Thermodynamic study on the Heavy Fermion superconductivity under high pressure

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<outline>
1. Memories of our studies at Prof. D. J. Kim’s lab.
2. Thermodynamic study on the heavy fermion superconductors
   ~ case of non-centrosymmetric superconductor CePt$_3$Si~
Studies at Prof. Kim’s laboratory

1. Bachelor of Science, Aoyama-Gakuin University, 03/1994
   Supervisor 徳洲先生

2. Study and life at Kim’lab
   (a) Basic study of magnetism
   (b) Numerical calculation.

Effect of the electron phonon interaction on the magnet volume effect in the itinerant ferromagnetism

Published in 1999, Kluwer Academic Pub. Presented at ICM 1994, Poland
Magnetism and superconductivity of the rare earth and actinide compounds (f-electron system)

5f or 4f electron(s) \[\rightarrow\]

Heavy fermion system (strongly correlated electron system)

Many body effect

1. Unconventional superconductivity, co-existence of the magnetism and superconductivity.
   \[\text{UPt}_3, \text{UPd}_2\text{Al}_3, \text{UNi}_2\text{Al}_3, \text{URu}_2\text{Si}_2, \text{UBe}_{13}, \text{CeCu}_2\text{Si}_2, \text{CeCoIn}_5…\]
2. Pressure-induced superconductivity: \[\text{CeCu}_2\text{Ge}_2, \text{CeRh}_2\text{Si}_2, \text{CeIn}_3, \text{UGe}_2\]
3. ‘Quantum critical’ behavior: \[\text{CeCu}_{6-x}\text{Au}_x, \text{YbRh}_2\text{Si}_2…\]
4. Multipole degrees of freedom in the f electron(s) \[\text{NpO}_2, \text{Ce}_{1-x}\text{La}_x\text{B}_6, \text{PrFe}_4\text{P}_{12}, \text{SmFe}_4\text{P}_{12}…\]
5. Novel type of the ground state: \[\text{URu}_2\text{Si}_2, \text{hidden order?}\]
My research subjects from 1994-2007

(a) Magnetic property of $U_3Pd_{20}Si_6$ (ph.D work)
   rare example of the localized $5f$ electrons system in the uranium metallic compound

(b) Magnetic and superconducting properties of $UNi_2Al_3$
   co-existence of the antiferromagnetism and superconductivity, triplet pairing state.

(c) Pressure induced superconductivity in $UGe_2$
   Co-existence of the ferromagnetism and superconductivity

(e) Development of the measurement system for
   the ac heat capacity under pressure (now).
   non centrosymmetric superconductors $CePt_3Si$, $CeIrSi_3$, UIr.

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High Pressure Study

**Electrical resistivity**
main method

**Heat capacity**
1. bulk nature of the superconducting transition
2. Temperature dependence of heat capacity
Thermodynamic study on the superconductivity in non-centrosymmetric compound CePt$_3$Si under high pressure

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Ce: 4$f^1$ electron system

Superconductor at ambient pressure
CeCu$_2$Si$_2$ (1979-), CeCoIn$_5$

Pressure induced superconductivity
CeIn$_3$, CeRh$_2$Si$_2$, CePd$_2$Si$_2$, CeCu$_2$Ge$_2$
CeRhIn$_5$
Non-Centrosymmetric Superconductors

CePt$_3$Si
$T_N = 2.2$ K, $T_{sc} = 0.7$ K 1 bar
Bauer et al., PRL 92, 027003 (2004)

CeRhSi$_3$
$T_N = 3$ K(1bar), $T_{sc} = 1.0$ K at 2.0 GPa
N. Kimura et al., PRL 95, 247004 (2005)

CeIrSi$_3$
$T_N = 3$ K(1bar), $T_{sc} = 1.4$ K at 2.3 GPa
I. Sugitani et al., JPSJ. 75 043703 (2006)

CeCoGe$_3$
$T_N = 5$ K(1bar), $T_{sc} = 0.8$ K at 5 GPa
R. Settai et al., submitted

UIr
$T_C = 46$ K(1bar), $T_{sc} = 0.15$ K at 2.6 GPa
T. Akazawa et al., JPSJ. 73 3129 (2004)

Cd$_2$Re$_2$O$_7$, Li$_2$Pd$_3$B, Li$_2$Pt$_3$B…

Single electron hamiltonian

$H = \frac{p^2}{2m} + \alpha \hat{n} \times \vec{p} \cdot \vec{\sigma}$

Rashba term

“Spin-orbit” interaction
due to the lack of inversion symmetry

Microscopic theories
of non-centrosymmetric superconductors
(Edel’stein 1985, Mineev and Samokhin 1994,
Gor’kov and Rashba 2001, Barzykin and Gor’kov 2002)

1. mixture of $s$ and $p$ wave pairings
2. Rashba-type spin-orbit interaction changes the paramagnetic effect
CePt$_3$Si


- **Antiferromagnetism**
  
  \[ T_N = 2.2 \text{ K} \]

  - \( Q = (0 \ 0 \ 0.5) \)
  - \( \mu_{\text{ord}} = 0.16 \, \mu_B/\text{Ce} \)
  - low magnetic entropy
    \[ \sim 0.2 \text{Rln2} \ @ T_N \]
  - \( \gamma \sim 350 \text{ mJ/K}^2\text{mol} \)

- **Superconductivity**
  
  \[ T_c = 0.75 \text{ K} \]

  - \( \Delta C_p/(\gamma T_c) \sim 0.25 \)
  - \( dH_{c2}/dT \sim -8.5 \text{ T/K} \)
  - \( H_{c2}(0) \sim 5 \text{ T} \)
  - \( >> H_p \sim 1.4 \text{ T} \)
  - \( H_p \): Pauli limit

Fermi surface study (dHvA) of LaPt$_3$Si

Band splitting : 1200K for \( \alpha - \beta \) branches

(T. Takeuchi et al., submitted)


Spin-triplet superconductivity ?
Experimental studies on the SC state

Penetration depth

**NMR**

M. Yogi et al., PRL 93 (2004) 027003

**Thermal conductivity**


**Magnetic field dependence of $\gamma$**

T. Takeuchi et al., submitted

1. Possible spin-triplet states in the presence of spin-orbit coupling


\[ H_{\text{eff}} = \sum_{k,s} \gamma_k c_{ks}^+ c_{ks} + \frac{1}{2} \sum_{k,k'} \sum_{s,s'} V_{k,k'} c_{ks}^+ c_{-k's'} c_{-k's'} c_{k's} \]

\[ H_p = \alpha \sum_{k,s,s'} \vec{g}_k \cdot \vec{\sigma}_{ss'} c_{ks}^+ c_{ks} \quad \text{antisymmetric spin-orbit interaction} \]

In CePt\textsubscript{3}Si \( \vec{g}_k \propto k \times \hat{z} = \hat{y}k_x - \hat{x}k_y \)

highest \( T_c \) is obtained when \( \vec{d}(k) \parallel \vec{g}_k \)

point node in the superconducting gap....

2. Mixing state of spin-singlet and triplet components


\[ \Delta(k) = \left\{ \Psi(k)\sigma_0 + \vec{d}(k) \cdot \vec{\sigma} \right\} i\sigma_y \]

\[ \vec{d}(k) = \Delta(-k_y, k_x, 0) \parallel \vec{g}_k \]

Superconducting gaps

\[ \begin{vmatrix} \Psi + \Delta \sin \theta \end{vmatrix}, \Psi > 0, \Delta > 0 \text{ and } \Psi < \Delta \]

\[ \begin{vmatrix} \Psi - \Delta \sin \theta \end{vmatrix} \]
Purpose of this work

We investigate the relation between the magnetism and superconductivity of CePt₃Si by ac Calorimetry.

Ac Calorimetry

\[ T_{ac}(\omega) = \frac{P_{ac}(\omega)}{(\kappa + i\omega C)} \]

- \( P_{ac}(\omega) \): heat power
- \( T_{ac}(\omega) \): temperature Oscillation
- \( \kappa \): thermal conductivity
- \( C \): heat capacity

V_{ac} = S(T) * T_{ac}

- \( V_{ac} \): voltage of a thermocouple
- \( S(T) \): thermopower of a thermocouple
Purpose of this work

We investigate the relation between the magnetism and superconductivity CePt$_3$Si by ac Calorimetry.

Single crystal sample

Grown by the Bridgeman method
(It was cut from the same ingot for the dHvA experiment.)

Residual resistivity ratio: RRR ~ 100

Pressure transmitting medium: Daphne oil
Heat Capacity of CePt$_3$Si

$P = 0$ GPa

$\Delta C_{ac}/C_{ac}(T_{sc}) = 0.33$

Critical pressure of the antiferromagnetic state

$P_{AF} \sim 0.6$ GPa
Heat Capacity of CePt$_3$Si

Critical pressure of the antiferromagnetic state $P_{AF} \sim 0.6$ GPa
Pressure phase diagram

CePt$_3$ Si

- $T_N$
- AF
- AF + SC
- SC
- $T_{sc}$
- $P_{AF}$
- $P_{sc}$

Symbols:
- C
- $\rho$
- $\chi_{ac}$
Pressure dependence of $\Delta C_{ac}/C_{ac}$ at $T_{sc}$

$\Delta C_{ac}/C_{ac}$: relative width of the superconducting transition in the resistivity

CePt$_3$Si

Pressure phase diagram


$P_{AF}$

AF, PM

$P_{sc}$

$\Delta T_{ac}/T_{ac}$

CeRhIn$_5$

Pressure dependence of $A$ and $\gamma$

$$\rho = \rho_0 + AT^2$$

Divergent behavior of $A$ in Ce antiferromagnets under pressures CeAl$_2$, CeRh$_2$Si$_2$, CeIn$_3$, CePd$_2$Si$_2$, ....

Pressure-induced superconductivity
1. Critical pressures of the AF and SC states

\[ P_{AF} \sim 0.6 \text{ GPa}, \quad P_{sc} \sim 1.5 \text{ GPa} \]

The stable co-existence in the wider pressure range is a characteristic feature of CePt\(_3\)Si.

2. No divergent behavior of \( A \) and \( \gamma \) around \( P_{AF} \)

\( P_{AF} \) is not second order quantum critical point.
Conclusion

1. Critical pressures of the AF and SC states

\[ P_{\text{AF}} \sim 0.6 \text{ GPa}, \quad P_{\text{sc}} \sim 1.5 \text{ GPa} \]

Antiferromagnetic phase disappears rapidly around \( P_{\text{AF}} \sim 0.6 \text{ GPa} \) but the bulk superconducting phase exists in the wider pressure region from 0 to \( P_{\text{sc}} \sim 1.5 \text{ GPa} \). The stable co-existence in the wider pressure range is a characteristic feature of CePt\(_3\)Si.

2. No divergent behavior of \( A \) and \( \gamma \) around \( P_{\text{AF}} \)

The absence of the divergent behavior of \( A \) and \( \gamma \) suggests that \( P_{\text{AF}} \) is not second order quantum critical point. The superconductivity in CePt\(_3\)Si may be different from those appeared around the magnetic instability.