Unconventional Superconductivity in Heavy Fermion Systems

Changkai Zhang

Fakultät für Physik
Ludwig-Maximilians-Universität München

High-T_c Superconductivity
January 27, 2020

F. Steglich, S. Wirth, Rep. Prog. Phys. 79 084502 (2016)
P. Coleman, Heavy Fermions, arXiv:cond-mat/0612006

Table of Contents

Table of Contents

Magnetic Impurities and Kondo Effect

The resistance unexpectedly increases as temperature decreases in Cu and Au-specimens.

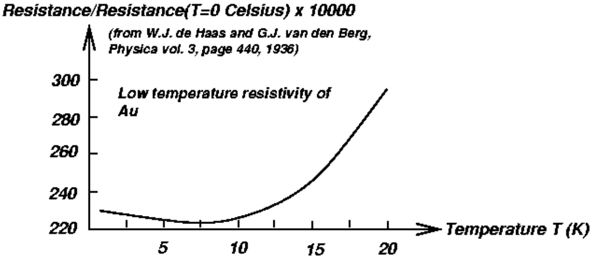


Figure: W. J. de Haas, G. J. van den Berg, *Physica* vol.3 (1936)

The resistance versus temperature of *pure* Au.
Observe an increase of resistance below $8\,\mathrm{K}$.

Magnetic Impurities and Kondo Effect

Magnetic impurities (e.g. Fe, Ce) can scatter conduction electrons and lead to extra resistance.

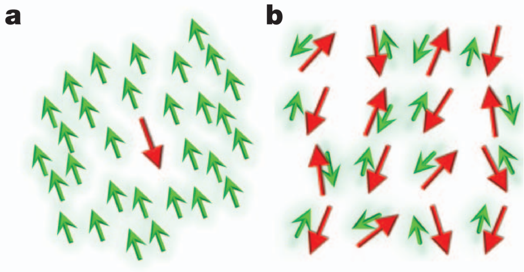


Figure: P. Aynajian, A. Gyenis *et al.* *Nature* **486**, 201–206 (2012)

Left: Single magnetic impurity screened antiferromagnetically by conduction electrons.
Right: Kondo lattice created by 100% magnetic impurity doping.

Magnetic Impurities and Kondo Effect

Jun Kondo explained this by the AF coupling between the spin of localized $3d$ or $4f$ electrons & that of conduction electrons.

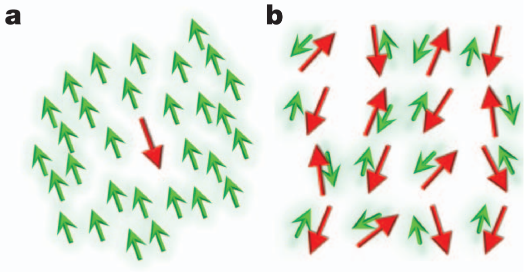


Figure: P. Aynajian, A. Gyenis *et al.* *Nature* **486**, 201–206 (2012)

Left: Single magnetic impurity screened antiferromagnetically by conduction electrons.
Right: Kondo lattice created by 100% magnetic impurity doping.

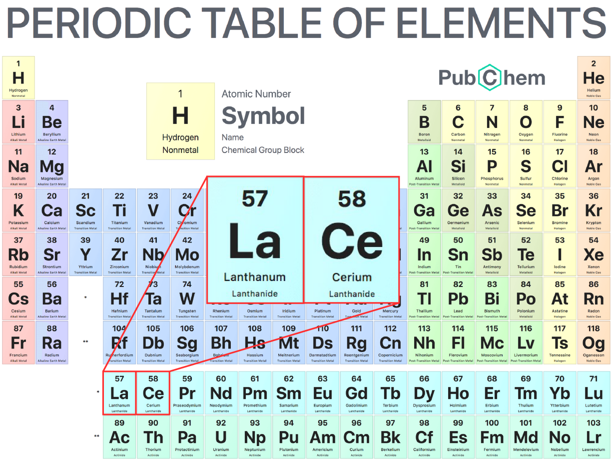
Anderson Impurity Model

In 1961, Anderson gave the first microscopic model for the formation of magnetic moments in metals:

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

where the first line is the kinetic terms of conduction and $4f$ electrons and the interaction between $4f$ electrons; the second line describes the interaction between conduction electrons and impurity spins.

Experimental Platform Using Lathanide Elements



Kondo Lattice and Localized Fermions

Kondo effect can be studied by La-based material doped by Ce as magnetic impurities. 100% doping creates Kondo lattice.

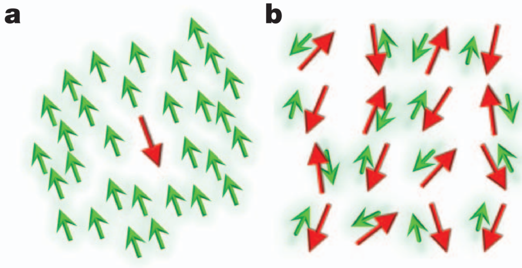


Figure: P. Aynajian, A. Gyenis *et al.* *Nature* **486**, 201–206 (2012)

Left: Single magnetic impurity screened antiferromagnetically by conduction electrons.
Right: Kondo lattice created by 100% magnetic impurity doping.

Kondo Lattice Model

In 1961, Anderson gave the first microscopic model for the formation of magnetic moments in metals:

$$H = \cdots + \sum_{k,\sigma} V(k)[c_{k\sigma}^{\dagger} f_{\sigma} + f_{\sigma}^{\dagger} c_{k\sigma}]$$

Kondo lattice model of heavy fermion systems is simply a periodic version of the Anderson impurity model:

$$H = \sum_{k,\sigma} \epsilon_k n_{k\sigma} + \sum_{j,\sigma} E_f n_{j,\sigma}^f + U \sum_{j} n_{j\uparrow}^f n_{j\downarrow}^f + \frac{V}{\sqrt{N}} \sum_{k,j,\sigma} [c_{k\sigma}^{\dagger} f_{j,\sigma} e^{-\mathrm{i}k\cdot j} + f_{j,\sigma}^{\dagger} c_{k\sigma} e^{\mathrm{i}k\cdot j}]$$

Table of Contents

Band Structure in Heavy Fermion Materials

Hybridization between 4*d* electrons and conduction electrons gives rise to a peak in the quasi-particle density of states.

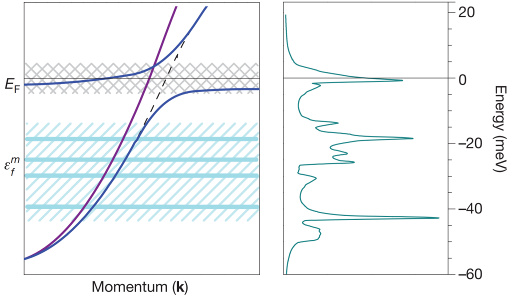


Figure: S. Ernst, S. Kirchner et al. *Nature* **474**, 362–366 (2011)

Left: Renormalized energy band structure of quasi-particles. Flat band occurs near Fermi energy.
Right: Renormalized quasi-particle density of states. A peak emerges near Fermi energy.

Consequences of Heavy Fermions

Flat energy band implies:

- Large electron effective mass
- Large density of states
- Highly localized wave function

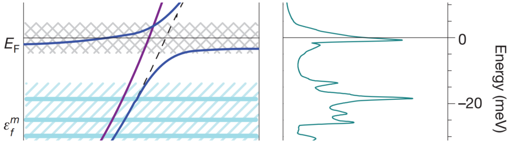


Figure: S. Ernst, S. Kirchner et al. *Nature* **474**, 362–366 (2011)

Left: Renormalized energy band structure of quasi-particles. Flat band occurs near Fermi energy.
Right: Renormalized quasi-particle density of states. A peak emerges near Fermi energy.

Table of Contents

Magnetic Impurities & BCS Superconductivity

Magnetic impurities introduces spin-exchange scattering of conduction electrons off the local $4f$-shell.

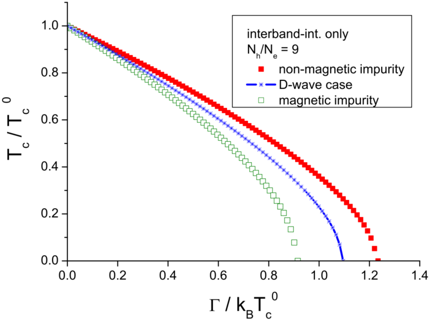


Figure: Y. Bang, H. Choi, H. Won, Phys. Rev. B **79**, 054529 (2009)

Normalized critical temperature versus normalized impurity scattering strength. Critical temperature drops to zero as the amount of magnetic impurities increase.

Unconventional Superconductivity in $CeCu_2Si_2$

$CeCu_2Si_2$ was discovered to have unconventional bulk superconductivity below $T_c \approx 0.6\,\mathrm{K}$.

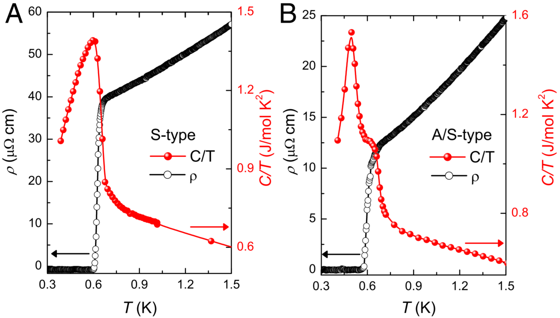


Figure: G. Pang, M. Smidman, J. Zhang *et al.* PNAS, **115(21)** (2018)

Specific heat and resistivity of S-type (superconducting) $CeCu_2Si_2$ and S/A-type (superconducting/antiferromagnetic) $CeCu_2Si_2$.

Unconventional Superconductivity in $\mathrm{CeCu_2Si_2}$

- Non-magnetic reference system $\mathrm{LaCu_2Si_2}$ (replacing Ce with La) is not superconducting.
- Doping with non-magnetic impurities in $\mathrm{CeCu_2Si_2}$ destroys superconductivity.
- High-quality single crystals of $\mathrm{CeCu_2Si_2}$ grown in 1983 confirms the finding.
- Same year, heavy fermion superconductivity was reported for U-based materials, e.g. $\mathrm{UPt_3}$, $\mathrm{U_2PtC_3}$, $\mathrm{URu_2Si_2}$.
- Electron-phonon interaction can not account for the superconductivity. New pairing mechanism must be operational.

Small Band Gap Created by Hybridization

Hybridization between conduction and $4f$ electrons opens a small band gap which can lead to insulating states.

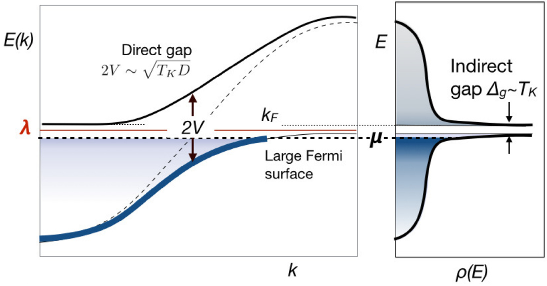


Figure: Piers Coleman, arXiv:1509.05769

Left: Dispersion for the Kondo lattice mean-field theory.
Right: Renormalized density of states, showing a *hybridization gap*.

Kondo Insulating States in SmB_6

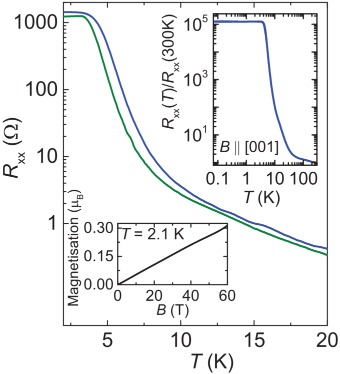


Figure: B. S. Tan et al, Science **349** 6245 (2015)

Main: Resistance as a function of temperature on a SmB_6 sample.

Top inset: Logrithmic plot of measured resistance from 80 mK up to high temperatures.

Kondo Screening vs RKKY Interaction

Kondo screening and fundamental magnetic RKKY interaction are two competing interactions depending on the exchange integral J.

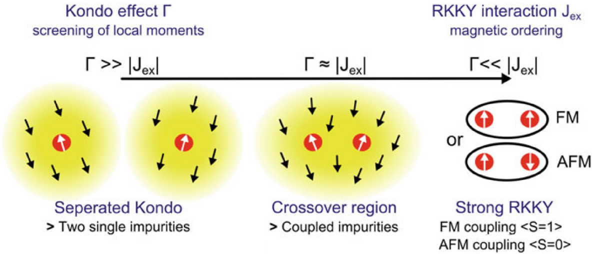


Figure: H. Prüser, *Springer Thesis*, Springer (2014)

Kondo effect and RKKY interaction between two magnetic impurities.
Two competing interactions create two phases and a quantum critical point.

Emerging Quantum Critical Point

A quantum critical point (QCP) emerges at zero-temperature between the AF phase and heavy Fermi liquid phase.

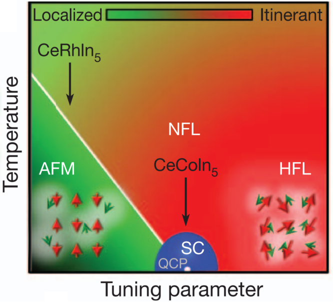


Figure: P. Aynajian, A. Gyenis *et al.* *Nature* **486**, 201–206 (2012)

Schematic phase diagram of heavy fermion systems, where the electronic ground state can be tuned from antiferromagnetism to a heavy Fermi liquid.

Mechanism of Heavy Fermion Materials

One of the most interesting questions is the microscopic origin of heavy fermion superconductivity:

- U-based: antiferromagnetic fluctuations
- $CeCu_2Si_2$: *valence* charge fluctuations
- $PrOs_4Sb_{12}$: plus quadrupole fluctuations
- UCoGe: Ferromagnetic spin fluctuations

How Strong is Heavy Fermion Superconductivity?

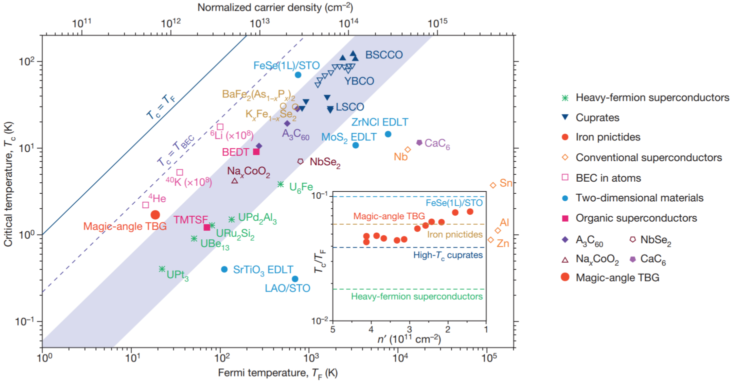


Figure: Cao Y et al. Nature, 2018, 556(7699): 43.

Logarithmic plot of critical temperature T_c vs Fermi temperature T_F for various superconductors
Heavy fermion superconductivity is much stronger than conventional BCS superconductivity.

Summary

- Localized electrons have an enormous effective mass, leading to a flat energy band and thus a large density of states, which allows unconventional strong correlated physics to emerge.
- Hybridization between $4f$ electrons of magnetic impurities and conduction electrons creates localized profile and thus heavy fermions.
- Unconventional superconductivity much stronger than BCS has been observed in heavy fermion systems near the quantum critical point between the antiferromagnetism and the heavy Fermi liquid.