Interplay between crystal electric field and magnetic exchange anisotropies in the heavy fermion antiferromagnet YbRhSb under pressure

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**Introduction**

Pressure effect on the magnetism of Yb compounds

- Applying pressure
  - Ce comp.
  - Yb comp.

- Change of magnetic state \((\text{YbNiSn})[2,3]\)

- Quantum critical point (QCP)

- Appearance of another QCP at \(P^* (\text{YbRh}_2\text{Si}_2)[4]\)

- YbRhSb

- CeRh_3Si_2

- CeRh_2Ge_2

- CeRh_3B_2

- YbCuAl

\[ \alpha = |\text{JN}(E_F)| \]

- Ferromagnetic state

- Complex magnetic state

\[ T_0/ T_0^{\text{max}} \]

\[ T(K) \]

\[ P(GPa) \]
Yb compounds with the orthorhombic $\varepsilon$-TiNiSi type structure

Yb compounds with the orthorhombic $\varepsilon$-TiNiSi type structure:

- YbNiSn (Ferro. $T_C = 5.6$ K) [2,3]
- YbPtAl (Antiferro. $T_N = 5.8$ K) [5]
- YbRhSb (Weak ferro. $T_M = 2.7$ K) [1]

Complicated magnetic behavior arises from the competition between the anisotropic exchange interaction with the easy $c$-axis and the CEF anisotropy with the easy $a$-axis.
Weak ferromagnetism of YbRhSb \( (T_M = 2.7 \text{K}, \ Mr = 3 \times 10^{-3} \mu_B/Yb)[1] \)

- A small remanent moment \( Mr \) of \( 3 \times 10^{-3} \mu_B/Yb \) \( (B//b) \) \( \approx 1 \times 10^{-3} \mu_B/Yb \) \( (B//a, B//c) \)

- AF arrangement with a canted component

- Maximum in \( M/B(T) \)

- Spin flop in \( M(B) \)
Heavy-fermion behaviour of YbRhSb [1]

**Inverse susceptibility**

YbRhSb

\[ B \parallel c \]

\[ B \parallel b \]

\[ B \parallel a \]

\[ \mu_{\text{eff}} = 4.4 \mu_B \]

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**Electrical resistivity**

YbRhSb

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In the paramagnetic state, easy axis is \( a \)-axis. \( \Leftarrow \) CEF anisotropy

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**Specific heat**

\( C_m \) vs. \( T \)

\( S_m / Rn2 \)

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**Specific heat**

YbRhSb

\[ \gamma = 370 \text{ mJ/K}^2\text{mol} \]

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**Broad maximum at 100 K)**

\( \Rightarrow \) Kondo effect
Determine pressure dependences of the Kondo and RKKY interactions.

Experiments

1. Resistivity ($\rho$)
   AC 4-terminal method
   Pressure cell: piston-cylinder type
   $P_{\text{max}}=2.5$ GPa
   $T: 0.3 \, \text{K} \sim 300 \, \text{K}$

2. Magnetization ($M$)
   SQUID magnetometer (MPMS)
   $B: 0 \sim 5$ T
   Pressure cell: indenter cell [6]
   Gasket: NiCrAl+Cu-Be
   $P_{\text{max}}=2.5$ GPa

Pressure medium: Daphne oil
To isolate thermally the gasket from the anvil

The hollow at the anvil top ⇒ It prevents expansion of the sample space over the anvil top.

Pressure ⇒ superconducting temperature of In.

• $P_{\text{max}} = 3$ GPa.

• $0.5 < T < 7$ K ($^3$He cryostat)

• Detection of AC component of the sample temperature ⇒ Lock-in Amp.
Experiments up to 20 GPa

1. Resistivity ($\rho$)
   DC 4-terminal method
   Pressure cell: a diamond anvil cell (DAC)
   $T$: 1.5 K $\sim$ 300 K
   Pressure determination: ruby luminescence method

2. Pressure dependence of lattice parameters
   Pressure cell: DAC
   Pressure medium: $N_2$
   Pressure determination: gold marker in the sample chamber
   energy-dispersive x-ray diffraction (EDXRD) at the Hamburger Synchrotronstrahlungslabor (HASYLAB)
Resistivity under pressures

$\rho (\mu \Omega \text{cm})$

YbRhSb

$T_{\text{M1}}$

$T_{\text{M2}}$

$T_{\text{M3}}$

$T_{\text{max}}$

$P > 1.37 \text{ GPa}$, another magnetic transition occurs at $T_{\text{M2}}$ above $T_{\text{M1}}$.

$T_{\text{max}} (\propto T_K)$ decreases with pressure.

(Data sets for each value of $P$ are shifted upward consecutively by 60 $\mu \Omega \text{cm}$ for clarity).
Magnetic susceptibility \( M/B(T) \) for \( B \parallel a \) and \( B \parallel b \) under various pressures.

- \( P = 1.59 \) GPa
  - Broad maximum at \( T_{M2} = 3.5 \) K
  - Increment below 2.7 K

- \( P \geq 2.2 \) GPa
  - Hysteresis of \( M/B \) at low \( T \)

- \( P = 1.39 \) GPa: Broad maximum at \( T_{M2} = 3.5 \) K
- Increase of \( \chi_{dc} \) for \( P \geq 2 \) GPa \( \Rightarrow \) Ferromagnetic state?
Magnetization curves of YbRhSb under various pressures

- **B || a**
  - Metamagnetic anomaly shifts from 2.5 T to 1.5 T with $P$.

- **B || b**
  - $P \geq 2.5$ GPa, ferromagnetic behavior with the $M_r$ of 0.4 $\mu_B/Yb$.

- **B || c**
  - $P > 1.75$ GPa, ferromagnetic behavior with the $M_r$ of 0.3 $\mu_B/Yb$.

Weak ferromagnetic moment disappears above $T_{M1}$.
$T$-dependence of $B/M$ under various pressures

The slope of $B/M(T)$ for $P > 100K$ hardly changes with pressure.

$\Rightarrow \mu_{\text{eff}}$ does not change on pressure.

$|\theta_p(B//a)|$ and $|\theta_p(B//b)|$ at 2 GPa decrease by 50% and 20%, respectively, from the values at 0 GPa.

$|\theta_p| = nT_K$, $n=2\sim4$ [8]

$\Rightarrow T_K$ decreases with pressure.
Specific heat of YbRhSb under various pressures

$P=0$
The data agrees with the previous one [6].

$P=1.5$ GPa
Thermal hysteresis of $C(T)$ around $T_{M1}$
$\Rightarrow$ 1st order transition

$P>2$ GPa
Specific heat jumps become larger.

(Data sets for each value of $P$ are shifted upward consecutively by 0.5 J/K$^2$mol for clarity.)
Magnetic entropy of YbRhSb under various pressures

\[
S_m/T = \int \frac{C(YbRhSb) - C(LaRhSb)}{T} dT
\]

\[
C(LaRhSb) = \gamma T + \beta T^3
\]

\[
\gamma = 6.7 \text{ mJ/K}^2\text{mol} \quad \beta = 0.34 \text{ mJ/K}^4\text{mol}
\]

Broken lines: \( S_K(T_M/T_K) = S_{\text{mag}}(T_M) \)

\( \Rightarrow T_K [9] \)

\( S_K; s=1/2 \) single-impurity Kondo model

\[
S_m(T_M)/(R \ln 2) = 0.24 \quad @ \quad P=0 \quad \Rightarrow \quad 0.45 \quad @ \quad P=2.5 \text{ GPa}
\]

\( \Rightarrow T_K \) decreases with pressures.
**T - P phase diagram of YbRhSb**

Minimum of $T_M$ at 1.7 GPa

- **I**: Canted Antiferro.
- **II**: Antiferro.
- **III**: Ferro. $M_r \approx 0.3 \sim 0.4 \mu_B/\text{Yb}$

$T_K$ decreases rapidly with increasing pressure, but remains at a constant value above 1.5 GPa.

The complicated pressure-induced magnetic phase of YbRhSb is attributed to the enhancement of inter-site exchange interaction causing easy $b$-$c$ plane anisotropy.
A canted antiferromagnetic structure with ordered moments of $0.1 \ \mu_B/Yb$ lying almost parallel to the $b$ axis below $T_{M1}$ [10].

Ferromagnetic component appears along the $c$ axis below $T_{M3}$. 

A ferromagnetic structure with moments of $0.4 \ \mu_B/Yb$ lying in the $b$-$c$ plane.
Resistivity of YbRhSb under various pressures up to 20 GPa

$\rho(T, P)$ shows a double maximum structure.

The broad maximum at high temperatures is suggested to be due to an incoherent scattering of the conduction electrons at the first excited crystal field level.

With increasing pressure, the maximum at high temperature (around 105 K at ambient pressure) is shifted to higher temperatures.
Pressure dependence of $T_{M3}$

$T_{M3}$ steeply increases up about 7 K, showing a broad maximum, and then slightly decreases with increasing pressure above 8 GPa.
We obtain a smooth variation of the lattice parameters ($a$, $b$ and $c$) and the volume which exclude any structural changes up to 19 GPa.

bulk modulus $B_0 = 114(9)$ GPa and its pressure derivative $dB_0/dP = 5(1)$
At higher pressures, we find that $T_{M3}$ for YbRhSb exhibits qualitatively similar pressure dependence as the Curie temperature ($T_C$) of YbNiSn.
Summary I  Pressure-induced ferromagnetic order in YbRhSb

- For a weak ferromagnet YbRhSb with $T_{M1} = 2.7$ K at $P = 0$, resistivity, DC magnetization and specific heat have been measured on a single crystal under pressures up to 2.5 GPa.

- For $0.9 < P < 1.5$ GPa, another magnetic transition occurs at $T_{M2}$ above $T_{M1}$, and $T_{M1}$ has a deep minimum of 2.5 K at $P_C = 1.7$ GPa.

- $T_K$ decreases rapidly with increasing pressure, but remains at a constant value above 1.5 GPa.

- For $P \geq 2.5$ GPa, a ferromagnetic state is induced with ordered moments lying in the $b$-$c$ plane.

- In the ferromagnetic state, the magnetization curve for $B \parallel a$ exhibits a sharp metamagnetic transition at around 1.5 T.

- The change of the magnetically ordered state arises from the competition among the Kondo effect ($T_K$), anisotropic RKKY interaction ($T_{RKKY}$), and CEF anisotropic energy ($T_{\Delta}$).

- The above competition among the three interactions determine the complex magnetism of Yb compounds.

Future studies

Magnetic structures under pressures $\leftrightarrow$ Neutron diffraction and Mössbauer spectroscopy
The pressure dependence of the ordering temperature $T_{M3}$ of the FM state has been further investigated up to about 20 GPa using electrical resistivity measurements.

We found that for $P > 2.5$ GPa $T_{M3}$ rapidly increases to about 7 K, going through a broad maximum, and then slightly decreases with increasing pressure above 8 GPa.

No structural change up to 19 GPa was observed by x-ray diffraction measurements at room temperature.

The enhancement of $T_{M3}$ for $P > 2.5$ GPa is attributed to an increase of the CEF anisotropy with respect to magnetic exchange anisotropy.

The obtained magnetic phase diagram of YbRhSb as a function of the unit cell volume has been compared with that of the isostructural HF ferromagnet YbNiSn.
References