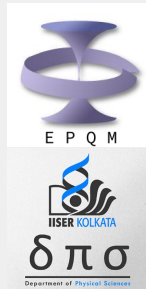


KONDO EFFECT & ITS BREAKDOWN: INTERPLAY OF FLUCTUATIONS IN ZERO DIMENSION

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PP65: PHYSICS TRENDS @ IISER KOLKATA
JULY 2022





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~~~~~  
**A huge thanks to all my collaborators!**  
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~~~~~



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INTRODUCING THE KONDO EFFECT

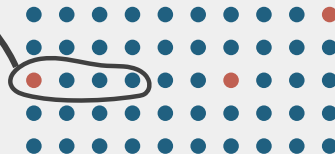
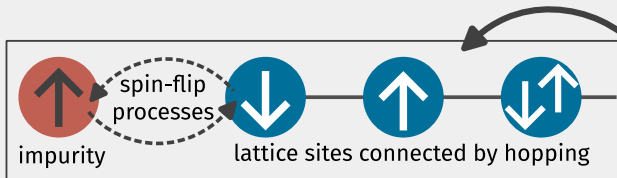
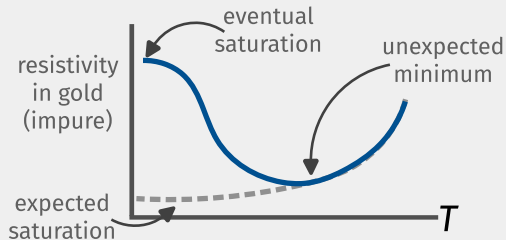
WHERE IT ALL BEGAN

WHAT IS THE KONDO EFFECT?

Dilute metallic alloys show anomalous resistivity **minimum** and eventual saturation.

Can be explained using the **Kondo model**:

$$H_{\text{Kondo}} = KE_{\text{bath}} + J\vec{S}_{\text{imp}} \cdot \vec{S}_{\text{bath}}$$



Second order perturbation theory explains resistivity minimum.
However, solution **diverges** at $T \rightarrow 0$!

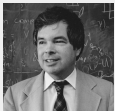


HOW TO EXPLAIN THE RESISTANCE MINIMUM & EVENTUAL SATURATION?

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



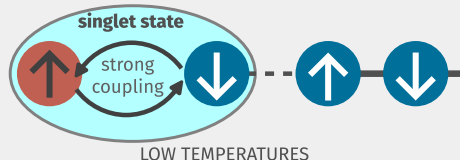
(Ian Affleck)

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

local moment



(crossover)



SOME IMPORTANT QUESTIONS

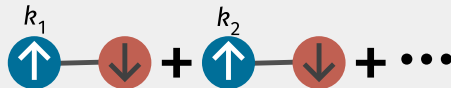
How do we describe the dynamics of the electrons that screen the impurity (the so-called **Kondo cloud**)?

[Mukherjee et al 2023 Phys. Rev. B 105, 085119]



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

[Mukherjee et al 2023 arXiv:2302.02328]



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

[Patra et al 2023 J. Phys.: Condens. Matter 35 315601]



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

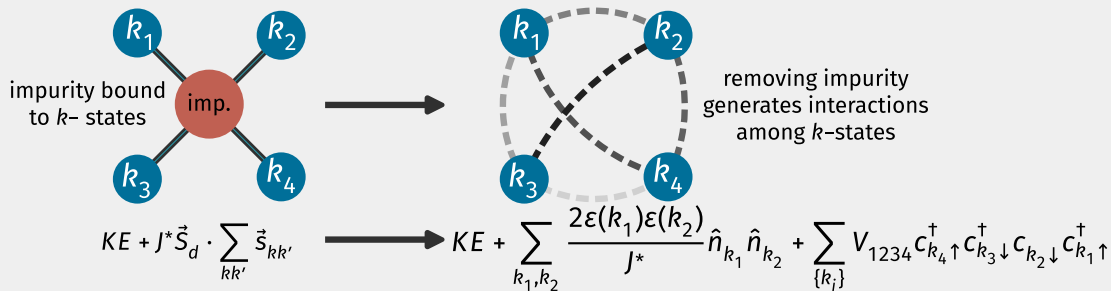
Anirban Mukherjee, Abhirup Mukherjee, N. S. Vidhyadhiraja, A. Taraphder, and Siddhartha Lal

Phys. Rev. B **105**, 085119 – Published 14 February 2022

EFFECTIVE HAMILTONIAN FOR THE KONDO CLOUD

We first applied the **unitary RG** to obtain a low energy fixed point theory.

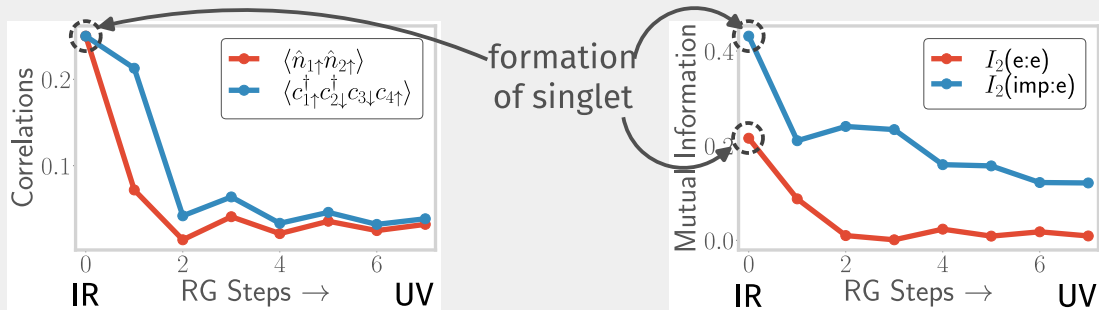
To obtain a theory for the Kondo cloud, we **trace out impurity** from fixed point Hamiltonian.



- 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.



- Both entanglement and k -space correlations **increase** as RG proceeds from UV to IR.
- This shows the formation of the **Kondo singlet** and the growth of two-particle correlations in the **Kondo cloud**.

DISTORTING THE KONDO SINGLET: THE MULTI-CHANNEL KONDO PROBLEM



Journal of Physics: Condensed Matter

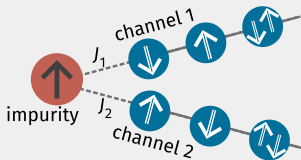
Frustration shapes multi-channel Kondo
physics: a star graph perspective

Siddhartha Patra¹, Abhirup Mukherjee¹, Anirban Mukherjee¹,
N S Vidhyadhiraja², A Taraphder³ and Siddhartha Lal^{4,1}

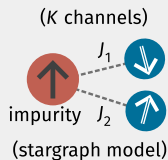
WHAT IS THE MULTICHANNEL KONDO PROBLEM?

Single impurity interacting with **multiple channels** in the bath

$$H_{\text{Kondo}} = K E_{\text{bath}} + \sum_l J_l \vec{S}_{\text{imp}} \cdot \vec{S}^{(l)}$$



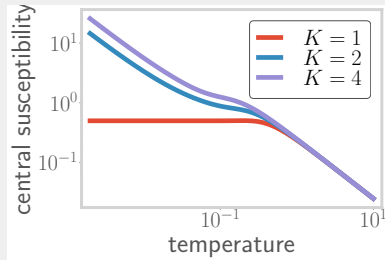
consider only zero energy k -state



Known to display divergent $T = 0$ impurity susceptibility (incomplete screening), and orthogonality catastrophe, **non-Fermi liquid** excitations.

Zero bandwidth limit is (analytically) solvable: $\{|S_{\text{tot}}^z\rangle\}$

- Ground state degeneracy for $K > 1$ explains **orthogonality catastrophe**
- $S_{\text{tot}}^z \neq 0$ in ground states shows incomplete screening
- Excitations shows **non-Fermi liquid** physics in the form of inter-channel scattering.



HOW TO DESTROY THE KONDO CLOUD: EFFECT OF LOCAL INTERACTIONS IN THE BATH

arXiv > cond-mat > arXiv:2302.02328

Condensed Matter > Strongly Correlated Electrons

[Submitted on 5 Feb 2023]

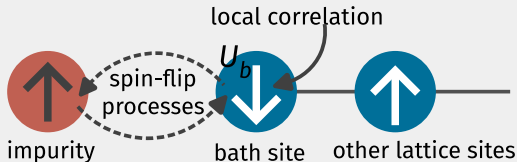
Kondo frustration via charge fluctuations: a route to Mott localisation

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

WHAT IS THE NEW PHYSICS INGREDIENT?

Add **local correlation** on bath (zeroth) site coupled to impurity

$$KE_{\text{bath}} + J\vec{S}_{\text{imp}} \cdot \vec{S}_{\text{bath}} - U_b (\vec{S}_{\text{bath}})^2$$



URG equations show that an **attractive** U_b frustrates the zeroth site.

$$\Delta J \sim J^2 + 4U_b J \implies \text{phase transition at } J = -4U_b$$



singlet state (favour J)

OR



decoupled local moment (favour U_b)

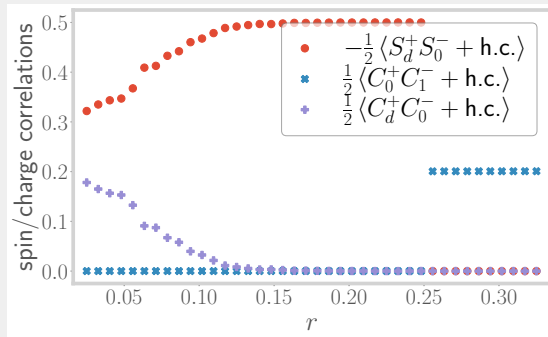
Such a model sheds light on the Mott MIT in ∞ -dimensions (as seen from DMFT).

NATURE OF THE TRANSITION

Across the transition,

- impurity correlations vanish
- bath correlations become non-zero

Shows that **pairing correlations** in the bath are responsible for the transition.

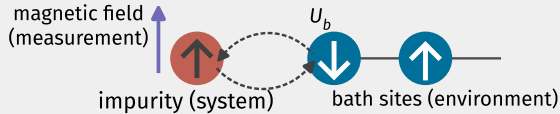


The state **precisely at the transition** is special:

- non-Fermi liquid excitations
- **fractional** impurity magnetisation and occupancy

CONCLUDING REMARKS

- Our analyses often link entanglement measures with correlations, providing bridges between the worlds of condensed matter and quantum information.
- Models of Kondo breakdown can be used to study the effects of measurement on a system coupled to a bath.



- The Kondo model with attractive U_b term has applications in studying the physics of Mott transitions.

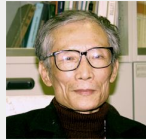


HOW TO EXPLAIN THE RESISTANCE MINIMUM & EVENTUAL SATURATION?

Second order perturbation theory in J gives:

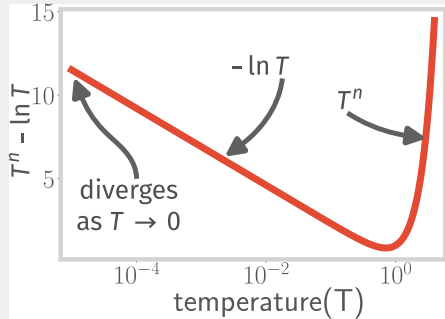
$$\rho \sim T^n - \ln T$$

Explains the **non-monotonic** behaviour!



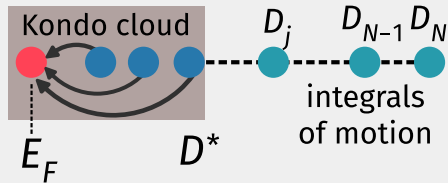
(Jun Kondo)

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

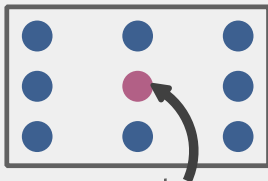


UNITARY RG APPROACH TO IMPURITY MODELS

- 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**

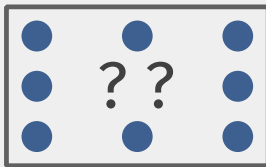


- Entanglement entropy $S(A) \Rightarrow$ quantifies how much **information is gained** about the rest of the system by measuring A



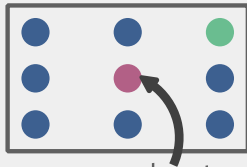
measure subsystem A

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



gain information about rest

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



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

