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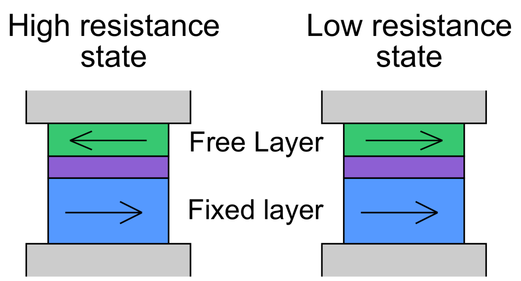
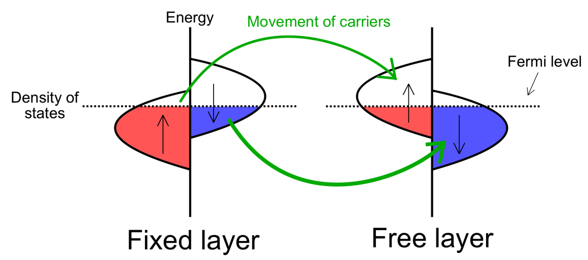
MBE growth of thin film heterostructures for spintronics

Magnetic tunnel junction



Spin transfer torque



Goal: low power consumption memory, non-volatile

Opportunities: spin-orbit torque, high magnetic susceptibility

Strongly Temperature-Dependent Spin-Orbit Torques in Heavy Fermion $YbAl_3$

Neal D. Reynolds,[1,*] Shouvik Chatterjee,[1,†] Gregory M. Stiehl,[1] Joseph A. Mittelstaedt,[1] Saba Karimeddiny,[1] Alexander J. Buser,[1] Darrell G. Schlom,[2,3,4] Kyle M. Shen,[1,3] and Daniel C. Ralph[1,3]

Spin-orbit coupling

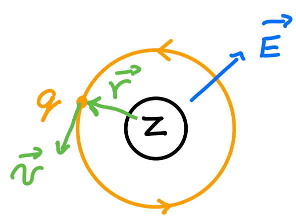
$$H = -\vec{m}\cdot\vec{B}$$

$$\sim \frac{\partial U}{\partial r}\vec{L}\cdot\vec{S}$$

grows with Z

∴ Rare Earths

$$\vec{m} = -g\mu_B \vec{S}/\hbar$$



$$\vec{B} = -\frac{1}{c^2}\vec{v}\times\vec{E}$$

$$= \frac{1}{mc^2}\frac{1}{r}\vec{r}\times\vec{p}\,|\vec{E}|$$

$$= \frac{1}{q\,mc^2}\frac{1}{r}\frac{\partial U}{\partial r}\vec{L}$$

Sommerfeld free electron theory

$E(\vec{k}) = \frac{\hbar^2}{2m}|\vec{k}|^2$ $\quad D(E) = \frac{(2m)^{3/2}}{2\pi^2\hbar^3}\sqrt{E}$ $\quad E_F = \frac{\hbar^2(3\pi^2 n)^{2/3}}{2m}$

$D(E_F) = \frac{3\, m\, n^{1/3}}{\hbar^2(3\pi^2)^{2/3}} \sim m$

Heat capacity: $C = \gamma T$ $\quad \gamma = \frac{2\pi^2}{3} k_B^2\, D(E_F) \sim m$

Paramagnetic susceptibility: $\chi = 2\mu_B^2\, D(E_F) \sim m$

Wilson ratio: $(\pi^2 k_B^2/\mu_B^2)\, \chi/\gamma \sim 3 \leftarrow$ universal

Heavy fermions

$m^* \gg m_e \leftarrow$ up to $1000\times$!

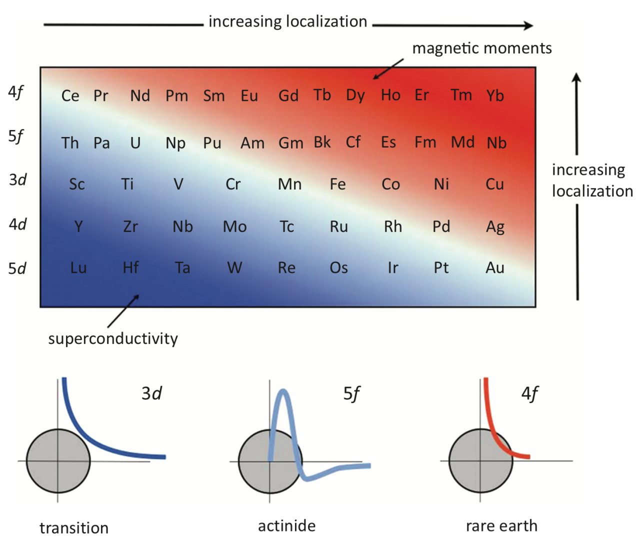
Origin: 1. Flat band $\frac{1}{m^*} = \frac{1}{\hbar^2}\frac{\partial^2 E}{\partial k^2}$

2. f-electron element (Rare earth)

Orbital radius $4f < 5f < 3d < 4d < 5d$

nl radius: $\uparrow$ as $n\uparrow$ due to radial nodes

$\downarrow$ as $l\uparrow$ due to higher Z



Kmetho-Smith diagram

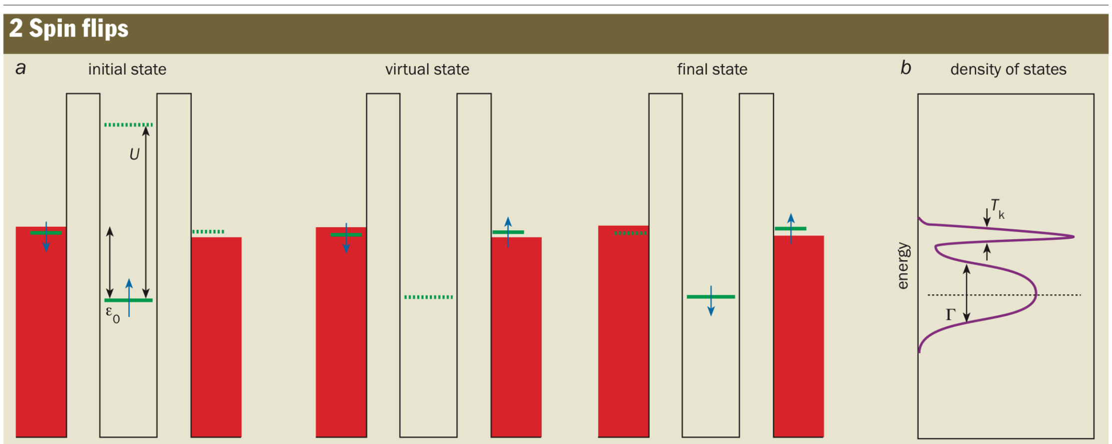
from P. Coleman

Localization of orbital

reduces hopping integral

$\Rightarrow$ flattens band, increases m^*

3. Kondo effect – magnetic moment hybridizes with conduction electrons



Kouwenhoven + Glazman (2001)

Enhanced electron scattering creates "resistance minimum"

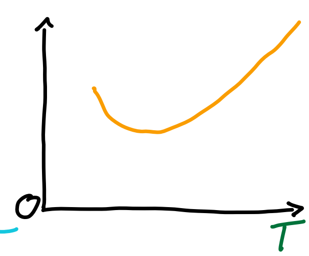
Kondo (1964) perturbative calculation

band width

$$R = \frac{m}{nq^2\tau} = aT^5 + c_{imp.}\left(R_0 + R_1 \ln \frac{D}{k_B T}\right)$$

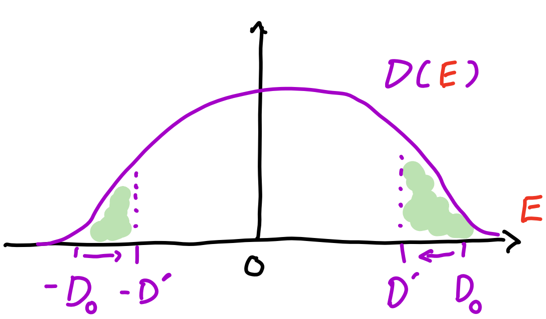
phonons   impurities

"Kondo Problem"
PT diverges at low T

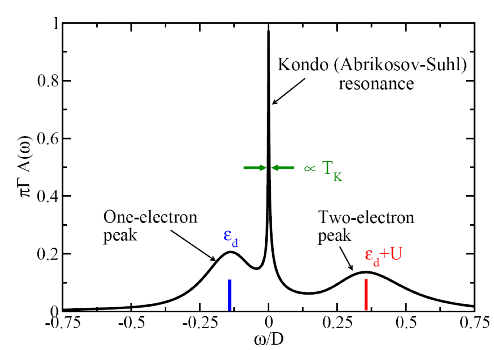


Renormalization group (Wilson, 1975)

$$H = \sum_{E(k)<D} E(\vec{k})\, c^\dagger_{k\sigma} c_{k\sigma} + J(D) \sum_{\substack{E(k)<D \\ E(k')<D}} c^\dagger_{k\sigma} \vec{\sigma}_{\sigma\sigma'} c_{k'\sigma'} \cdot \vec{S}_f$$



$\xrightarrow{R.G.}$



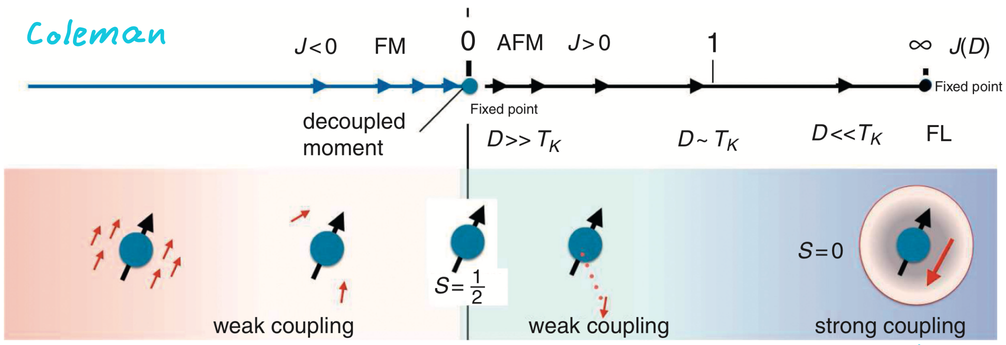
Frota, Oliveira, PRB **33**, 7871 (1986), Costi, Hewson, Zlatić, JPCM **6**, 2519 (1994)

Let $\rho \equiv D(E_F)$ $\quad g \equiv J\rho$ is effective coupling

RG flow $$\frac{\partial g}{\partial \ln D} = \beta(g) = -2g^2 \qquad \frac{\partial \ln g}{\partial \ln(D_0/D)} = 2g$$

Scaling $$J \rightarrow J(T) = J + 2J^2\rho \ln\left(\frac{D}{k_B T}\right)$$

Coleman



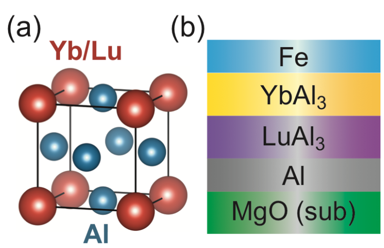
$\frac{1}{\sqrt{2}}(|\uparrow\downarrow\rangle - |\downarrow\uparrow\rangle)$

Spin-singlet

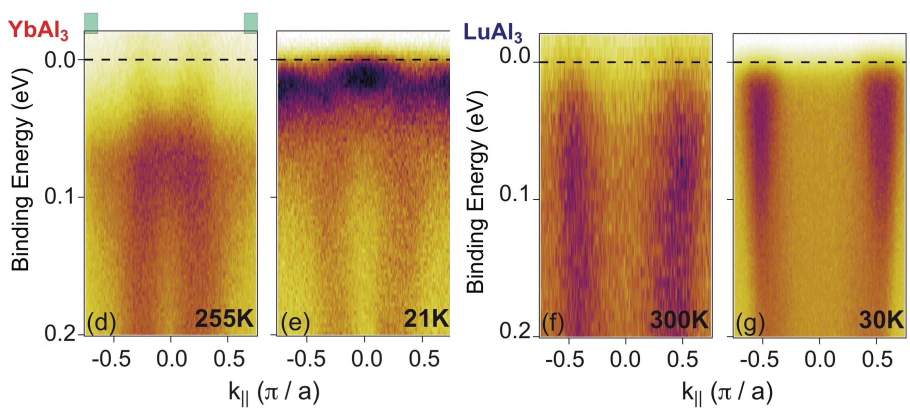
screened local moment

Chatterjee

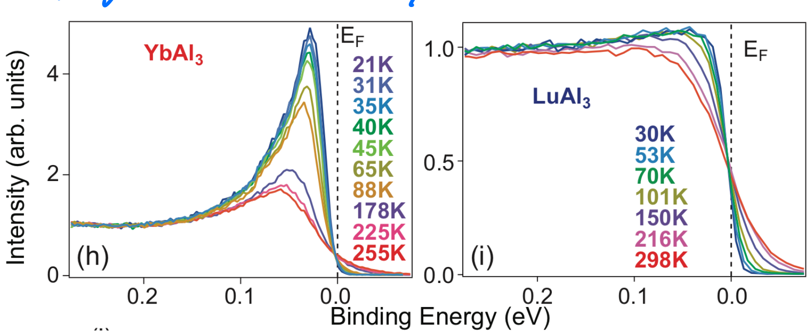
Arpes:



Yb^{3+} $4f^{13}$ $\quad Lu^{3+}$ $4f^{14}$



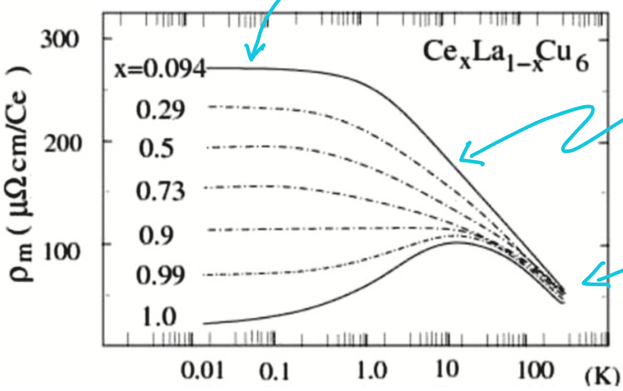
Integrated intensity



<u>Note:</u> Kondo lattice: $H = H_{kondo} + K \sum_{\langle ij \rangle} \vec{S}_i \cdot \vec{S}_j$

spin interactions

$\ln\left(\frac{D}{k_B T}\right)$ growth



resistance minimum