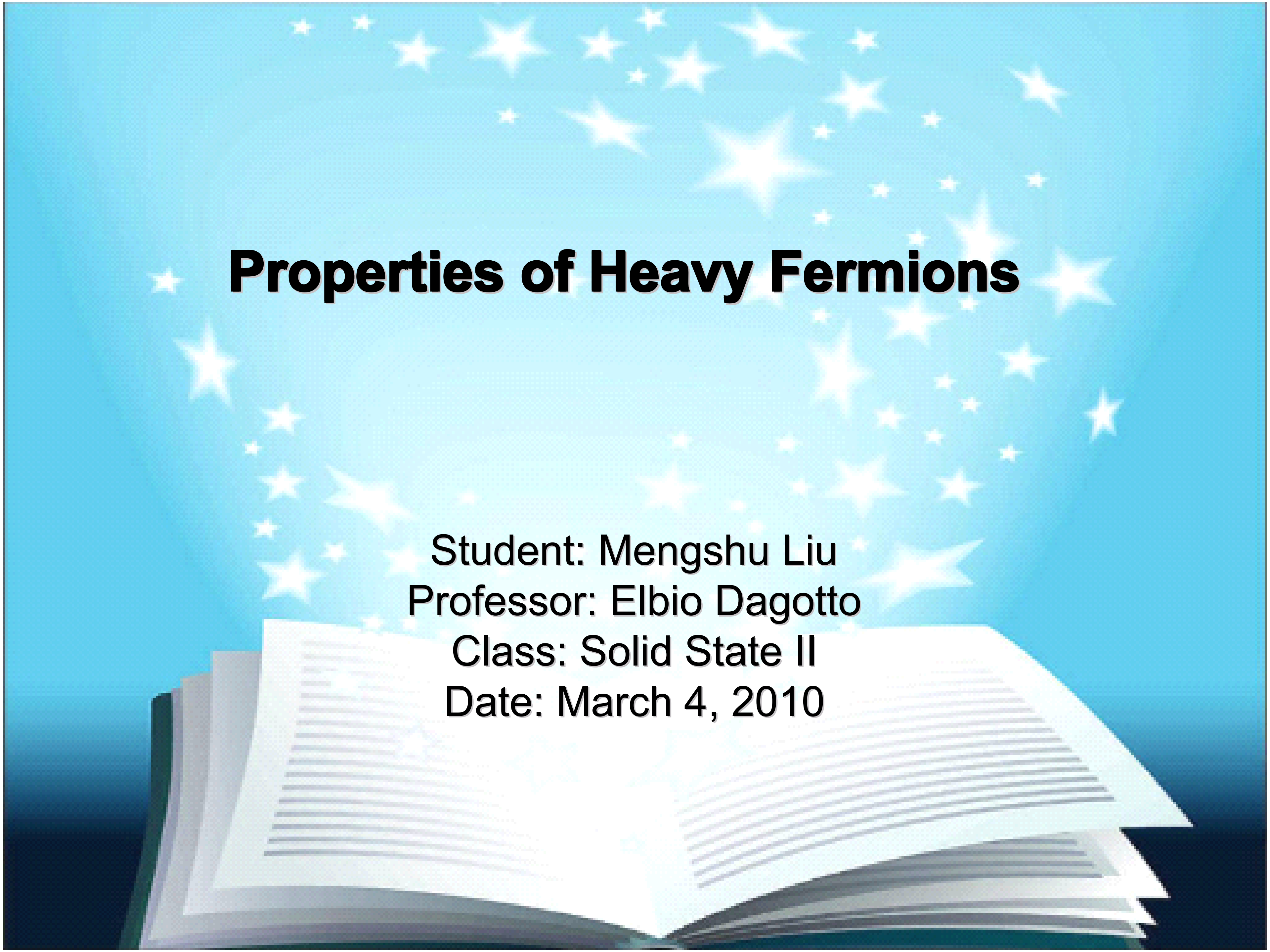

Properties of Heavy Fermions

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Class: Solid State II
Date: March 4, 2010

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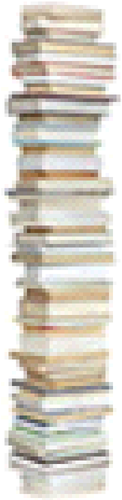
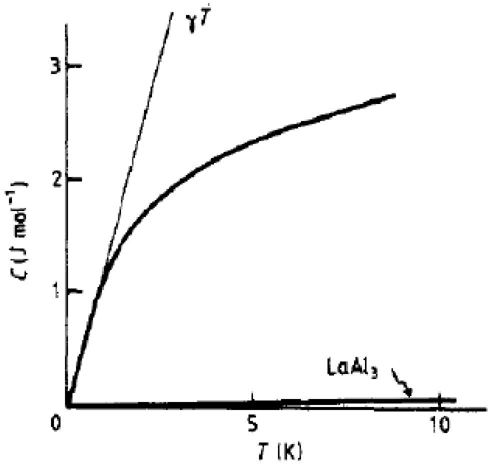


Introduction to Heavy Fermions

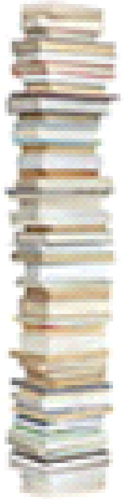
- Heavy fermion materials are a specific type of metallic compounds that have a low-temperature specific heat whose linear term is up to10 - 1000 times larger than the value expected from the free-electron theory.

$$C = \gamma T + AT^3$$

$$\gamma \propto m$$



First heavy fermion material: $CeAl_3$ by Andres et al.

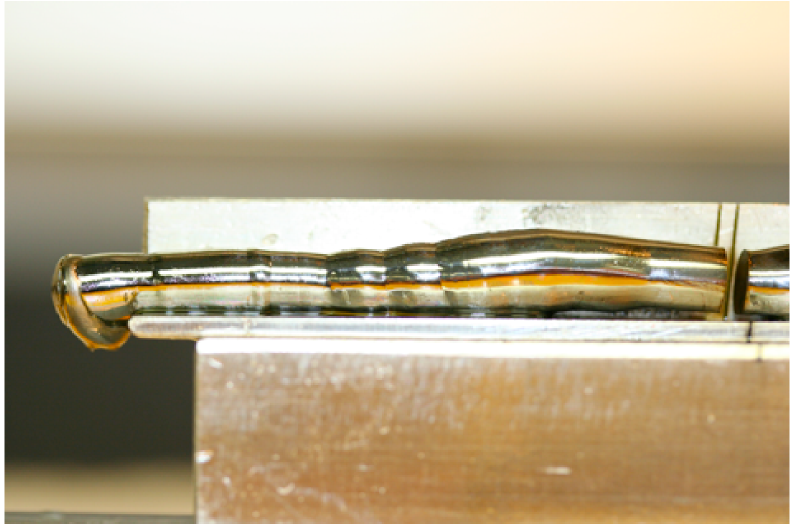


Introduction to Heavy Fermions

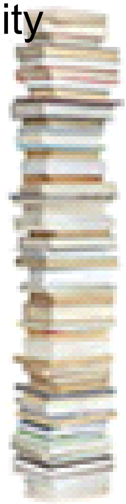
- The heavy fermion behaviour has been found in rare earth and actinide metal compounds at very low temperatures (<10 K) in a broad variety of states including metallic, superconducting, insulating and magnetic states.

- Typical HFs:

  $CeAl_3$, $CeCuSi_2$, $CeCu_6$, UBe_{13}, UPt_3, UCd_{11}, U_2Zn_{17}, $NpBe_{13}$



20 grams of single crystals of UPt3 from Northwestern University

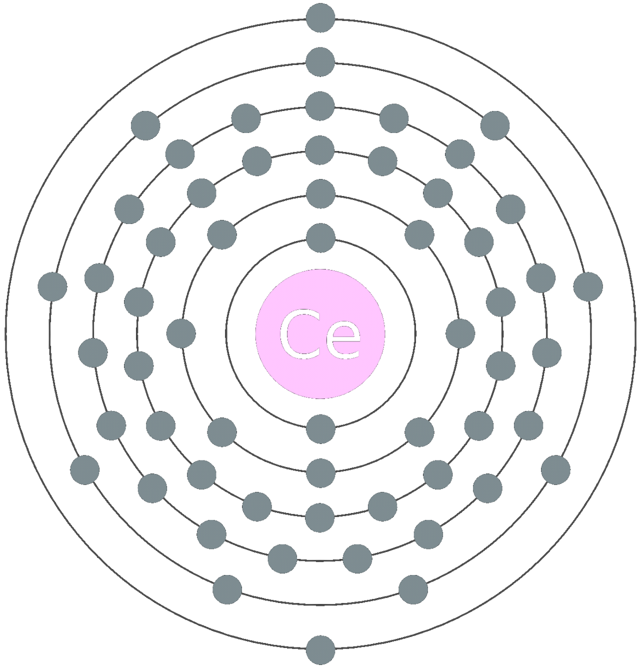


Introduction to Heavy Fermions

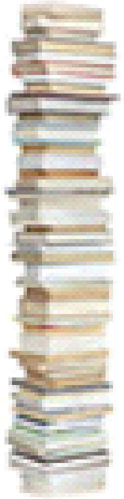
•Common Feature of HF:

These rare earth and actinide atoms all contain partially filled 4f- or 5f-electron shells.

La^{3+}: 4f^{0}
Ce^{3+}: 4f^{1} (J = 5/2)
Yb^{3+}: 4f^{13} (J = 7/2)



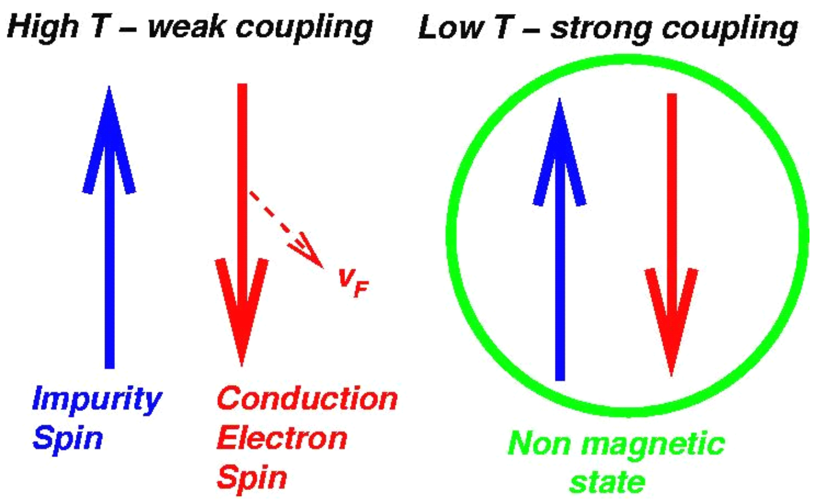
Ce^{3+}: 4f^{1}



Kondo Effect

- **Kondo Effect**

  A scattering mechanism of conduction electrons in a metal due to magnetic impurities. It is a measure of how electrical resistivity changes with temperature.



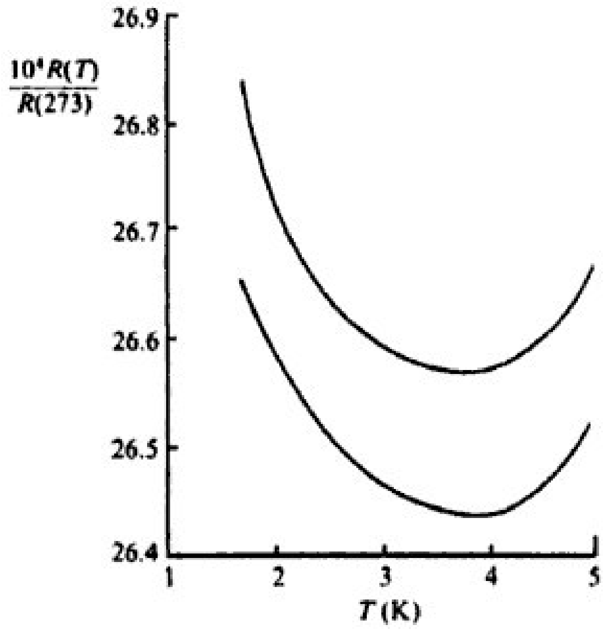
High T – weak coupling

Low T – strong coupling

Impurity Spin

Conduction Electron Spin

Non magnetic state

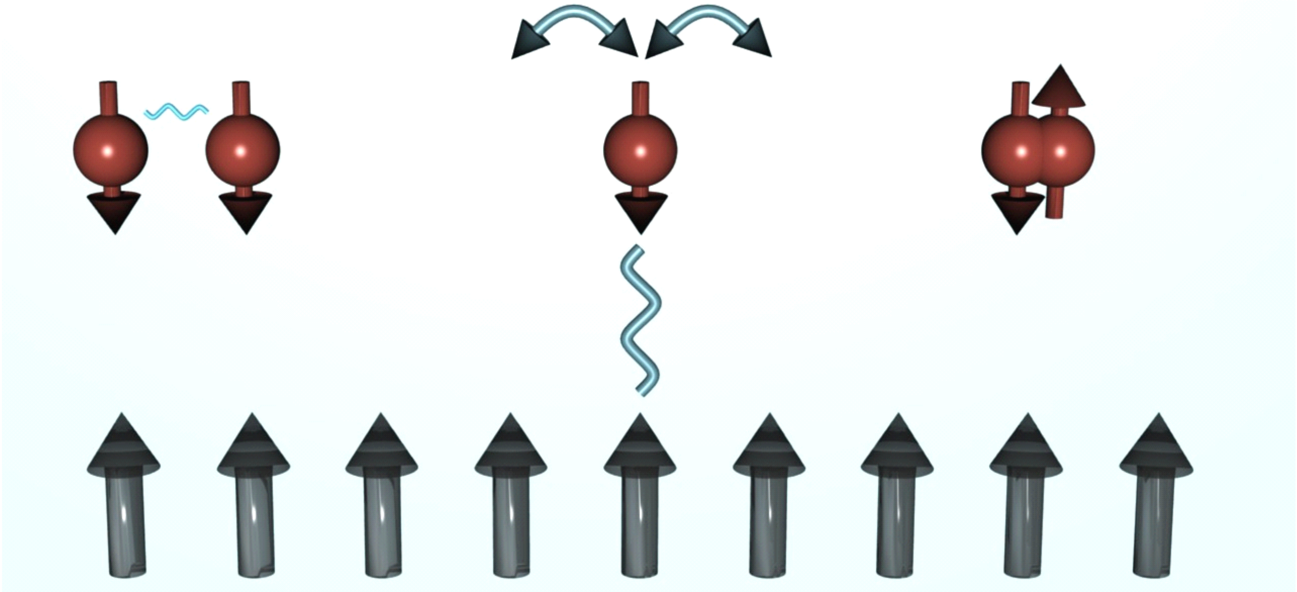


$$\rho(T) = \rho_0 + AT^2 + BT^5 + c_m \ln\left(\frac{\mu}{T}\right)$$

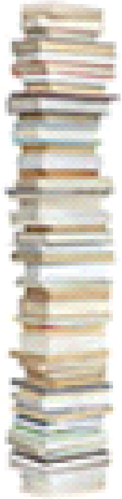
The minimum in the electrical resistivity of Au.
(de Haas, de Boer and Van den Berg, 1934)

Kondo Effect

- Kondo Lattice: Periodical magnetic impurity system.
- HF is a Kondo lattice system with large effective mass.

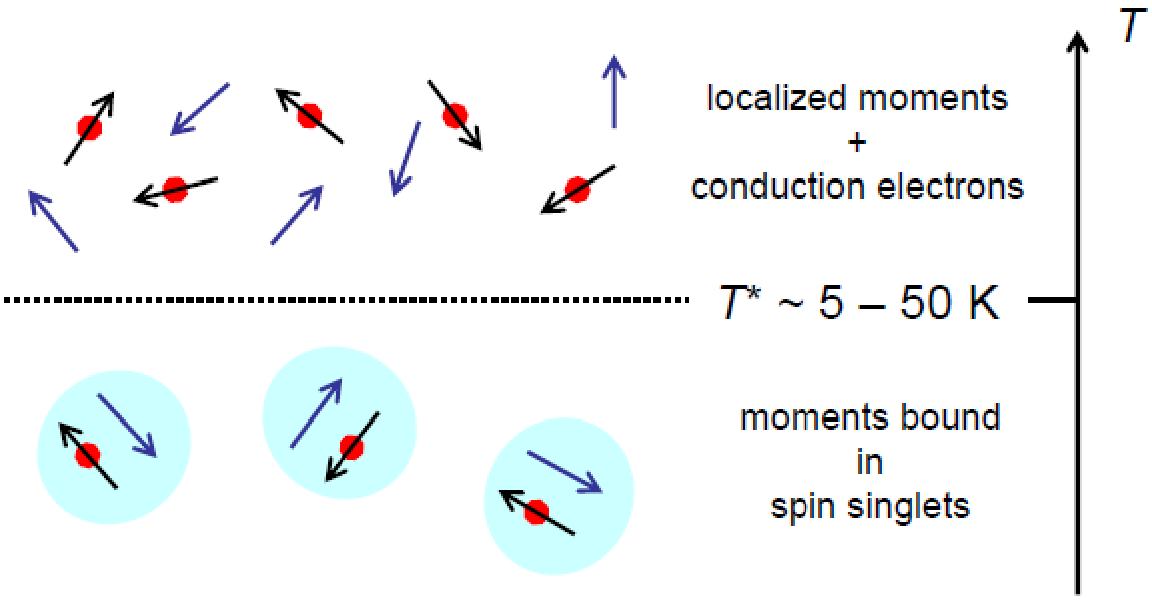


$$H = -t\sum_{i=1}^{L}\sum_{\sigma=\uparrow,\downarrow}(c_{i\sigma}^{\dagger}c_{i+1\sigma} + \mathrm{H.c.}) + J\sum_{i=1}^{L}\mathbf{S}_i\cdot\mathbf{s}_i,$$



Kondo Effect

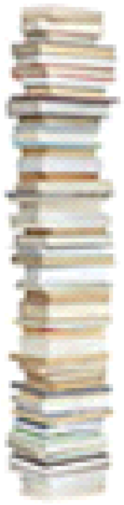
- At room temperatures and above, HF systems behave as a weakly interacting collection of f-electron moments and conducting electrons with quite ordinary masses.
- At low temperatures the f-electron moments become strongly coupled to the conduction electrons and to one another, and the conducting electron effective mass is typically 10 to 1000 times of the bare electron mass.



localized moments
+
conduction electrons

$T^* \sim 5 – 50$ K

moments bound
in
spin singlets



Superconducting Heavy Fermions

- A number of these systems become superconducting, a quite surprising result given the fact that in ordinary superconductors a dilute concentration of magnetic impurities destroys superconductivity.

- In the framework of the BCS theory, magnetic impurities in a metal will strongly destroy the superconducting transition temperature since its interaction with two electrons in a spin singlet state will break the pairing.

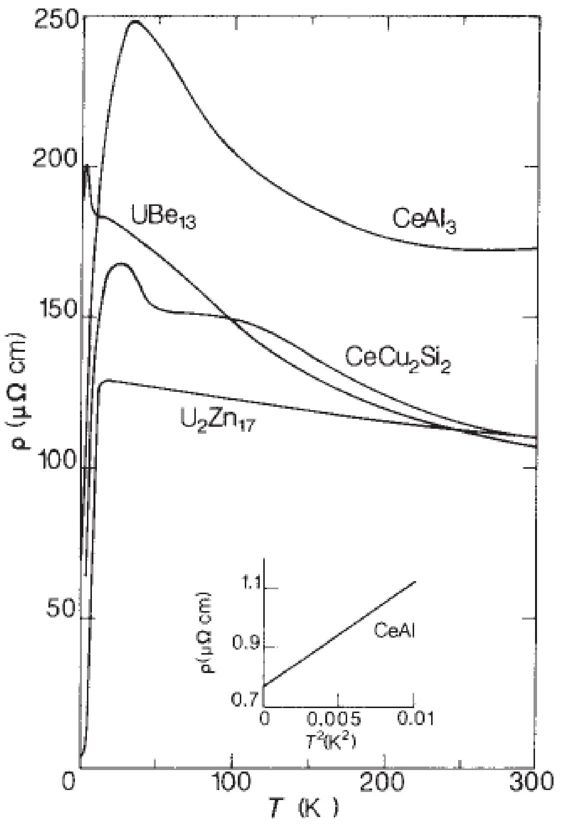


Fig. 1 Temperature dependence of the electrical resistivity ρ of four different heavy-electron compounds below room temperature. The high values indicate very strong scattering of the electrons but the distinct features and the resistivity decrease at low temperatures demonstrate that these are not simply 'dirty' metals. The inset reveals the T^2 dependence of the ρ of CeAl$_3$ at very low temperatures.

Fisk, Z., Ott, H.R., Rice, T.M., Smith, J.L.: Nature320, 124 (1986)

Superconducting Heavy Fermions

- A number of control parameters like substitution, pressure, magnetic field or valency allows to change the relevant interactions and thus the ground state of such systems.

- Dilute concentrations of non-magnetic impurities in conventional s-wave SC have little effect on the SC parameters. This is an evidence for non s-wave pairing.

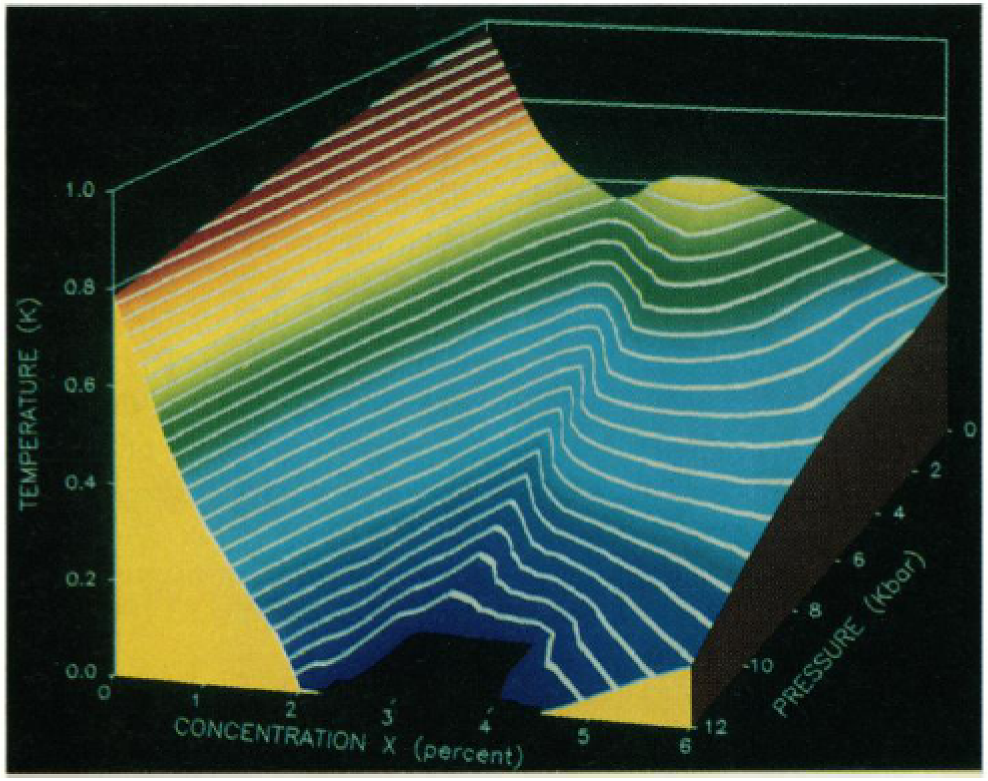
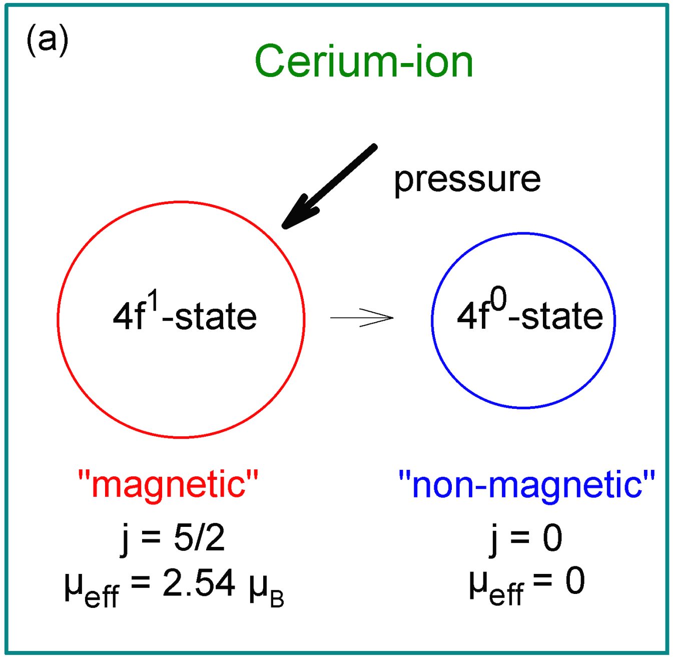


Fig. 1. The superconducting transition temperature (T_c) surface in pressure and concentration (x) space for $\mathrm{Th}_x\mathrm{U}_{1-x}\mathrm{Be}_{13}$.

Fisk Z. et al 1988 Science 239 33

Anomalies of Heavy Fermions

Pressure applied to typical systems based on Ce and Yb.


(a)

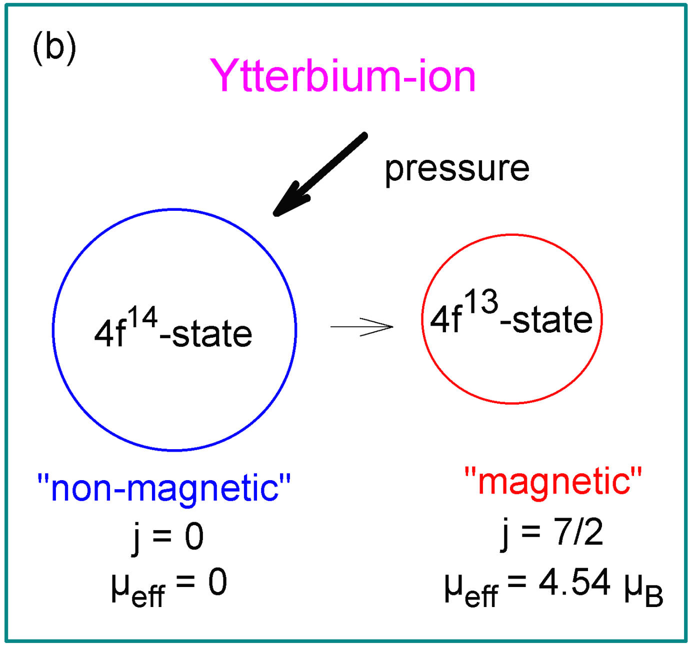
Cerium-ion

pressure

$4f^1$-state → $4f^0$-state

"magnetic"
$j = 5/2$
$\mu_{eff} = 2.54\ \mu_B$

"non-magnetic"
$j = 0$
$\mu_{eff} = 0$


(b)

Ytterbium-ion

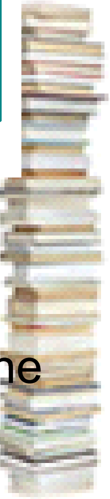
pressure

$4f^{14}$-state → $4f^{13}$-state

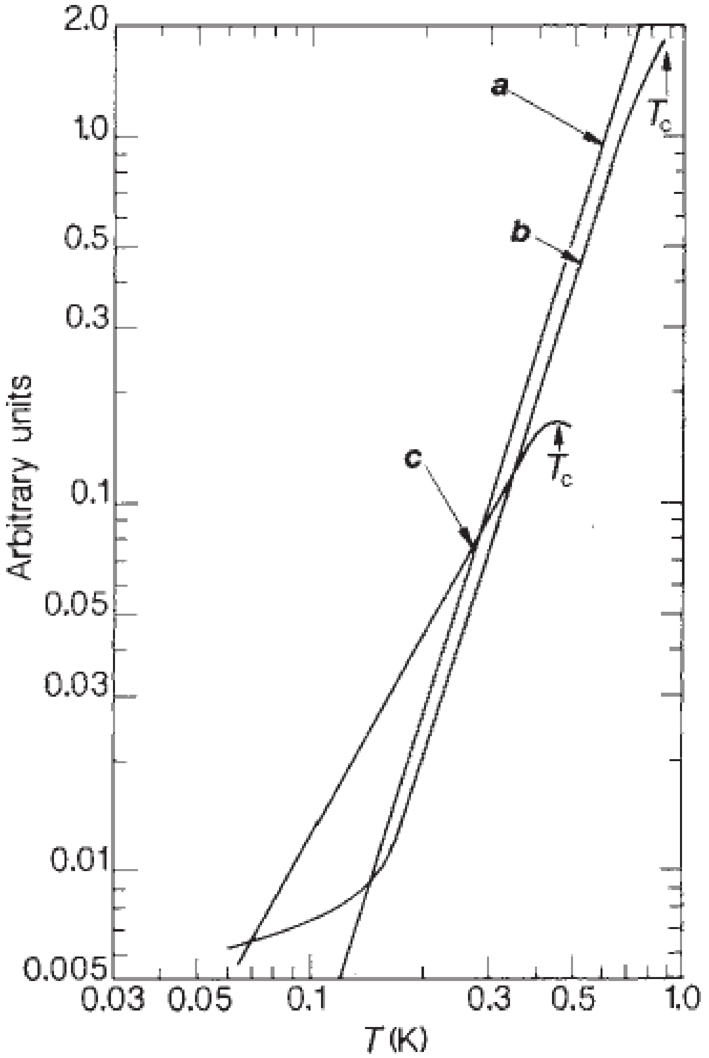
"non-magnetic"
$j = 0$
$\mu_{eff} = 0$

"magnetic"
$j = 7/2$
$\mu_{eff} = 4.54\ \mu_B$

While magnetism is "suppressed" for the former, since the 4f1 electron is squeezed out of the 4f shell, the magnetic state is stabilised for the latter (compare figure 1) and non-magnetic systems can become magnetic by the application of pressure.



Superconducting Heavy Fermions



Fisk, Z., Ott, H.R., Rice, T.M., Smith, J.L.: Nature320, 124 (1986)

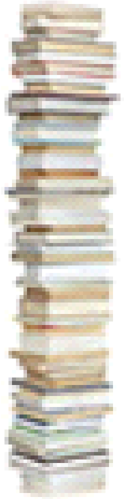
- Very low energy excitations in SCs with isotropic gaps will differ from those in SC with anisotropic gaps which vanish in certain directions.

- Isotropy: C_p goes exponentially as T->0.
- Anisotropy: C_p exhibit power-law as T->0.
- This figure is taken by many as evidence for anisotropic SC. But a decisive way is lacking.

Fig. 4 Examples of the power-law-type temperature dependence of various properties in the superconducting state of UBe_{13} and UPt_3, indicating anisotropic gaps in the electronic excitation spectrum. Conventional isotropic superconductivity would result in exponential temperature dependences for all these physical quantitities. *a*, Specific heat of UBe_{13} ($\propto T^3$); *b*, inverse spin-lattice relaxation rate of ^9Be in UBe_{13} ($\propto T^3$); *c*, ultrasonic attenuation in UPt_3 ($\propto T^2$).

Conclusion

- Heavy fermion is one of the most challenging and attractive areas in condensed matter physics.
- Kondo Effect and Kondo Lattice Model is used to explain the minimum of resistivity at low temperature.
- Superconducting heavy Fermion has many exotic behaviour which is different from conventional S-wave superconductor.



The end,thank you!