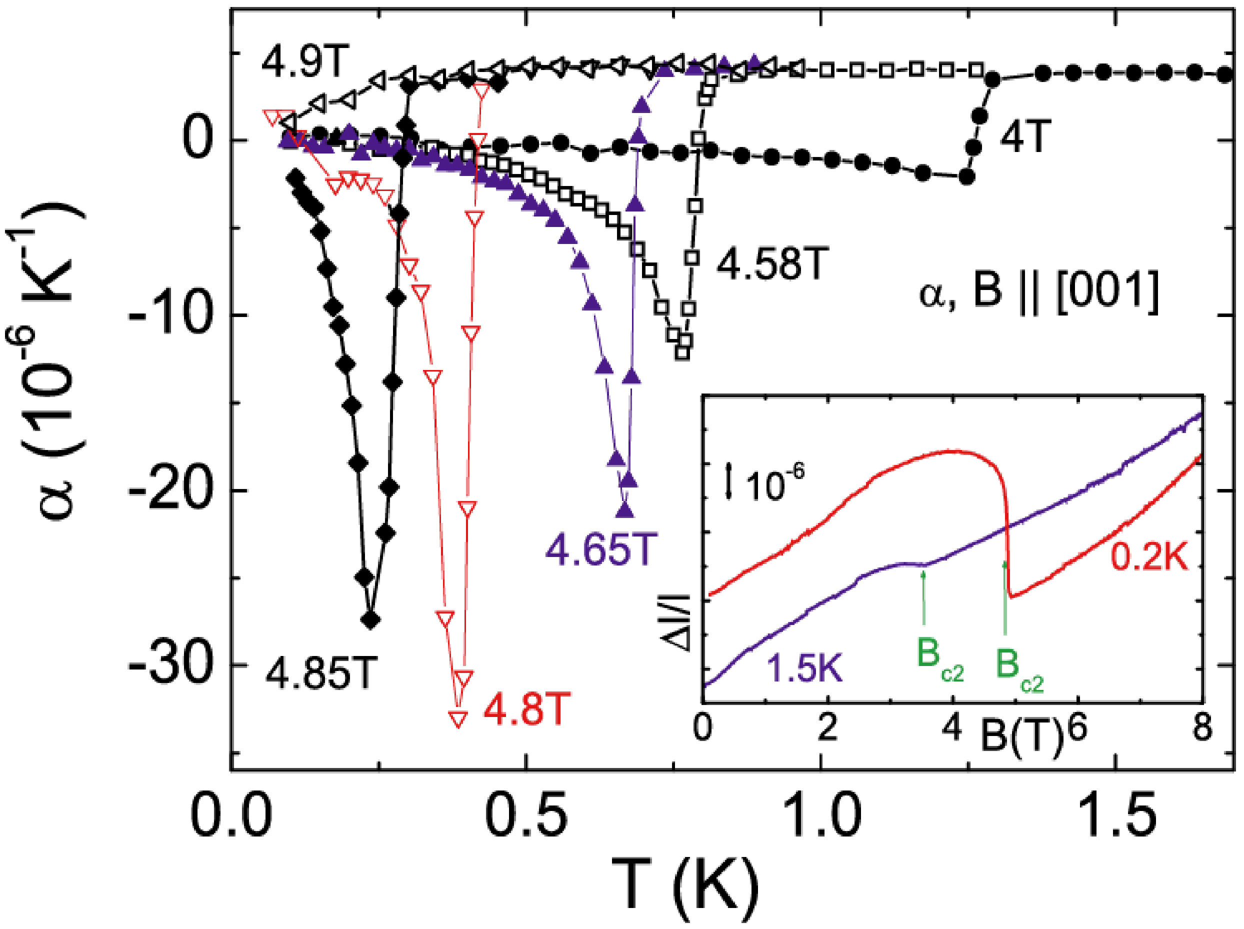
A. Bianchi *et al.*, PRL 89, 137002 (2002)

$CeCoIn_5$ – Jump in T at the crossing of the phase boundary



A. Bianchi *et al.*, PRL 89, 137002 (2002)

$CeCoIn_5$: Thermal expansion – magnetostriction



N. Oeschler, P. Gegenwart, and F. Steglich

A. Bianchi *et al.*, PRL **89**, 137002 (2002)

Angular Position of Nodes in the Superconducting Gap of Quasi-2D Heavy-Fermion Superconductor $CeCoIn_5$

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[1] Institute for Solid State Physics, University of Tokyo, Kashiwa, Chiba 277-8581, Japan
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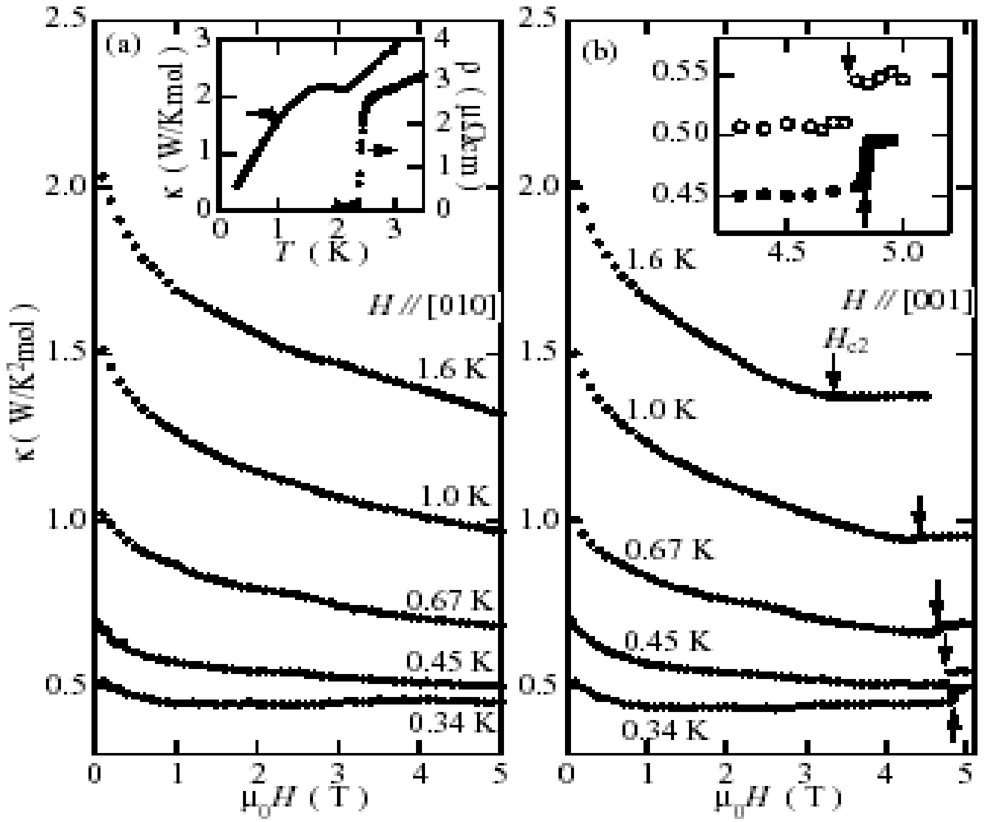


FIG. 1. Thermal conductivity as a function of H for (a) $\boldsymbol{H} \parallel [001]$ and (b) $\boldsymbol{H} \parallel [010]$ below T_c. The thermal current $\boldsymbol{q}$ is applied along [100]-direction. Inset of (a) : κ and ρ in zero field. Inset of (b) : H-dependence of κ near H_{c2} at 0.45 K ($\circ$) and 0.34 K ($\bullet$)

Magnetization of $CeCoIn_5$

- Hysteresis for H||[100]

⇒ First order SC transition

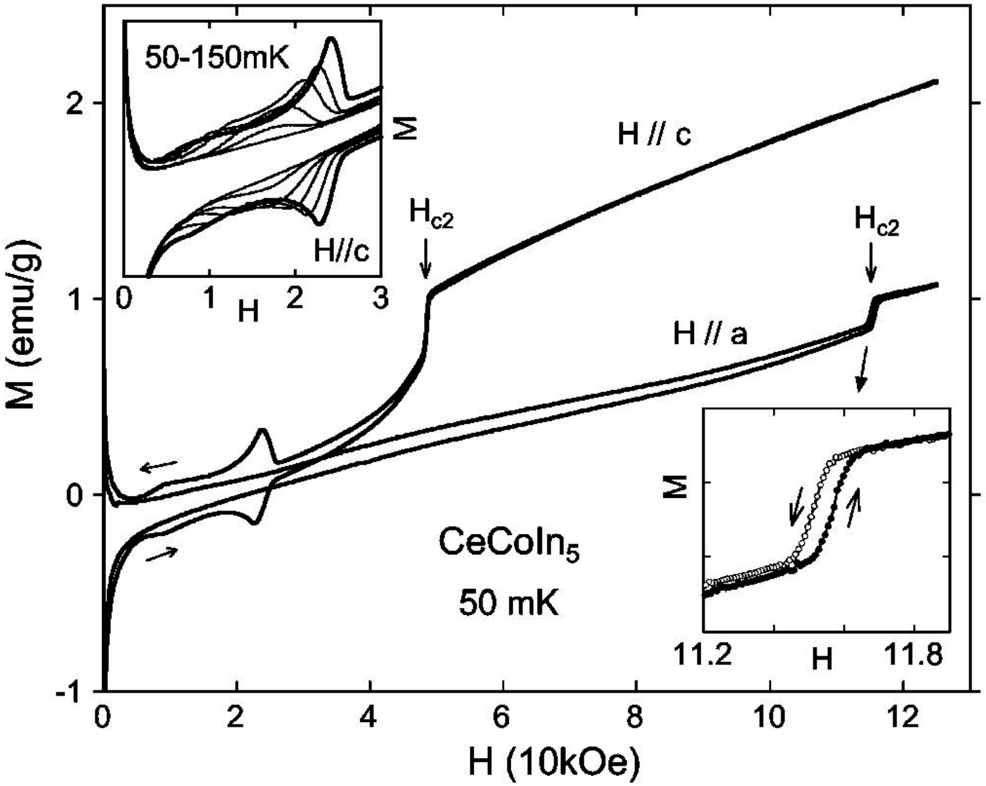
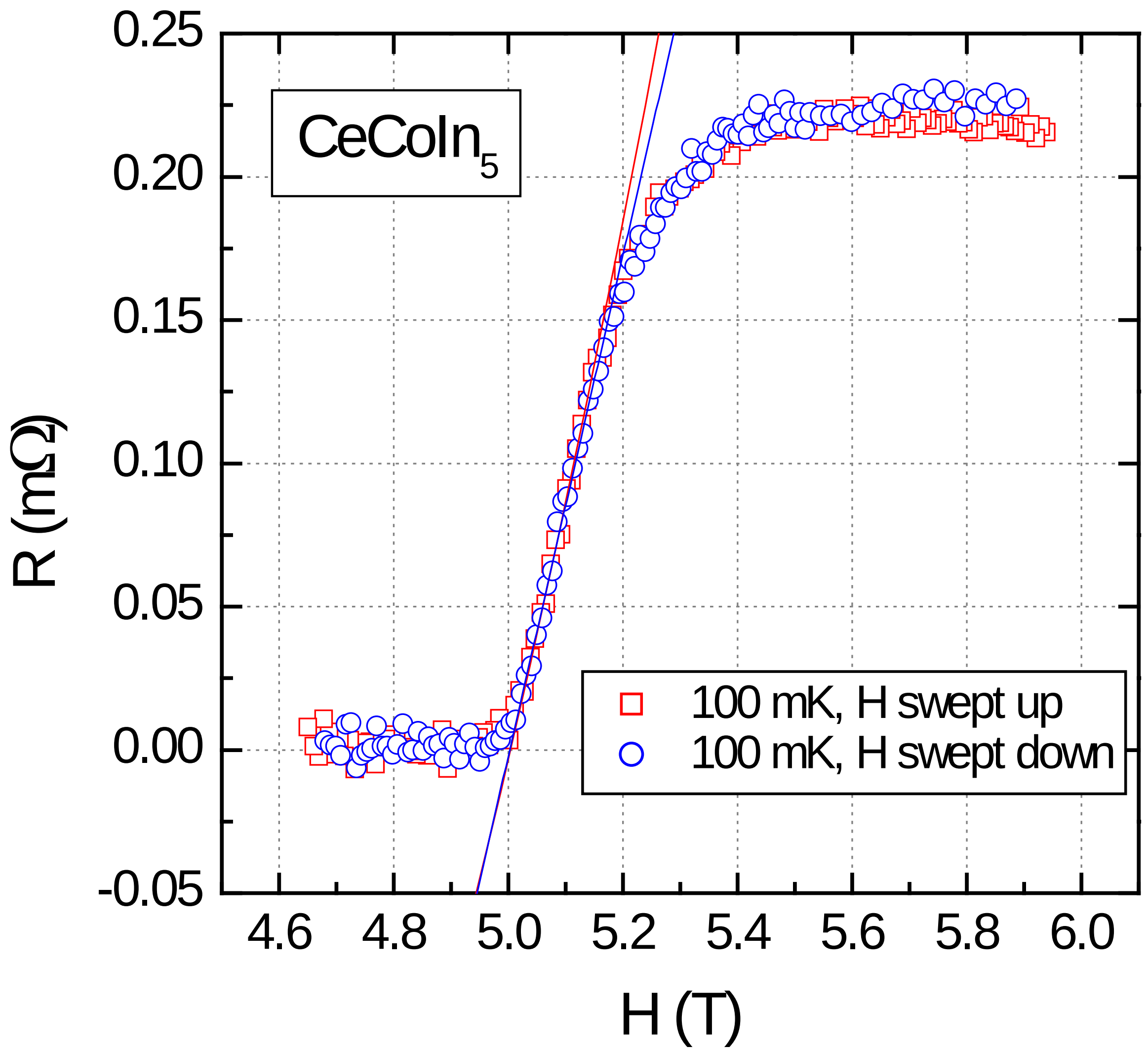


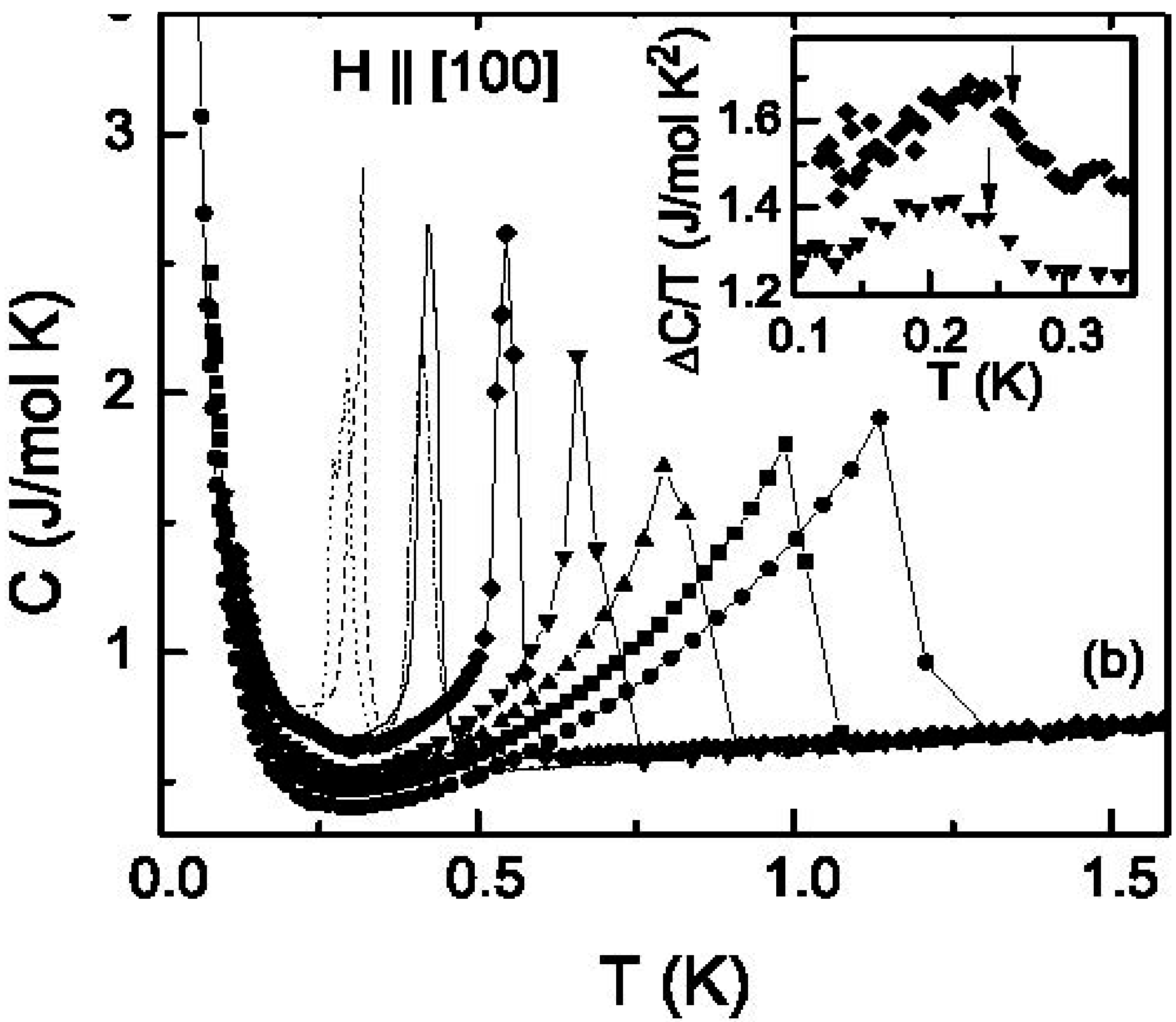
FIG. 1. Isothermal dc magnetization curves $M(H)$ of a single crystal of $CeCoIn_5$ at base temperature of 50 mK in fields applied along the tetragonal c and a axes with the enlarged plot around the upper critical field (lower inset). The upper inset shows the low-field part around the peak effect at several temperatures below 150 mK. The temperature for each curve is 50, 70, 90, 110, 120, and 150 mK in order from the outside.

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

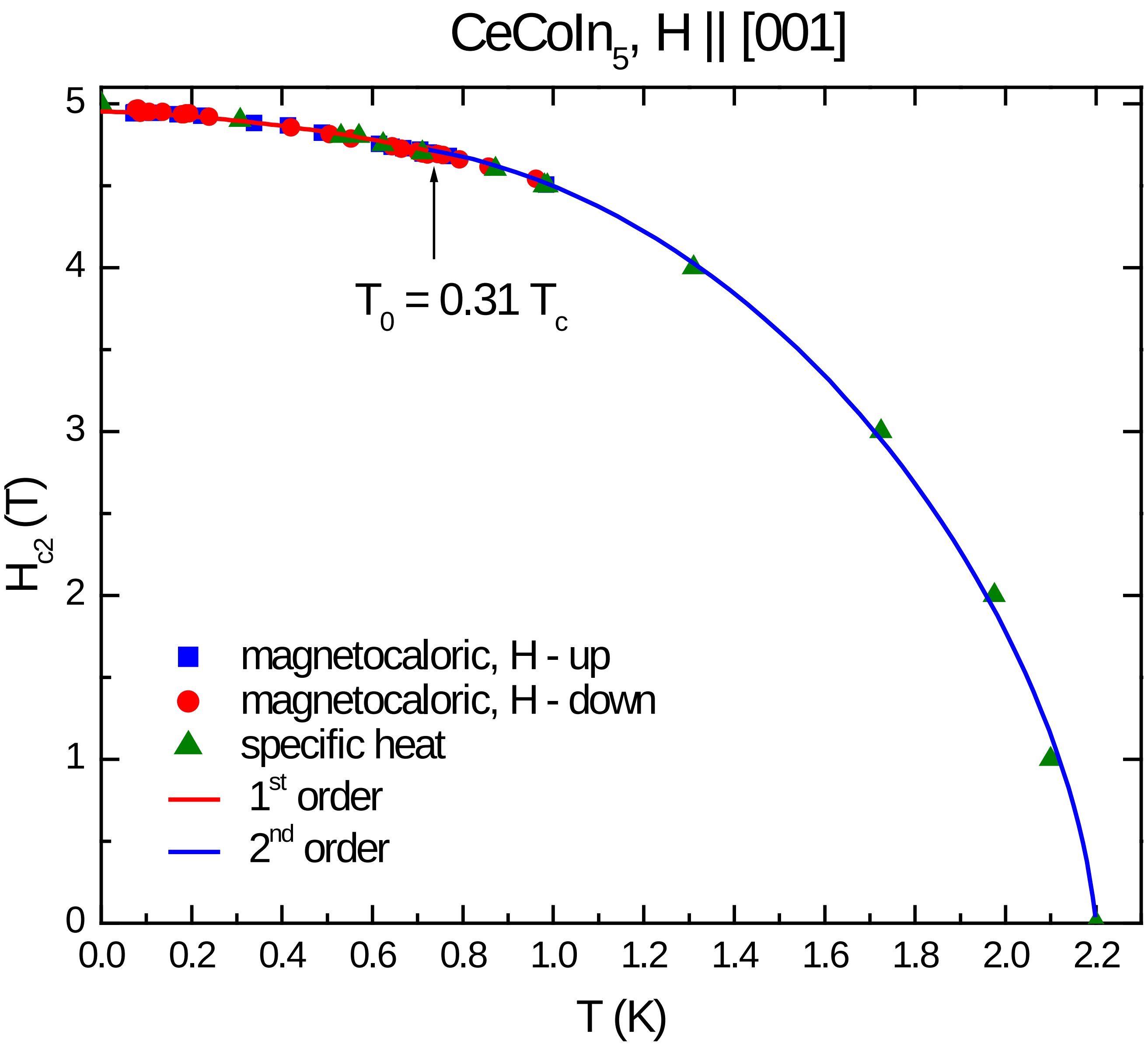
Resistivity for H||[001]
 – no hysteresis.



Hysteresis in specific heat at SC transition at 300 mK
$\Rightarrow$ 1st order transition.



A. Bianchi *et al.*, PRL 91, 187004 (2003)



A. Bianchi *et al.*, *Phys. Rev. Lett.* **89**, 137002 (2002).

Pauli limiting

PL is due to the competition between Zeeman energy of electrons in the normal state and the superconducting condensation energy. PL is mostly pronounced for the singlet superconductivity, with S = 0.
However, triplet states with non-zero S_z component also will exhibit PL, e.g. ^{3}He-B.

From Clogston, PRL 9, 266 (1962), PL for s-wave BCS singlet superconductor is

$$H_p = \Delta_0 \Big/ \sqrt{2}\,\frac{g}{2}\mu_B$$

For $CeCoIn_5$: H_p = 4.2 T, if we use weak coupling BSC value for $\Delta_0 = 1.76\,T_c$ and g = 2.

Calculations for d-wave, K. Yang and S. L. Sondhi, PRB 57, 8566 (1998):

$$H^{d-wave}{}_p = 0.56\cdot\Delta_0 \Big/ \frac{g}{2}\mu_B$$

= 4.1 T for $\Delta_0 = 2.14T_c$ and g = 2.

Problem: experimental values: H_{c2} = 5 T for H || [001] and H_{c2} = 12 T for H || [110] !!!
Solution: g ≠ 2, strong coupling.

Pauli limiting: H_p is an upper bound on the superconducting critical field (measured) H_{c2}

Comment on "First-Order Superconducting Phase Transition in CeCoIn5" (N. Fortune et al., comment to PRL)

$H_{orb}(0) = h^*(0)(-dH_{c2}/dT)|_{Tc} T_c$ (1)

$$H^{d-wave}{}_p = \frac{0.56 \cdot \Delta_0}{\frac{g}{2}\mu_B} = 1.78\,Tc = 4.1\,\text{tesla} \qquad (2)$$

Using eqs. (1) and (2) (H_p = 4.1 T), we (Fortune et al.) calculate that α = 6.4 instead of 3.6.

For H ||[100], $(dH/dT)_{Tc}$ = 24 T/K, H_{orb}|[100] = 40.1 T, H_p = 4.2 T and α = 13.9.

Exp:

H_{c2} = 4.95 T

H_{c2} = 12 T

N. Fortune et al., cond-mat-0305390

The Pauli limit dilemma in $CeCoIn_5$

The Pauli limit is the upper limit for the superconducting critical field, as is indicated in the title of one of the articles cited in the Comment, "Upper limit for the critical field in hard superconductors" by A. M. Clogston, Phys. Rev. Lett. 9, 266 (1962), as well as in the title "A note on the maximum critical field of high-field superconductors" of an article by B. S. Chandrasekhar, Appl. Phys. Lett. 1, 7 (1962).

H_p = 4.1 T is therefore unphysical for both H||[001] (H_{c2}^{exp} = 5 T), and H||[100] (H_{c2}^{exp} =12 T).

The problem lies in taking a final formula for $H_p = 1.78T_c$ without appreciating the underlying assumption that electron g-factor is taken to be 2.

The resolution of the dilemma with unphysical H_p then is that $g \neq 2$.

H ∥ [001]

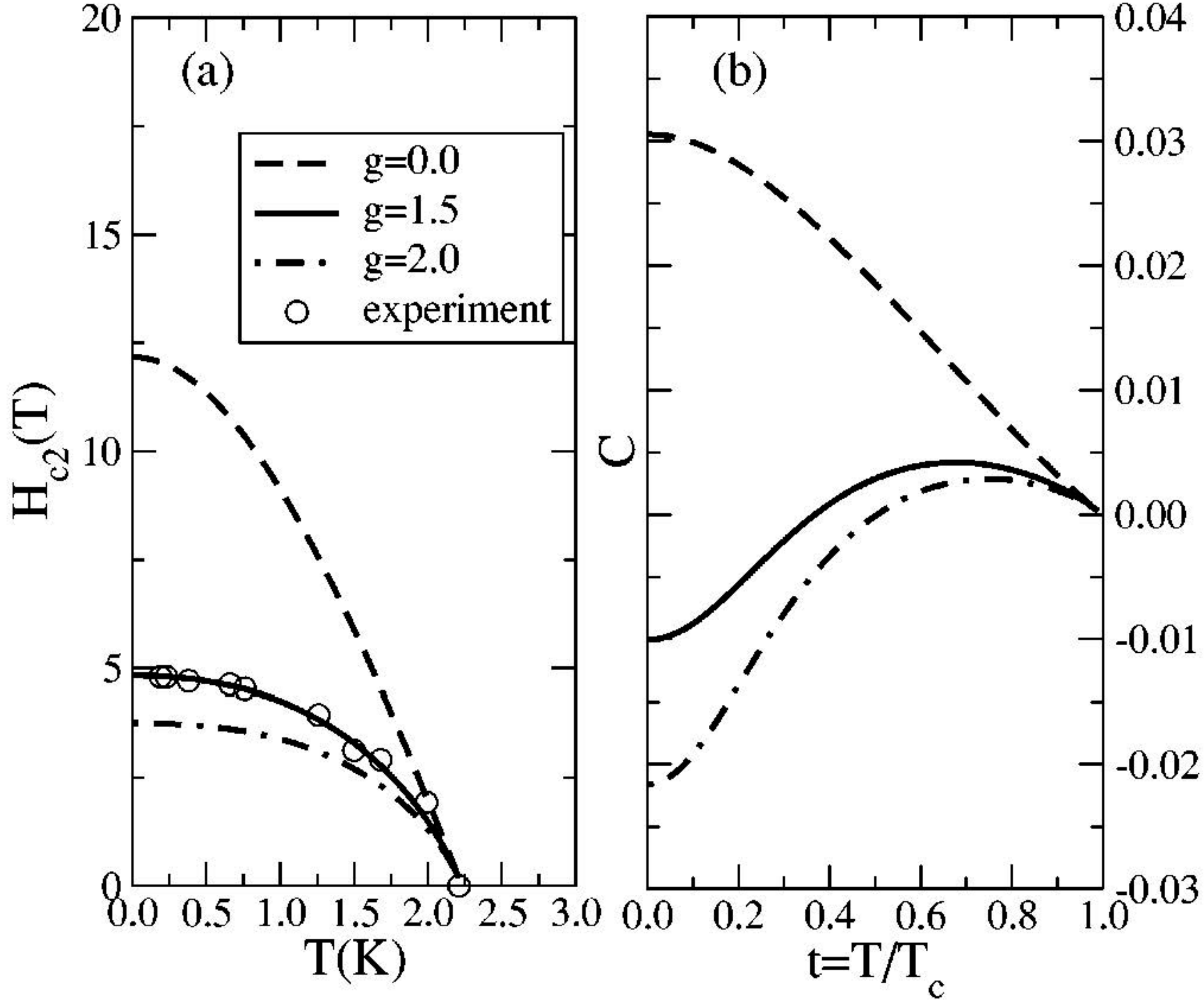


FIG. 1. Temperature dependence of (a) the upper critical field and (b) the admixture parameter C in a $d_{x^2-y^2}$-wave superconductor with g factors $g=0$, 1.5, and 2. The magnetic field is applied along the crystal c direction.

H_p = 5.5 T , α = 3.1 for H ∥ [001]
Compare to H_p = 5.8 T , α = 3.3, from GG with H_{orb} = 13.2 T

H. Won, K. Maki *et al.,* Phys. Rev. B **69**, 180504(R) (2004)

H_p = 12.8 T for H || [100], α = 4.5, $t=T^*/T_c$ = 0.31.

p signifies presence of the FFLO
$p \rightarrow 0$ at t = 0.31 – same as where the SC transition switches from second to first order!

This calculation is equivalent to Gruenberg and Gunther, but for d-wave superconductor!

H. Won, K. Maki *et al.*,
Phys. Rev. B **69**, 180504(R) (2004)

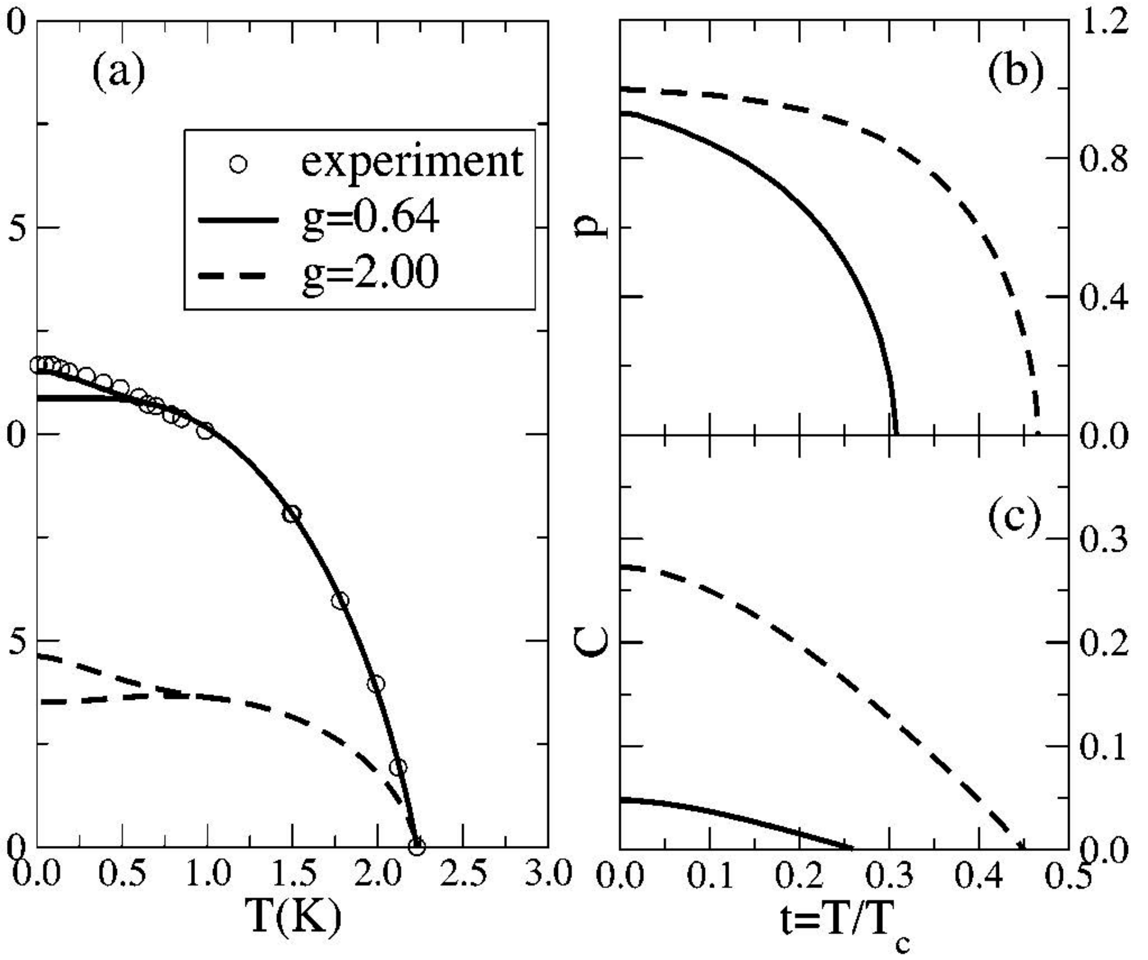


FIG. 2. Temperature dependence of (a) the upper critical field, (b) the $\vec{v}\cdot\vec{q}/(2H)=p\cos\phi$ term, and (c) the admixture parameter C in a $d_{x^2-y^2}$-wave superconductor with g factors $g=0.64$ (solid lines) and 2 (dashed lines). Here $t\equiv T/T_c$ is the reduced temperature. In (a) the lower curves represent $p(t)=0$, i.e., absence of FFLO, whereas the upper curves have $p(t=0)=0.9$. The magnetic field is applied along the crystal a direction. The experimental data (circles) are best described by $g=0.64$ and $p(t=0)=0.9$.

The origin of the first order phase transition – Pauli limiting.

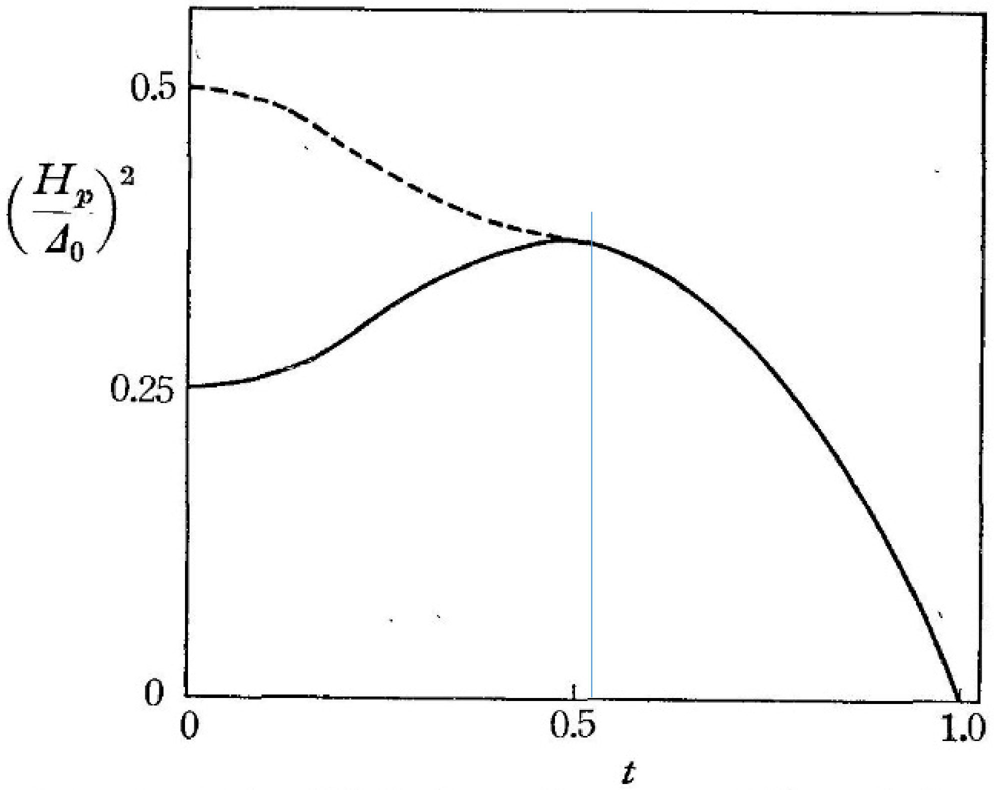


Fig. 1. The H-T phase diagram. The solid curve is the critical field of the second order transition determined by Eq. (12), and the dotted line is that of the first order transition $(F_s - F_n) = 0$. Above the critical point $(t_0 = 0.556)$, the transition is of the second order. For $t < t_0$, the solid curve gives the supercooling critical field.

When orbital effects are neglected:

The effect of Pauli paramagneitsm on superconductors is discussed in detail… The phase transition is of second order for $t=T_c/T$ larger than t_0 = 0.556 …. For smaller values of t the transition becomes one of the first order…

K. Maki and T. Tsuneto, Prog. Theor. Phys. 31, 945 (1964).

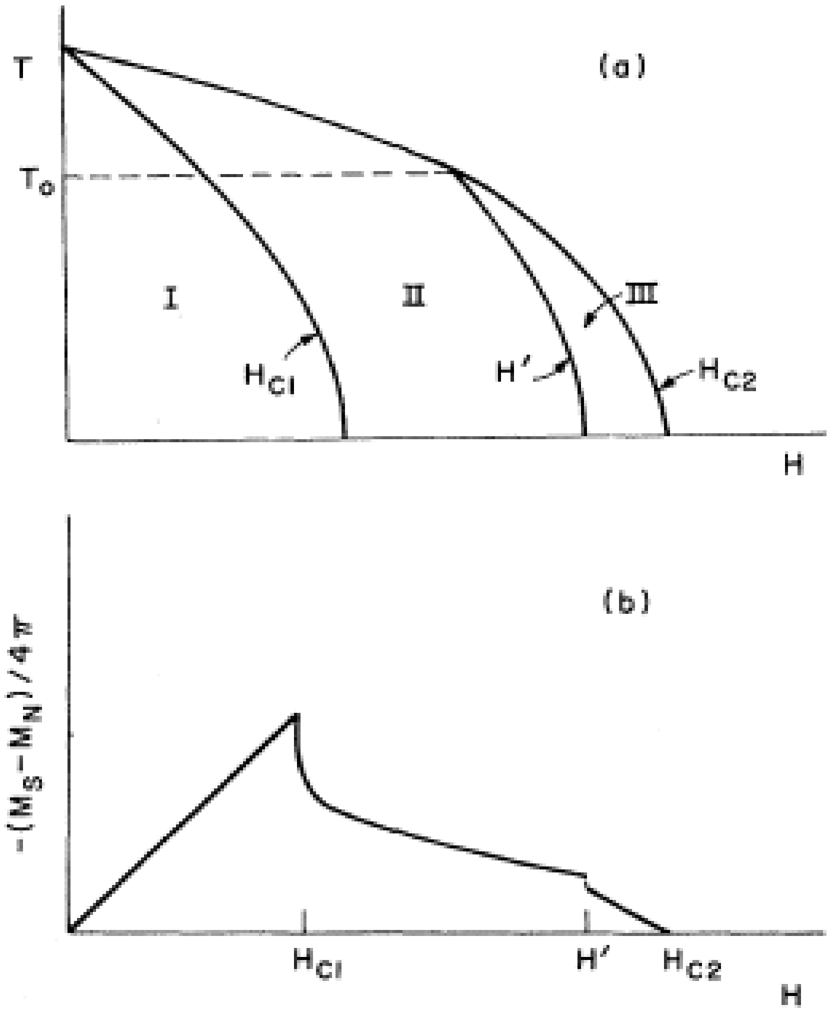


FIG. 2. (a) Phase diagram for a high-α superconductor: (I) diamagnetic state; (II) mixed state; (III) Fulde-Ferrell state. (b) Magnetization as a function of field for a high-α superconductor.

L.W. Gruenberg and L. Gunther PRL **16**, 996 (1966).

Onset of the first order SC transition

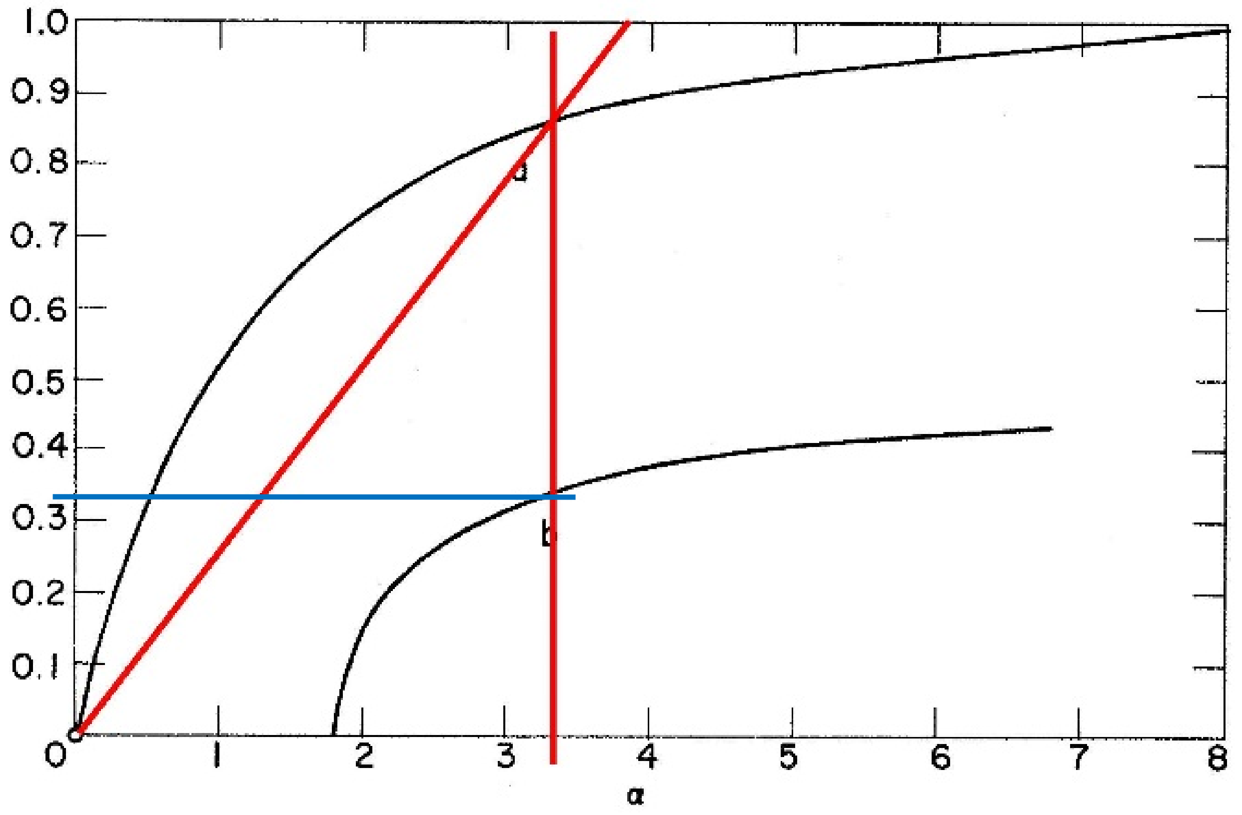


FIG. 1. (a) H_{c2}/H_p as a function of α. (b) $Q\xi_0$ as a function of α.

L.W. Gruenberg and L. Gunther PRL **16**, 996 (1966).

Exp: H_{c2} = 4.95 T; H_{c2}^0 = 13.2 T ➔ $\alpha/(H_{c2}/H_p) = (\sqrt{2}\, H_{c2}^0/H_p)/(H_{c2}/H_p) = \sqrt{2}\, H_{c2}^0/H_{c2} = 3.8$

$\Rightarrow \alpha$ = 3.3, H_p = 5.8 T, and $T_0/T_c = 0.33$. compare with experimental $T_0/T_c = 0.31$.

$\Rightarrow$ theory based of Pauli limiting is consistent with experiment.

Onset of the first order SC transition for H||[100]

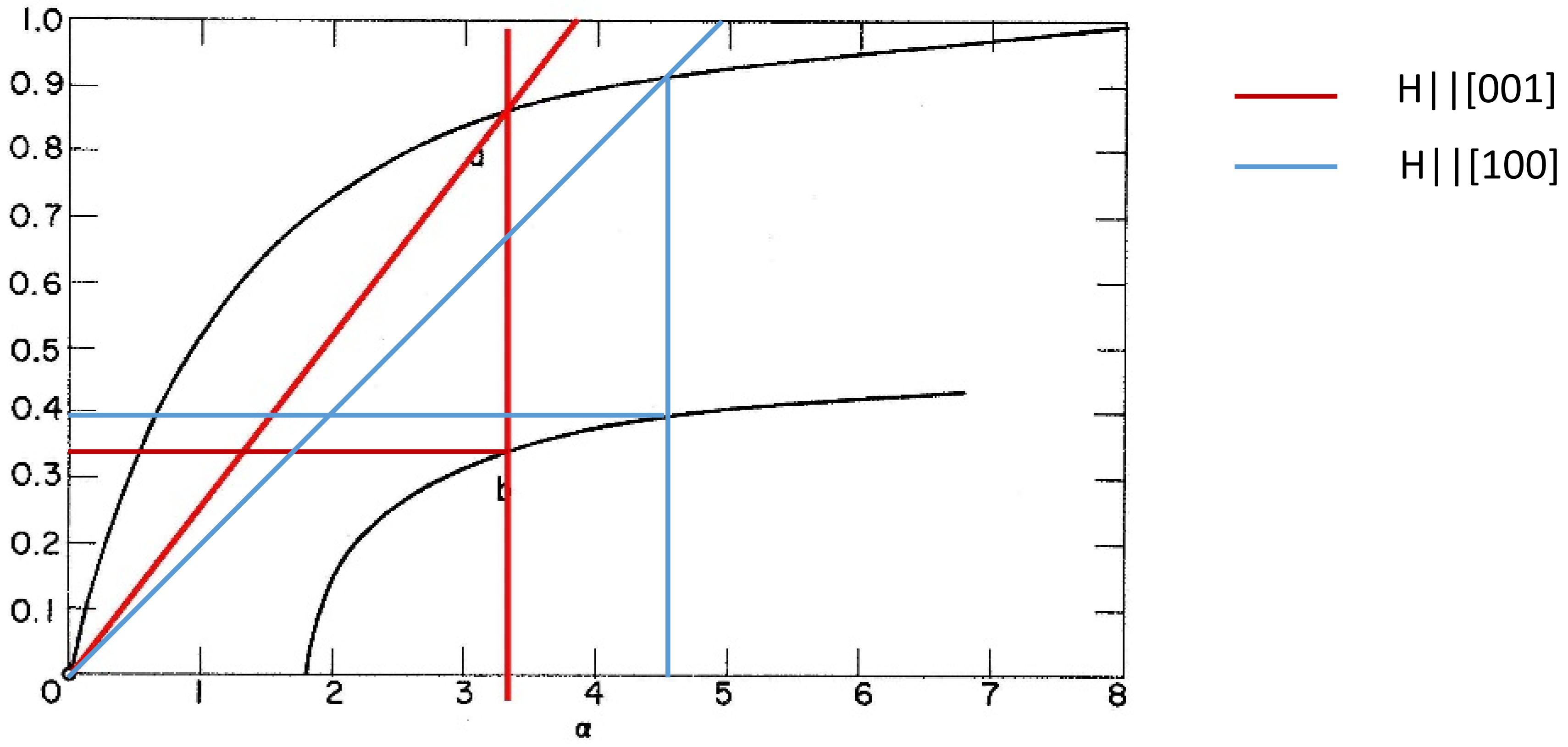


FIG. 1. (a) H_{c2}/H_p as a function of α. (b) $Q\xi_0$ as a function of α.

L.W. Gruenberg and L. Gunther PRL **16**, 996 (1966).

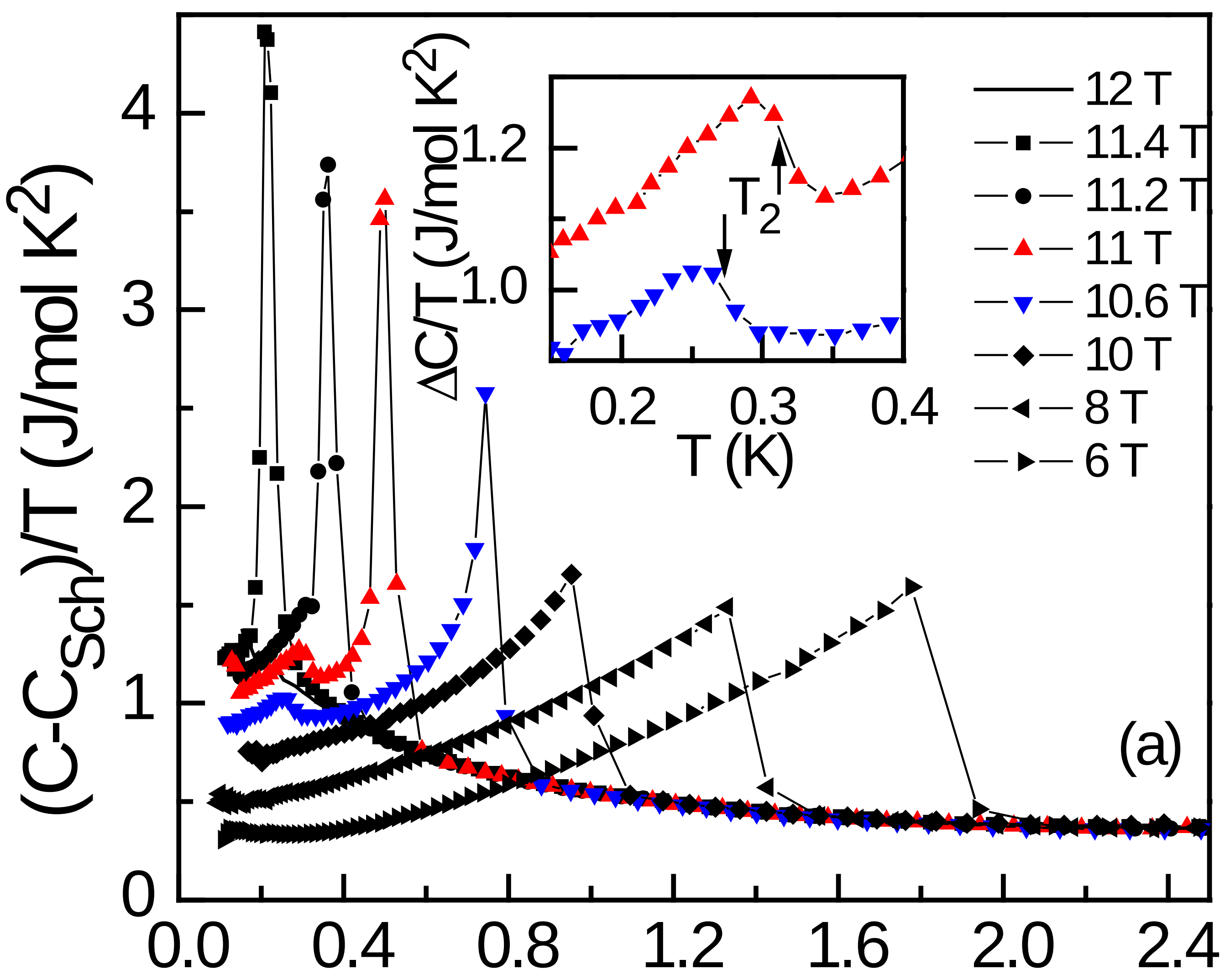
Exp: H_{c2} = 11.6T T; H_{c2}^0 = 40.3 T ➔ $\alpha/(H_{c2}/H_p) = (\sqrt{2}\, H_{c2}^0/H_p)/(H_{c2}/H_p) = \sqrt{2}\, H_{c2}^0/H_{c2} = 4.91$

α = 4.5, H_p = 12.7 T, and $t=T_0/T_c = 0.39$. (1) compare with experimental $T_0/T_c = 0.31$.

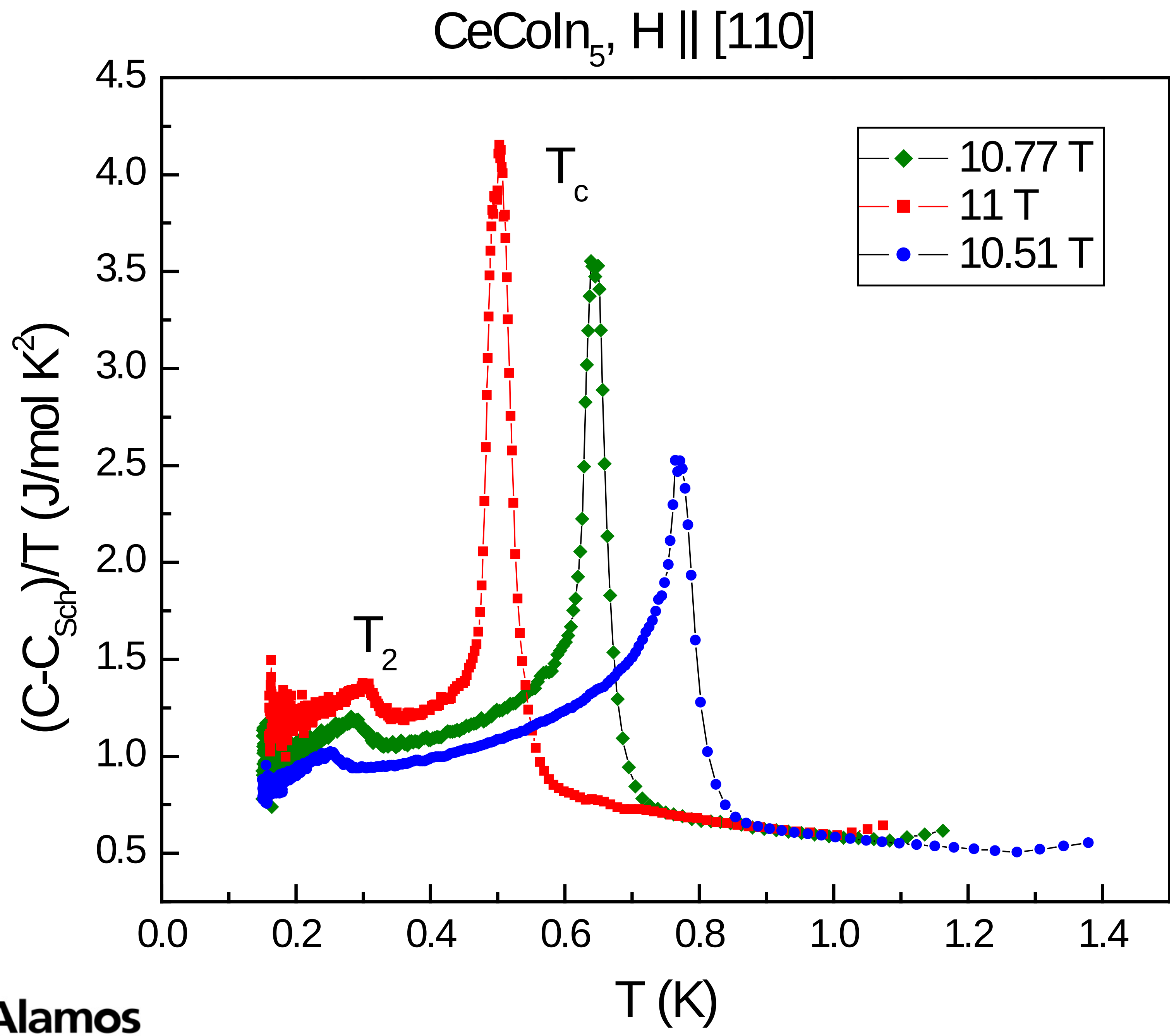
(2) Compare with Won and Maki: α = 4.5, H_p = 12.8 T, $t = T_0/T_c = 0.31$.

Good agreement between GG and WM! GG misses experimental value of $t=T_0/T_c$ by about 25%.

CeCoIn$_5$, H || [110]



A. Bianchi *et al.*, PRL 91, 187004 (2003)



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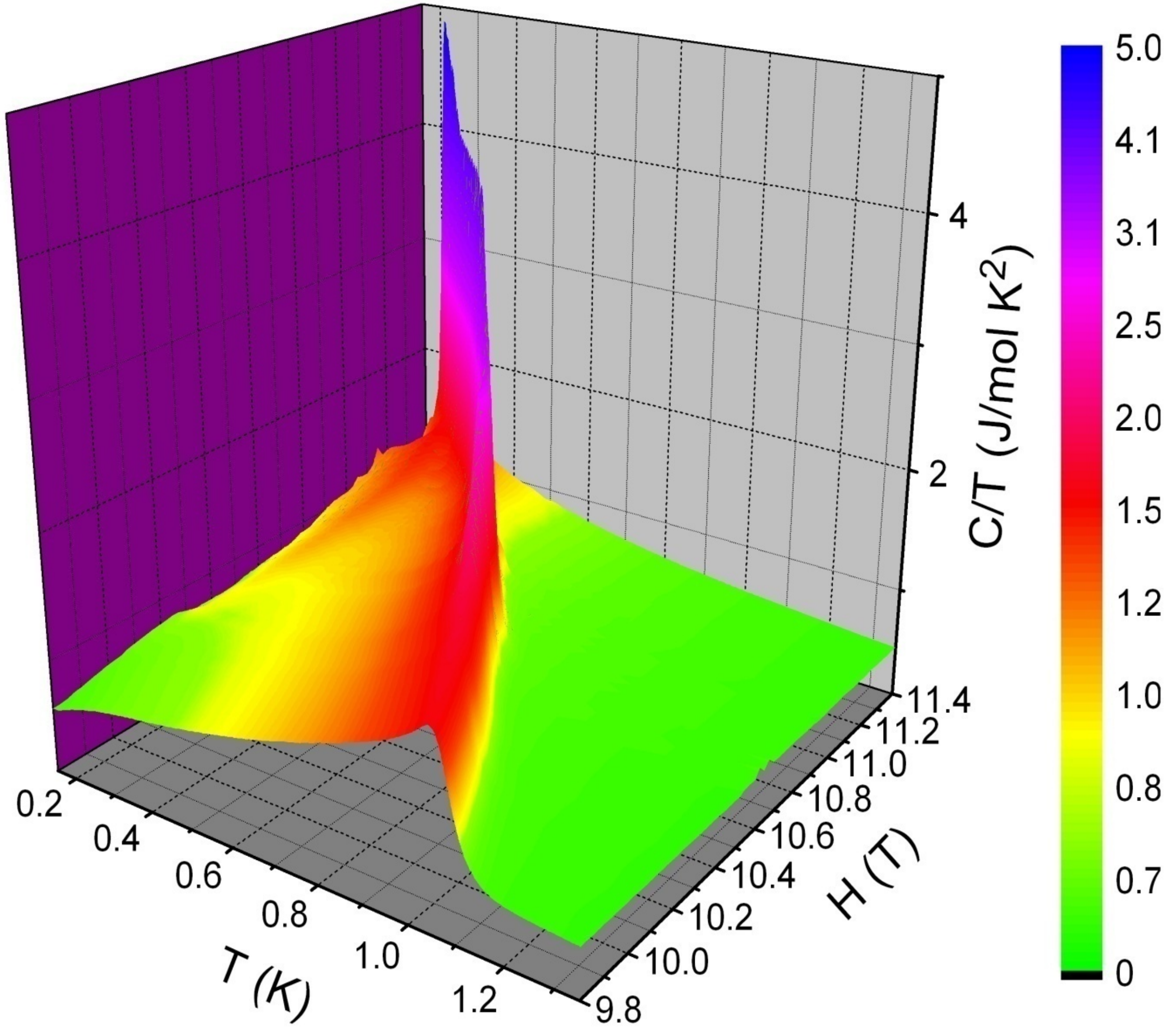
Specific heat of $CeCoIn_5$: SC and the high field phase



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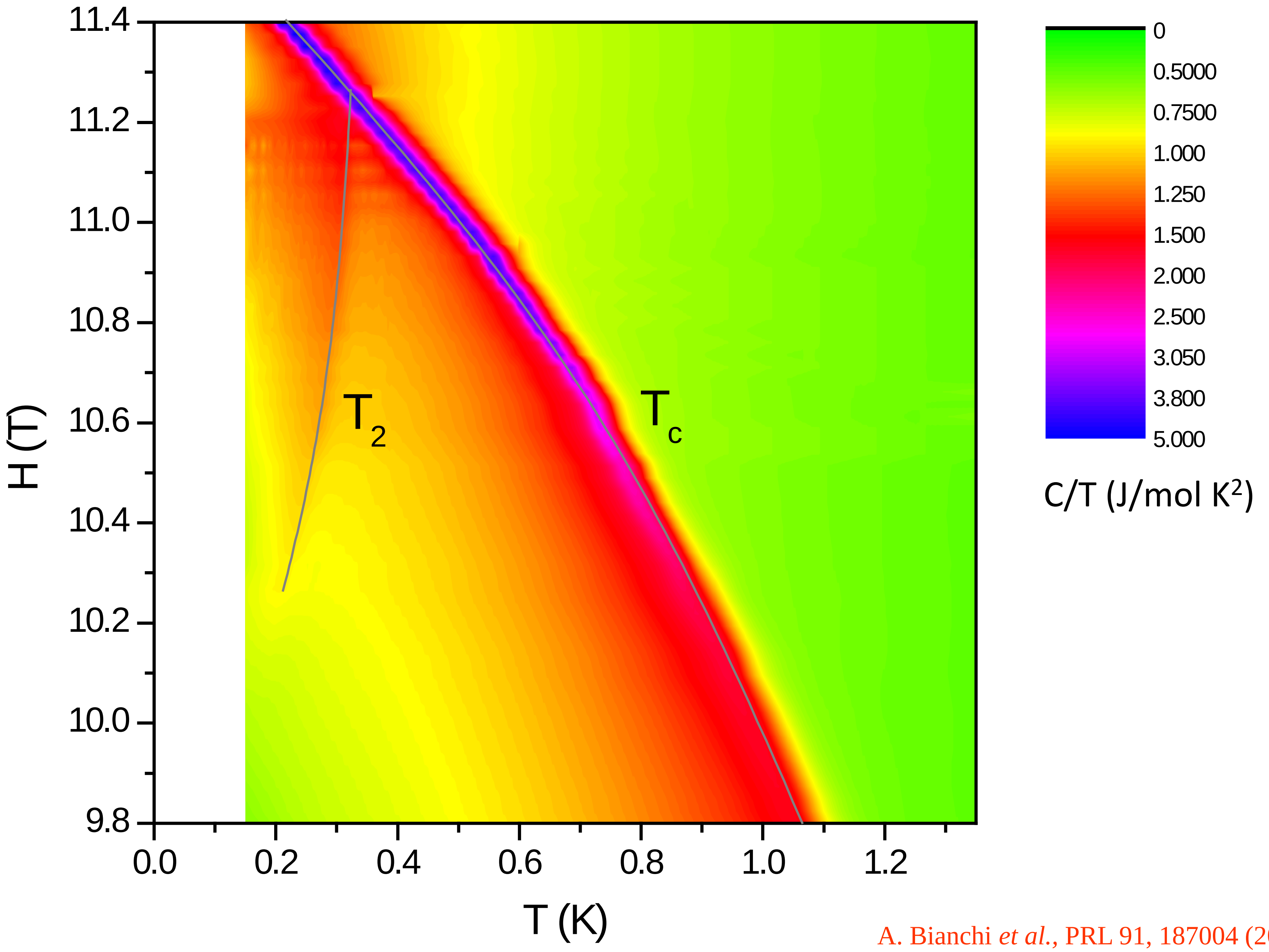
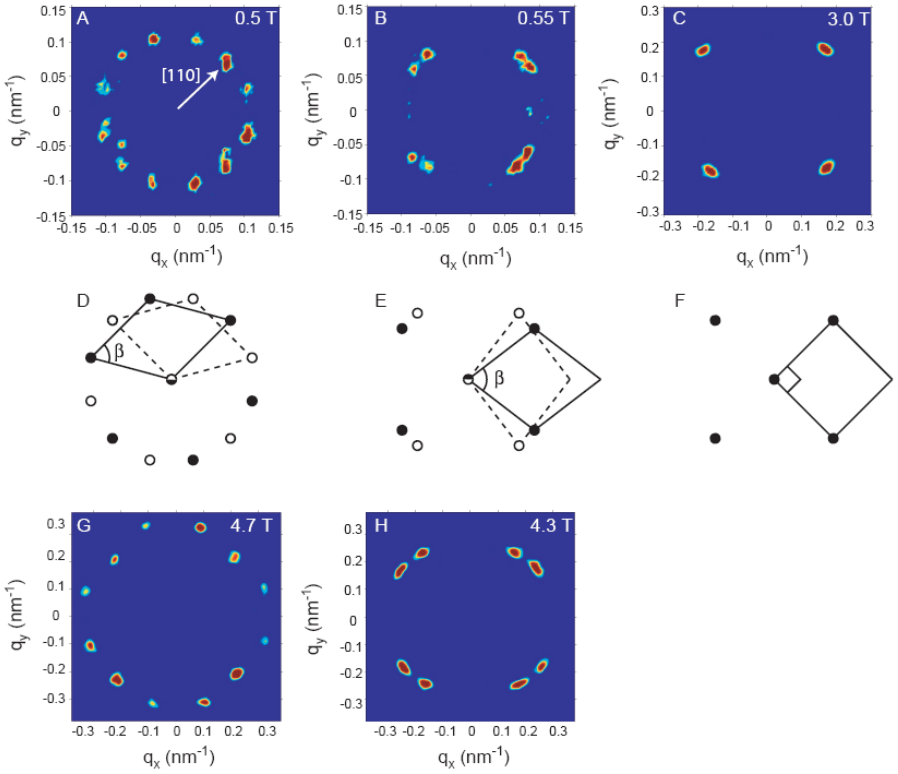
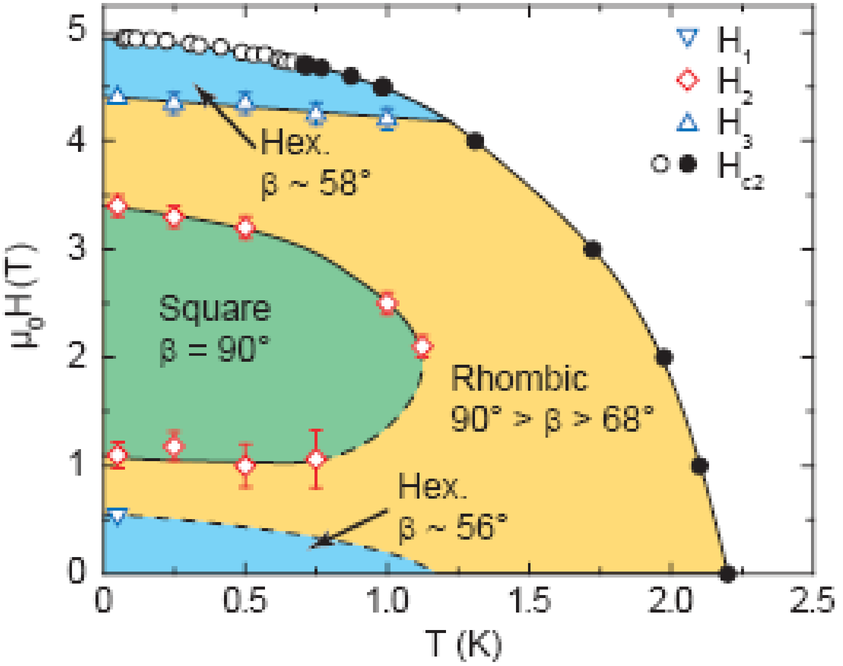


A. Bianchi *et al.*, PRL 91, 187004 (2003)

SANS investigations of the superconducting state in $CeCoIn_5$ vortex phase diagram

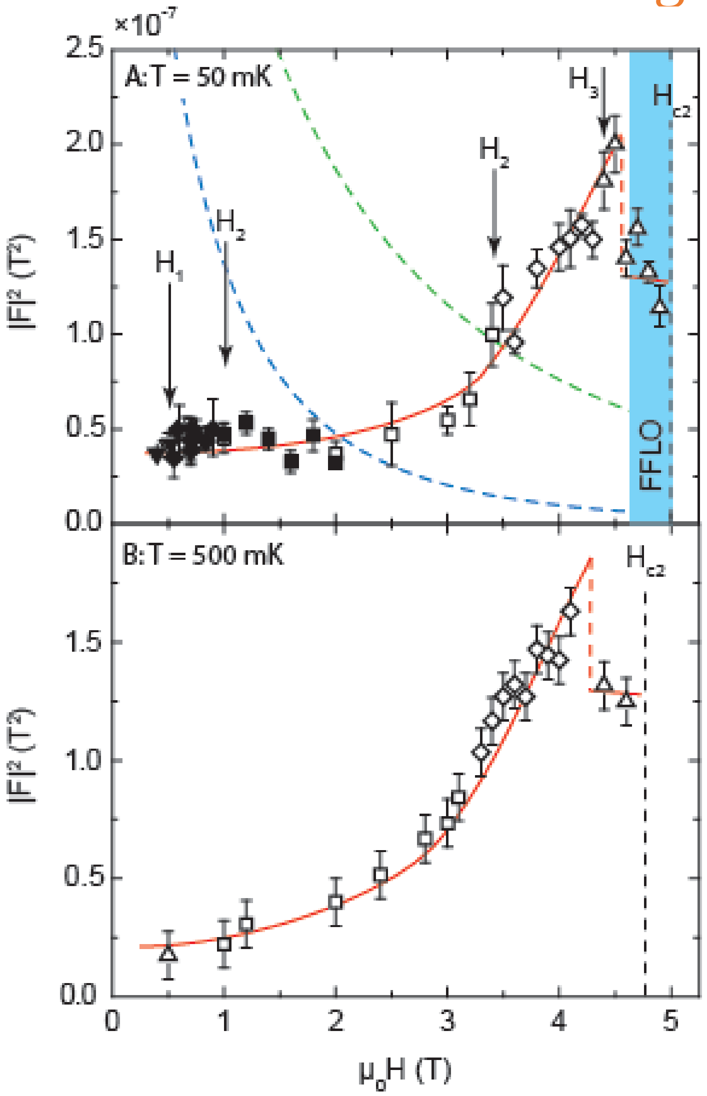




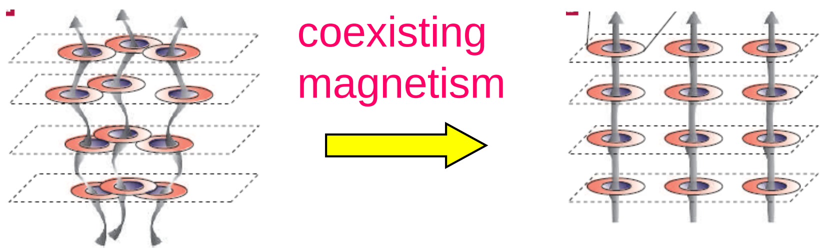
A. Bianchi *et al.*, Science **319**, 177 (2008)

Rich vortex phase diagram reflects unconventional superconducting order parameter; sharp reflections are result high regularity of the VL due to low vortex pinning and high purity of $CeCoIn_5$

SANS investigations of the superconducting state in $CeCoIn_5$: magnetic form factor



- Abrikovsov-Gorkov theory of Type II superconductors expects decrease of the magnetic form factor (variation of magnetization in the sample) in type II sc with increased magnetic field (dashed lines).
- Unusual form factor evolution with field implies enhanced magnetism in the vortex cores, and possibly reflects the approach to the QCP at H_{c2} which would result in decrease of SC coherence length ξ_0.
- Enhanced magnetism may lead to stronger vortex pinning.



A. Bianchi *et al.*, Science **319**, 177 (2008)

Conclusions:

- $CeCoIn_5$ is a Pauli limited superconductor via H-T phase diagram.
- Superconducting transition becomes first order below critical temperature $t_0 = T_0/T_c = 0.31$, $T_0 = .72$ K
- 1st order SC transition was predicted by K. Maki in 1964 in Pauli limited superconductors (no orbital limiting) below $t_0 = 0.56$.
- Including orbital limiting and FFLO state, Gruenberg and Gunther for s-wave superconductors (1966) and Won and Maki (2004) for a *d*-wave $CeCoIn_5$ reproduces the experimental t_0.