Tu-264

Hidden first order phase transition in Pauli-limited multiband superconductors

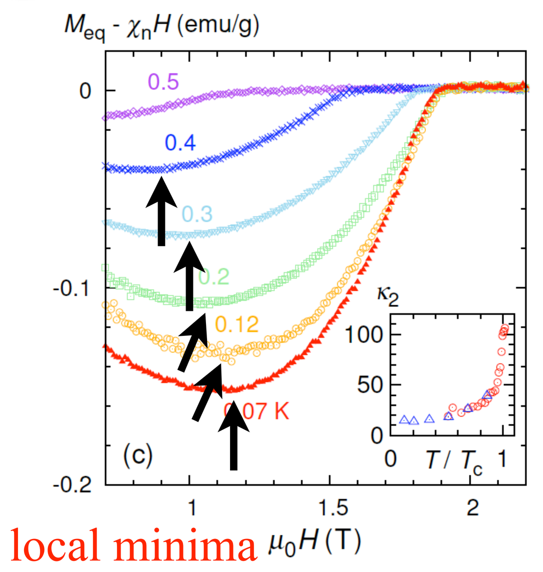
Yasumasa Tsutsumi[1], Noriyuki Nakai[2], Masanori Ichioka[2], and Kazushige Machida[2]
[1]Condensed Matter Theory Laboratory, RIKEN, [2]Department of Physics, Okayama University

Introduction

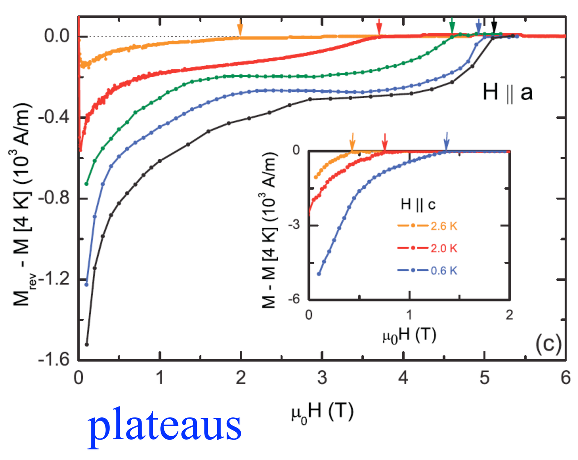
Multiband superconductors

$CeCu_2Si_2$ KFe_2As_2 UBe_{13}

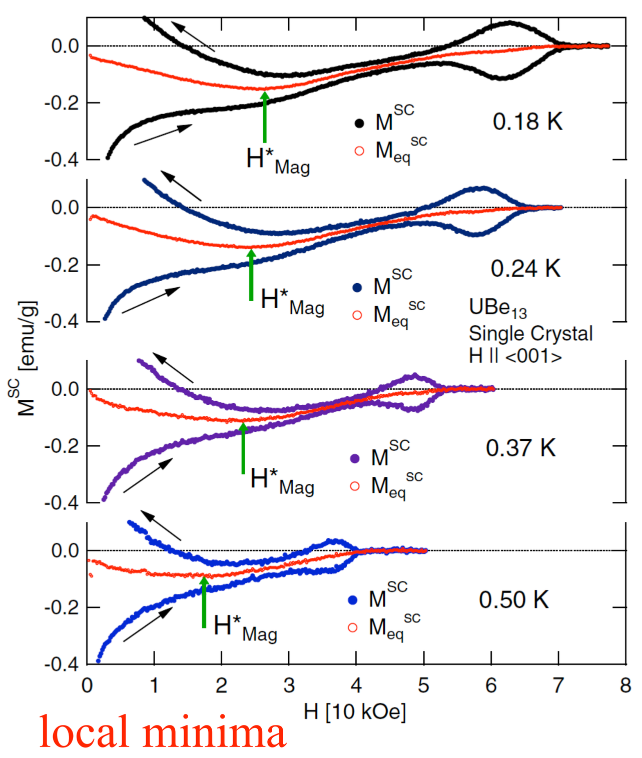
Magnetization



S. Kittaka *et al.*, PRL **112**, 067002 (2014).

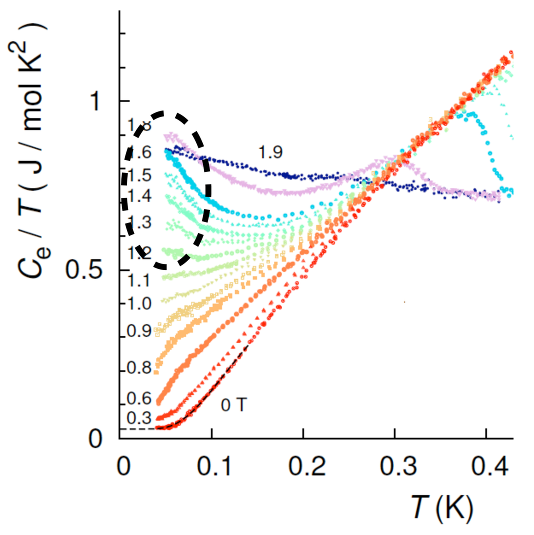


P. Burger *et al.*, PRB **88**, 014517 (2013).

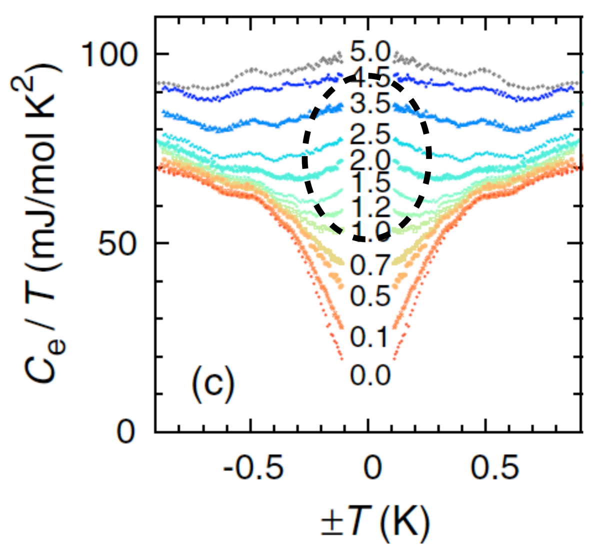


Y. Shimizu *et al.*, PRL **109**, 217001 (2012).

Specific heat



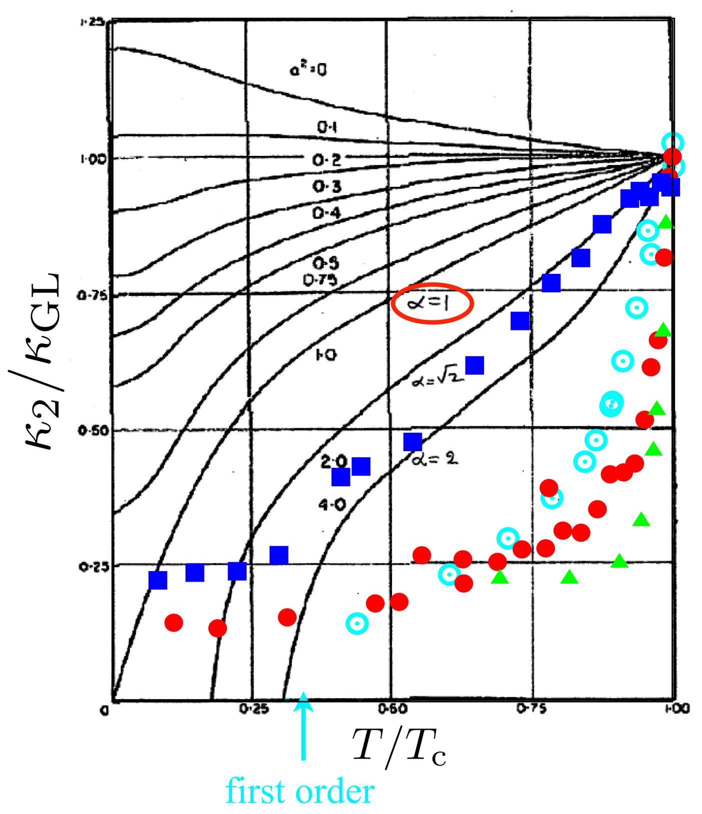
S. Kittaka *et al.*, PRL **112**, 067002 (2014).



S. Kittaka *et al.*, J. Phys. Soc. Jpn. **83**, 013704 (2014).

upturn toward low-temperature under high-field

Maki parameter (indicator of Pauli paramagnetic effect)



D. Saint-James *et al.*, *Type II Superconductivity* (1969).

- $CeCoIn_5$: S. Ikeda *et al.*, JPSJ **70**, 2248 (2001).
- $CeCu_2Si_2$: S. Kittaka *et al.*, PRL **112**, 067002 (2014).
- UBe_{13}: Y. Shimizu *et al.*, JPSJ **80**, 093701 (2011).
- KFe_2As_2: F. Hardy, private communication.

without first order phase transition (CeCu2Si2, UBe13); weak first order phase transition (KFe2As2)

Maki parameter κ_2 depends on magnetization at critical field.
$\kappa_2 \sim 0$: first order phase transition

$\alpha < 1$: second order phase transition at critical field
$\alpha > 1$: first order phase transition in low-temperatures

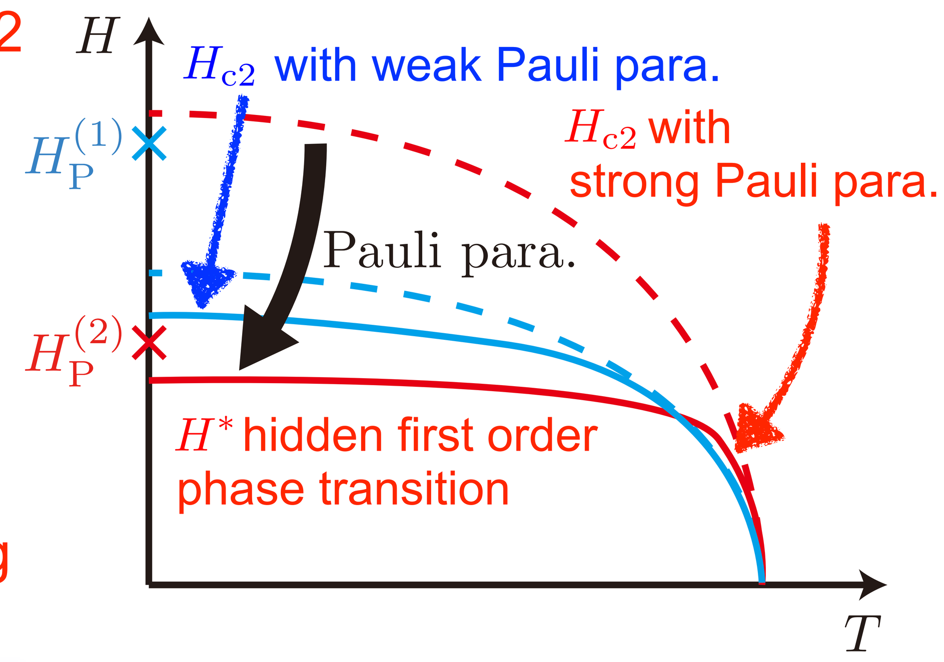
Features

- ☑ Multiband superconductors
- ☑ Magnetization: There are local minima or plateaus.
- ☑ Specific heat: upturn toward low-temperature under high-field
- ☑ Strong Pauli paramagnetic effect in high-temperature but without or weak first order phase transition

We can understand them by Pauli-limited multiband model.

Pauli-limited multiband model

	band-1	band-2
orbital limit	$H^{(1)}_{orb} < H^{(2)}_{orb}$	
s-wave gap	$\Delta_1 > \Delta_2$	
Pauli limit $H_P = \frac{\Delta}{\sqrt{2}\mu_B}$	$H^{(1)}_P > H^{(2)}_P$	
Pauli para.	weak	strong



Quasiclassical theory

Eilenberger equation

$$\{\omega_n + i\mu B(\boldsymbol{r}) + \boldsymbol{v}_j(\boldsymbol{k})\cdot[\boldsymbol{\nabla} + i\boldsymbol{A}(\boldsymbol{r})]\} f_j(\boldsymbol{k},\boldsymbol{r},\omega_n) = \Delta_j(\boldsymbol{r}) g_j(\boldsymbol{k},\boldsymbol{r},\omega_n)$$

$$\{\omega_n + i\mu B(\boldsymbol{r}) - \boldsymbol{v}_j(\boldsymbol{k})\cdot[\boldsymbol{\nabla} - i\boldsymbol{A}(\boldsymbol{r})]\} \underline{f}_j(\boldsymbol{k},\boldsymbol{r},\omega_n) = \Delta^*_j(\boldsymbol{r}) g_j(\boldsymbol{k},\boldsymbol{r},\omega_n)$$

$f_j,\ \underline{f}_j,\ g_j$ ↓ ↑ $\Delta_j,\ \boldsymbol{A}$

Self-consistent condition

s-wave gap

$$\begin{pmatrix}\Delta_1\\ \Delta_2\end{pmatrix} = T\sum_{\omega_n>0}\begin{pmatrix}V_{11} & V_{12}\\ V_{21} & V_{22}\end{pmatrix}\begin{pmatrix}N_{F1}\langle f_1 + \underline{f}^*_1\rangle_{\boldsymbol{k}}\\ N_{F2}\langle f_2 + \underline{f}^*_2\rangle_{\boldsymbol{k}}\end{pmatrix}$$

current

$$\boldsymbol{J} = \boldsymbol{\nabla}\times\boldsymbol{\nabla}\times\boldsymbol{A} = \boldsymbol{\nabla}\times\boldsymbol{M}_{para} - \kappa^2 T\sum_{\omega_n}\sum_j N_{Fj}\langle \boldsymbol{v}_j \mathrm{Im} g_j\rangle_{\boldsymbol{k}}$$

paramagnetic moment

$$\frac{M_{para}}{M_0} = \frac{B(\boldsymbol{r})}{\bar{B}} - \frac{T}{\mu\bar{B}}\sum_{\omega_n}\sum_j N_{Fj}\langle \mathrm{Im} g_j\rangle_{\boldsymbol{k}}$$

Density of states (related to specific heat)

$$N(E) = \sum_j N_j(E) = \sum_j\sum_\sigma N_{Fj}\langle \mathrm{Re}[g_j(\boldsymbol{k},\boldsymbol{r},\omega_n + i\sigma\mu B)|_{i\omega_n\to E+i\eta}]\rangle_{\boldsymbol{k},\boldsymbol{r}}$$

Magnetization

$$M_{total} = \bar{B} - H$$

External field H is derived from quasiclassical Green's function. (details in M. Ichioka and K. Machida, PRB **76**, 064502 (2007))

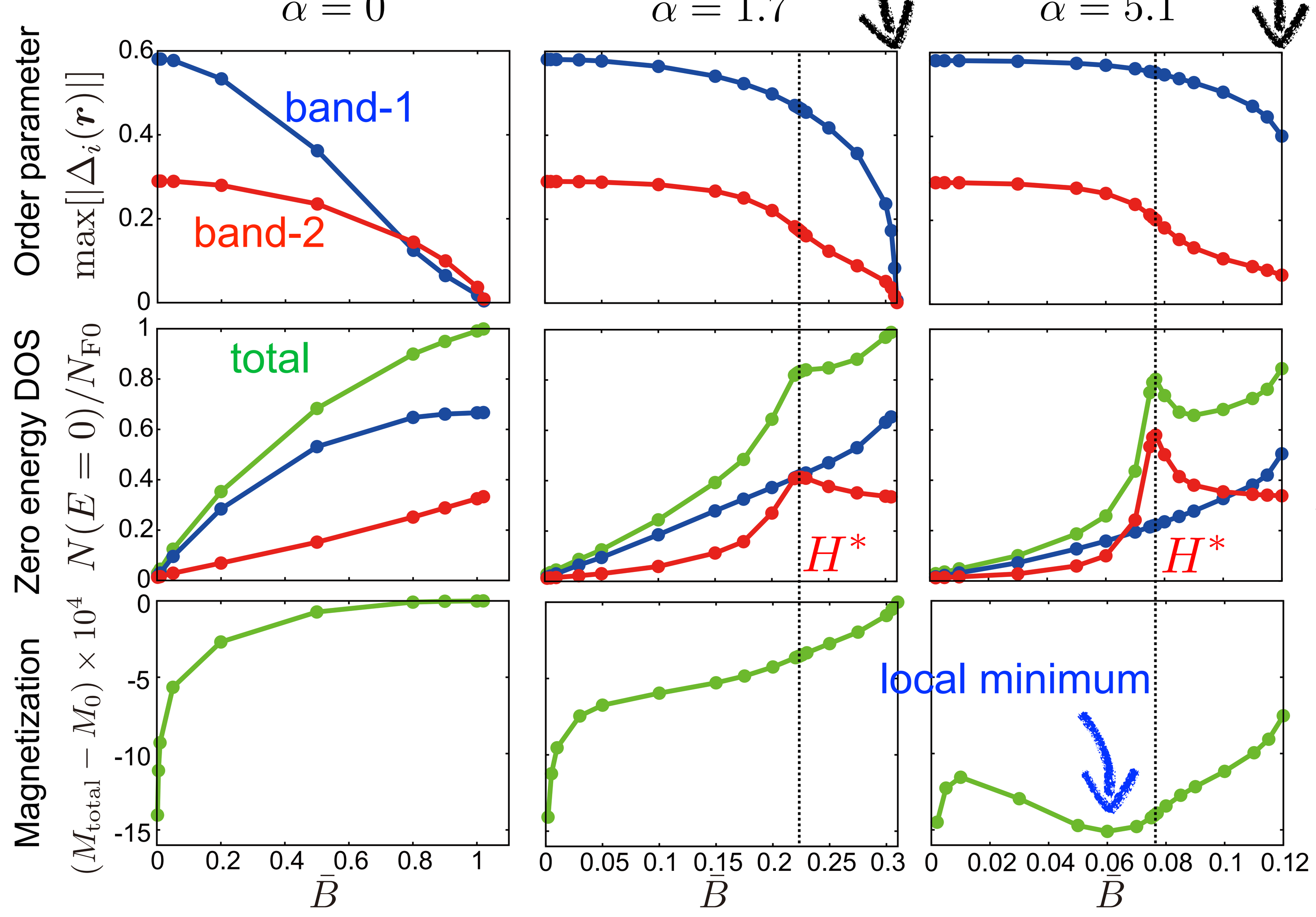
Parameters

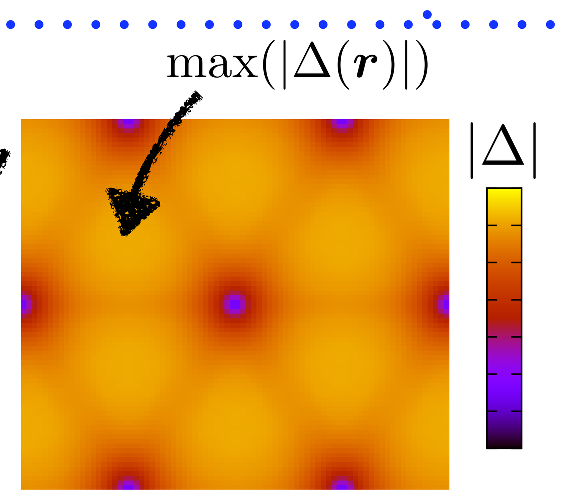
$$V_{11} = V_0,\ V_{22} = 1.5V_0,\ V_{12} = V_{21} = 0.05V_0 \ \Rightarrow\ \frac{\Delta_1}{\Delta_2} \sim 2$$

$$\frac{N_{F1}}{N_{F0}} = \frac{2}{3},\ \frac{N_{F2}}{N_{F0}} = \frac{1}{3}$$

two-gap α-model in $CeCu_2Si_2$
S. Kittaka *et al.*, PRL **112**, 067002 (2014)

Results





$\bar{B}$: flux density ∝ area of a unit vortex lattice

H^* : peak of zero energy DOS in band-2 (beyond normal state DOS)

$$\frac{C_e}{T} \equiv \gamma(T)$$

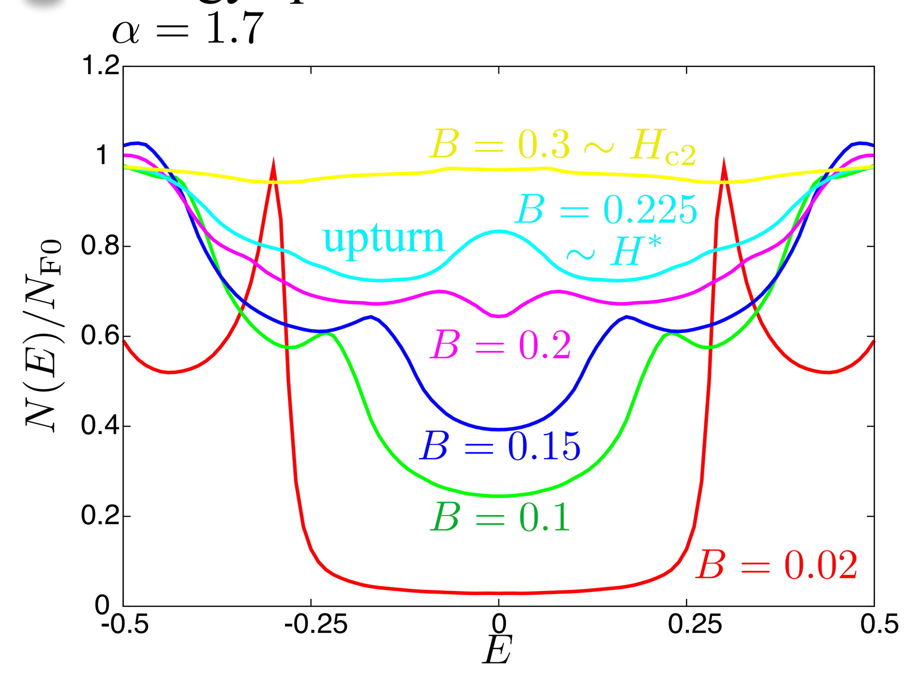
$$\gamma(T=0) \propto N(E=0)$$

$\kappa \gg 1$ ➡ $H_{c1} \sim 0$

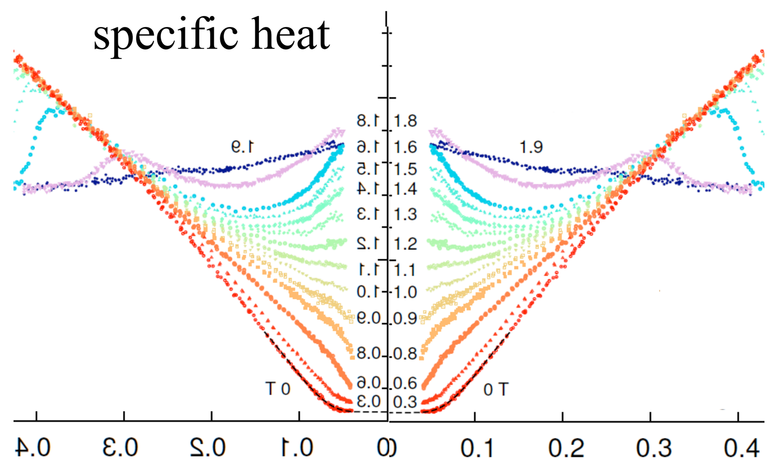
Areas of magnetization below normal state are the same condensation energy.

Strong suppression of $H^{(2)}_{orb}$ to H^* by Pauli paramagnetic effect makes local minimum of magnetization.

Energy spectrum of DOS



If $N(E) = N(0) + a|E|^n$,
$\gamma(T) = \gamma(0) + a'T^n$,
where $\mathrm{sgn}(a) = \mathrm{sgn}(a')$.



S. Kittaka *et al.*, PRL **112**, 067002 (2014).

Upturn of specific heat toward low-temperature under high-field is due to gap edge of band-2 shifted by Pauli paramagnetic effect around H^*.

Summary

We can understand features of magnetization and specific heat for $CeCu_2Si_2$, KFe_2As_2, and UBe_{13} by Pauli-limited multiband model.

- ☑ local minima or plateaus of magnetization curve
  strong suppression of $H^{(2)}_{orb}$ to H^* by Pauli paramagnetic effect
- ☑ upturn of specific heat toward low-temperature under high-field
  gap edge of band-2 shifted by Pauli paramagnetic effect around H^*

Critical field of band-2 not directly giving H_{c2} is visible on magnetization and specific heat.