HIROSHIMA UNIVERSITY

Heavy Electrons

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

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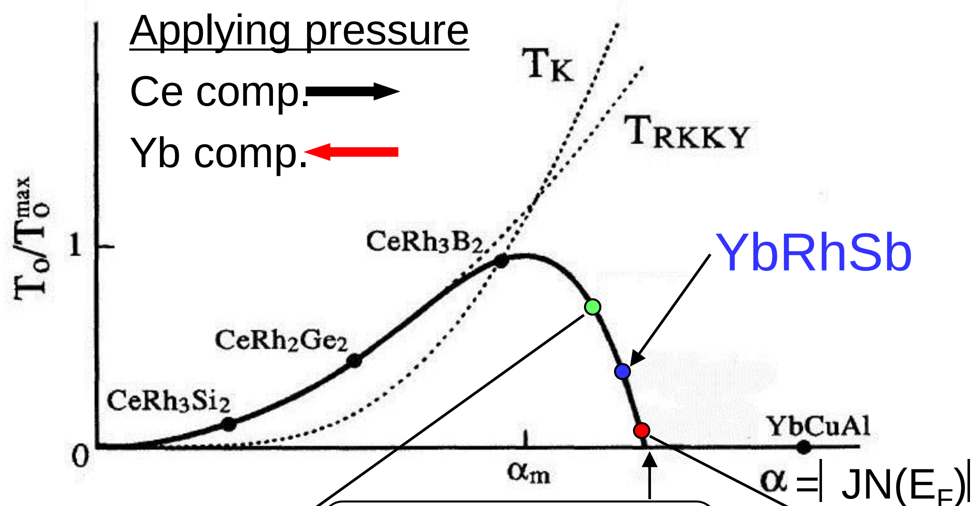
Introduction

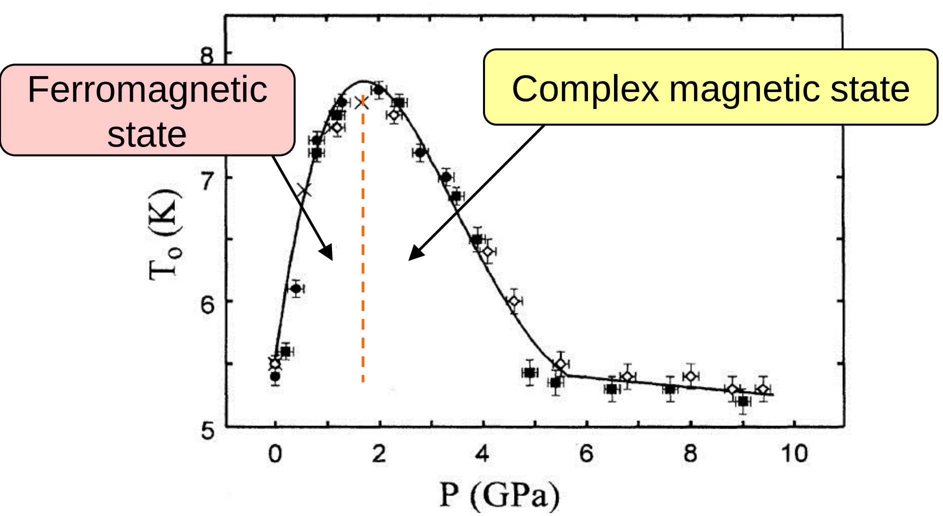
Pressure effect on the magnetism of Yb compounds

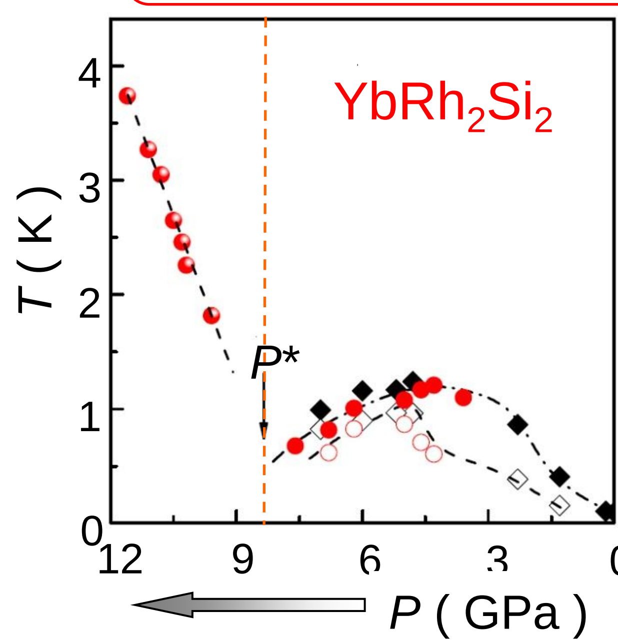


Quantum critical point (QCP)

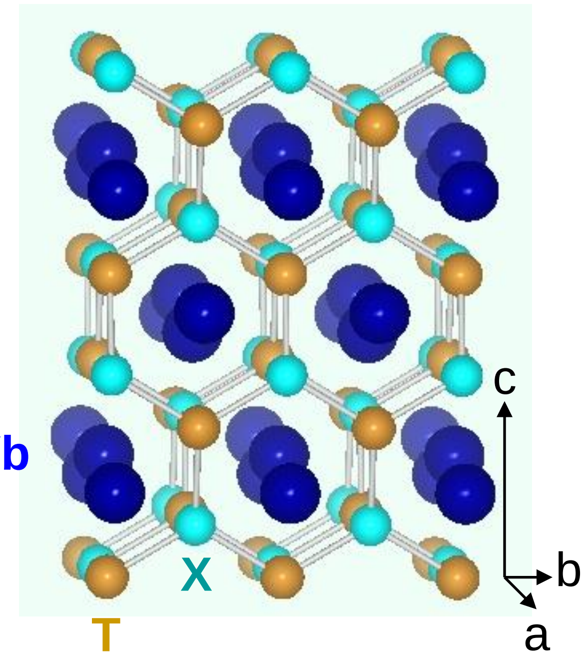
Appearance of another QCP at P^* ($YbRh_2Si_2$) [4]

Change of magnetic state (YbNiSn) [2,3]



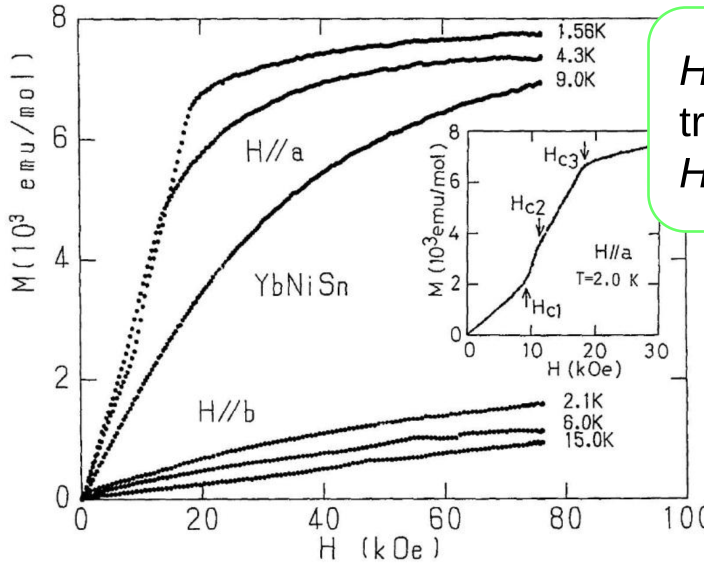


Yb compounds with the orthorhombic ε-TiNiSi type structure ③

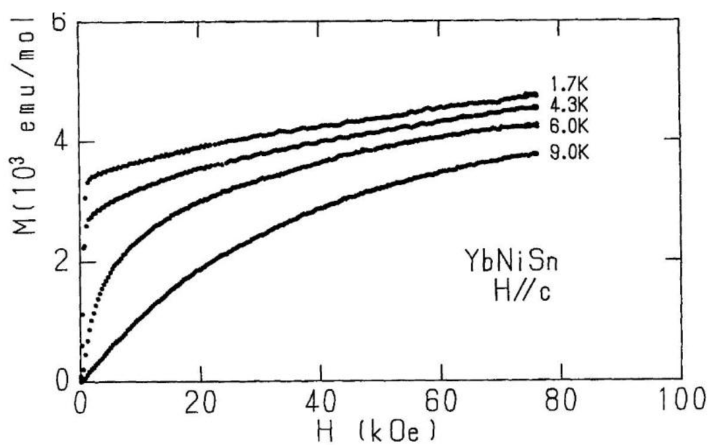


YbNiSn (Ferro. T_C= 5.6 K) [2,3]
YbPtAl (Antiferro. T_N= 5.8 K) [5]
YbRhSb (Weak ferro. T_M= 2.7 K) [1]

Magnetization of YbNiSn [2]



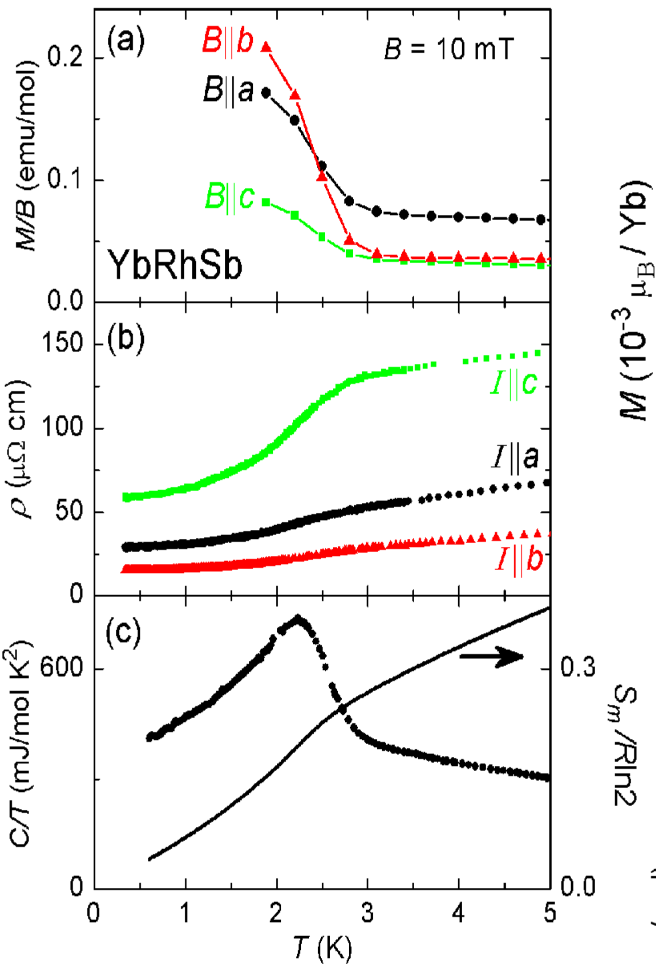
H II a: Metamagnetic transition,
H II c: Ferromagnetism

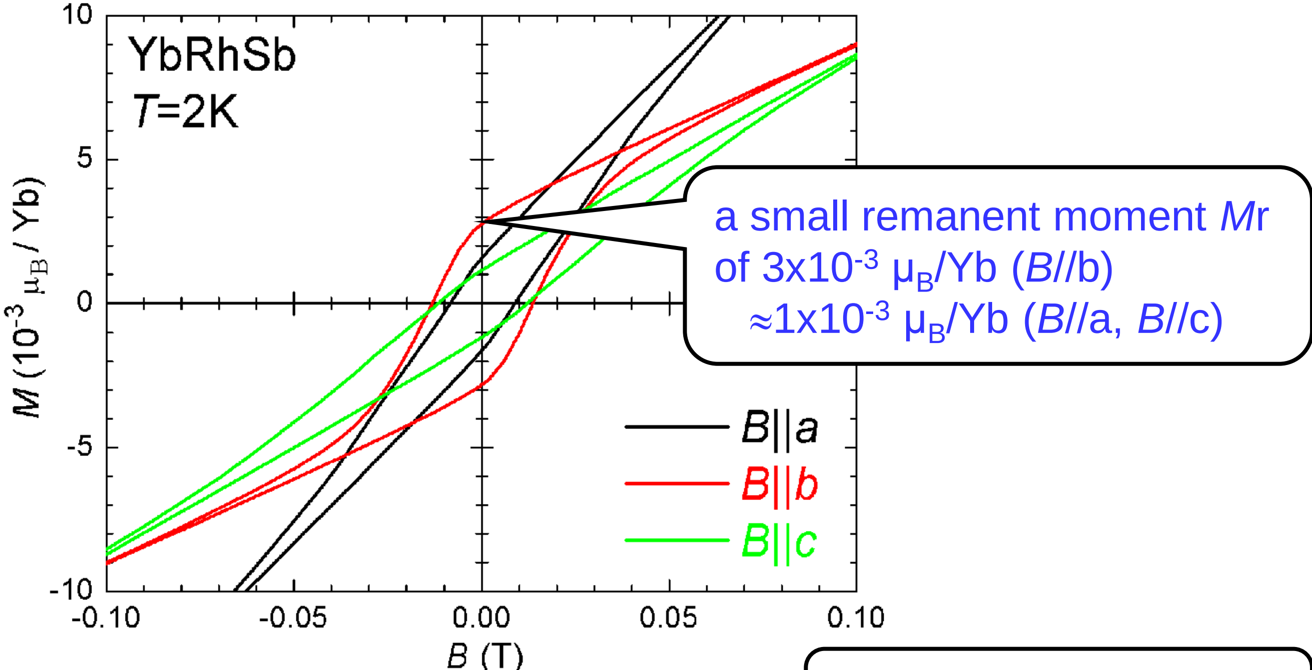


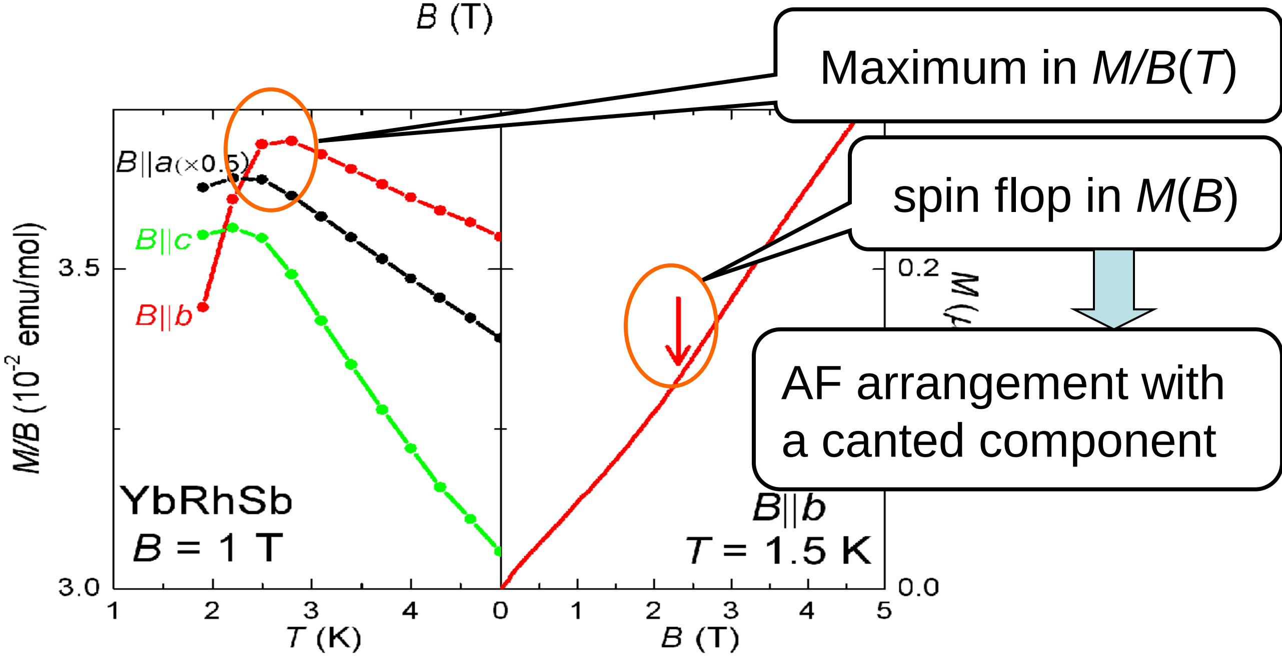
Complicated magnetic behavior arises from the competition between the anisotropic exchange interaction with the easy *c*-axis and the CEF anisotropy with the easy *a*-axis.

Weak ferromagnetism of YbRhSb

(T_M=2.7K, Mr = 3x$10^{-3}\mu_B$/Yb)[1] ④

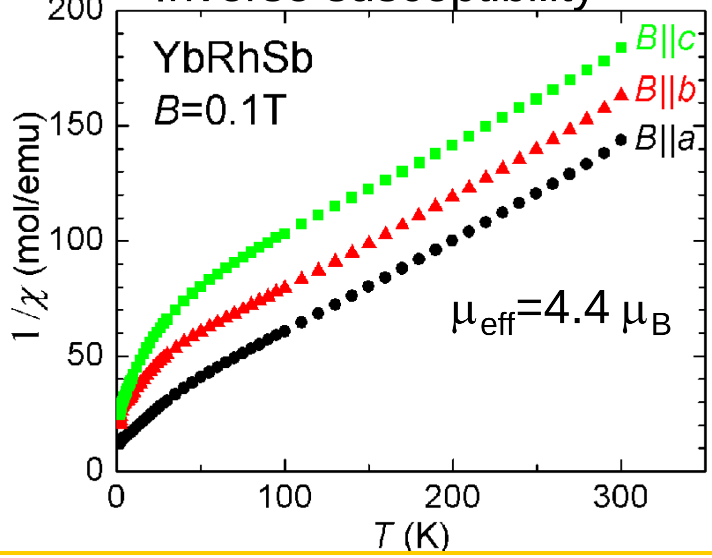




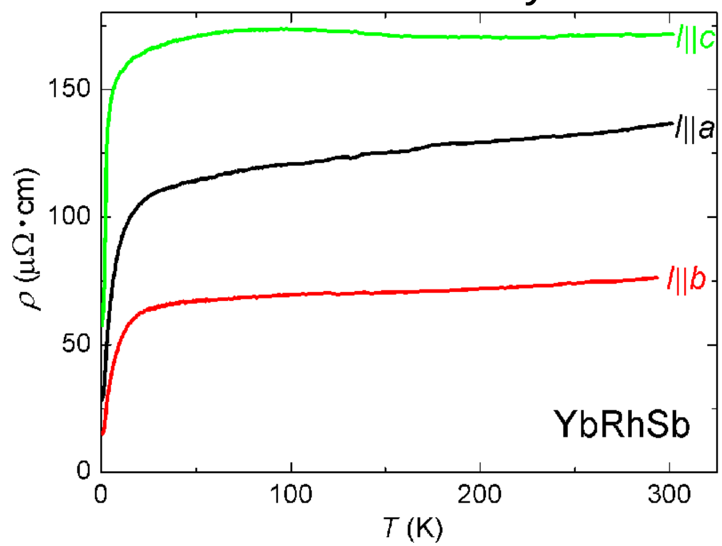


Heavy-fermion behaviour of YbRhSb [1]

Inverse susceptibility



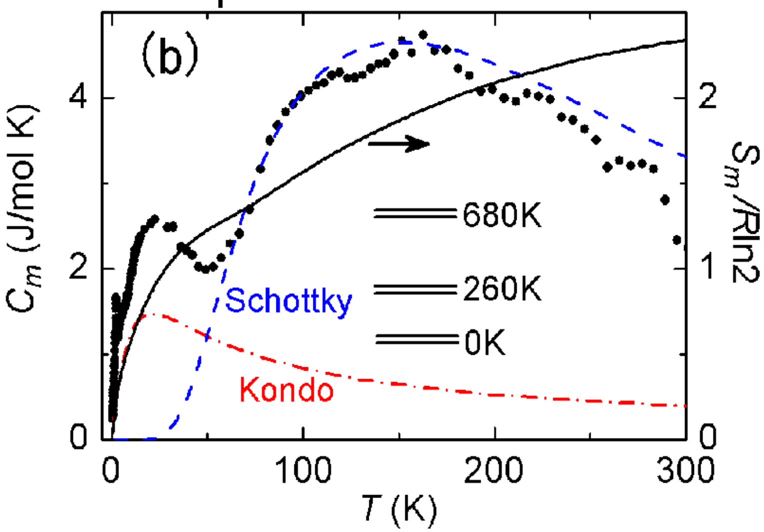
Electrical resistivity

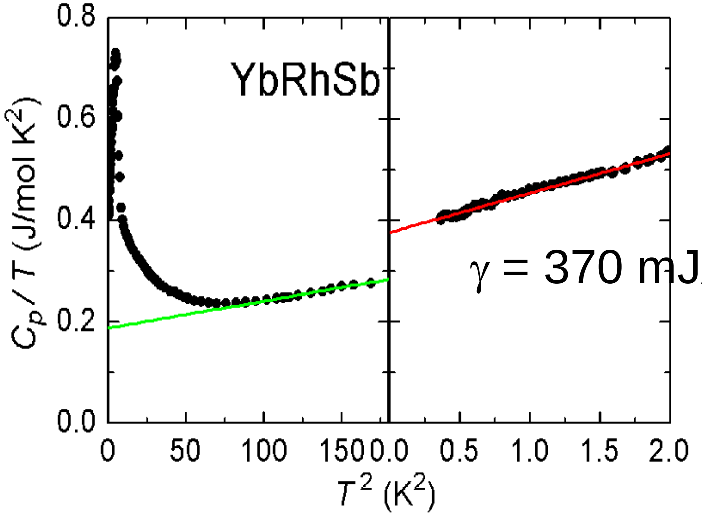


In the paramagnetic state,
easy axis is *a*-axis. ⇐CEF anisotropy

Broad maximum at 100 K
⇒Kondo effect

Specific heat





γ = 370 mJ/K^{2}mol

Purpose

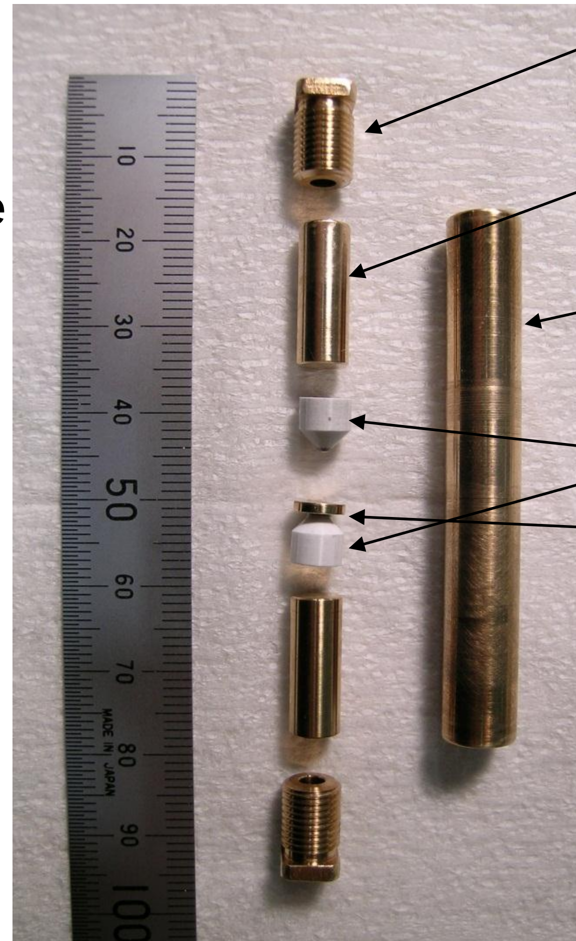
Determine pressure dependences of the Kondo and RKKY interactions.

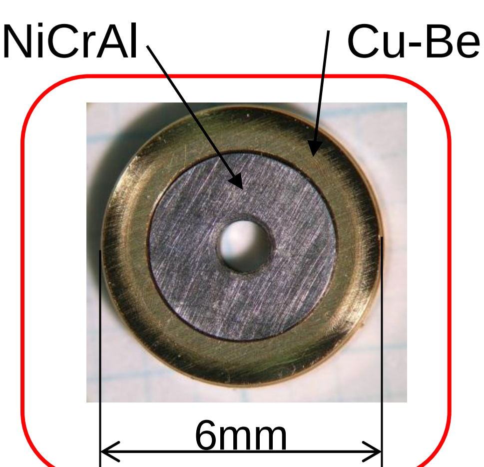
Experiments

1. Resistivity (ρ)
   AC 4-terminal method
   Pressure cell : piston-cylinder type
   P_{max}=2.5 GPa
   T : 0.3 K ~ 300 K

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

Pressure medium : Daphne oil



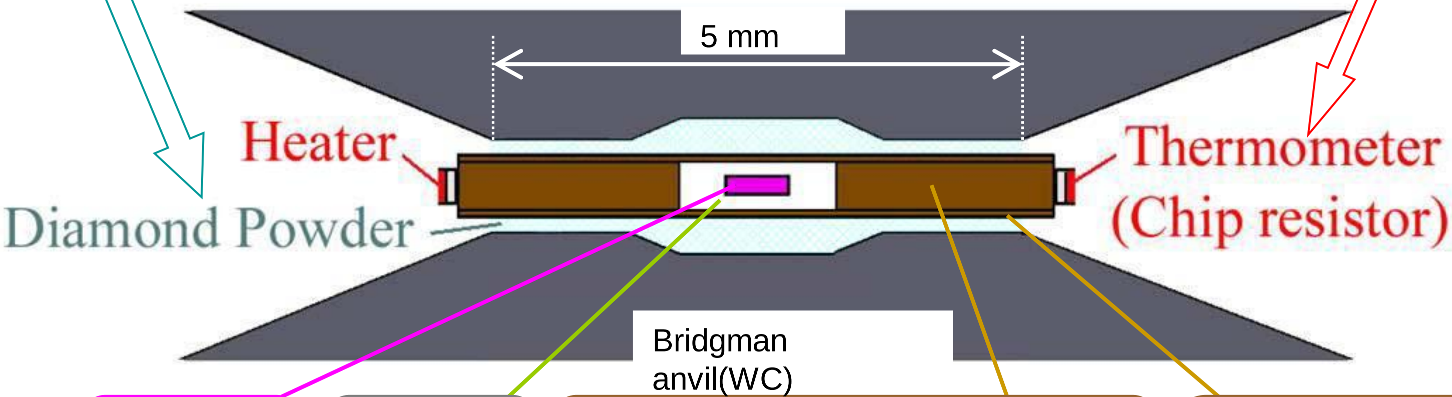


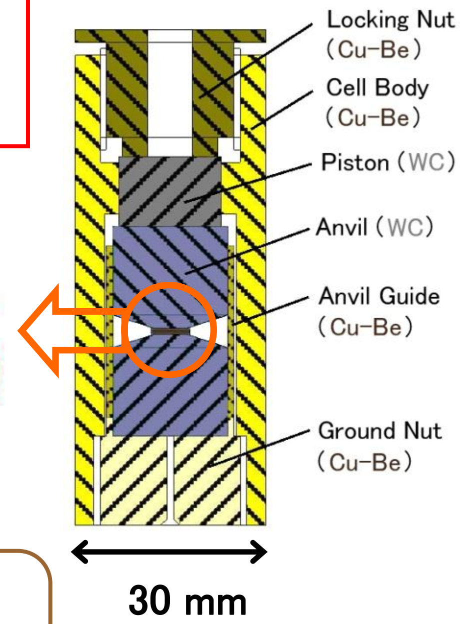
Home-made indenter cell

Design of our calorimeter for high pressures [7]

To isolate thermally the gasket from the anvil

The thermometer is mounted on the felly of the gasket. ⇒ The sensitivity doesn't change with pressure.





YbRhSb
3.37 mg

In
5.39 mg

Cu-Be gasket : 142.92 mg
I.d.= 1.6 mm, t = 0.7 mm

Cu-Be plate
16.53 mg
t = 0.05 mm

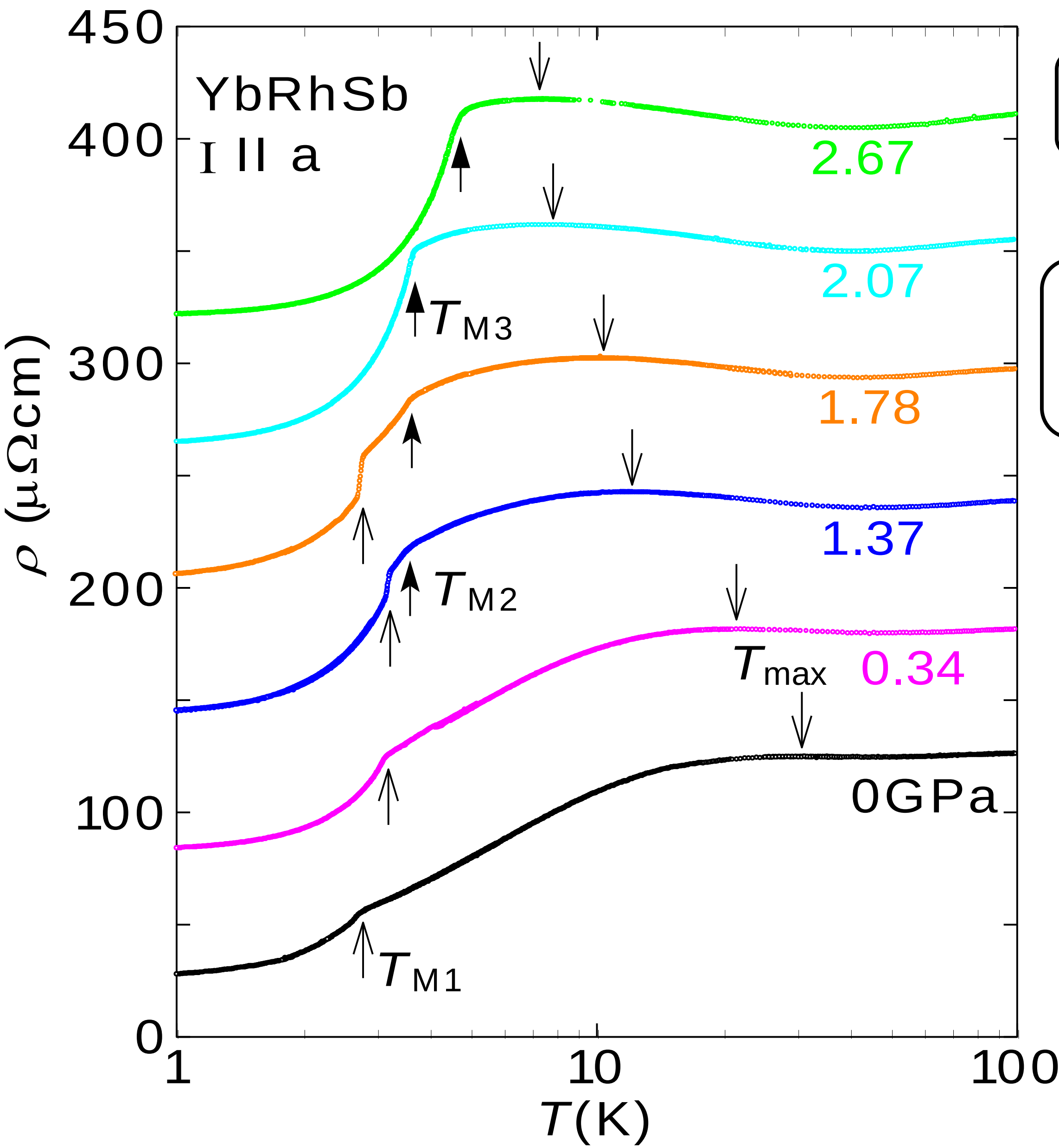
- The hollow at the anvil top⇒ It prevents expansion of the sample space over the anvil top.
- Pressure ⇒ superconducting temperature of In.
- P_{max}=3 GPa.
- 0.5 < T < 7 K (^{3}He cryostat)
- Detection of AC component of the sample temperature ⇒ Lock-in Amp.

Experiments up to 20 GPa

1. Resistivity (ρ)
   DC 4-terminal method
   Pressure cell : a diamond anvil cell (DAC)
   T : 1.5 K ~ 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

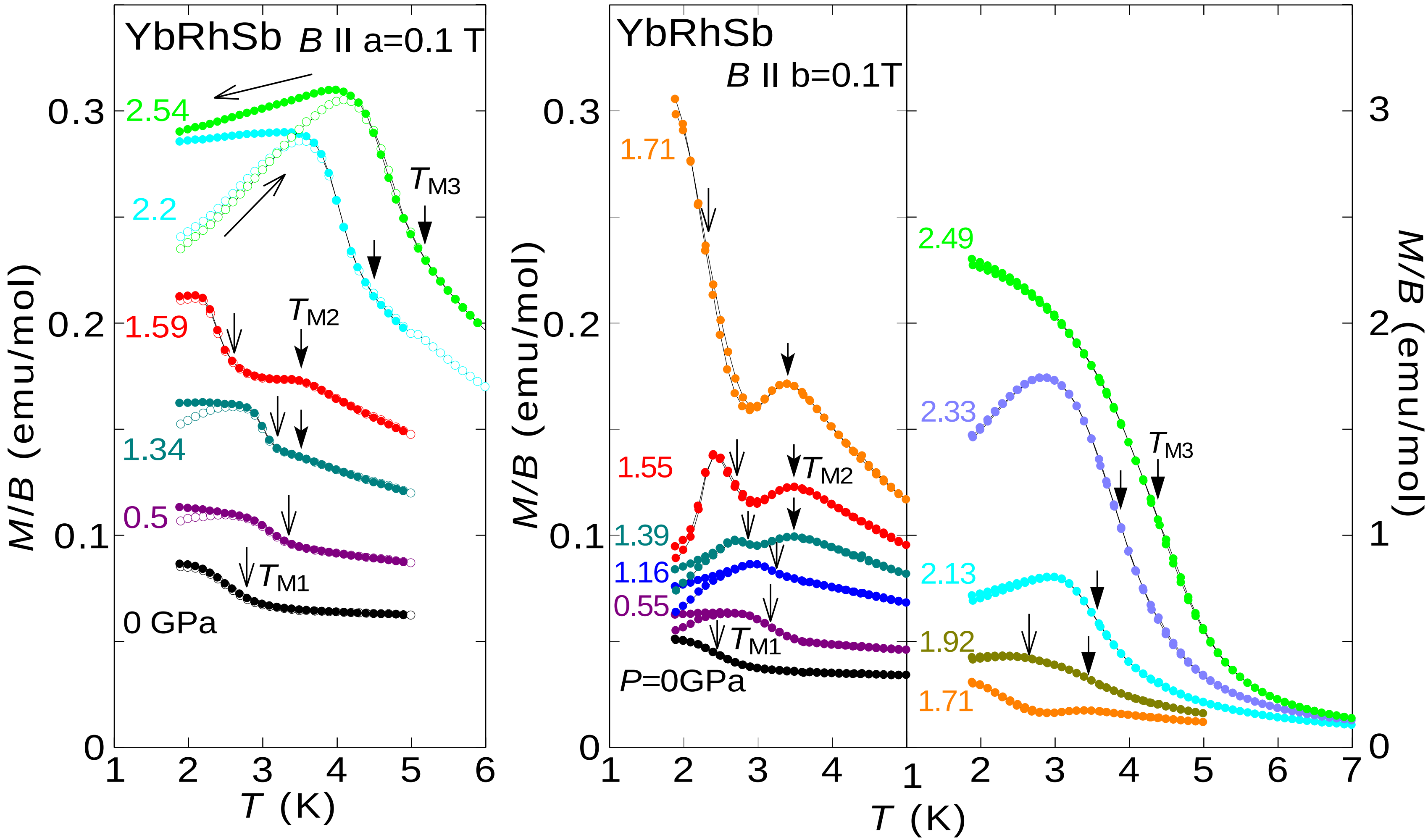


T_{max} ($\propto T_K$) decreases with pressure.

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

(Data sets for each value of P are shifted upward consecutively by 60 μΩcm for clarity).

Magnetic susceptibility $M/B(T)$ for $B \parallel a$ and $B \parallel b$ under various pressures ⑩

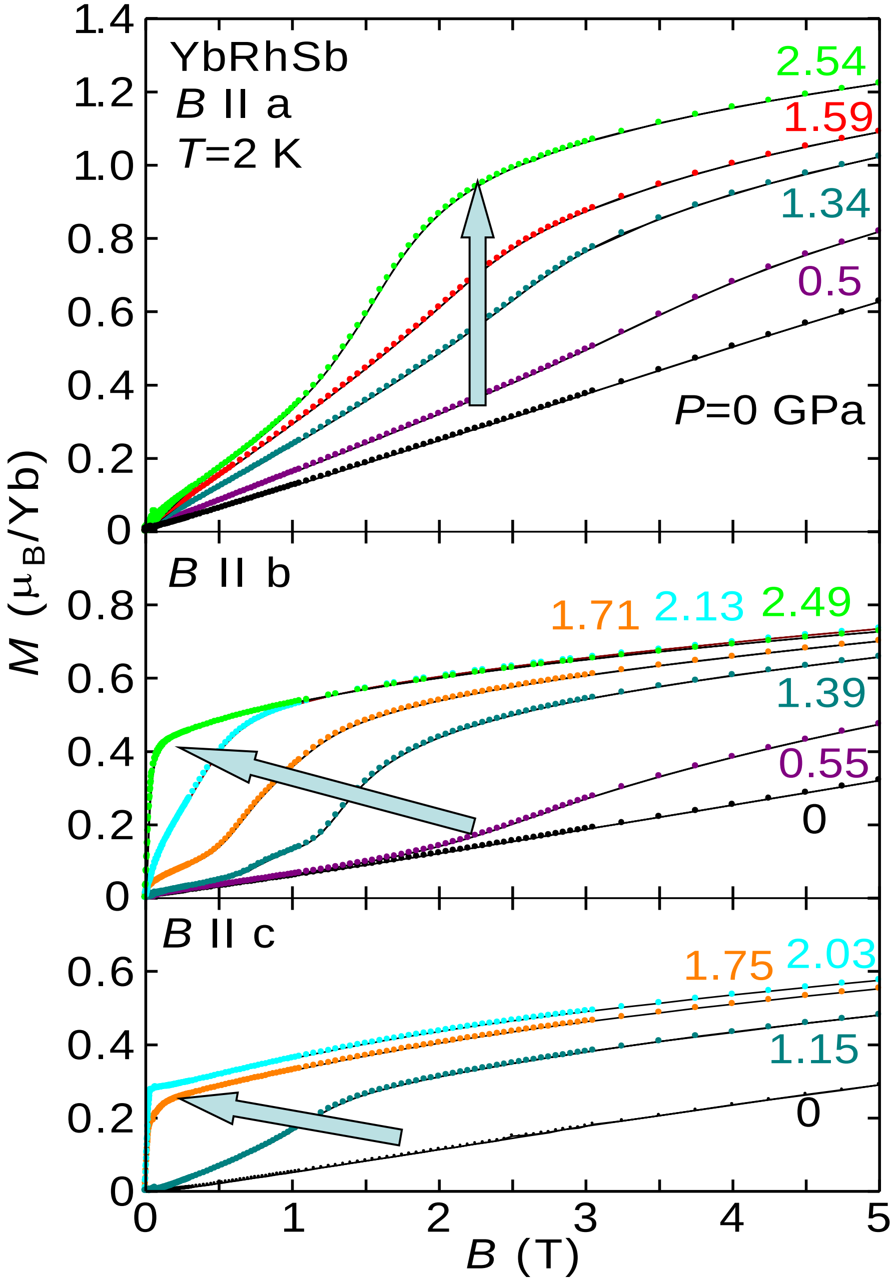


P =1.59 GPa
Broad maximum at T_{M2}=3.5 K
Increment below 2.7 K

$P \geq$ 2.2 GPa
Hysteresis of M/B at low T

- M/B increases with increasing pressure.
- P =1.39 GPa : Broad maximum at T_{M2}=3.5 K
- Increase of χ_{dc} for $P \geq$ 2 GPa ⇒ Ferromagnetic state?

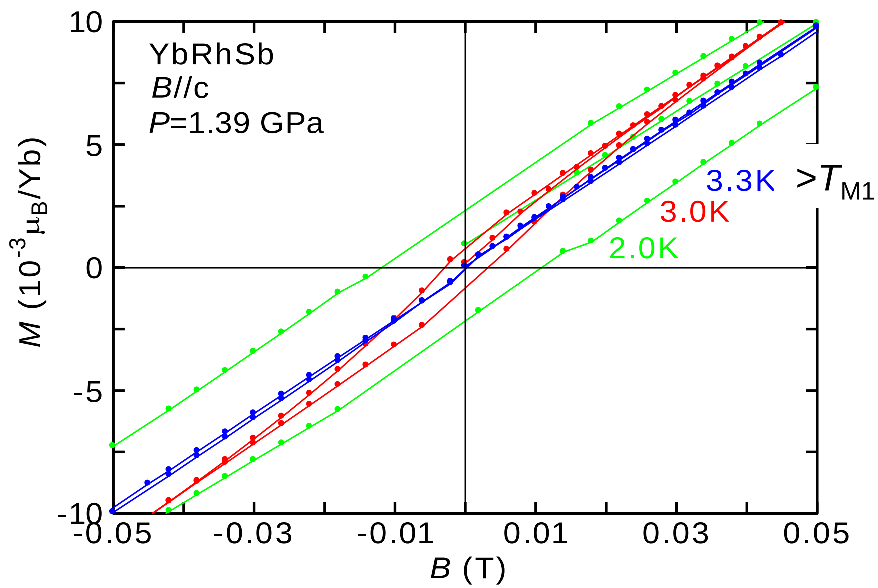
Magnetization curves of YbRhSb under various pressures



B II a
Metamagnetic anomaly shifts from 2.5 T to 1.5 T with *P*.

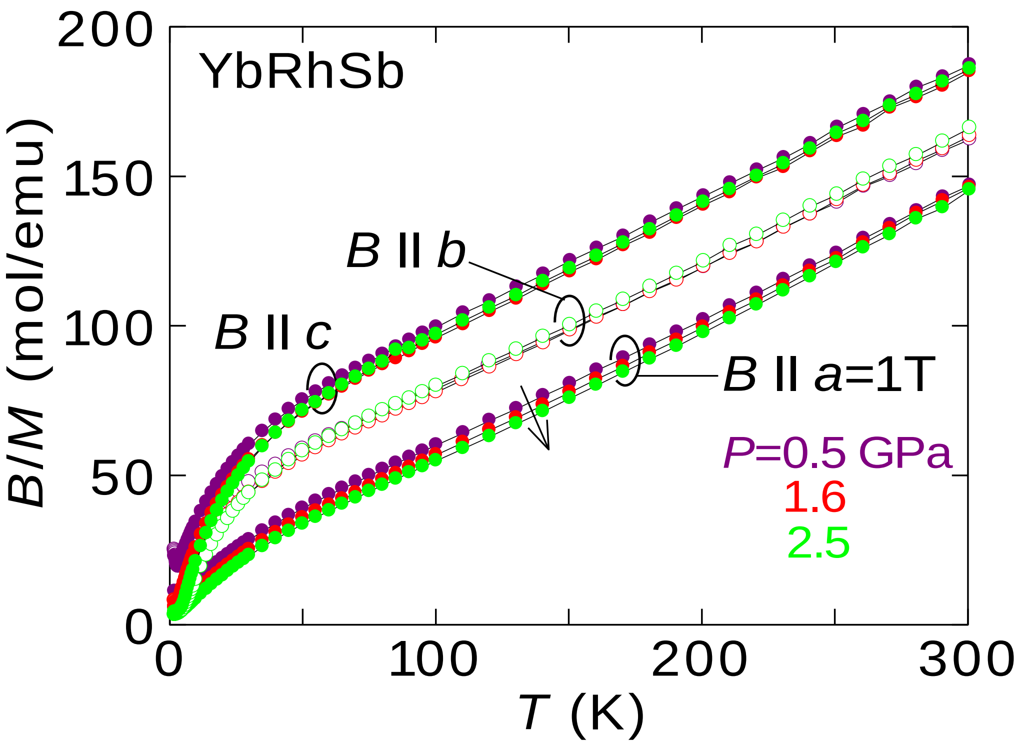
B II b
P ≥ 2.5 GPa, ferromagnetic behavior with the *M*r of 0.4 μ_B/Yb

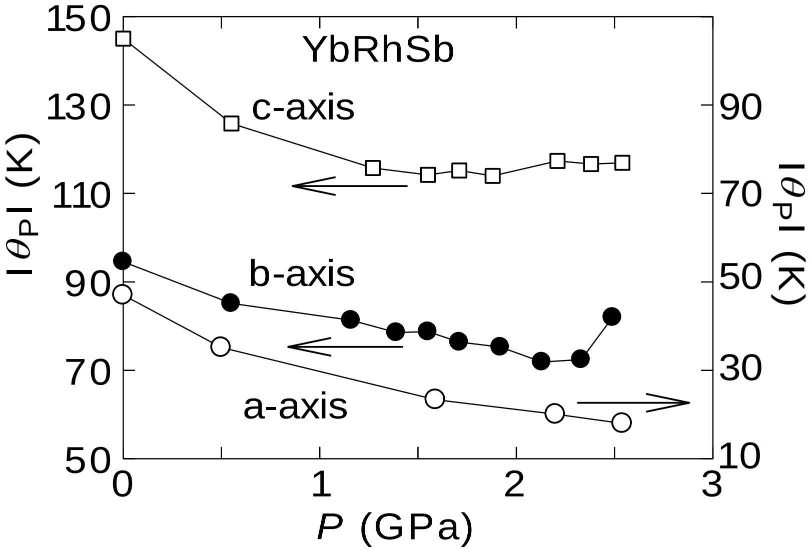
B II c
P >1.75 GPa, ferromagnetic behavior with the *M*r of 0.3 μ_B/Yb



Weak ferromagnetic moment disappears above T_{M1}.

T-dependence of *B*/*M* under various pressures





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

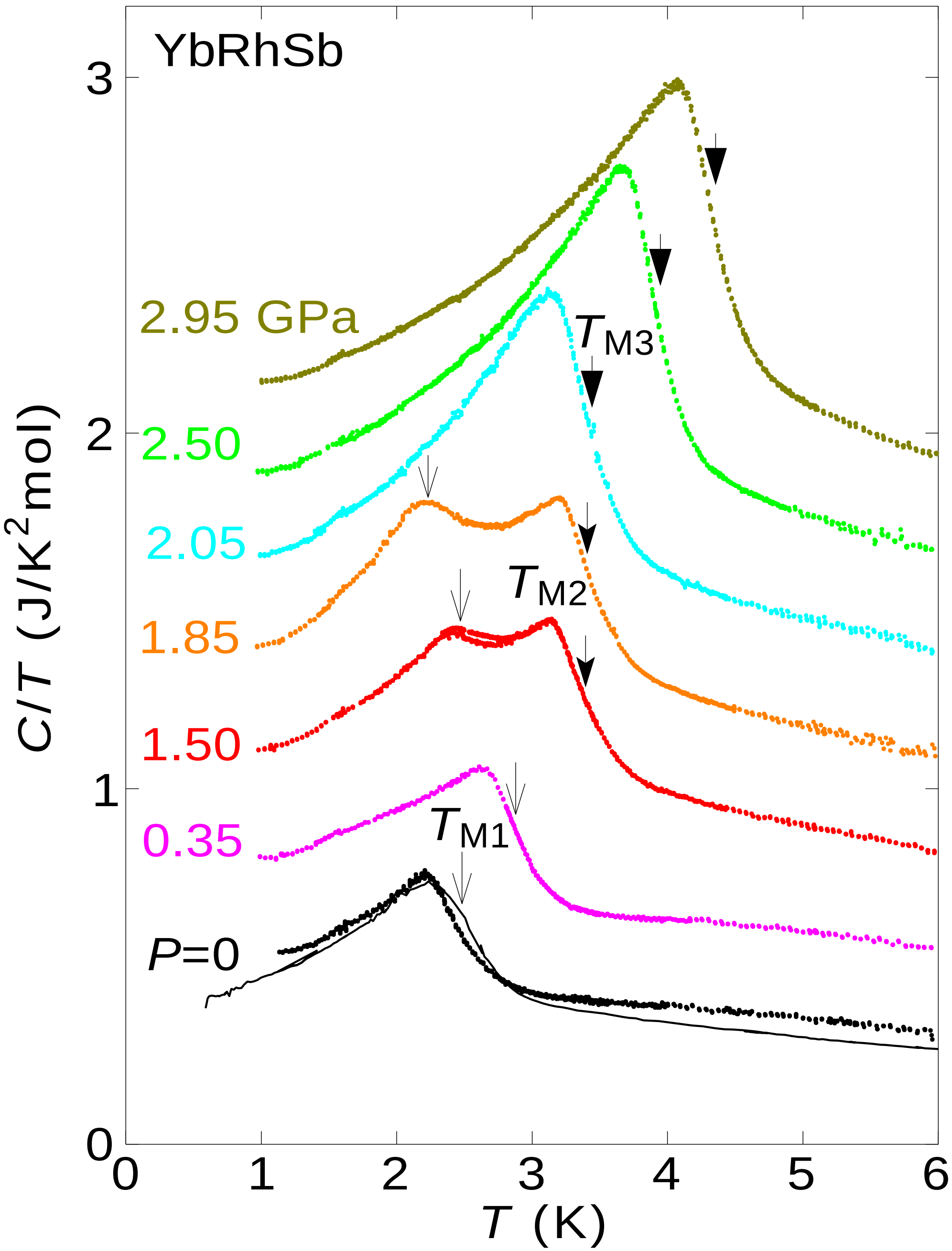
The slop of *B*/*M*(*T*) for *P* >100K hardly changes with pressure.

⇒ μ_{eff} does not change on pressure.

$|\theta_p| = nT_K$, n=2∼4 [8]

⇒T_K decreases with pressure.

Specific heat of YbRhSb under various pressures



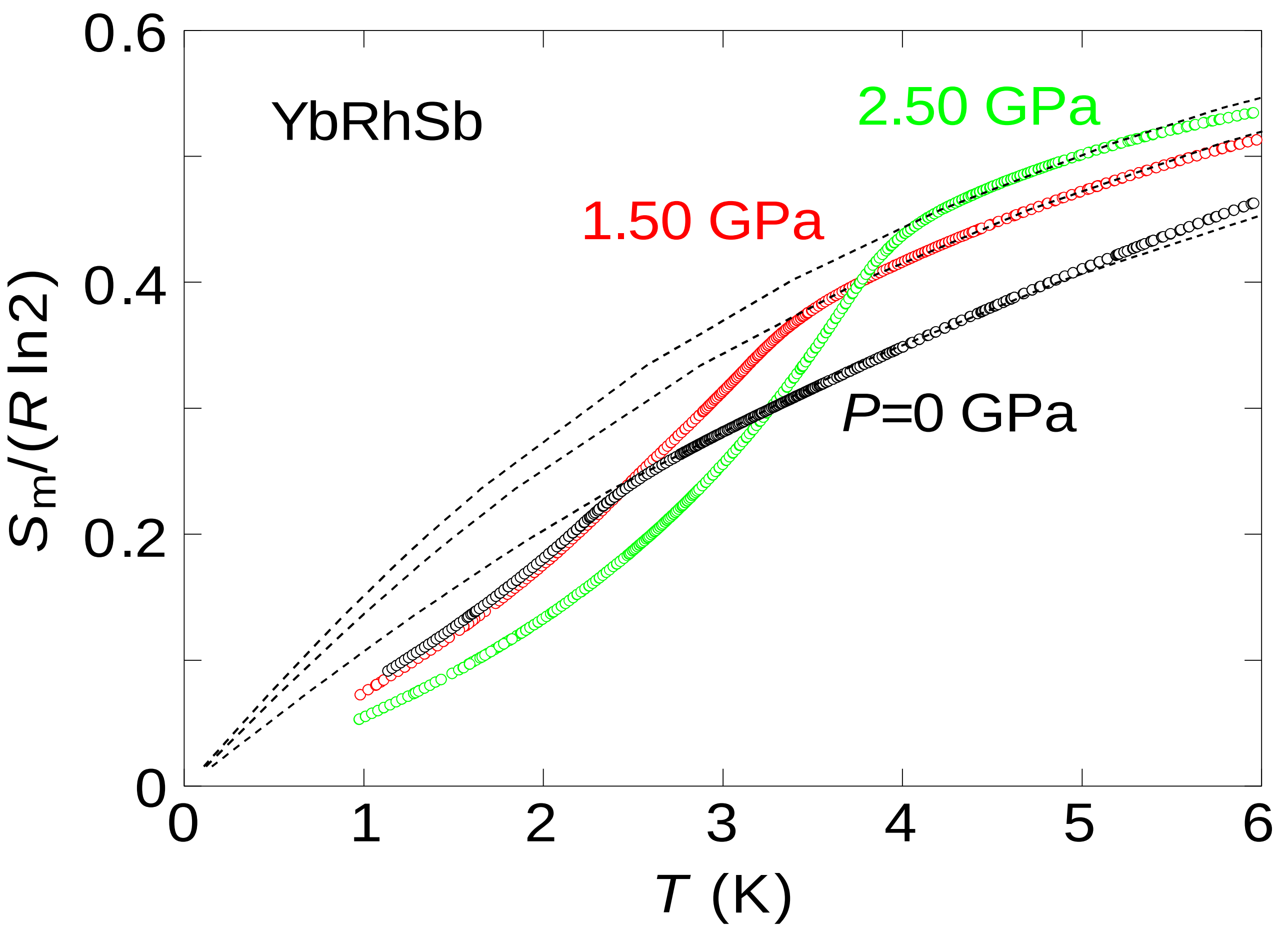
P=0
The data agrees with the previous one [6].

P=1.5 GPa
Thermal hysteresis of $C(T)$ around T_{M1}
⇒ 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^2mol for clarity.)

Magnetic entropy of YbRhSb under various pressures



$$S_m = \int \frac{C(\text{YbRhSb}) - C(\text{LaRhSb})}{T}\, dT$$

$C(\text{LaRhSb}) = \gamma T + \beta T^3$

$\gamma = 6.7$ mJ/K^{2}mol

$\beta = 0.34$ mJ/K^{4}mol

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

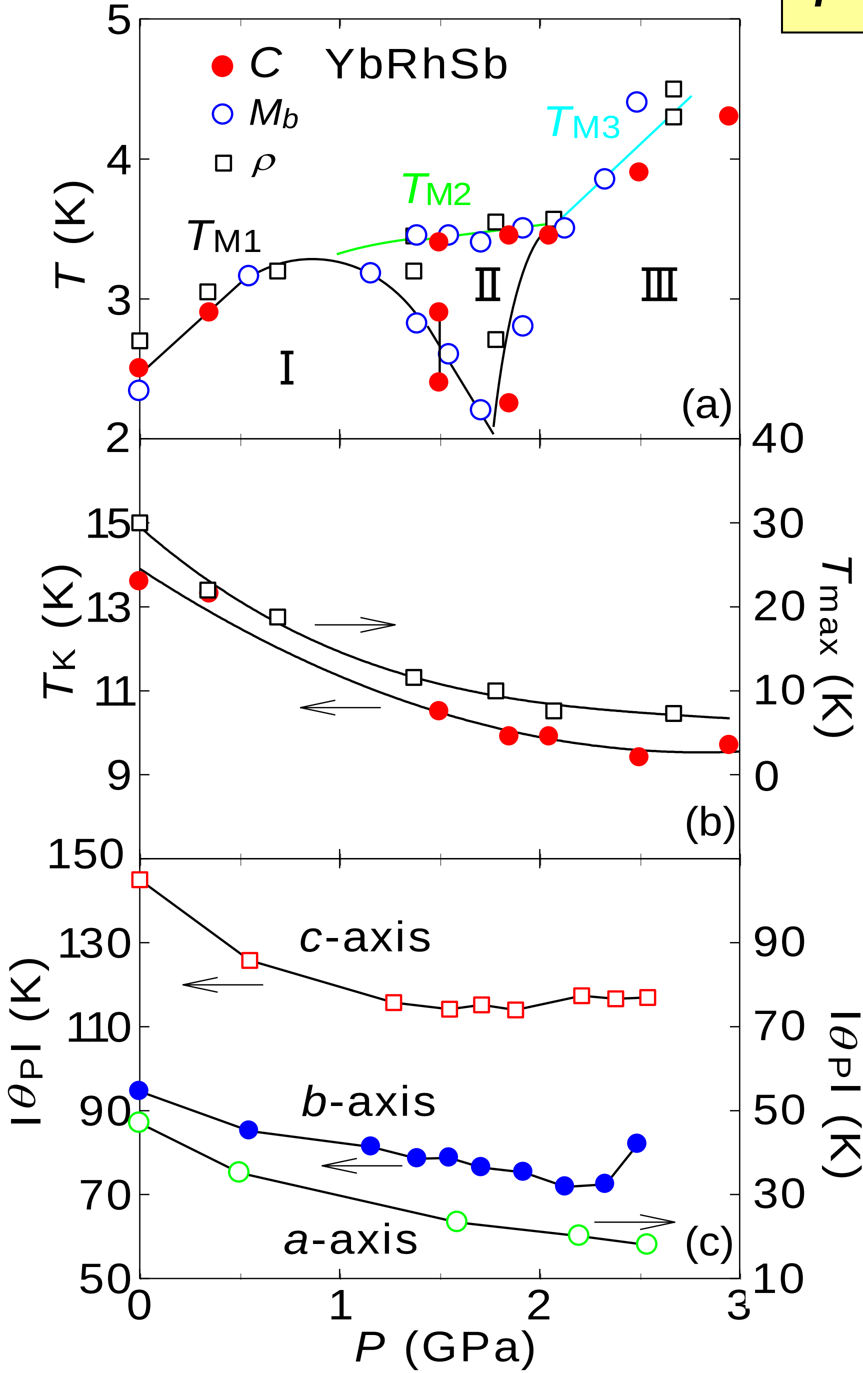
$\Rightarrow T_K$ [9]

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

$S_m(T_M)/(R\ln 2) = 0.24$ @ $P=0 \Rightarrow 0.45$ @ $P=2.5$ GPa

$\Rightarrow T_K$ decreases with pressures.

T - P phase diagram of YbRhSb



Minimum of T_M at 1.7 GPa

Ⅰ : Canted Antifferro.

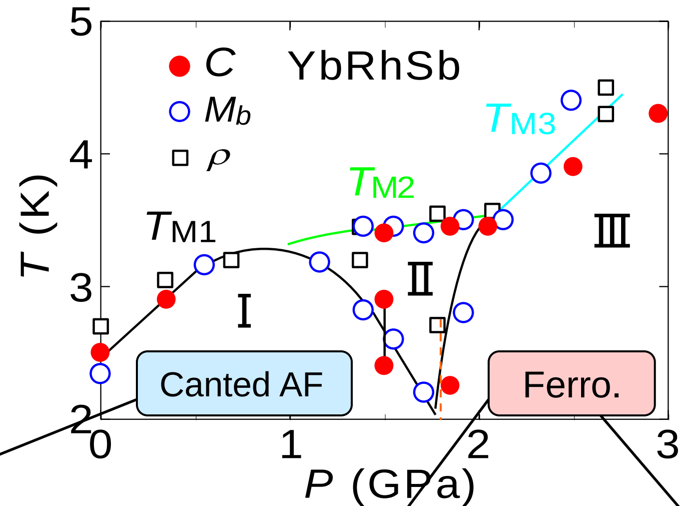
Ⅱ : Antiferro.

Ⅲ : Ferro. $Mr \approx 0.3 \sim 0.4\ \mu_B$/Yb

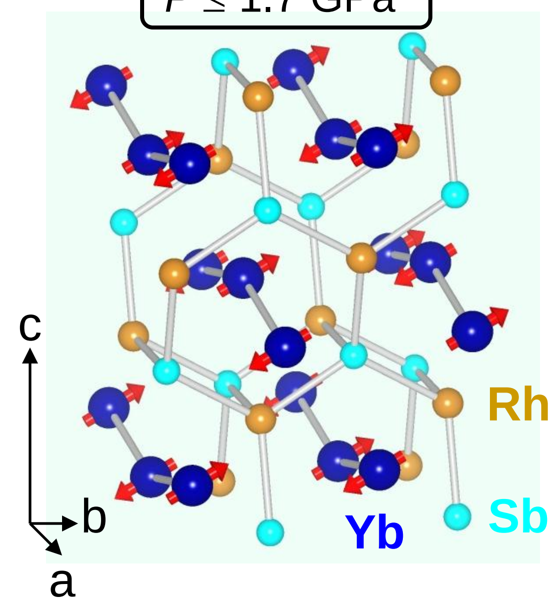
T_K decreases rapidly with increasing pressure, but remains at a constant value above 1.5 GPa.

The complicated pressure-induced magnetic phase of YbRhSb is attributed to the enhancement of inter-site exchange interaction causing easy *b-c* plane anisotropy.

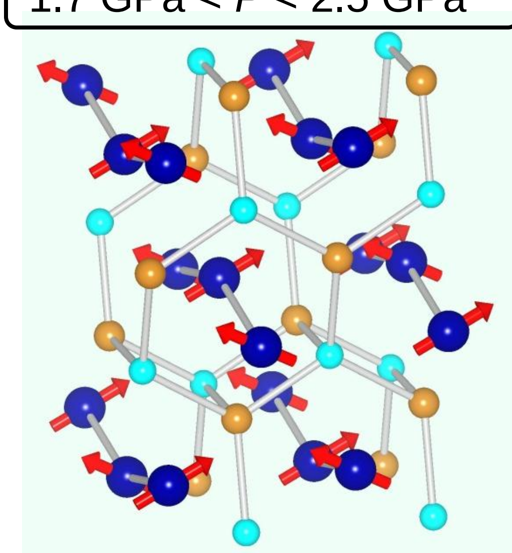
Model of magnetic structure of YbRhSb



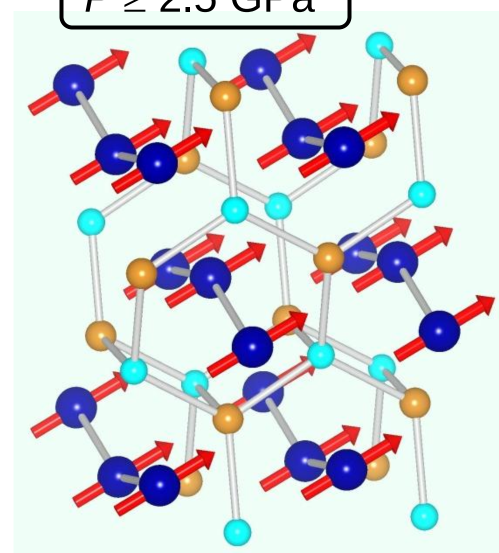
$P \leq 1.7$ GPa



1.7 GPa $< P < 2.5$ GPa



$P \geq 2.5$ GPa

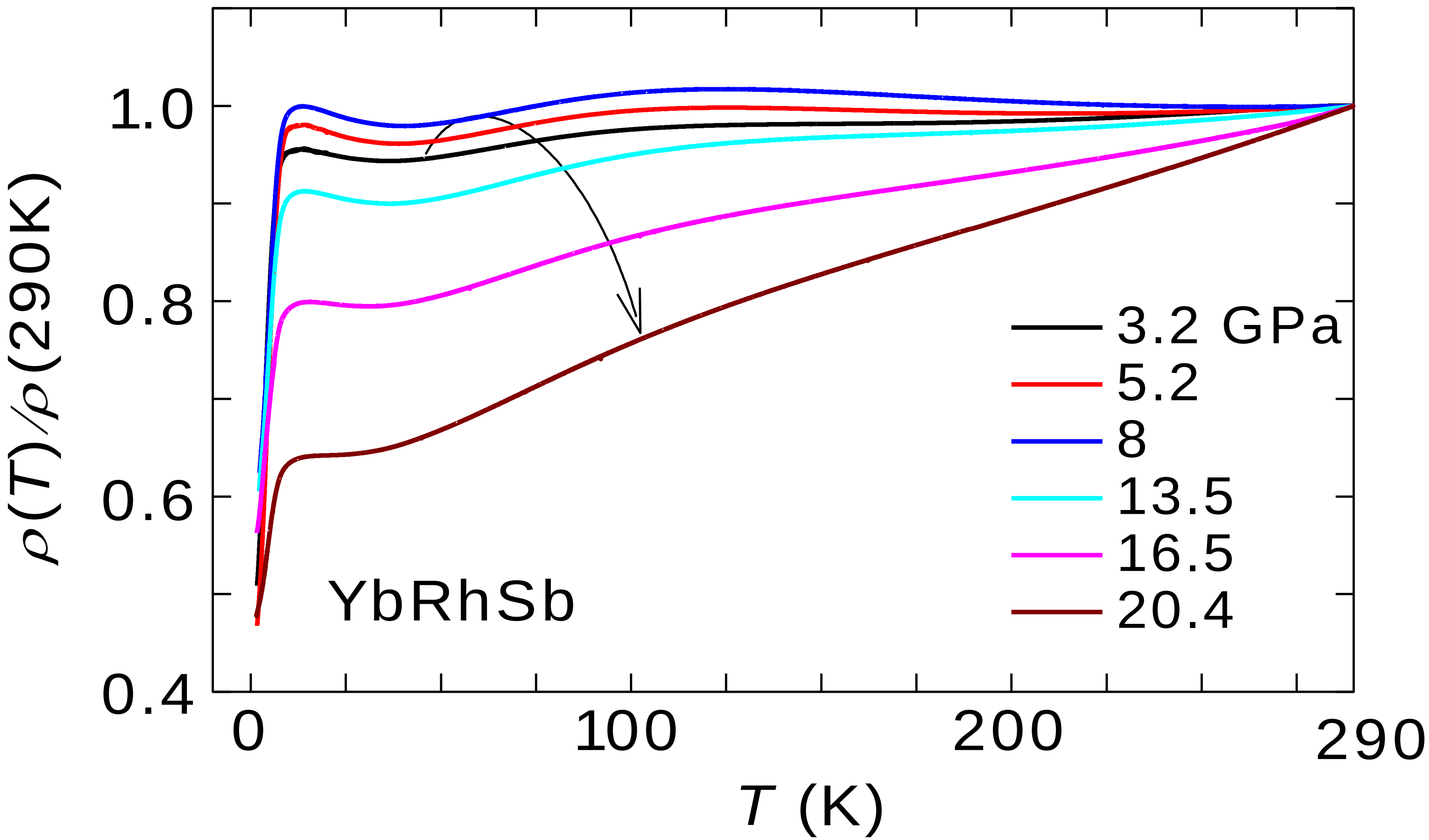


A canted antiferromagnetic structure with ordered moments of 0.1 μ_B/Yb lying almost parallel to the *b* axis below T_{M1} [10].

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

A ferromagnetic structure with moments of 0.4 μ_B/Yb lying in the *b*-*c* plane.

Resistivity of YbRhSb under various pressures up to 20 GPa

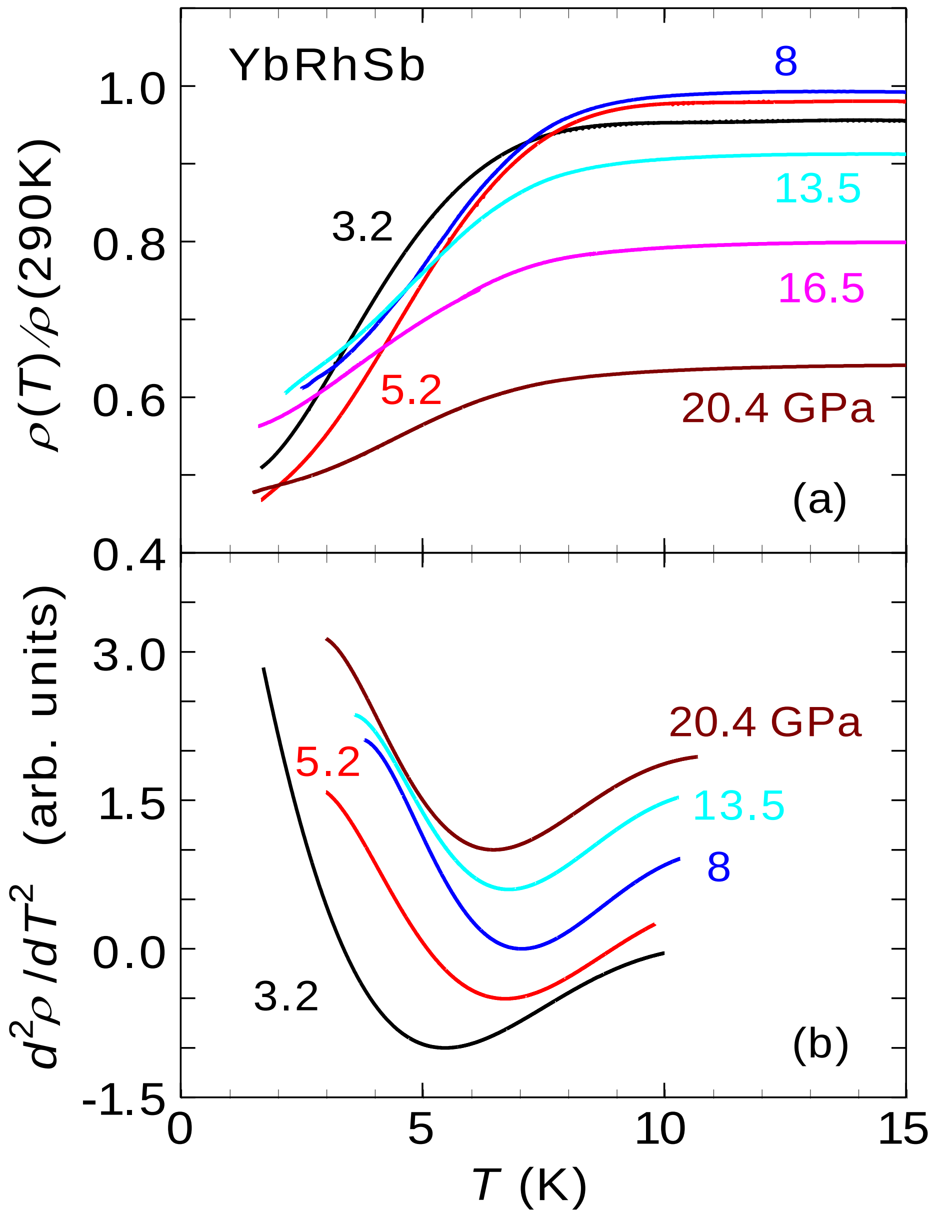


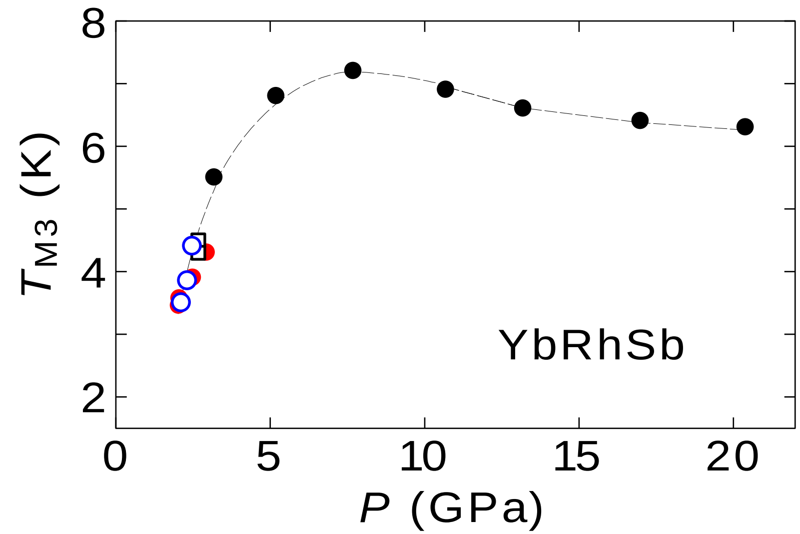
$\rho(T, P)$ shows a double maximum structure.

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.

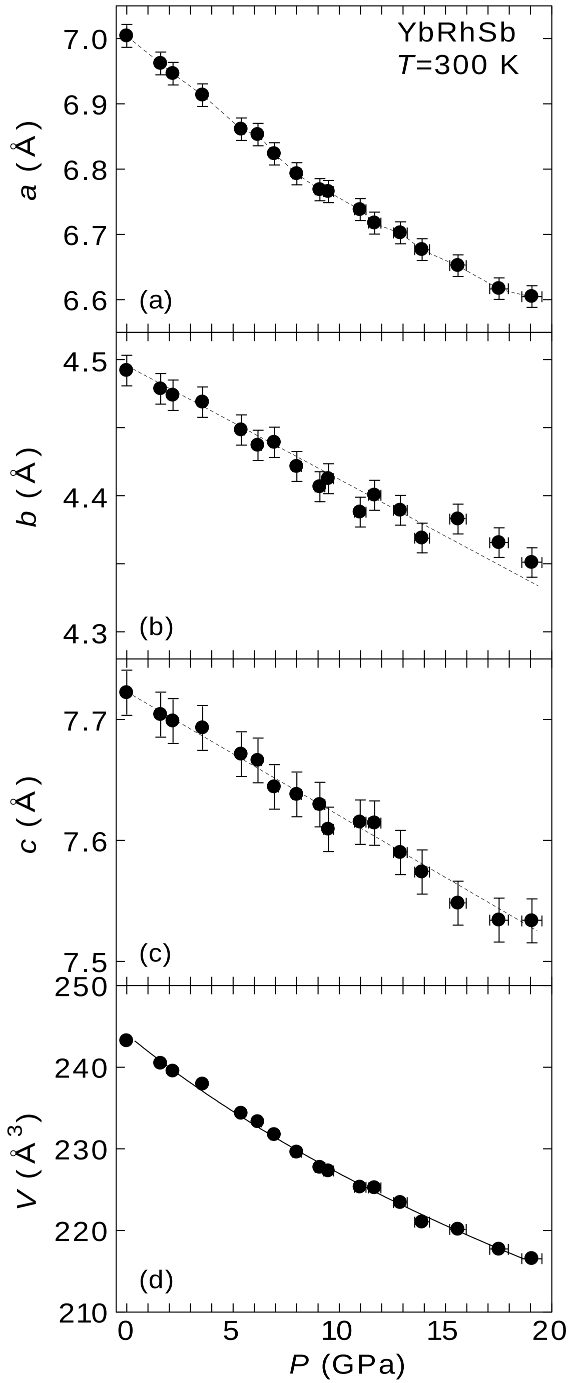
Pressure dependence of T_{M3}





T_{M3} steeply increases up about 7 K, showing a broad maximum, and then slightly decreases with increasing pressure above 8 GPa.

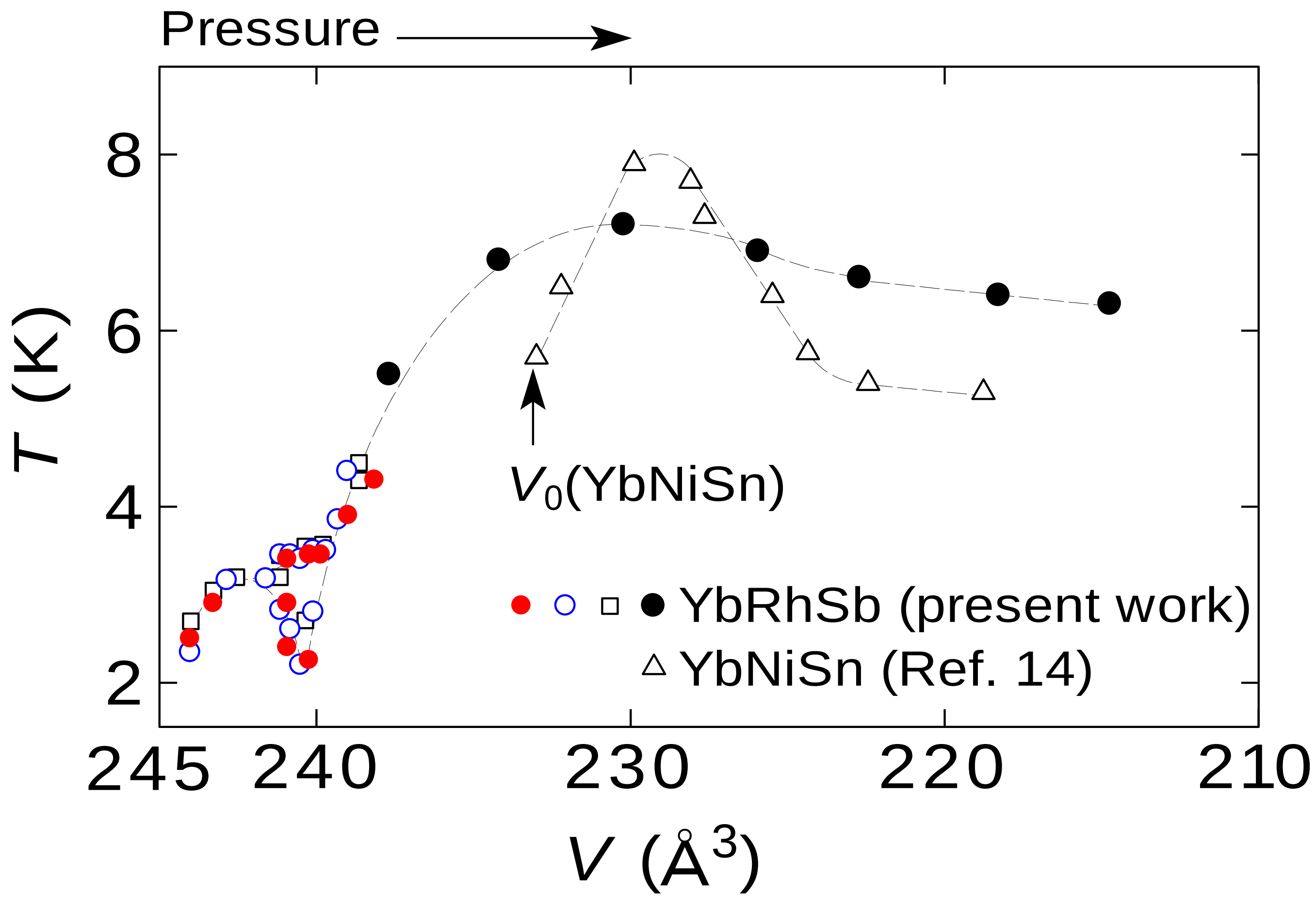
Pressure dependence of lattice parameters



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)

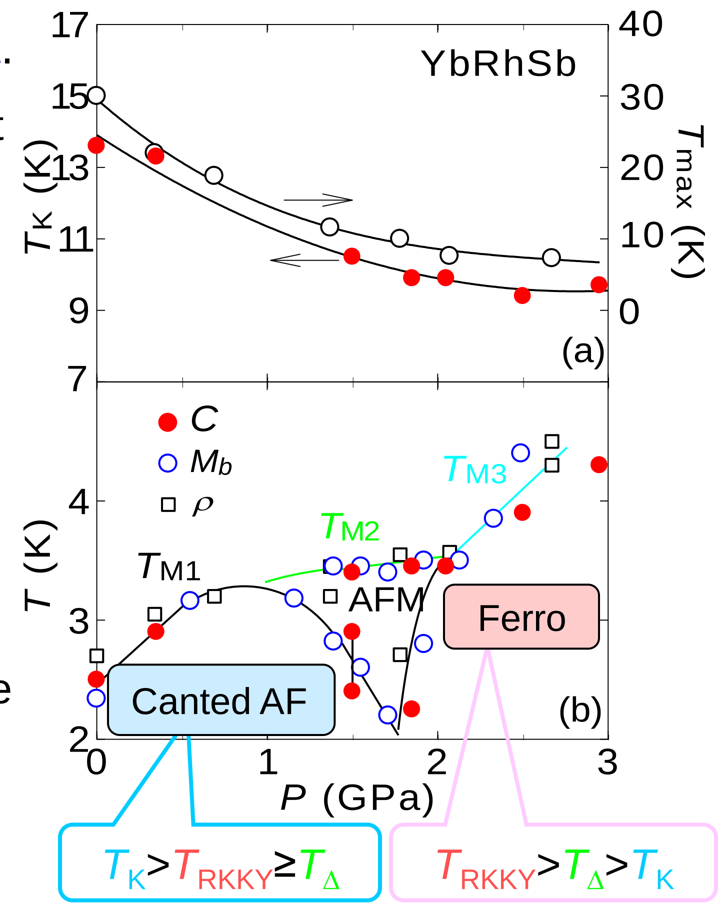
Volume dependence of T_M for YbRhSb and YbNiSn



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



Future studies

Magnetic structures under pressures ⇐ Neutron diffraction and Mössbauer spectroscopy

Summary Ⅱ Ferromagnetic order in YbRhSb at high pressures

- 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 the 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

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