A Glimpse of Heavy Fermions

Hua Chen

Solid State II

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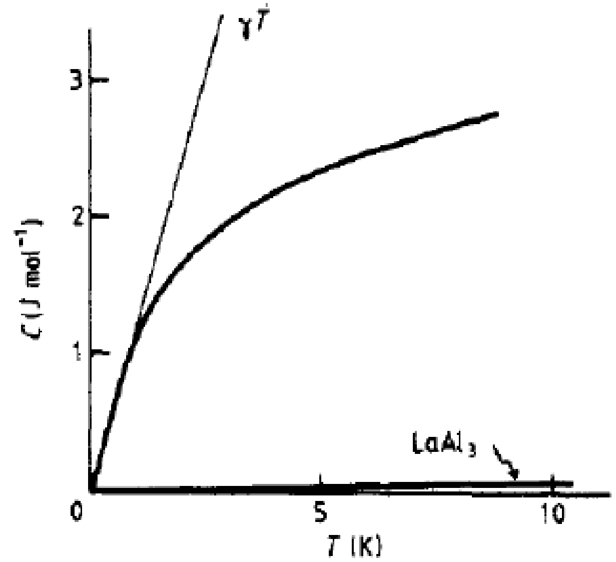
Why "heavy"

$$C = \gamma T + AT^3 \qquad \gamma \propto m^*$$

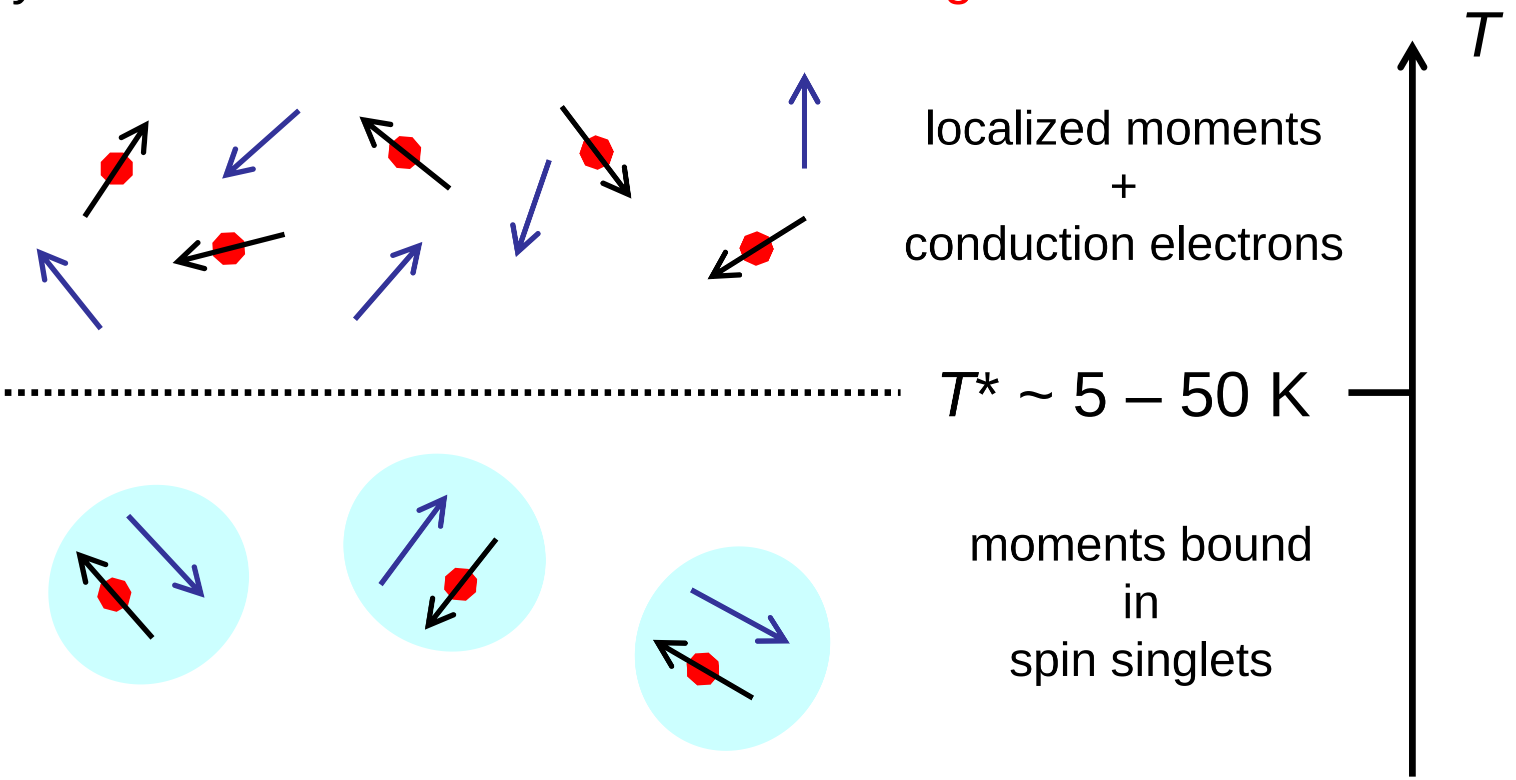
- **In heavy fermion materials, the effective mass can be as large as 1000*m_e**

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



What's special in heavy fermion systems: f-electrons

- Lattice of certain *f*-electrons (most Ce, Yb or U) in metallic environment
- La^{3+}: $4f^0$, Ce^{3+}: $4f^1$ (J = 5/2), Yb^{3+}: $4f^{13}$ (J = 7/2)
- partially filled inner 4f/5f shells → localized magnetic moment



Preliminary: Kondo effect

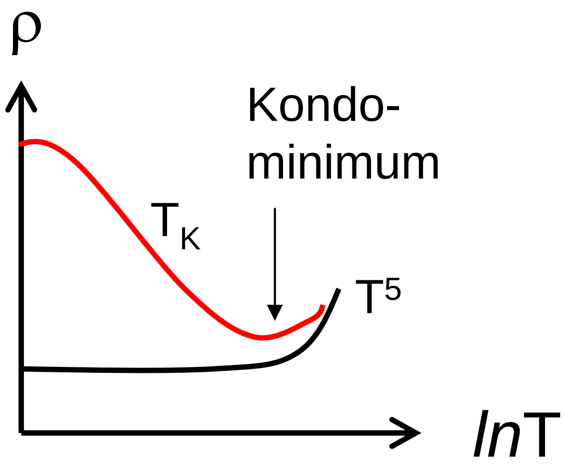
(Jun Kondo ´63)

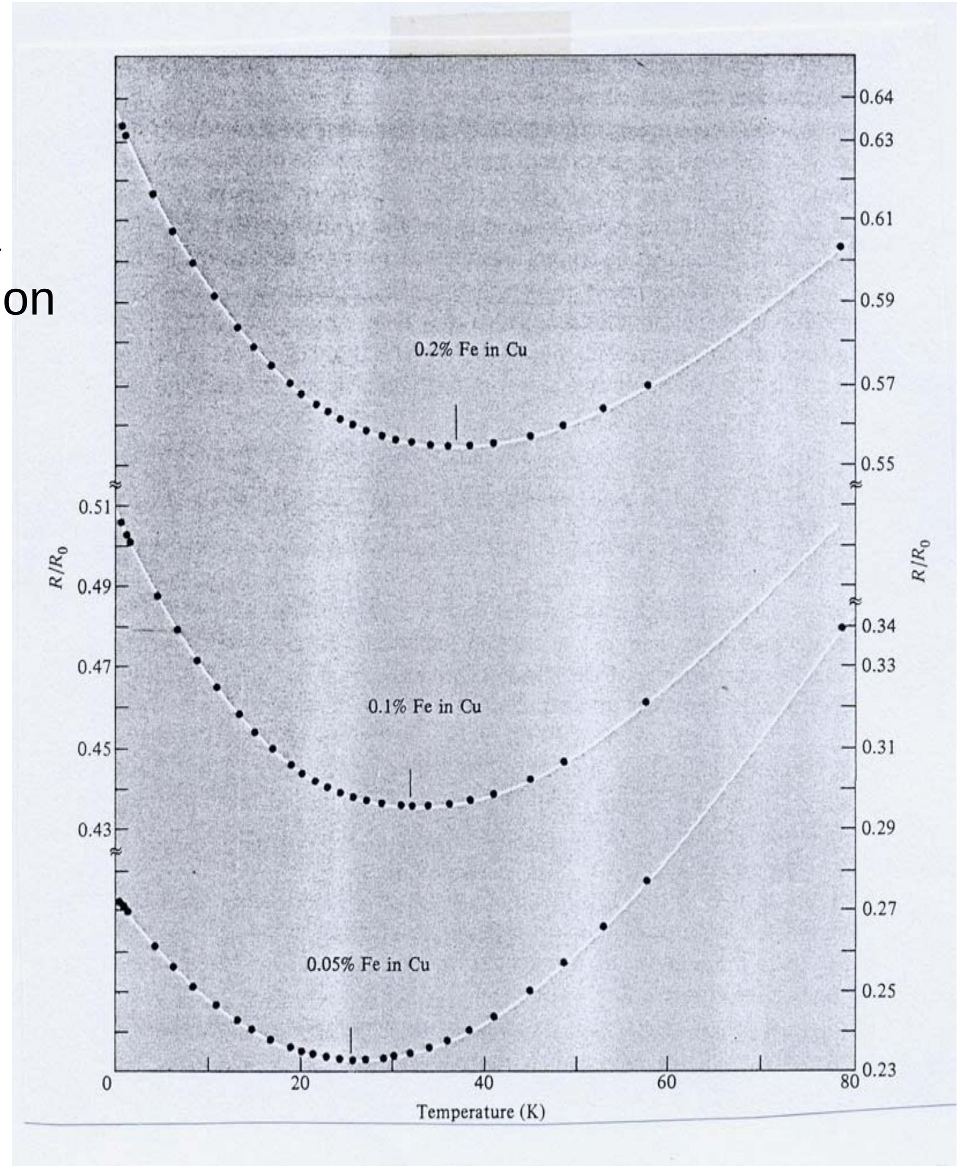
$$H_{sd} = J \cdot \vec{S} \cdot \vec{s}$$

local moment — conduction electron

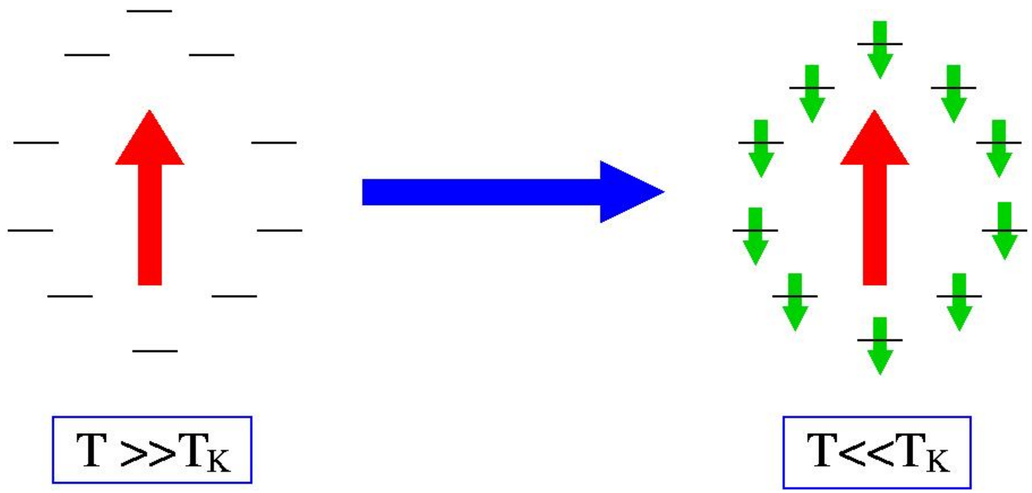
J: hybridization

AF coupling $J < 0$





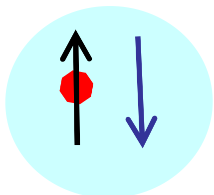
Kondo effect (cont.)



T_K: characteristic Kondo temperature

$$T_K \propto \exp(-1/\rho J)$$

Below T_K impurity spin is progressively screened: Kondo singlet



Microscopic model of impurities: Anderson model

$$H = H_s + H_f + H_{sf} + H_U$$

Conduction electron — *f-electron* — hybridization — on-site Coulomb repulsion

$$\begin{aligned} H &= \sum_{k,\mu} \epsilon_k n_{k\mu} + \sum_{k,\mu} V(k)[c^\dagger_{k\mu} f_\mu + f^\dagger_\mu c_{k\mu}] \\ &+ E_f n_f + U n_{f\uparrow} n_{f\downarrow}. \end{aligned}$$

Hybridization width $\Gamma = \pi \rho_F V^2$

$\Gamma << -\varepsilon_d, U + \varepsilon_d$ → formation of local moment

s-d (*s-f*) exchange model

$$H = \sum_{k,\mu} \epsilon_k n_{k\mu} - (\frac{J}{N}) \sum_{k,k'} \sum_{\mu,\mu'} \hat{S} \cdot \hat{\boldsymbol{\sigma}}_{\mu\mu'} c^{\dagger}_{k\mu} c_{k'\mu'}$$

Second order perturbation

$$R_{impurity} = R_0[1 + 4J\rho_F \ln\left(\frac{k_B T}{D}\right) + \cdots]$$

Temperature dependent second order term in resistivity

Antiferromagetic coupling → **Resistivity minimum**

Microscopic model of heavy fermion: Anderson lattice model

Kondo system: → **Heavy fermion system:**

Single *d* (or *f*) impurity → **periodic *f* ions**

Anderson model → **Anderson lattice model**

$$H = \sum_{k,\mu} \epsilon_k n_{k\mu} + \sum_{l,\mu} E_0 n^f_{l\mu} + U \sum_{l} n^f_{l\uparrow} n^f_{l\downarrow}$$
$$+ \frac{V}{\sqrt{N}} \sum_{k,l,\mu} [c^\dagger_{k\mu} f_{l\mu} e^{-i\boldsymbol{k}\cdot\boldsymbol{l}} + f^\dagger_{l\mu} c_{k\mu} e^{i\boldsymbol{k}\cdot\boldsymbol{l}}].$$

Calculation techniques and approximations

On-site Coulomb repulsion is typically very large (~15eV)

→ **Infinite U approximation (strong correlation)**

Resulting operators are neither fermions nor bosons

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Coleman's slave boson technique

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Read and Newns: slave boson mean-field approach

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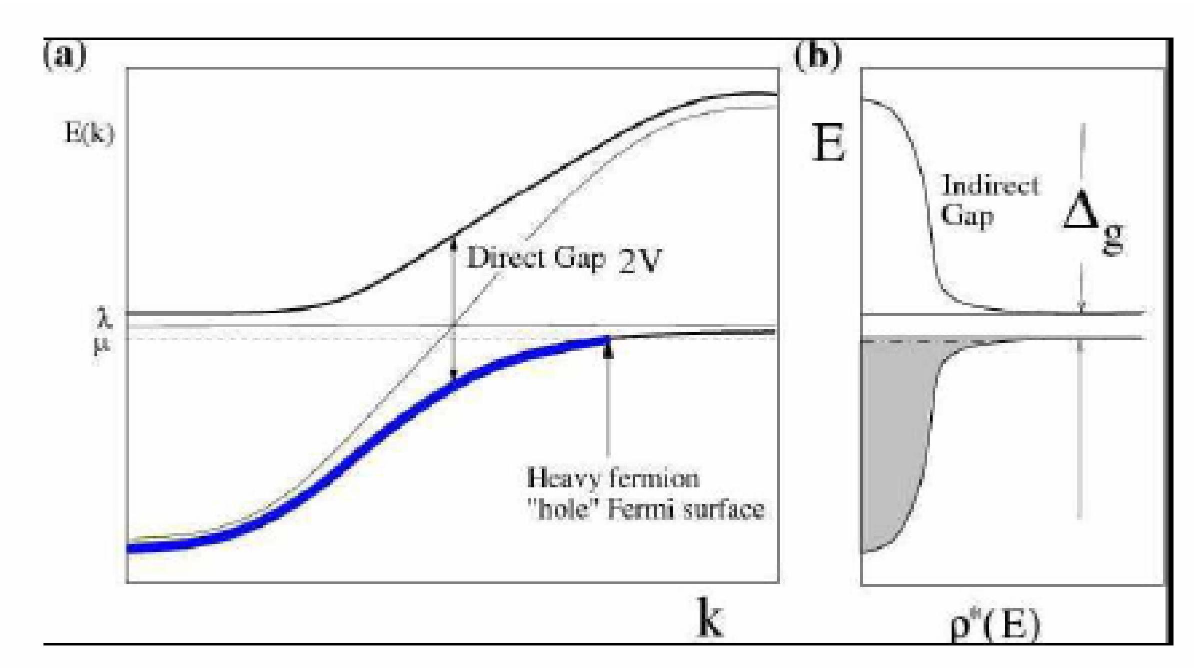
Renormalized hybridized band model

Results

V is the strength of the slave boson field



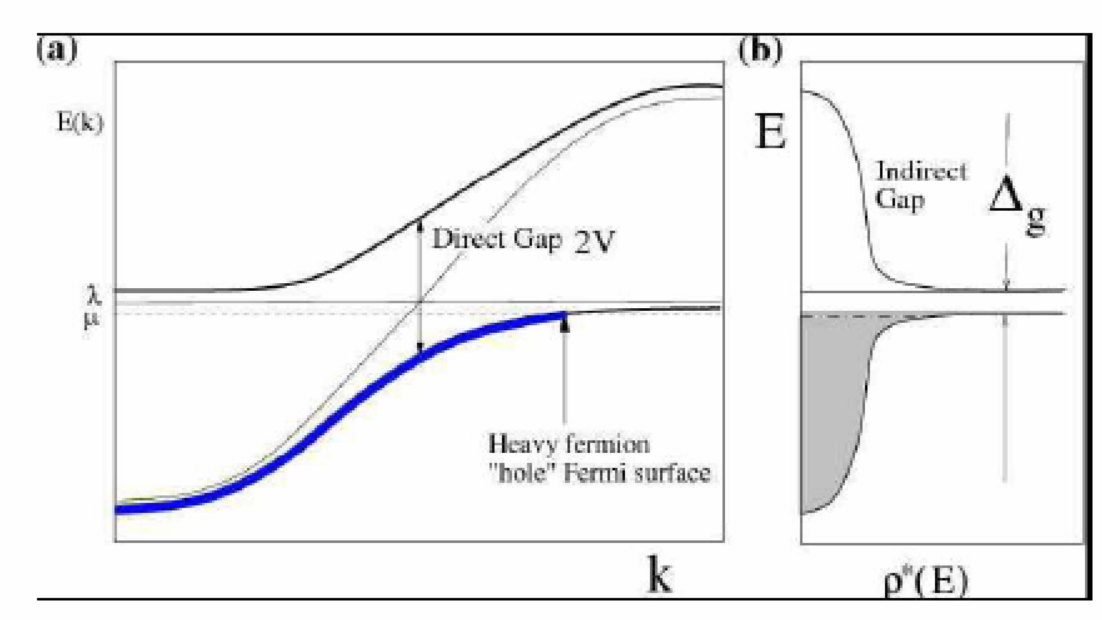
$$\Delta_g \sim T_K$$

- (a) Dispersion relation. (b) Renormalized density of states

The peaks of density of states near the Fermi energy lead to the large effective mass

$$\frac{m^*}{m} = \frac{\rho^*}{\rho}$$

Kondo insulator



- If the lower band is filled, the system is an insulator (or semiconductor)
- The gap is dependent on temperature (different from conventional semiconductors)

Summary

- Heavy fermion is one of the most challenging and attractive areas in condensed matter physics.
  - Many important concepts and areas originate from the study of this problem:
    - Slave boson, composite fermion, even high T_c superconductivity
  - Current interests:
    - Heavy fermion superconductivity
    - Quantum criticality in heavy fermion systems