Unconventional SC and order parameter symmetry thermodynamic and transport measurements.

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- Previous investigations of thermal conductivity and specific heat of $CeCoIn_5$ in rotating magnetic field. – thermal conductivity with heat current J || [100]
- Four-fold oscillation term is sensitive to band structure and varies (even sign) in the H-T plane.
- Thermal conductivity with J || [110] : rich response to field rotation
- Resonances of thermal conductivity for H || J ($\Theta = 0$) and for $\Theta = 33°$.
- $\Theta = 33°$ at present is a mystery!!!

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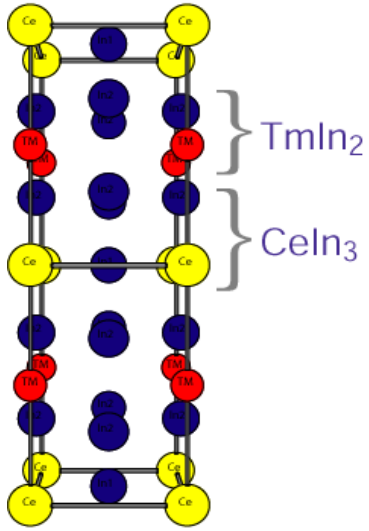
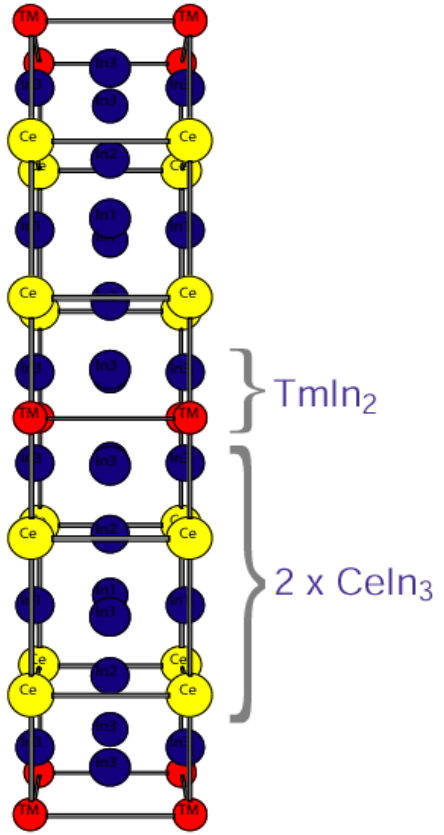
Crystal structures of the $Ce_nTm_mIn_{3n+2m}$ family

H

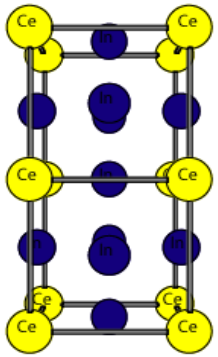
Tm = Rh,Co, or Ir



$CeTmIn_5$



Ce_2TmIn_8

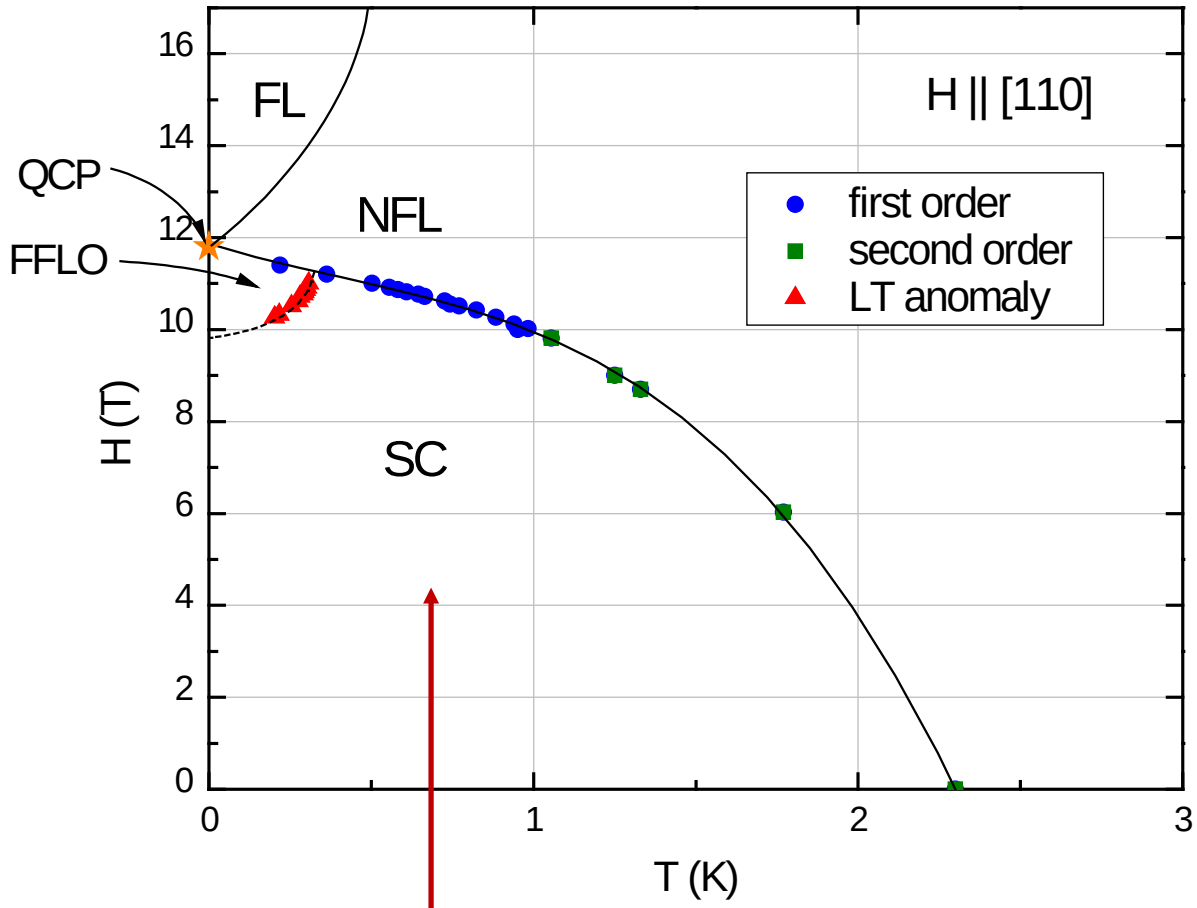


$CeIn_3$

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?

In this talk focus on the uniform superconducting SC part of the phase diagram.

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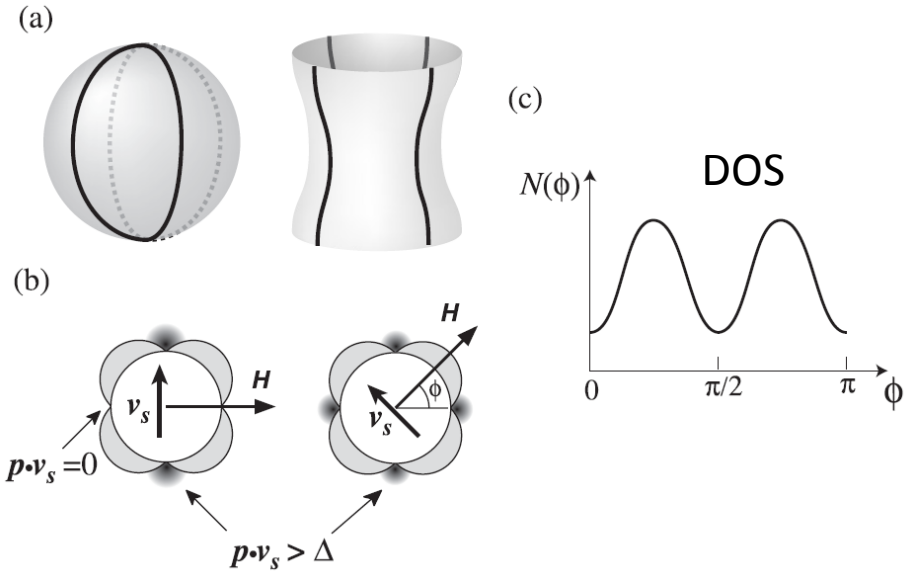
Angle resolved thermal transport measurements

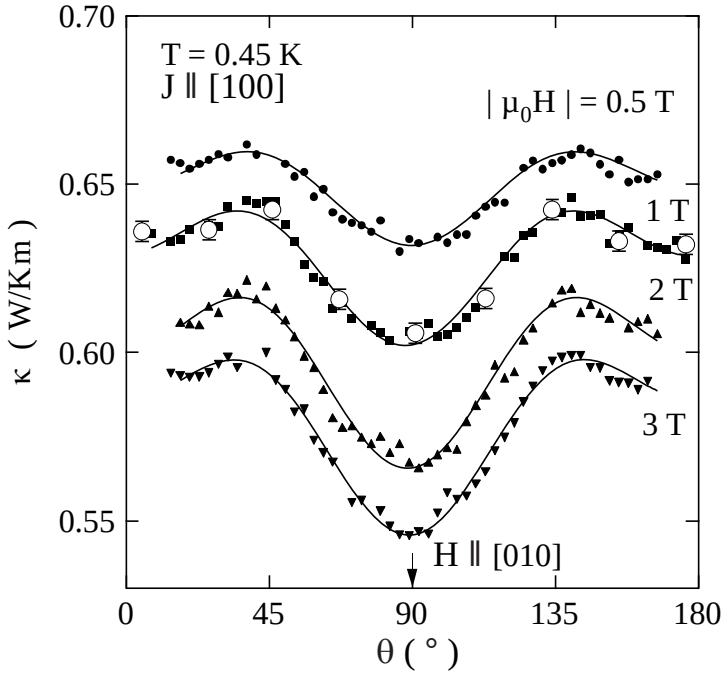
Doppler shift of the quasiparticle spectrum

$$\varepsilon(\mathbf{k}) \rightarrow \varepsilon(\mathbf{k}) - \hbar\mathbf{k}\cdot\mathbf{v}_s$$

In the presence of supercurrent v_s, the energy of a quasiparticle with momentum **k** is Doppler shifted.



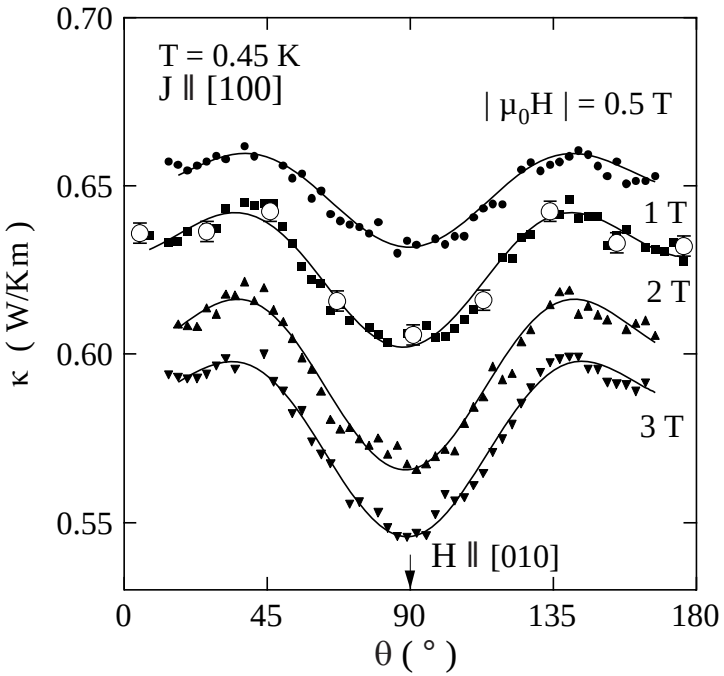
Y. Matsuda, K. Izawa, and I. Vekhter, J. Phys. Condens. Matter **18**, R705 (2006)



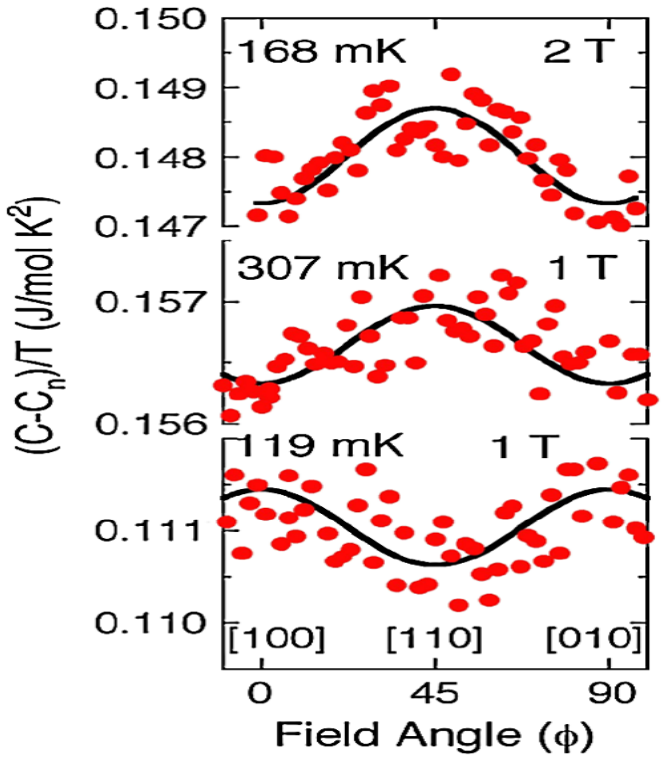
K. Izawa *et al.*, Phys. Rev. Lett. **87**, 057002 (2001)

Field-Angle dependent Thermal Conductivity and specific heat of $CeCoIn_5$

Heat current J || [100]



K. Izawa *et al.*, Phys. Rev. Lett. **87**, 057002 (2001)



K. An, T. Sakakibara, R. Settai, Y. Onuki, M. Hiragi, M. Ichioka, and K. Machida, Phys. Rev. Lett. **104**, 37002 (2010)

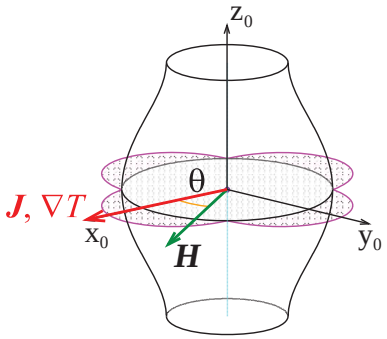
!!! problem

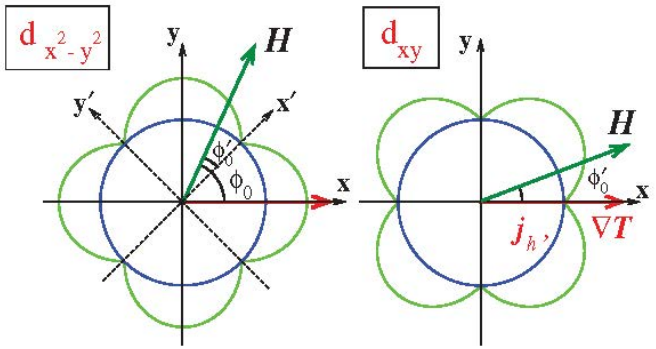
SC OP was identified as d_{x2-y2} nodes along [110]

SC OP was identified as d_{xy} nodes along [100]

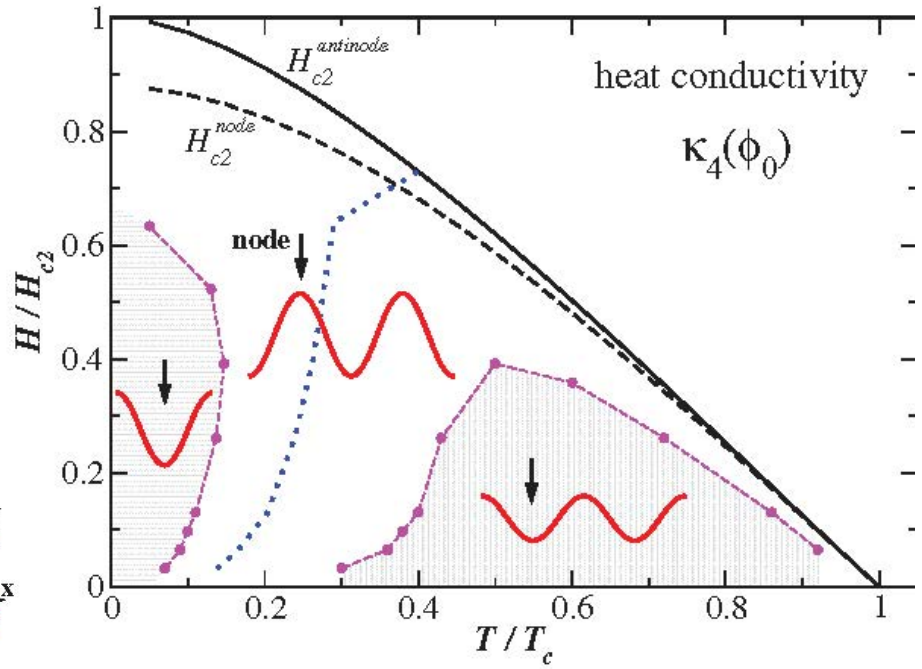
Angle resolved thermal transport and specific heat

Quasi-cylindrical Fermi Surface of $CeCoIn_5$

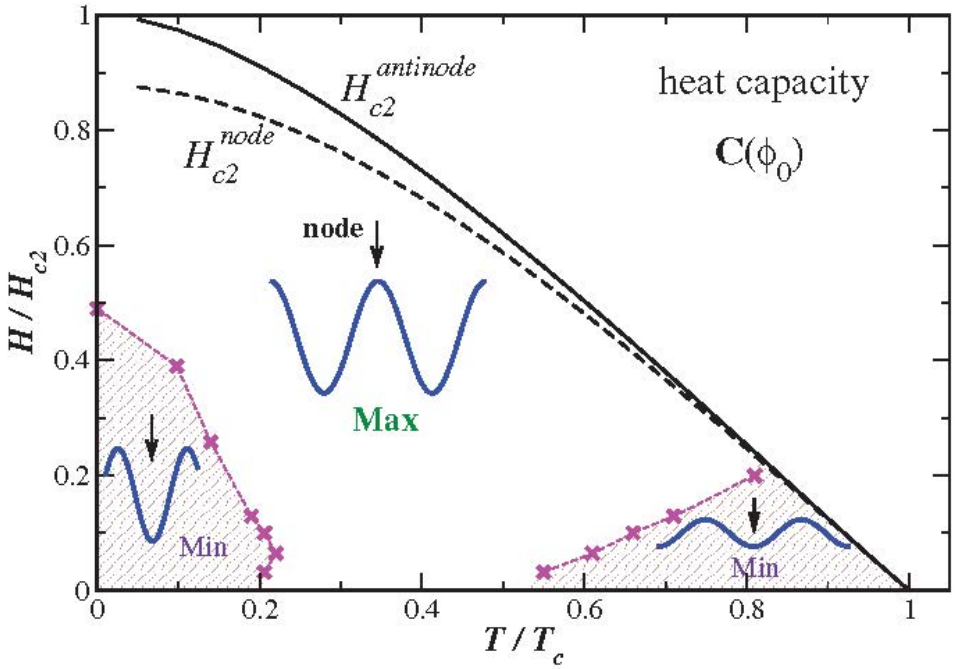




Thermal transport is a combined effect of the density of states and scattering time.



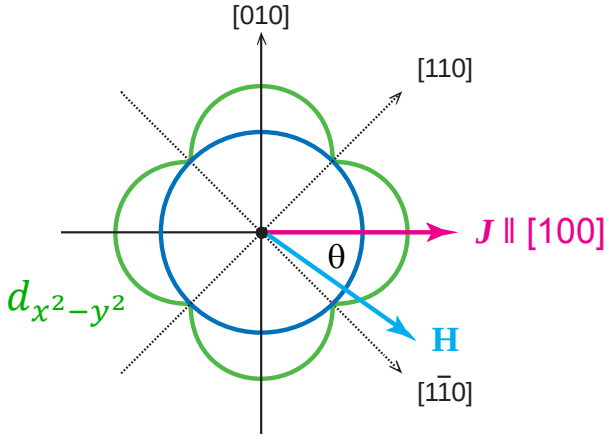
Specific heat depends only on the density of states .

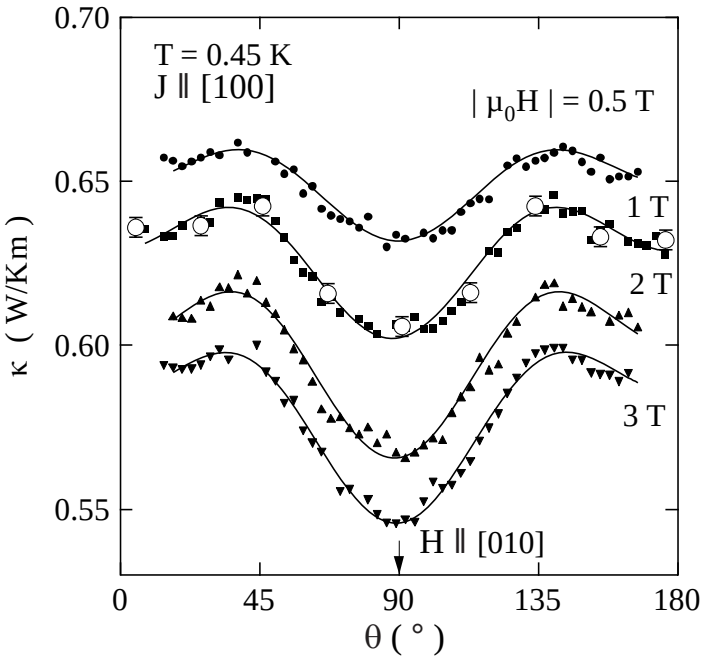


A. B. Vorontsov and I. Vekhter, Phys. Rev. B **75**, 224502 (2007)

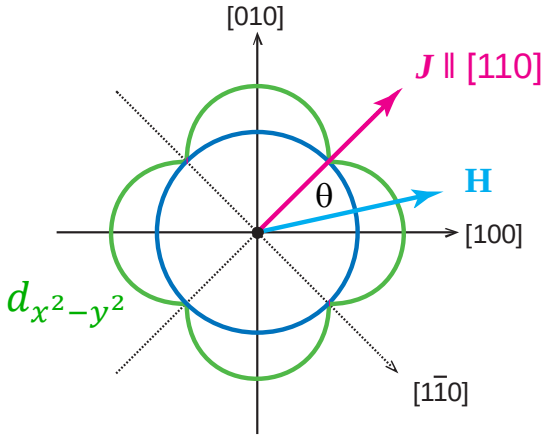
Field-Angle dependent Thermal Conductivity of $CeCoIn_5$

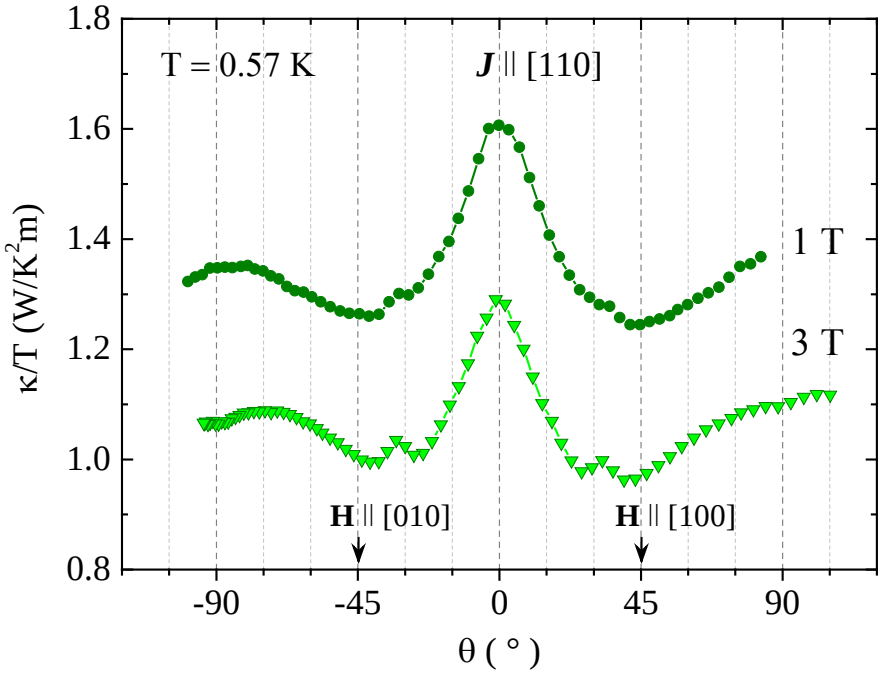
J along anti-nodal direction





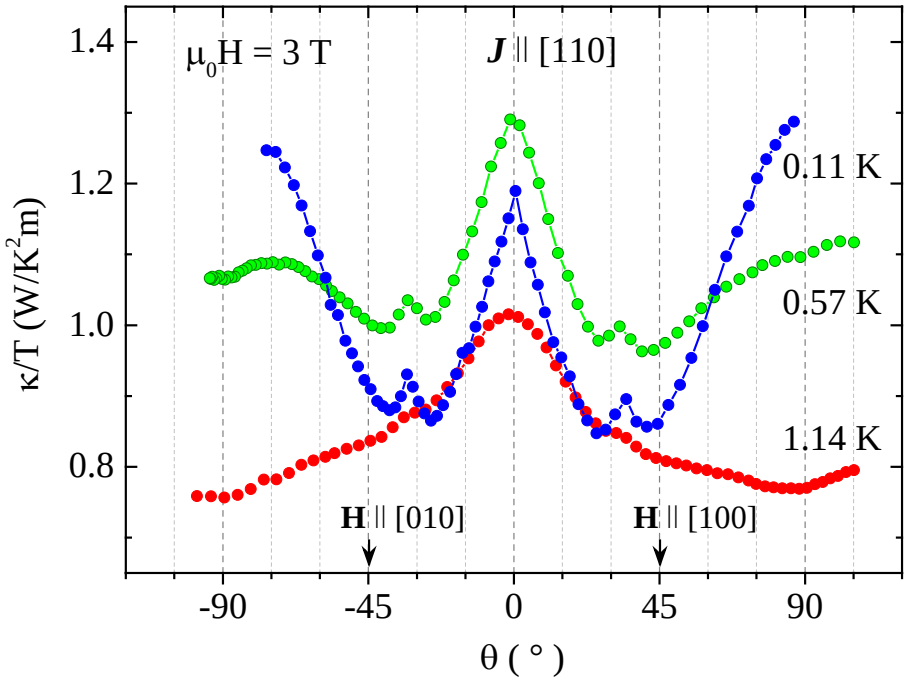
J along nodal direction





K. Izawa *et al.*, Phys. Rev. Lett. **87**, 057002 (2001)

Temperature-dependent evolution of Scattering



Thermal transport is a combined effect of the density of states and scattering time.

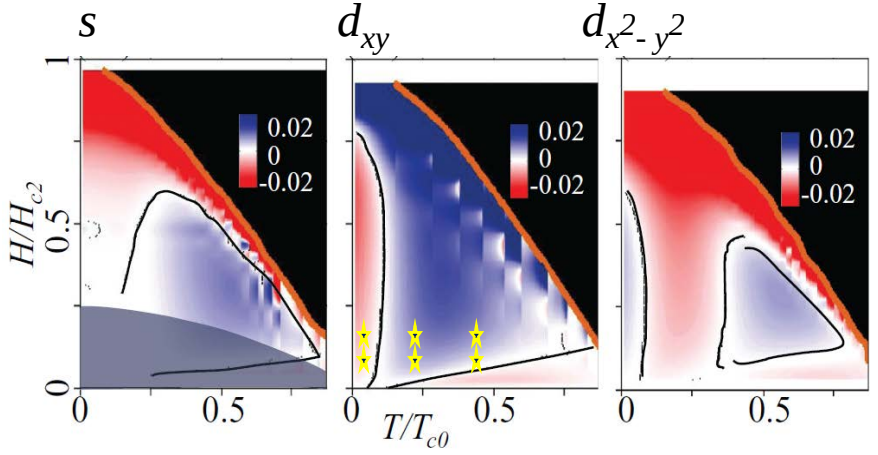
$$\kappa_{xx} \sim N(\varphi) v_F l\, T$$

$N(\varphi)$: Density of state

v_F : Fermi velocity

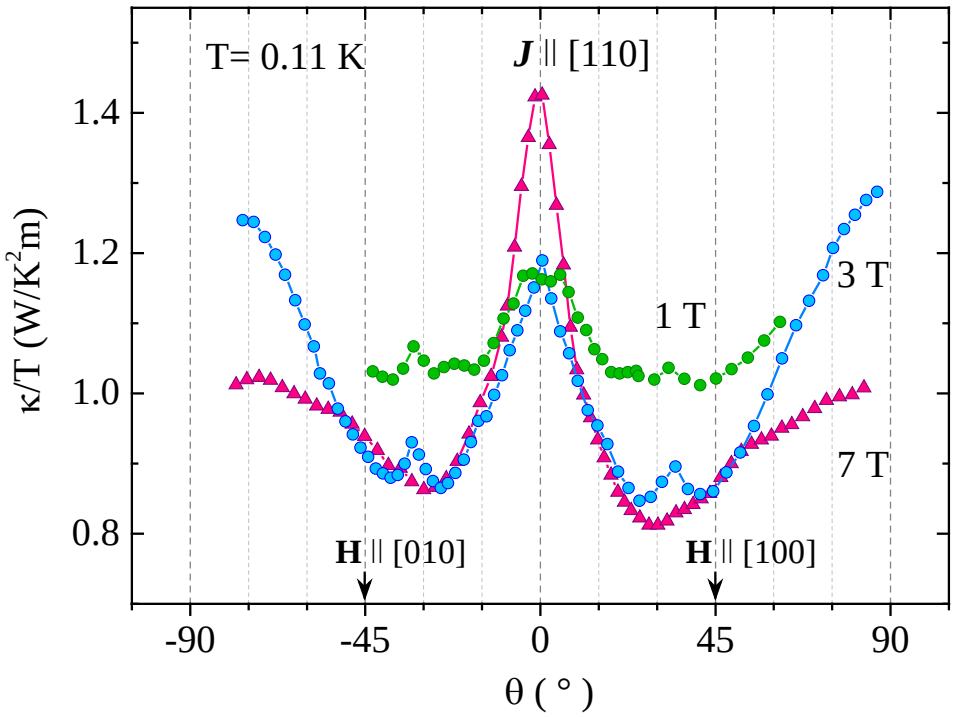
l : Mean free path

Calculated Four-fold Oscillation Amplitude

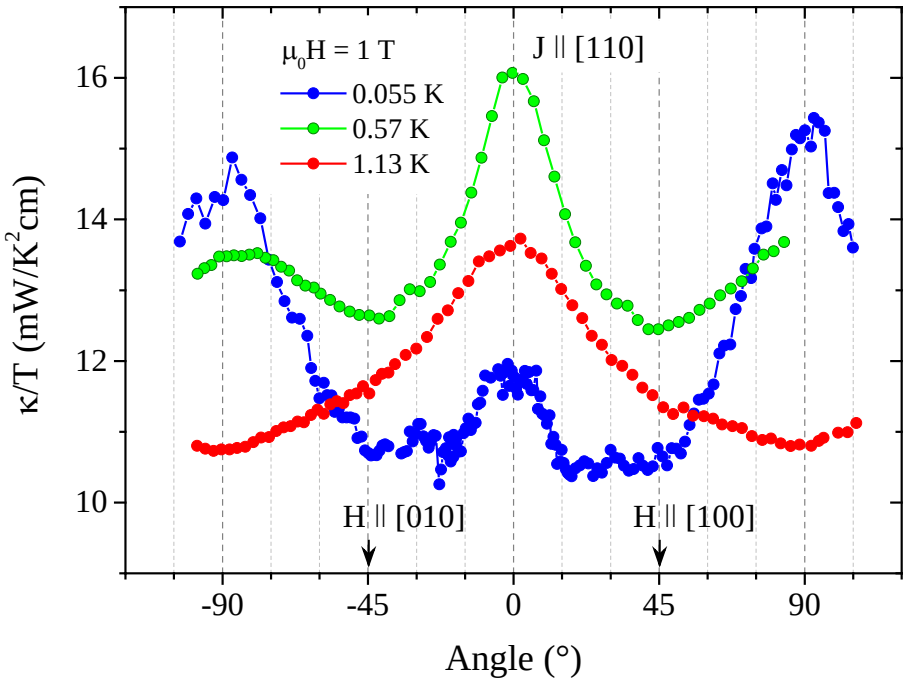


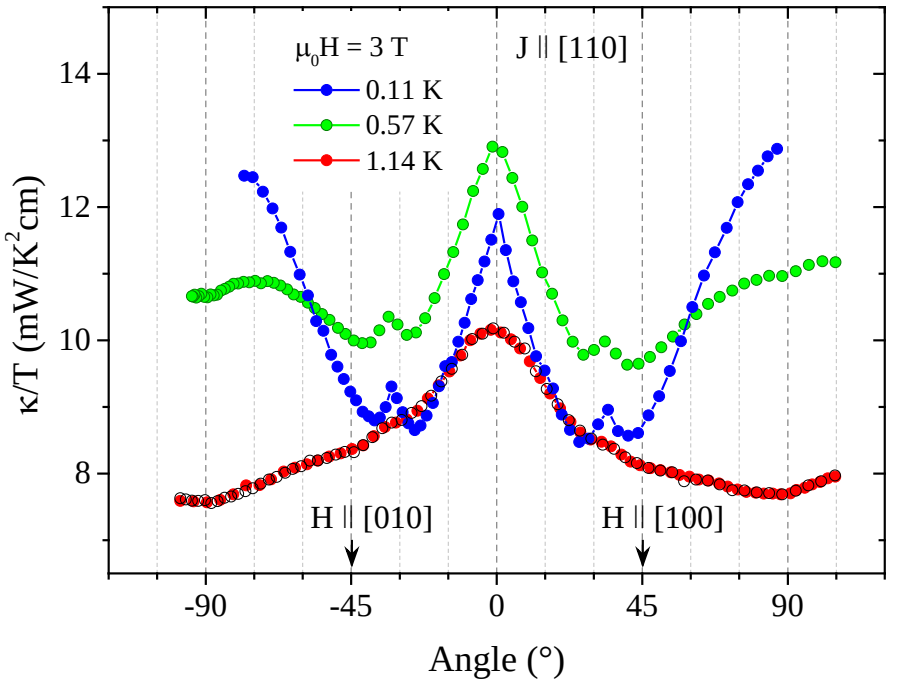
T. Das, A. B. Vorontsov, I. Vekhter, and M. J. Graf, Phys. Rev. B **87**, 174514 (2013)

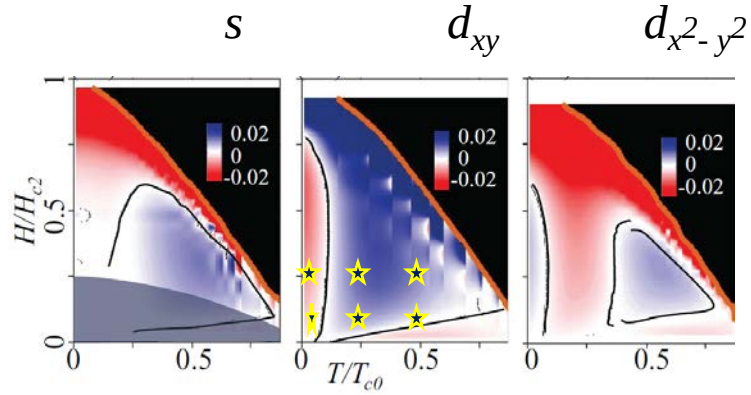
Strong enhancement of thermal conductivity for H || J, Θ = 0, with increasing field



Angle dependent κ at Low field for several temperatures



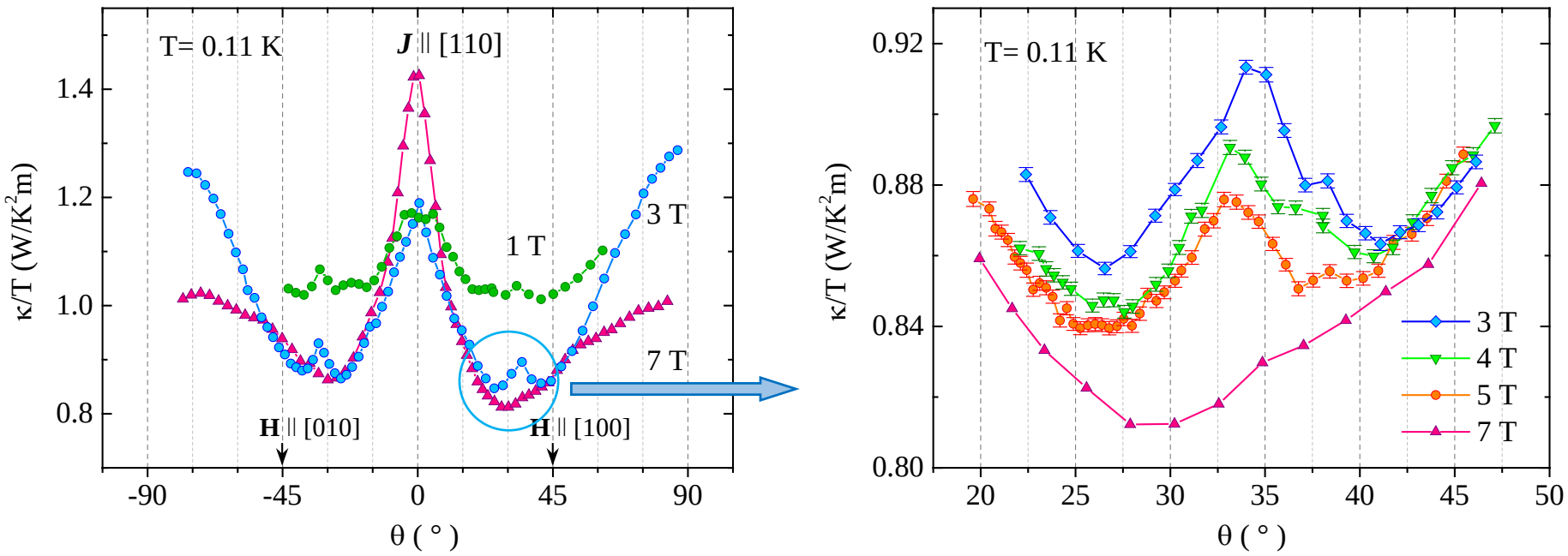




Theoretical prediction of fourfold amplitude oscillation

T. Das, A. B. Vorontsov, I. Vekhter, and M. J. Graf, Phys. Rev. B **87**, 174514 (2013)

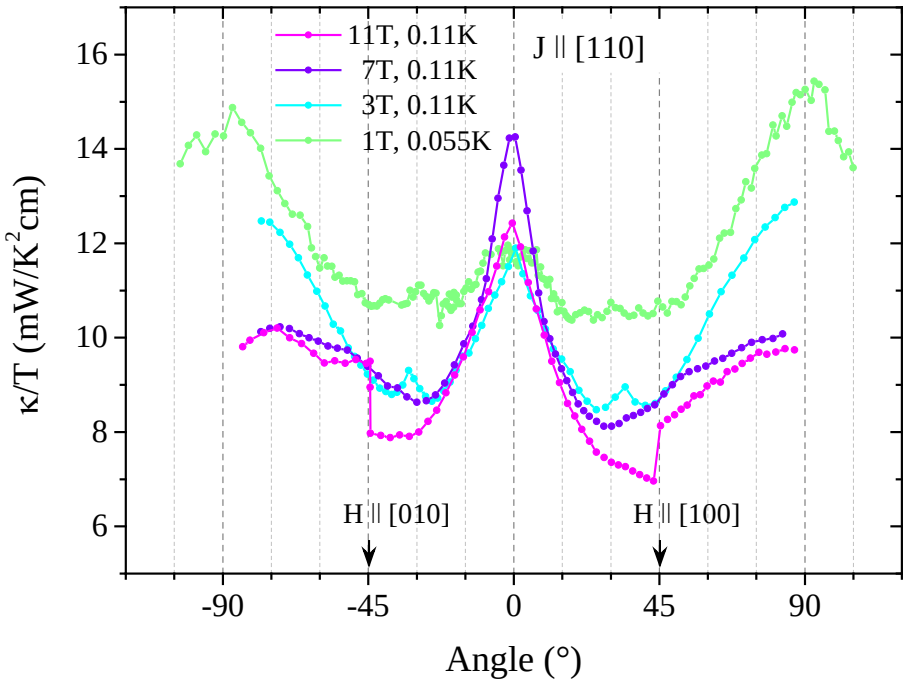
Anomalous Peak near 33°



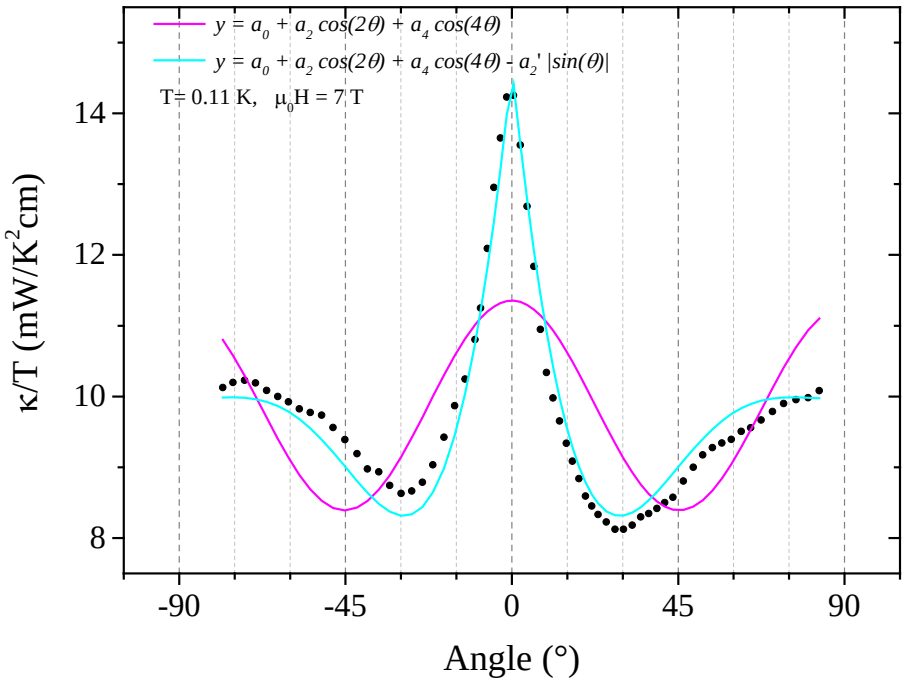
- Possible Fermi Surface Anomaly

Fits to the sum of two- and four-fold symmetric terms I

with Increasing Field



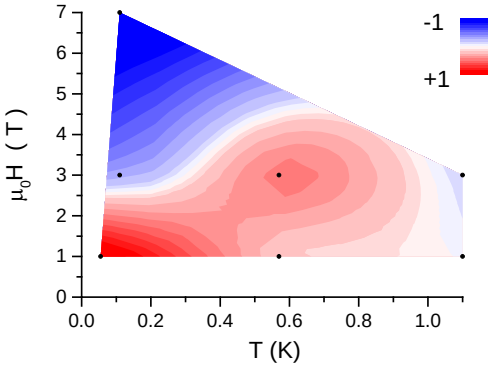
Analysis

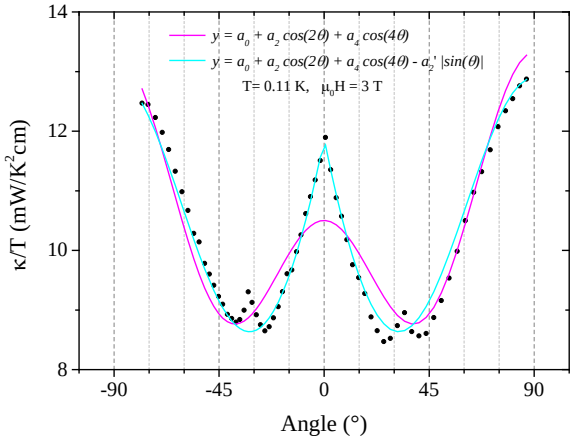


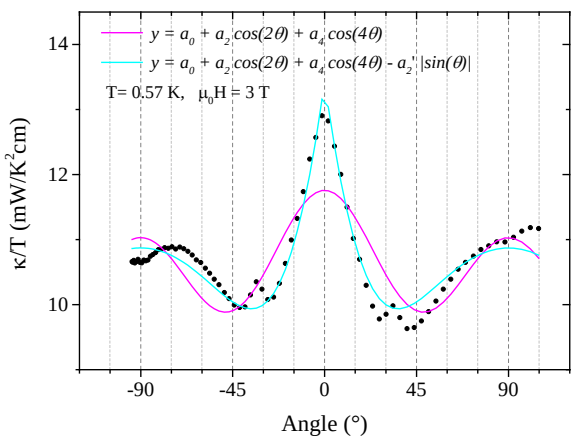
- Twofold – Scattering parallel or perpendicular to the vortex
- Fourfold - $d_{x^2-y^2}$ symmetry

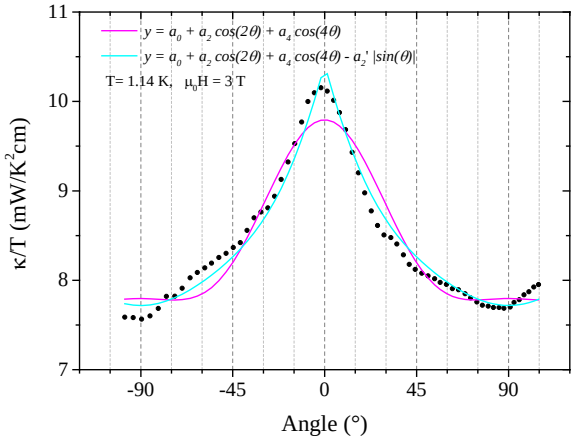
Fits to the sum of two- and four-fold symmetric terms II

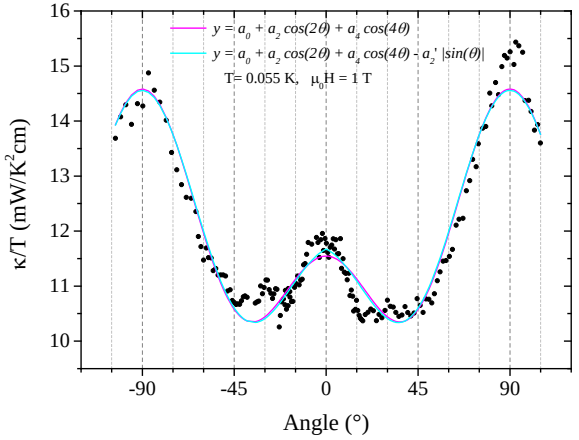
Fourfold Amplitude (a_4)

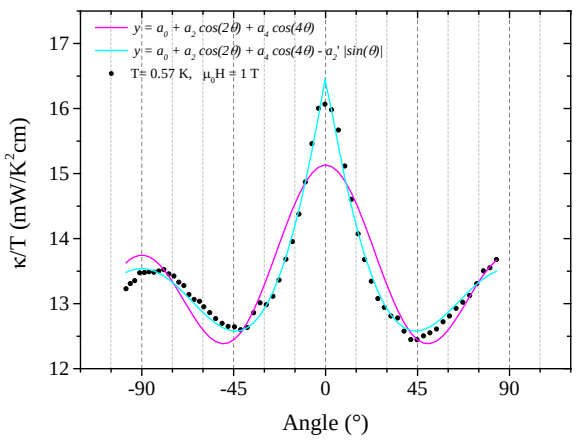


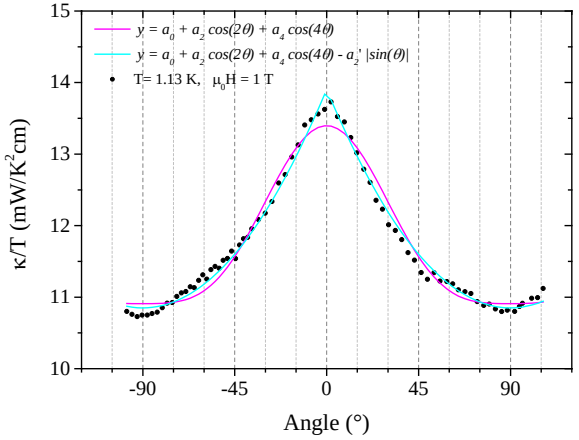






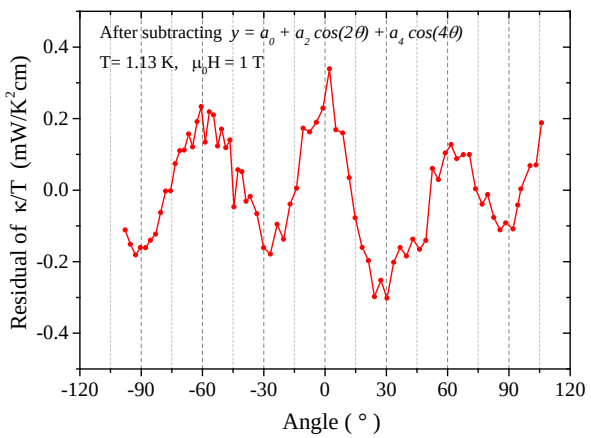


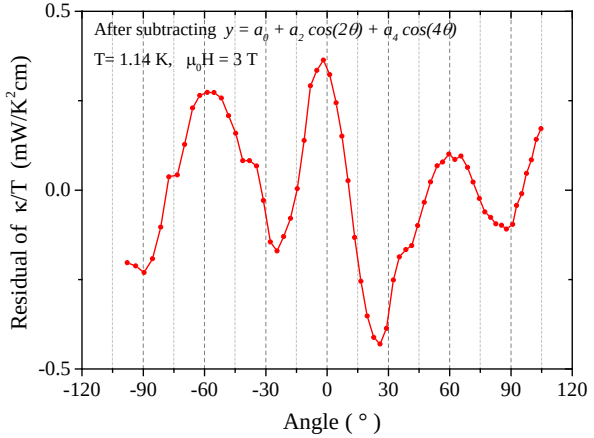


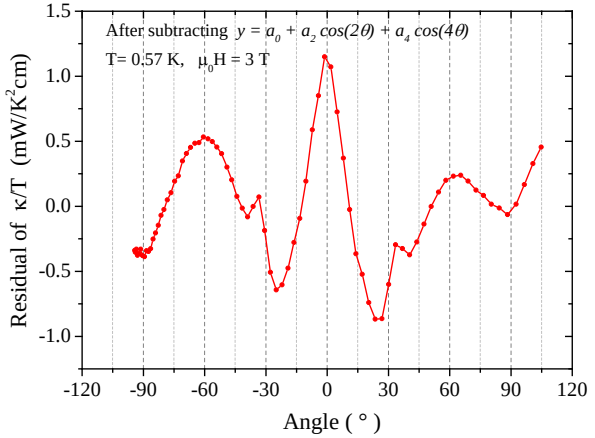


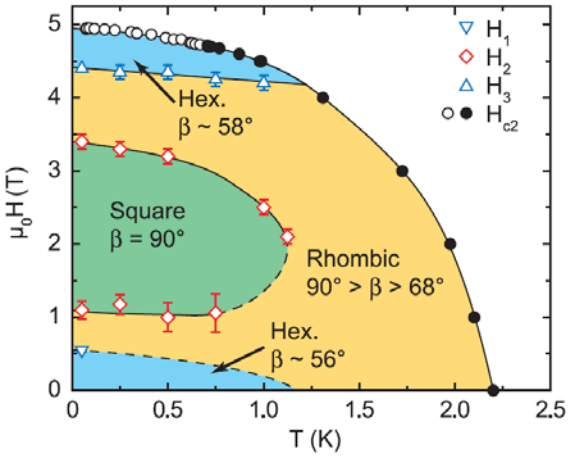
Fits to the sum of two- and four-fold symmetric terms III

After subtracting two-and four-fold symmetric terms: remainder - six-fold oscillation?
No, most likely the angle dependence is complicated by the resonances.









Structure of the
Vortex Lattice
H || c

Bianchi, A. D. et al, Science 319, 177180 (2008).

Summary

- The thermal conductivity of $CeCoIn_5$ was measured with the heat current along the nodal direction of the *d*-wave superconducting gap.

- Sharp increase of thermal conductivity was observed when the heat current is parallel to the magnetic field.

- Anomalous peaks in the angle scan indicate a Fermi surface anomaly.