Kondo Effect & Its Breakdown: Interplay of fluctuations in zero dimension

Abhirup Mukherjee

Emergent Phenomena in Quantum Matter Group
Department of Physical Sciences, IISER Kolkata

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Siddhartha Lal
IISER K

Anirban Mukherjee
IISER K (Graduated)

Siddhartha Patra
IISER K (Graduated)

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Arghya Taraphder
IIT Kharagpur

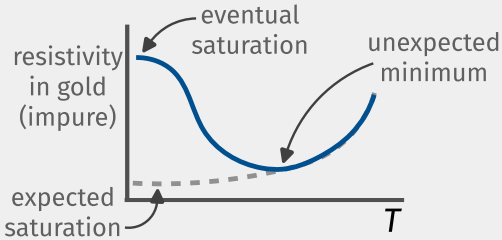
N. S. Vidhyadhiraja
JNCASR Bangalore

Introducing the Kondo effect

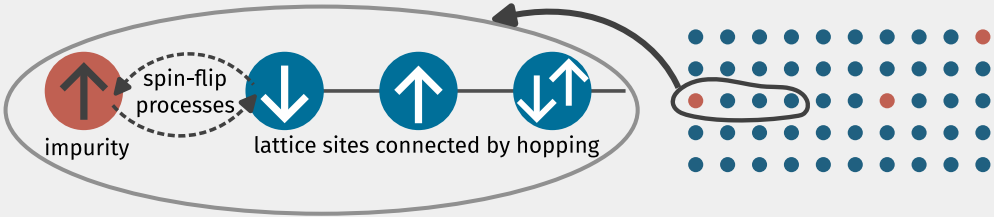
Where it all began

What is the Kondo effect?

- metal resistivity is **monotonic**: $\rho \sim T^n$
- dilute alloys show anomalous **minimum**
- resistivity eventually becomes **constant**



Can be explained using the **Kondo model**: $H_{\text{Kondo}} = KE_{\text{bath}} + J\vec{S}_{\text{imp}} \cdot \vec{S}_{\text{bath}}$



de Haas et al. 1934; Sarachik et al. 1964; Heeger 1969.

How to explain the resistance minimum & eventual saturation?

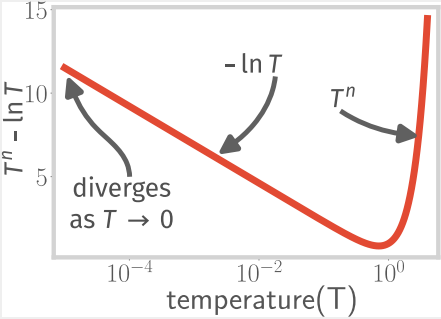
Second order perturbation theory in J gives:

$$\rho \sim T^n - \ln T$$

Explains the **non-monotonic** behaviour!

(Jun Kondo)

However, solution **diverges** at $T \to 0$!



Kondo 1964.

How to explain the resistance minimum & eventual saturation?

Breakdown of perturbation theory indicates a **change in ground state**!

Obtaining $T = 0$ ground state requires more **powerful methods**

Numerical RG

(K. G. Wilson)

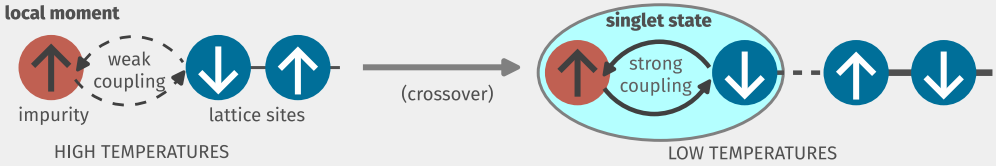
Bethe ansatz

(Natan Andrei)

Conf. field theory

(Ian Affleck)

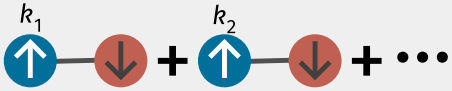
- impurity becomes **strongly coupled** at low temperatures
- local moment crosses over into **nonmagnetic** singlet



Wilson 1975; Andrei 1980; Wiegmann 1981; Affleck 1995.

Some important questions

1. How do we describe the dynamics of the electrons that screen the impurity (the so-called **Kondo cloud**)?



2. What kind of physics can **disturb the Kondo screening** effect and distort the singlet state?

3. What is the simplest impurity model that completely destroys the Kondo effect and leads to a **phase transition**?

The single-channel Kondo problem: Anatomy of the Kondo cloud

PHYSICAL REVIEW B
covering condensed matter and materials physics

Unveiling the Kondo cloud: Unitary renormalization-group study of the Kondo model

Anirban Mukherjee, Abhirup Mukherjee, N. S. Vidhyadhiraja, A. Taraphder, and Siddhartha Lal

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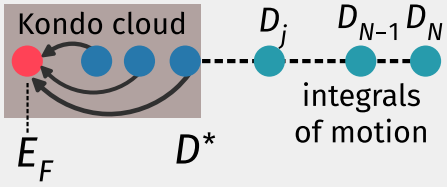
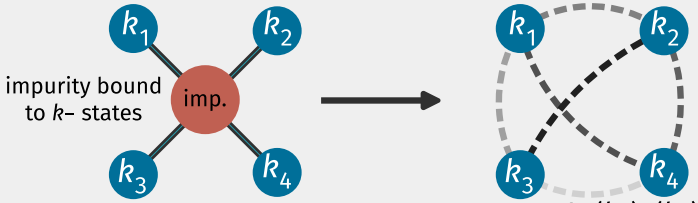
Unitary RG approach to impurity models

- Integrate out **high energy fluctuations** to reach strong-coupling low-energy theory
- Leads to **singlet ground state** and decoupled high-energy k-states
- Decoupling is carried out through **unitary transformations**



Effective Hamiltonian for the Kondo cloud

In order to obtain a theory for the Kondo cloud,
we **trace out impurity** from fixed point Hamiltonian.

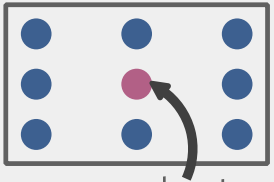


- all-to-all interactions between momentum states, **large entanglement**
- 2-particle interaction terms **not** present in Fermi liquid, are **responsible for screening**

Quantifying entanglement within the Kondo cloud

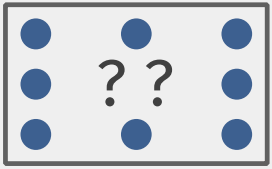
In order to demonstrate formation of Kondo cloud, we study the **variation of entanglement** and correlations under RG transformations.

- Entanglement entropy $S(A) \Longrightarrow$ quantifies how much **information is gained** about the rest of the system by measuring A



measure subsystem A

$$S(A) = \text{Trace}\left(\rho_A \ln \rho_A\right)$$

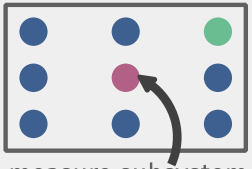


gain information about rest

Quantifying entanglement within the Kondo cloud

In order to demonstrate formation of Kondo cloud, we study the **variation of entanglement** and correlations under RG transformations.

- Entanglement entropy $S(A) \Longrightarrow$ quantifies how much **information is gained** about the rest of the system by measuring A
- Mutual information $I_2(A:B) \Longrightarrow$ quantifies how much **information about subsystem A** is gained by measuring B



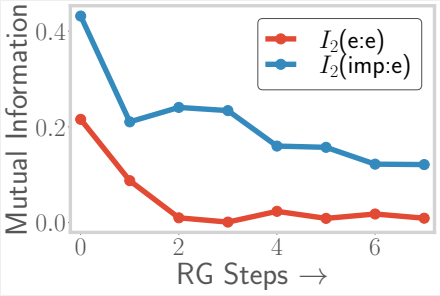
measure subsystem A

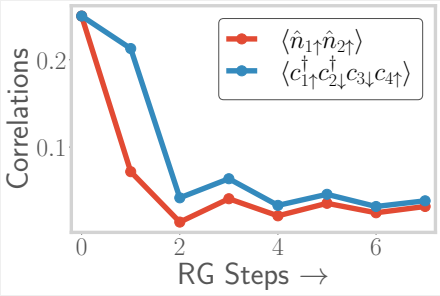
$$I_2(A:B) = S(A) + S(B) - S(A \cup B)$$

gain information about B

Quantifying entanglement within the Kondo cloud

Both entanglement and k-space correlations **increase** as RG proceeds from UV to IR.





- The former shows the formation of the **Kondo singlet**
- The latter shows the growth of two-particle correlations in the **Kondo cloud**

Distorting the Kondo singlet

The multi-channel Kondo Problem

How to destroy the Kondo cloud

Effect of local interactions in the bath