

Local metal-insulator transition in a generalised impurity Anderson model

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I. INTRODUCTION

The Hubbard model has become one of the fundamental and prototypical models for describing strongly correlated systems in quantum condensed matter physics. strong electronic correlation; in its simplest form, it features a single band of conduction electrons hopping on a lattice and interacting via local correlations that provide a cost U if any site is doubly occupied. There are two trivial limits of the model. At $U = 0$, the bath consists of just a kinetic energy part, and the ground state is just a filled Fermi sea. At $t = 0$, each lattice site decouples from the rest and becomes a local moment, which under symmetry-breaking becomes a Neel antiferromagnet. This suggests that on increasing U/t beyond some critical value, the system might undergo a phase transition from a metallic state to an insulating state [1]. This transition is reflected in the local spectral function - while it has a well-defined zero energy peak in the metallic phase, it is gapped in the insulating phase.

One method of studying Hubbard models is through auxiliary models, described in the next section. Auxiliary models are simpler versions of the full Hamiltonian that are able to capture the essential physics. For eg, a correlated impurity interacting with a conduction bath is a potential auxiliary model for the Hubbard Hamiltonian: The impurity has onsite energy ϵ_d and an onsite correlation U . It hybridises into the bath through V .

If the impurity site hybridises with a *non-interacting* bath defined by a uniform density of states, the impurity

spectral function is found to have a well-defined Kondo resonance at low temperatures. Increasing the impurity correlation U only serves to reduce the width of the central peak at the cost of the appearance of side bands at energy scales of the order of U , but the resonance never dies. The situation is however different if the impurity is embedded in a correlated conduction bath with a non-trivial density of states. For the case of a conduction band with the DOS shown in the right of the figure below, the impurity hybridises into a reduced bandwidth because of the correlation on the lattice [2].

This difference in the type of conduction baths is utilized in dynamical mean-field theory to describe various phases of the bulk system. This is done through the DMFT algorithm: one starts with a non-interacting bath, but depending on the value of U , the conduction bath then gets modified and we ultimately end up with something that is different from what we started with. For small U , the bath does not change much and we retain the central resonance of the impurity spectral function. This then describes a metal in the bulk. For larger values of U , however, the bath changes significantly such that its density of states becomes non-constant. Above a critical U_c , the impurity spectral function gets gapped out, and that then describes the insulating phase in the bulk. *This leaves open the following question:* What is the minimal correlation one can insert into the non-interacting bath (of a single-impurity Anderson model) that can capture both the metallic and insulating phases of the bulk model?

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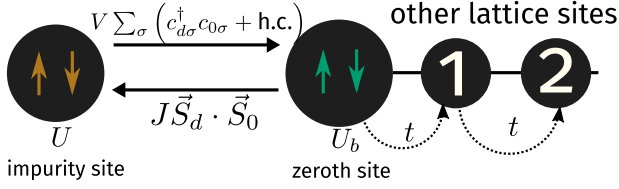


FIG. 2. While we have studied the full model under renormalisation group, often we will turn to a simplified zero-bandwidth version of the model that is obtained by ignoring the kinetic energy part of the Hamiltonian. This zero-bandwidth model is effectively a two site model.

malisation group analysis of the associated Hamiltonian (eq. 2) using the recently developed unitary renormalisation group (URG) method [3–11]. The unitary RG transformations lead to a series of Hamiltonians $H_{(j)}$ related to the Hamiltonian at the previous step through a unitary transformation; the unitary transformations are defined by the requirement that they remove number fluctuations in high-energy k -states, thus making the Hamiltonian progressively more block-diagonal in momentum space. The high-energy degrees of freedom that get decoupled in the process become integrals of motion (IOMs) for the Hamiltonian and enter the Hamiltonian only in a purely number-diagonal form.

To be more precise, we first choose a complete basis $\{|j\rangle\}$ and arrange these states from high-energy (UV) to low-energy (IR). Typically we take these states to be the momentum eigenstates $(|j\rangle = \{|\vec{k}\uparrow\rangle, |\vec{k}\downarrow\rangle\})$, and the isoenergetic shells $\{D_{(j)}\}$ then define the sequence of states, such that the momenta far away from the Fermi surface (taken to be at higher j and having $|D_{(j)}| \gg |\epsilon_F|$) are taken to be the UV states while those near the Fermi surface (taken to be at lower j and having $D_{(j)} \sim \epsilon_F$) comprise the IR states. This scheme is shown in Fig. 3.

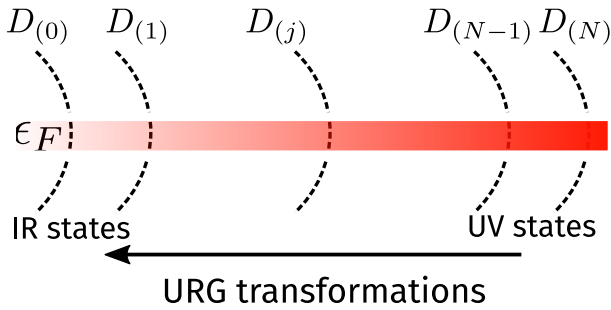


FIG. 3. High energy - low energy scheme defined and used in the URG method. The states away from the Fermi surface form the UV subspace and are decoupled first, leading to a Hamiltonian which is more block-diagonal and comprised of only the IR states near the Fermi surface.

At a given RG step j , the Hamiltonian $H_{(j)}$ involves number fluctuations between the k -states that have energies lower than $D_{(j+1)}$. So the most energetic states that are still non-trivially present in $H_{(j)}$ are those on

the energy contour $D_{(j)}$, and the Hamiltonian $H_{(j)}$ will, in general, not conserve the number of particles in this energy (or momentum) state: $[H_{(j)}, \hat{n}_j] \neq 0$. The unitary transformation $U_{(j)}$ is then defined so as to remove this number fluctuation at the next RG step [5, 6]:

$$H_{(j-1)} = U_{(j)} H_{(j)} U_{(j)}^{\dagger}, \quad [H_{(j-1)}, \hat{n}_j] = 0. \quad (3)$$

The unitary transformations can be expressed in terms of a generator $\eta_{(j)}$ that has fermionic algebra [5, 6]:

$$U_{(j)} = \frac{1}{\sqrt{2}} \left(1 + \eta_{(j)} - \eta_{(j)}^{\dagger} \right), \quad \left\{ \eta_{(j)}, \eta_{(j)}^{\dagger} \right\}_{\pm} = 1, \quad (4)$$

where $\{A, B\}_{\pm} = AB \pm BA$. The generator itself is given by the expression [5, 6]

$$\eta_{(j)}^{\dagger} = \frac{1}{\hat{\omega}_{(j)} - \text{Tr}(H_{(j)} \hat{n}_j)} c_j^{\dagger} \text{Tr}(H_{(j)} c_j). \quad (5)$$

The important operator $\hat{\omega}_{(j)}$ originates from the quantum fluctuations that exist in the problem because of the non-commutation of the kinetic energy terms and the interaction terms in the Hamiltonian:

$$\hat{\omega}_{(j)} = H_{(j-1)} - H_{(j)}^i. \quad (6)$$

$H_{(j)}^i$ is the part of $H_{(j)}$ that commutes with \hat{n}_j but does *not* commute with at least one \hat{n}_l for $l < j$. The RG flow continues up to energy D^* , where a fixed point is reached from the vanishing of the RG function.

B. URG equations for the GAIM

The derivation of the RG equations for the generalised Anderson impurity model (GAIM) Hamiltonian is shown in the appendix. We provide below the RG equations for a given quantum fluctuation scale ω :

$$\Delta U_b = 0, \quad (7)$$

$$\Delta U = 4V^2 n_j \left(\frac{1}{d_1} - \frac{1}{d_0} \right) - n_j \frac{J^2}{d_2}, \quad (8)$$

$$\Delta V = -\frac{3n_j V}{8} \left[J \left(\frac{1}{d_2} + \frac{1}{d_1} \right) + \frac{4U_b}{3} \sum_{i=1}^4 \frac{1}{d_i} \right], \quad (9)$$

$$\Delta J = -\frac{n_j J (J + 4U_b)}{d_2}. \quad (10)$$

The denominators d_i used in these equations are given by

$$d_0 = \omega - \frac{D}{2} + \frac{U_b}{2} - \frac{U}{2}, \quad d_2 = \omega - \frac{D}{2} + \frac{U_b}{2} + \frac{J}{4}, \quad (11)$$

$$d_1 = \omega - \frac{D}{2} + \frac{U_b}{2} + \frac{U}{2} + \frac{J}{4}, \quad d_3 = \omega - \frac{D}{2} + \frac{U_b}{2}. \quad (12)$$

The symbols used in the RG equations have the following meanings: ΔU represents the renormalisation in the coupling U in going from the j^{th} Hamiltonian to the $(j-1)^{\text{th}}$

Hamiltonian by decoupling the isoenergetic shell at energy $D_{(j)}$. n_j is the number of electronic states on the shell $D_{(j)}$.

We will discuss the consequences of these RG equations in the next sections, but we clarify here that the labels U_0, J_0, V_0 that might occur in the figures or elsewhere in the text represent the bare values of the associated couplings U, J and V . We also point out here that throughout the upcoming results, the bare value of U_b is set to the negative of the bare value of U_0 : $U_b = -U_0/10$. This means that whenever we vary U_0 along the axis of a plot, we are simultaneously varying U_b . The reason for choosing the negative sign of U_b will be clarified in the next section.

IV. RG FLOWS AND PHASE DIAGRAM

We start the discussion on the nature of the RG flows by noting that the bath correlation U_b is marginal, and the spin-exchange coupling J has a critical point ($\Delta J = 0$) at $r \equiv -U_b/J = 1/4 \equiv r_c$. We will look at the RG flows of the couplings U, V and J on both sides of this critical point by tuning the ratio r across the critical value r_c , and see what phases they lead to. We will work in the regime of quantum fluctuations where all the denominators are negative: $d_i < 0 \forall i$. Before we start, note that:

- Since J is positive, this means that we can capture both relevant and irrelevant RG flows of J by keeping U_b negative. U_b is found to be marginal under the RG transformation, and we set U_b to $-U_0/10$ hereafter.
- The critical point has been chosen from the RG equation of J and not of V ; this is because, the RG irrelevance of J is sufficient to make V irrelevant as well, and on the other hand, the RG relevance of J is sufficient to screen the impurity.

A. RG flows for $r < r_c$

In this regime, J is relevant and flows to large positive values. It is also easy to deduce from its RG equation that V is also relevant. U is more non-trivial, because its RG equation involves both V and J . Nevertheless, the RG equations were solved numerically with bare values of the couplings and the bandwidth, and it was found that while V and J are relevant, U is irrelevant. These findings are shown in the blue curves of Fig. 4. The fixed point values can be summarised as:

$$U^* = 0, \quad V^* \gg 1, \quad J^* \gg 1, \quad U_b \sim \mathcal{O}(1) \quad (13)$$

B. RG flows for $r > r_c$

The RG β -function function for J changes sign as r grows greater than r_c upon tuning U_b to less than $-J_0/4$, and J becomes irrelevant. As for V , note that in the RG equation for V , it is J that drives V to be relevant while U_b drives V to irrelevance; if J itself is irrelevant, then ΔV will be dominated by U_b and V will be ultimately irrelevant. The behaviour of U is again non-trivial and analytically not tractable, so we solve the RG equations numerically. It turns out that although U is slightly irrelevant, it saturates to an appreciable value near the fixed point. These RG flows are shown in the purple curves of Fig. 4. The fixed point values in this regime can be summarised as:

$$U^* \sim \mathcal{O}(1), \quad V^* = 0, \quad J^* = 0, \quad U_b \sim \mathcal{O}(1) \quad (14)$$

C. Phase diagram: impurity phase transition

The low-energy RG phase diagram is obtained by solving the RG equations for ranges of couplings, and is shown in Fig. 5. There are four distinct phases in the space of couplings U_0 vs J_0 , with U_b constrained at $-U_0/10$ and V_0 set to $2J_0$. The red phase (phase A in the legend) is composed of those Hamiltonians which lead to RG relevant V, J and RG irrelevant U . In other words, this is the phase where the impurity moment is screened by the conduction electrons. This is the low-energy phase of the AIM that has U and V . The blue phase (phase B in the legend) consists of those Hamiltonians which produce irrelevant J, V and a relevant U ; here, the conduction electrons fail to screen the impurity and a residual local moment survives on the impurity at low energies. The yellow phase (phase C in the legend) lies in between these two phases, and is defined by non-negligible V^*, U^* but zero J^* . In this phase, the impurity still gets screened, but there is more charge content on the impurity site compared to phase B. On going to the thermodynamic limit by increasing the bandwidth D_0 , this light green phase disappears. The gray phase (phase D in the legend) is a “dead” phase where U, V, J are all RG irrelevant. The various phases are summarised in table. I.

The black line in Fig. 5 represents a line of critical points $U_b = J_0$, and separates the two major phases of the impurity. Such a *phase transition* between the screened impurity and the local moment phases is absent in the AIM without the attractive correlation U_b . In fact, only the purple screened phase is adiabatically connected the AIM.

D. Growth of charge isospin fluctuations in the bath

The low-energy phase of the AIM is characterised by enhanced spin-fluctuation $\langle S_d^+ S_0^- + \text{h.c.} \rangle$; these fluctu-

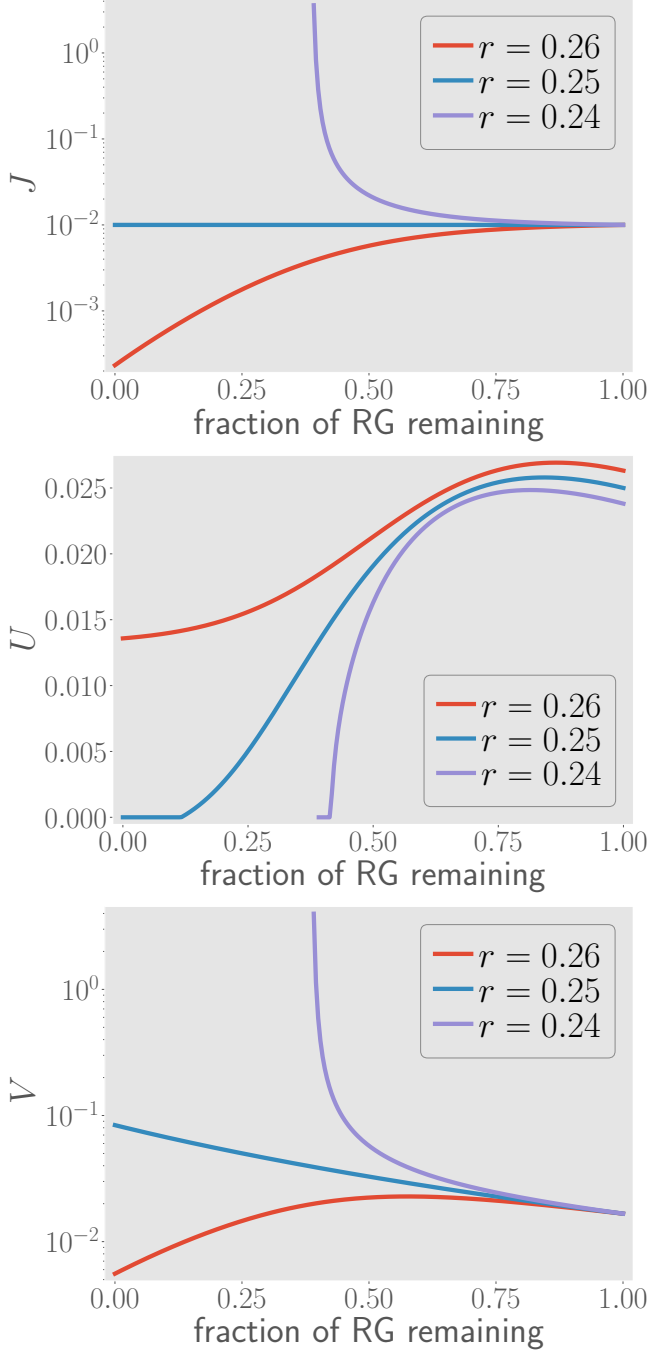


FIG. 4. Variation of couplings U, V and J along the RG transformations, for three values of the transition-tuning ratio r . x-axis represents the RG steps, the rightmost point is the first RG step and leftmost point is the final RG step. The values of the bare couplings are given in the title. All values are in units of the half-bandwidth D_0 , which is chosen to be 10. The blue curves represent the flows for $r > r_c$, where J is relevant. The purple curves represent the RG flows for $r < r_c$, where J is irrelevant. The red curves are exactly at the critical point $r = r_c$, where J is marginal.

ations arise from the Kondo cloud and they serve to

| phase | RG flow | fixed point |
|-------|--|---------------------------|
| A | $\Delta U < 0, \Delta J, \Delta V > 0$ | $U^* \ll V^* \ll J^*$ |
| B | $\Delta U > 0, \Delta J, \Delta V < 0$ | $U^* \gg 1, V^*, J^* = 0$ |
| C | $\Delta U, \Delta J < 0, \Delta V > 0$ | $J^* < U^* \ll V^*$ |
| D | $\Delta U, \Delta J, \Delta V < 0$ | $U^*, V^*, J^* = 0$ |

TABLE I. Summary of the various fixed point phases

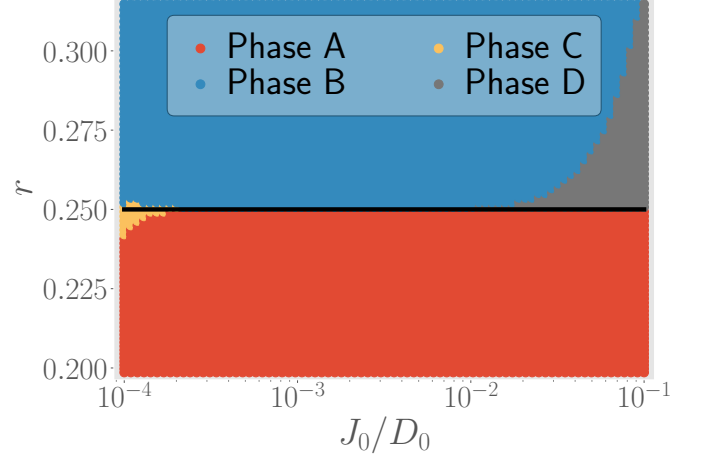


FIG. 5. Phase diagram of the GAIM, in the space of couplings U_0 and J_0 . U_b is set to $-U_0/10$ and V_0 is set to $2J_0$. The various phases A through D are characterised in the text.

screen the local moment. For the system to undergo a transition into an unscreened regime, these fluctuations must get replaced by those of a different kind. This is shown in Fig. 6, where we plot not only the spin fluctuations mentioned, but also two-particle charge fluctuations $\langle c_{k\uparrow}^\dagger c_{k\downarrow}^\dagger c_{\vec{k}'\uparrow} c_{\vec{k}'\downarrow} \rangle$ in the bath that transfer holons and doublons across k -states. We find that while the former decrease towards the transition, the latter pick up; the spin-fluctuations are getting replaced by the charge fluctuations. This is substantiated by the inset of the same figure, which shows the behaviour of these fluctuations even after the transition. While the spin-fluctuations vanish beyond the transition, the charge fluctuations undergo an abrupt increase.

V. LOW-ENERGY EFFECTIVE HAMILTONIAN AND THE GROUND STATE

The RG fixed point Hamiltonian describes the low-energy phase of the system. In general, if the RG fixed point is reached at an energy scale D^* , the fixed point Hamiltonian \mathcal{H}^* is obtained simply from the fixed point values of the couplings, and by noting that the states

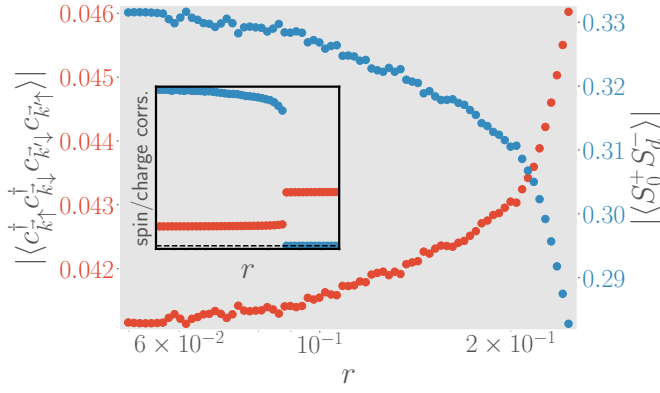


FIG. 6. Growth in the pair-fluctuation terms $c_{k\uparrow}^\dagger c_{k\downarrow}^\dagger c_{k'\downarrow} c_{k'\uparrow}$, as $r \rightarrow 0.25$. This comes at the cost of the spin-flip fluctuations $S_d^+ S_0^- + \text{h.c.}$, which decrease towards the transition. The inset plots the same quantities but for a larger range of r , and the pair fluctuations are seen to pick up abruptly after the transition while the spin fluctuations vanish.

above D^* are now part of the IOMs:

$$\mathcal{H}^* = -\frac{1}{2}U^*(\hat{n}_{d\uparrow} - \hat{n}_{d\downarrow})^2 + \sum_{\sigma, \vec{k}: |\epsilon_{\vec{k}}| < D^*} \epsilon_{\vec{k}} \tau_{\vec{k}, \sigma} - U_b^* \hat{n}_{0\uparrow} \hat{n}_{0\downarrow} + V^* \sum_{\sigma} (c_{d\sigma}^\dagger c_{0\sigma} + \text{h.c.}) + J^* \vec{S}_d \cdot \vec{S}_0 \quad (15)$$

A. Screened regime

U is irrelevant in this regime. Moreover, as we go towards the thermodynamic limit by increasing the bandwidth D_0 , we find that $J^* \gg V^*$ (see Fig. 7), and the fixed point Hamiltonian is determined purely by the spin-exchange part; combining this with the local bath correlation U_b that is marginal then gives the low-energy Hamiltonian for the screened regime:

$$H_{\text{eff}}^{\text{sc}} = J^* \vec{S}_d \cdot \vec{S}_0 - U_b \hat{n}_{0\uparrow} \hat{n}_{0\downarrow} + \sum_{\sigma, \vec{k}: |\epsilon_{\vec{k}}| < D^*} \epsilon_{\vec{k}} \tau_{\vec{k}, \sigma} \quad (16)$$

Since the high momentum modes have been decoupled, the ground state in this regime can be estimated by compressing the kinetic energy to the zero bandwidth limit:

$$\sum_{\sigma, \vec{k}: |\epsilon_{\vec{k}}| < D^*} \epsilon_{\vec{k}} \tau_{\vec{k}, \sigma} \sim \epsilon_F \sum_{\vec{k}_F, \sigma} \tau_{\vec{k}_F, \sigma} \quad (17)$$

Choosing the chemical potential such that ϵ_F vanishes results in a *two-site Hamiltonian* composed of the impurity site and the zeroth site (see Fig. 8):

$$H_{\text{eff}}^{\text{sc}} \sim J^* \vec{S}_d \cdot \vec{S}_0 - U_b \hat{n}_{0\uparrow} \hat{n}_{0\downarrow} \quad (18)$$

This model is easily solved and the ground state is a

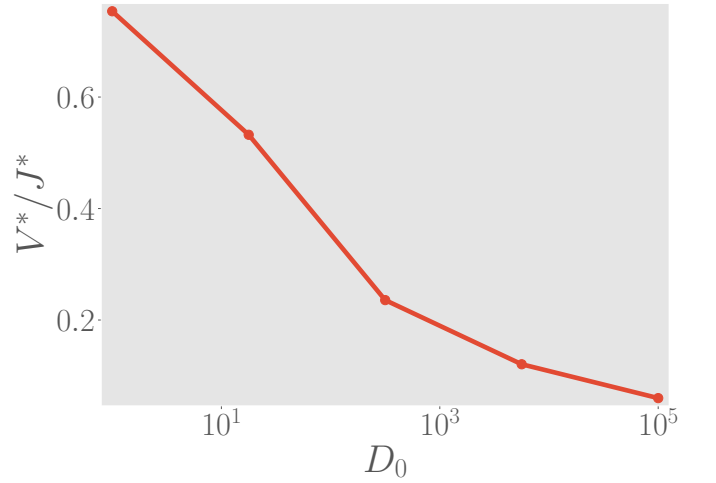


FIG. 7. Increase of J^* in comparison to V^* when going towards the thermodynamic limit.

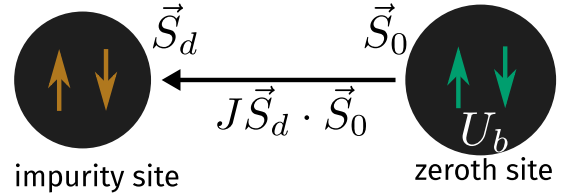


FIG. 8. Two site Hamiltonian obtained by taking the zero bandwidth limit of the effective Hamiltonian in the screened regime.

maximally-entangled spin singlet formed by \vec{S}_d and \vec{S}_0 ; the ground state energy is $E_{\text{gs}}^{\text{sc}} = -\frac{3}{4}J^* - U_b$:

$$|\Psi\rangle_{\text{gs}}^{\text{sc}} = \frac{1}{\sqrt{2}} (|\uparrow_d, \downarrow_0\rangle - |\downarrow_d, \uparrow_0\rangle) \quad (19)$$

where $\{|\uparrow_d, \downarrow_d\rangle\}, \{|\uparrow_0, \downarrow_0\rangle\}$ are the spin states of the impurity and zeroth sites respectively. As mentioned before, this regime in the GAIM is adiabatically connected to the AIM, and indeed, such a spin-singlet ground state is also obtained in the AIM from other methods like Poor Man's scaling [12, 13], numerical renormalisation group [14, 15], Bethe ansatz [], conformal field theory methods [[CITE]] and the URG analysis of the Kondo model [11].

B. Unscreened regime

This regime is simpler than the screened regime, because both V and J are irrelevant, and only U is relevant. The effective Hamiltonian then consists of an impurity spin that is decoupled from the conduction bath:

$$H_{\text{eff}}^{\text{uns}} = -\frac{1}{2}U^*(\hat{n}_{d\uparrow} - \hat{n}_{d\downarrow})^2 - U_b \hat{n}_{0\uparrow} \hat{n}_{0\downarrow} + \sum_{\sigma, \vec{k}: |\epsilon_{\vec{k}}| < D^*} \epsilon_{\vec{k}} \tau_{\vec{k}, \sigma} \quad (20)$$

The impurity site has a doubly-degenerate ground state $\{|\uparrow_d\rangle, |\downarrow_d\rangle\}$, and the total ground state is the impurity state in direct product with the ground state $|\Psi\rangle_{\text{gs, bath}}$ of the conduction bath Hamiltonian $H_{\text{eff, bath}}^{\text{uns}} = -U_b \hat{n}_{0\uparrow} \hat{n}_{0\downarrow} + \sum_{\sigma, \vec{k}: |\epsilon_{\vec{k}}| < D^*} \epsilon_{\vec{k}} \tau_{\vec{k}, \sigma}$:

$$|\Psi\rangle_{\text{gs}}^{\text{uns}} = |\sigma_d\rangle \otimes |\Psi\rangle_{\text{gs, bath}}, \quad \sigma = \uparrow, \downarrow \quad (21)$$

C. The critical point: $4U_b + J = 0$

Along the critical points, J is marginal and U is irrelevant, while V is slightly relevant (see Fig. 4). This leads to enhanced fluctuations in both the spin and charge sectors of the impurity site. The effective Hamiltonian is

$$H_{\text{eff}}^{\text{crit}} = \sum_{\sigma, \vec{k}: |\epsilon_{\vec{k}}| < D^*} \epsilon_{\vec{k}} \tau_{\vec{k}, \sigma} - U_b^* \hat{n}_{0\uparrow} \hat{n}_{0\downarrow} + J^* \vec{S}_d \cdot \vec{S}_0 + V^* \sum_{\sigma} \left(c_{d\sigma}^\dagger c_{0\sigma} + \text{h.c.} \right) \quad (22)$$

Since the interactions are marginal or only slightly relevant, the kinetic energy is no longer negligible compared to them, and it is not possible to faithfully take a zero bandwidth limit of the problem.

D. Nature of ground state near the critical point

We can obtain more insight on the change in the ground state as the system moves towards the transition by tracking its overlap with the singlet state $|\text{ss}\rangle \equiv |\Psi\rangle_{\text{gs}}^{\text{sc}}$ and the entangled state among the charge isospin triplets, $|\text{ct}\rangle \equiv \frac{1}{\sqrt{2}}(|\uparrow_d \downarrow_d, 0\rangle + |0, \uparrow_0 \downarrow_0\rangle)$. The ground state $|\Psi\rangle_{\text{gs}}$ is obtained by numerically solving the fixed point Hamiltonian for various bare values of the couplings. The overlaps are shown in Fig. 9, and we see a continuous increase in the charge content at the cost of the spin content as r approaches the critical value $r_c = 0.25$. The spin and charge overlaps approach equality towards the transition, leading to an *extra emergent symmetry of spin-charge interchange* at the critical point.

VI. DESCRIPTORS OF THE TRANSITION

In this section, we will discuss various diagnostics that track the impurity phase transition; these diagnostics or probes will answer several interesting questions:

1. How is spectral weight transferred across energy scales, as the system undergoes the transition?
2. How do entanglement measures behave across the transition?
3. How does the Kondo screening cloud [CITE] respond as the system is driven critical?

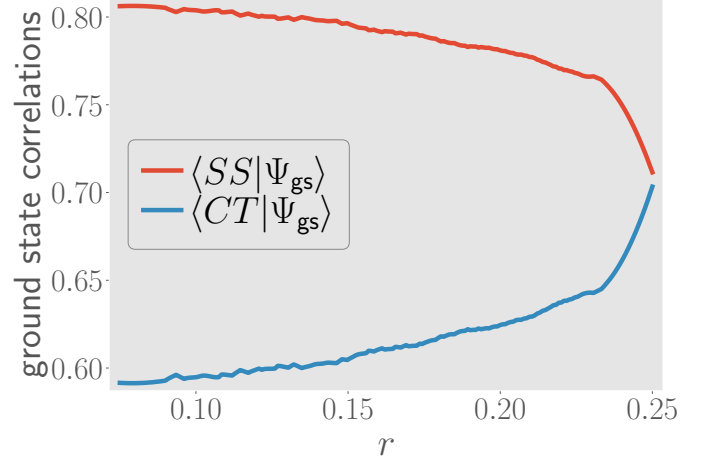


FIG. 9. Overlap of the RG fixed point ground state $|\Psi\rangle_{\text{gs}}$ with the spin singlet state $|\text{ss}\rangle$ and the charge triplet state $|\text{ct}\rangle$, for a range of values of the transition tuning ratio r . Beyond the critical point $r > 0.25$, both these overlaps vanish.

A. Impurity spectral function

One of the most obvious indicators of the transition is the appearance of a gap in the spectral function $A_d(\omega)$ of the impurity. In the AIM, the spectral function A_d has a single peak structure for small U , and two additional side peaks appear at large U . Although the central peak keeps getting sharper as U is increased, it never disappears, simply because the impurity is always able to bind with the zeroth site and form a single site; indeed, it is the local Fermi liquid excitations that appear on top of this singlet ground state that gives rise to the central Abrikosov-Suhl resonance in the spectral function [lots of CITE here].

In contrast, the GAIM shows the appearance of a gap as r crosses $1/4$ (see Fig. 10); the three-peak form survives only up to the critical point. The spectral functions are calculated by numerically diagonalising the effective Hamiltonian obtained from the RG. In the unscreened regime $r > 0.25$, the impurity spectral function has two peaks at energies $\omega = \pm U/2$ corresponding to the fluctuations that create a particle or a hole on the impurity site. The appearance of the gap shows that exactly at $r = 0.25$, the zero-energy pole in the impurity Greens function $G_d(\omega)$ gets replaced by a zero; this is accompanied by a zero energy divergence in the impurity self-energy $\Sigma_d = 1/G_d^{(0)}(\omega) - 1/G_d(\omega)$. The expression of the self-energy follows from Dyson's equation, $G_d^{(0)}(\omega)$ being the self-energy of the impurity at $U = 0$.

B. Using geometric entanglement to track the transition

The impurity Greens function can be given a spectral representation in terms of the eigenstates $\{|\Psi\rangle_n\}$ of the

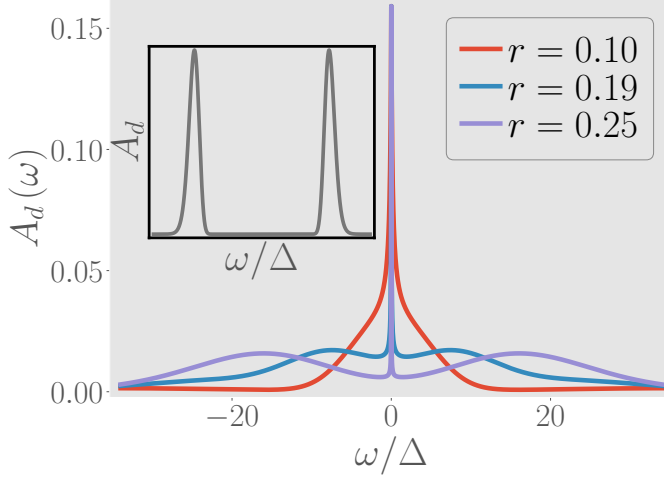


FIG. 10. Impurity spectral function $A_d(\omega)$ at three values of the ratio r . The central large plot is exactly at the critical point $r = 0.25$, the left (blue) inset is at $r < 0.25$ and the right (violet) inset is at $r > 0.25$.

GAIM:

$$G_d(\omega) = \sum_n \left[\frac{|\langle \Psi_{\text{gs}} | c_{d\sigma} | \Psi_n \rangle|^2}{\omega + E_{\text{gs}} - E_n} + \frac{|\langle \Psi_n | c_{d\sigma} | \Psi_{\text{gs}} \rangle|^2}{\omega - E_{\text{gs}} + E_n} \right] \quad (23)$$

We will now introduce a complete basis into the expression. The basis will be the set of eigenstates of the Hamiltonian $H = H_1 + H_2$, where H_1 is the two-site Hamiltonian in eq. 18, and H_2 is a tight-binding Hamiltonian formed by the remaining sites. Since the Hamiltonians are decoupled, the eigenstates $|\Psi\rangle_{m,n}$ will be direct product states formed by combining the eigenstates $|\phi\rangle_m, |\psi\rangle_n$ of the individual Hamiltonians H_1 and H_2 respectively: $|\Phi\rangle_{m,n} = |\phi\rangle_m \otimes |\psi\rangle_n$. Inserting this basis

leads to the expression:

$$|\Psi\rangle_{\text{gs}} = \sum_{m,n} |\Phi\rangle_{m,n} (\langle \phi_m | \otimes \langle \psi_n |) |\Psi_{\text{gs}}\rangle \quad (24)$$

The ground state of H_1 is the spin singlet: $|\phi\rangle_0 = |\text{ss}\rangle$. We denote the ground state of the tight-binding Hamiltonian H_2 by $|\psi\rangle_0$. Because of the highly renormalised couplings V and J , the impurity site is almost maximally entangled with the zeroth site, such that the ground state $|\Psi\rangle_{\text{gs}}$ in the $r < 0.25$ regime can be thought of as a direct product of the two-site ground state, $c|\text{ss}\rangle + \sqrt{1-c^2}|\text{ct}\rangle$, in direct product with the tight-binding ground state:

$$|\Psi\rangle_{\text{gs}} \simeq (c|\text{ss}\rangle + \sqrt{1-c^2}|\text{ct}\rangle) \otimes |\psi\rangle_0 = |\Phi\rangle_{\text{ss}} + |\Phi\rangle_{\text{ct}} \quad (25)$$

where $|\Phi\rangle_{\text{ss(ct)}} = |\text{ss(ct)}\rangle \otimes |\psi\rangle_0$. This suggests that not all terms in the summation of eq. 24 contribute; out of all $\{|\psi\rangle_n\}$, only the ground state $n = 0$ contributes, while only $|\text{ss}\rangle$ and $|\text{ct}\rangle$ contribute from the set $\{|\phi\rangle_m\}$. The summation then simplifies to

$$|\Psi\rangle_{\text{gs}} = |\Phi\rangle_{\text{ss}} \langle \text{ss} | \Psi_{\text{gs}}^{(2)} \rangle + |\Phi\rangle_{\text{ct}} \langle \text{ct} | \Psi_{\text{gs}}^{(2)} \rangle, \quad (26)$$

where $|\Psi_{\text{gs}}^{(2)}\rangle$ is the two-site part of the ground state and can be obtained by starting with the full ground state $|\Psi\rangle_{\text{gs}}$ and tracing over the other lattice sites of the system.

We assume that the global phase of the wavefunctions are real, and since the internal weights of the wavefunctions are real as well, the overlaps $\langle \text{ss} | \Psi_{\text{gs}}^{(2)} \rangle, \langle \text{ct} | \Psi_{\text{gs}}^{(2)} \rangle$ are also real. We can use these overlaps to define a geometric measure of entanglement:

$$\varepsilon(\psi_1, \psi_2) = 1 - |\langle \psi_1 | \psi_2 \rangle|^2 \quad (27)$$

[CITE] If $|\psi_1\rangle$ is thought of as a separable state, then $|\psi_2\rangle$ should be less entangled if its overlap with $|\psi_1\rangle$ is large, which is indeed borne out by the definition. The

overlaps then become $\langle \text{ss} | \Psi_{\text{gs}}^{(2)} \rangle = \sqrt{1 - \varepsilon(\text{ss}, \Psi_{\text{gs}}^{(2)})}$, and similarly for the state $|\text{ct}\rangle$. For brevity, we will use the notation $\varepsilon_{\text{ss}} \equiv \varepsilon(\text{ss}, \Psi_{\text{gs}}^{(2)})$, $\varepsilon_{\text{ct}} \equiv \varepsilon(\text{ct}, \Psi_{\text{gs}}^{(2)})$. The Greens function can now be written in terms of these measures:

$$G_d(\omega) = \sum_n \left[(1 - \varepsilon_{\text{ss}}) \left(\frac{|\langle \Phi_{\text{ss}} | c_{d\sigma} | \Psi_n \rangle|^2}{\omega + E_{\text{gs}} - E_n} + \frac{|\langle \Psi_n | c_{d\sigma} | \Phi_{\text{ss}} \rangle|^2}{\omega - E_{\text{gs}} + E_n} \right) + (1 - \varepsilon_{\text{ct}}) \left(\frac{|\langle \Phi_{\text{ct}} | c_{d\sigma} | \Psi_n \rangle|^2}{\omega + E_{\text{gs}} - E_n} + \frac{|\langle \Psi_n | c_{d\sigma} | \Phi_{\text{ct}} \rangle|^2}{\omega - E_{\text{gs}} + E_n} \right) \right. \\ \left. + \sqrt{(1 - \varepsilon_{\text{ss}})} \sqrt{(1 - \varepsilon_{\text{ct}})} \left(\frac{\langle \Phi_{\text{ss}} | c_{d\sigma} | \Psi_n \rangle \langle \Psi_n | c_{d\sigma}^\dagger | \Phi_{\text{ct}} \rangle + \text{h.c.}}{\omega + E_{\text{gs}} - E_n} + \frac{\langle \Phi_{\text{ct}} | c_{d\sigma} | \Psi_n \rangle \langle \Psi_n | c_{d\sigma}^\dagger | \Phi_{\text{ss}} \rangle + \text{h.c.}}{\omega - E_{\text{gs}} + E_n} \right) \right] \quad (28)$$

This expression is interesting because it relates the Greens function (measurable when converted into a spectral function) to measures of entanglement. These mea-

sures have been plotted up to the critical point in Fig. 11. While $\varepsilon_{\text{ss}}, \varepsilon_{\text{ct}}$ (plotted in the inset) are very similar to the overlaps plotted in Fig. 9, the cross-

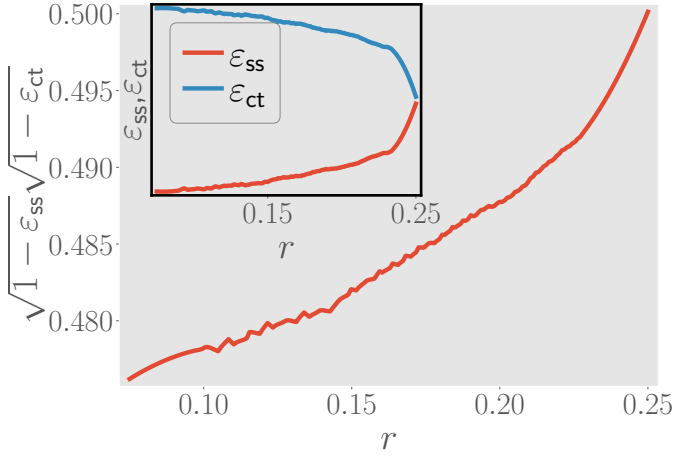


FIG. 11. Variation of $\sqrt{(1 - \epsilon_{ss})}\sqrt{(1 - \epsilon_{ct})}$ as r is increased towards the critical value 0.25. Inset shows the variation of the individual measures $\epsilon_{ss}, \epsilon_{ct}$.

term $\sqrt{(1 - \epsilon_{ss})}\sqrt{(1 - \epsilon_{ct})}$ plotted in the main figure has an overall monotonic incremental behaviour towards the transition. We can now use the knowledge of the behaviour of these measures to make some statements about the nature of the transition from the Greens function. Since ϵ_{ss} increases towards the transition, we find that the first major term in the Greens function decreases; this shows that scattering within the spin sector loses weight. On the other hand, since ϵ_{ct} decreases, the second major term in G_d increases, reflecting the growth in the participation of the charge sector in the scattering processes. The final major term also increases, due to the monotonic growth of $\sqrt{(1 - \epsilon_{ss})}\sqrt{(1 - \epsilon_{ct})}$, showing that there is a continual increase in the *mixing of the spin and charge sectors*.

C. Mutual information and entanglement entropy in the ground state: fate of the Kondo cloud

Since the system has to undergo a phase transition into an unscreened phase for $r > 0.25$, it is clear that the Kondo screening cloud must disappear. Indeed, this is captured by various entanglement measures like mutual information and entanglement entropy. The entanglement entropy $S(A)$ of subsystem A with the rest of the system is defined as the von Neumann entropy of the reduced density matrix ρ_A ,

$$S(A) = -\text{Tr}[\rho_A \ln \rho_A] , \quad (29)$$

where ρ_A is obtained by tracing the full density matrix $\rho = |\Psi\rangle_{\text{gs}}\langle\Psi|_{\text{gs}}$ over all subsystems apart from A . The mutual information between two subsystems A and B is then defined using this entanglement entropy:

$$I(A : B) = S(A) + S(B) - S(A \cup B) , \quad (30)$$

where $S(A \cup B)$ is the entanglement entropy of A and B with the rest. $I(A : B)$ represents the amount of information obtained about B on measuring A , or vice-versa. If the ground state $|\Psi\rangle_{\text{gs}}$ is a separable state where A is disentangled from the rest, then its entanglement entropy $S(A)$ will be 0. On the other hand, if the ground state cannot be written in separable form, $S(A)$ becomes non-zero, and the maximum value it can take is $\ln d$, where d is the dimension of the Hilbert space of A .

In the AIM or the Kondo model ground state, the impurity forms a maximally entangled singlet with the zeroth site [14–16]. This in turn leads to entanglement in k -space between the conduction electrons that screen the impurity and form the Kondo cloud [11]. These features change once we turn on the attractive correlation U_b and drive the system across the transition, as plotted in Figs. 12 and 13. The k -space mutual information $I(\vec{k}_1 : \vec{k}_2)$ between two distinct k -states plotted in the red curve of Fig. 12 is essentially the entanglement within the Kondo cloud, and we find that this entanglement decreases towards the transition, signalling the weakening of the Kondo cloud. This is also supported by the reduction in the mutual information $I(d \uparrow : \vec{k} \downarrow)$ between the impurity and k -space states plotted along the blue curve in the same figure. Beyond the transition, $I(d \uparrow : \vec{k} \downarrow)$ drops to zero, because the impurity is no longer coupled to the bath, while $I(\vec{k}_1 : \vec{k}_2)$ takes on a larger value because they are connected by the U_b -term and are no longer sharing entanglement with the impurity.

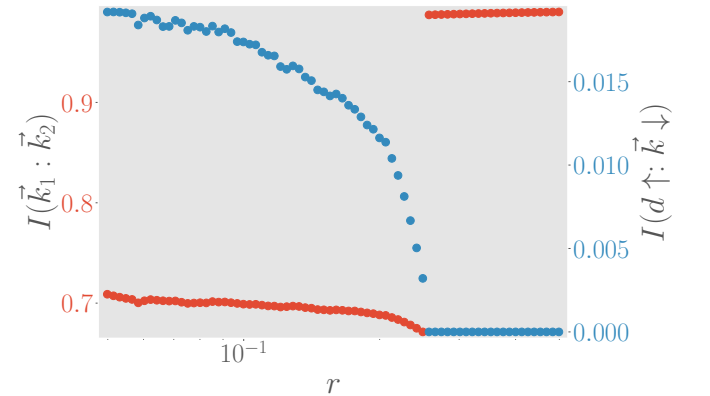


FIG. 12. Mutual information in k -space, across the transition. Red curve is the mutual information between two distinct k -states inside the Kondo cloud. Blue curve is the mutual information between a k -state and the impurity state of opposite spin.

VII. DISCUSSIONS AND OUTLOOK

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- discuss why the model is minimal

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Appendix: Derivation of RG equations for the generalised Anderson impurity model

1. Some preliminaries

The Hamiltonian we are working with is the generalised Anderson impurity model (Eq. 2):

$$\mathcal{H} = -\frac{1}{2}U(\hat{n}_{d\uparrow} - \hat{n}_{d\downarrow})^2 + \sum_{\vec{k},\sigma} \epsilon_{\vec{k}} \tau_{\vec{k},\sigma} + J \sum_{\vec{k},\vec{k}',\alpha,\beta} \vec{S}_d \cdot \vec{\sigma}_{\alpha\beta} c_{\vec{k},\alpha}^\dagger c_{\vec{k}',\beta} + V \sum_{\vec{k},\sigma} \left(c_{d\sigma}^\dagger c_{\vec{k},\sigma} + \text{h.c.} \right) - U_b \sum_{\vec{k},\vec{k}',\sigma} c_{\vec{k},\sigma}^\dagger c_{\vec{k}',\sigma} + U_b \sum_{\vec{k}_1,\vec{k}_2,\vec{k}_3,\vec{k}_4} c_{\vec{k}_1\uparrow}^\dagger c_{\vec{k}_2\uparrow} c_{\vec{k}_3\downarrow}^\dagger c_{\vec{k}_4\downarrow} \quad (\text{A.1})$$

The renormalisation in the Hamiltonian $H_{(j)}$ at the j^{th} RG step, upon decoupling an electronic state $q\beta$, is given by the expression:

$$(\Delta H_{(j)})_{\vec{q},\beta} = H_{(j-1)} - H_{(j)} = c_{\vec{q},\beta}^\dagger T_{\vec{q},\beta} \frac{1}{\omega_e - H_D} T_{\vec{q},\beta}^\dagger c_{\vec{q},\beta} + T_{\vec{q},\beta}^\dagger c_{\vec{q},\beta} \frac{1}{\omega_h - H_D} c_{\vec{q},\beta}^\dagger T_{\vec{q},\beta}, \quad (\text{A.2})$$

where $\omega_{e,h}$ are the quantum fluctuation scales for the electron and hole scattering channels, H_D is the part of the Hamiltonian that is diagonal in k -space, and $T_{\vec{q},\beta} + T_{\vec{q},\beta}^\dagger$ is the part of the Hamiltonian that does not commute with $\hat{n}_{\vec{q},\beta}$ (in short, it is the part that is off-diagonal with respect to a particular state \vec{q},β). This off-diagonal part is made up of contributions from V, J and U_b :

$$T_{\vec{q}\uparrow} = \left[V c_{d\uparrow}^\dagger + J \sum_{\vec{k}} S_d^+ c_{\vec{k}\downarrow}^\dagger + U_b \sum_{\vec{k}_1,\vec{k}_2,\vec{k}_3} c_{\vec{k}_1\uparrow}^\dagger c_{\vec{k}_3\downarrow}^\dagger c_{\vec{k}_4\downarrow} \right] c_{\vec{q}\uparrow}, \quad (\text{A.3})$$

while the diagonal part is given by

$$H_D = \epsilon_{\vec{q}} \tau_{q\uparrow} + \frac{1}{4} J S_d^z (\hat{n}_{q\uparrow} - \hat{n}_{q\downarrow}) - U_b (\tau_{\vec{q},\uparrow})^2, \quad (\text{A.4})$$

where we have rewritten $\hat{n}_{\vec{q},\beta}$ in terms of $\tau_{\vec{q},\beta} \equiv \hat{n}_{\vec{q},\beta} - \frac{1}{2}$ in the contribution from U_b . Note that we have ignored a potential scattering term in the off-diagonal part $T_{\vec{q}\beta}$. In the initial state $|\Psi\rangle_i$, we have $\langle \hat{n}_{q\beta} \rangle = 1/2 \implies \tau_{q\beta} = 0$, so the contribution of U_b to that state is 0. For both hole excitations $c_{q\beta} |\Psi\rangle_i$ as well as particle excitations $c_{q\beta}^\dagger |\Psi\rangle_i$, the intermediate state energy lowers to $-U_b/4$. Because the diagonal contribution from U_b always changes the energy of the excited energy by $-U_b/4$, the denominator will simply change by $U_b/4$ (H_D comes with a minus sign in the denominator). We will suppress this change for now and substitute in all the denominators at the end.

We define n_j as the number of states being decoupled on each side of the Fermi surface, at the j^{th} RG step. In order to treat both spin and isospin exchanges democratically, we take $|\Psi\rangle_i = \frac{1}{2} (|0\rangle + |q\uparrow\rangle + |q\downarrow\rangle + |q\uparrow, q\downarrow\rangle)$ as the *initial* state for the scattering processes. The intermediate states $|\Psi\rangle_{\text{int}}$ in the particle sector ($c_{q\beta} |\Psi\rangle_i$) and hole sector ($c_{q\beta}^\dagger |\Psi\rangle_i$) will then have both spin and isospin excitations which can couple with the corresponding impurity degree of freedom. We will assume that states $q > k_F$ ($\epsilon_q > 0$) above the Fermi surface can have only particle excitations and states below the Fermi surface can only have hole excitations. The kinetic energy part $\epsilon_q \tau_{q\beta}$ of H_D for $|\Psi\rangle_i$ is then zero, whereas it is always $D/2$ for $|\Psi\rangle_{\text{int}}$. To demonstrate this for a typical $q < k_F$, the hole excitation is $c_{q\uparrow} |\Psi\rangle_i = \frac{1}{\sqrt{2}} (|0\rangle + |q\downarrow\rangle)$. This has an isospin term in the form of the *holon* and a spin term in the form of the down state. Since $\tau_{q\uparrow} = -\frac{1}{2}$ in the excited state, the kinetic energy for $|\Psi\rangle_{\text{int}}$ is $\epsilon_q \tau_{q\uparrow} = (-D) \times (-\frac{1}{2}) = D/2$.

2. Renormalisation of U_b

U_b can renormalise only via itself. The relevant renormalisation term in the particle sector is

$$U_b^2 \sum_{q\beta} \sum_{k_1, k_2, k_3, k'_1, k'_2, k'_3} c_{q\beta}^\dagger c_{k_1\beta} c_{k_3\beta}^\dagger c_{k'_1\beta} \frac{1}{\omega - H_D} c_{k'_2\beta}^\dagger c_{k_3\beta} c_{k_2\beta}^\dagger c_{q\beta} \quad (\text{A.5})$$

In order to renormalise U_b , we need to contract one more pair of momenta. There are two choices. The first is by setting $k_3 = k'_3 = q$. The two internal states, then, are $q\beta$ and $q\bar{\beta}$. As discussed above, the intermediate state energy is $-U_b/4$. We therefore have

$$\frac{U_b^2 n_j}{\omega - D/2 + \frac{U_b}{2}} \sum_{\beta} \sum_{k_1, k_2, k'_1, k'_2} c_{k_1\beta} c_{k'_1\bar{\beta}} c_{k'_2\bar{\beta}}^\dagger c_{k_2\beta}^\dagger = \frac{U_b^2 n_j}{\omega - D/2 + \frac{U_b}{2}} \sum_{\beta} \sum_{k_1, k_2, k'_1, k'_2} c_{k'_2\bar{\beta}}^\dagger c_{k'_1\bar{\beta}} c_{k_2\beta}^\dagger c_{k_1\beta} \quad (\text{A.6})$$

Another way to contract the momenta is by setting $k'_1 = k'_2 = q$, which gives a renormalisation of

$$\frac{U_b^2 n_j}{\omega - D/2 + \frac{U_b}{2}} \sum_{\beta} \sum_{k_1, k_2, k_3, k'_3} c_{k_1\beta} c_{k_3\bar{\beta}}^\dagger c_{k'_3\bar{\beta}} c_{k_2\beta}^\dagger = -\frac{U_b^2 n_j}{\omega - D/2} \sum_{\beta} \sum_{k_1, k_2, k_3, k'_3} c_{k_3\bar{\beta}}^\dagger c_{k'_3\bar{\beta}} c_{k_2\beta}^\dagger c_{k_1\beta} \quad (\text{A.7})$$

The two contributions cancel each other. The same cancellation happens in the hole sector as well.

3. Renormalisation of the impurity correlation U

The coupling U is renormalised by two kinds of vertices: V^2 and J^2 . We will consider these processes one at a time. For convenience, we define $\epsilon_d = -U/2$.

The renormalisation arising from the first kind of terms, in the particle sector, is

$$\sum_{q\beta} c_{q\beta}^\dagger c_{d\beta} \frac{V^2}{\omega - H_D} c_{d\beta}^\dagger c_{q\beta} = \sum_{q\beta} V^2 \hat{n}_{q\beta} (1 - \hat{n}_{d\beta}) \left(\frac{1 - \hat{n}_{d\bar{\beta}}}{\omega - E_0} + \frac{\hat{n}_{d\bar{\beta}}}{\omega' - E_1} \right) = V^2 n_j \sum_{\beta} (1 - \hat{n}_{d\beta}) \left(\frac{1 - \hat{n}_{d\bar{\beta}}}{\omega_0 - E_0} + \frac{\hat{n}_{d\bar{\beta}}}{\omega_1 - E_1} \right) \quad (\text{A.8})$$

q runs over the momentum states that are being decoupled at this RG step: $|q| = \Lambda_j$. $E_{1,0}$ are the diagonal parts of the Hamiltonian at $\hat{n}_{d\bar{\beta}} = 1, 0$ respectively. We have $\hat{n}_{d\beta} = 1$ in the intermediate state because of the $c_{d\beta}^\dagger$ in front of

the Greens function. Applying $c_{q\beta}$ on the initial state $|\Psi\rangle_i$ leaves us with $C_q^z = -\frac{1}{2}$ and $s_q^z = \frac{1}{2}\bar{\beta}$. We also know that

$$\hat{n}_{d\beta} = 1, \begin{cases} \hat{n}_{d\bar{\beta}} = 0 & \implies S_d^z = \frac{1}{2}\beta, C_d^z = 0, \epsilon_d (\hat{n}_{d\uparrow} - \hat{n}_{d\downarrow})^2 = \epsilon_d \\ \hat{n}_{d\bar{\beta}} = 1 & \implies S_d^z = 0, C_d^z = \frac{1}{2}, \epsilon_d (\hat{n}_{d\uparrow} - \hat{n}_{d\downarrow})^2 = 0 \end{cases} \quad (\text{A.9})$$

Combining all this, we can write $E_1 = \frac{D}{2}$ and $E_0 = \frac{D}{2} + \epsilon_d - \frac{J}{4}$. In order to relate ω_0 with ω_1 with the common fluctuation scale ω for the conduction electrons, we will replace these quantum fluctuation scales by the current renormalised values of the single-particle self-energy for the initial state from which we started scattering. For $\hat{n}_{d\bar{\beta}} = 0$, there is no additional self-energy because the impurity does not have any spin: $\omega_0 = \omega$. For $\hat{n}_{d\bar{\beta}} = 1$, we have an additional self-energy of ϵ_d arising from the correlation on the impurity: $\omega_1 = \omega + \epsilon_d$. Substituting the values of $E_{0,1}$ and $\omega_{0,1}$, we get

$$V^2 n_j \sum_{\beta} (1 - \hat{n}_{d\beta}) \left(\frac{1 - \hat{n}_{d\bar{\beta}}}{\omega - \frac{D}{2} - \epsilon_d + \frac{J}{4}} + \frac{\hat{n}_{d\bar{\beta}}}{\omega - \frac{D}{2} + \epsilon_d} \right) \quad (\text{A.10})$$

Performing a similar calculation for the hole sector gives the contribution:

$$V^2 n_j \sum_{\beta} \hat{n}_{d\beta} \left(\frac{1 - \hat{n}_{d\bar{\beta}}}{\omega - \frac{D}{2} + \epsilon_d} + \frac{\hat{n}_{d\bar{\beta}}}{\omega - \frac{D}{2} - \epsilon_d + \frac{J}{4}} \right) \quad (\text{A.11})$$

We now come to the second type of terms: spin-spin. We first look at the particle sector:

$$\frac{J^2}{4} \sum_{q\beta} c_{d\bar{\beta}}^\dagger c_{d\beta} c_{q\beta}^\dagger c_{-q\bar{\beta}} \frac{1}{\omega - H_D} c_{d\beta}^\dagger c_{d\bar{\beta}} c_{q\bar{\beta}}^\dagger c_{q\beta} = \frac{J^2}{4} n_j \frac{1}{\omega - \frac{D}{2} + \frac{J}{4}} \sum_{\beta} \hat{n}_{d\bar{\beta}} (1 - \hat{n}_{d\beta}) \quad (\text{A.12})$$

The diagonal part in the denominator was simple to deduce in this case, because the nature of the scattering requires the spins S_d^z and $\frac{\beta}{2} (\hat{n}_{q\beta} - \hat{n}_{q\bar{\beta}})$ to be anti-parallel. This ensures that the intermediate state has an energy of $E = \frac{D}{2} + \epsilon_d - \frac{J}{4}$, and the quantum fluctuation scale is $\omega' = \omega + \epsilon_d$, such that $\omega' - E = \omega - \frac{D}{2} + \frac{J}{4}$. In the hole sector, we have

$$\frac{J^2}{4} n_j \frac{1}{\omega - \frac{D}{2} + \frac{J}{4}} \sum_{\beta} \hat{n}_{d\beta} (1 - \hat{n}_{d\bar{\beta}}) \quad (\text{A.13})$$

We now have all possible renormalisation to the impurity correlation U . To actually compute the renormalisation, we will first calculate the renormalisation in the energies ϵ_0, ϵ_1 and ϵ_2 of the impurity states $|\hat{n}_d = 0\rangle, |\hat{n}_d = 1\rangle, |\hat{n}_d = 2\rangle$ respectively. The renormalisation of these states are given by the following terms:

- $\Delta\epsilon_0$ is given by the renormalisation of the term $(1 - \hat{n}_{d\uparrow})(1 - \hat{n}_{d\downarrow})$
- $\Delta\epsilon_1$ is given by the renormalisation of either $(1 - \hat{n}_{d\uparrow})\hat{n}_{d\downarrow}$ or $(1 - \hat{n}_{d\downarrow})\hat{n}_{d\uparrow}$
- $\Delta\epsilon_2$ is given by the renormalisation of $\hat{n}_{d\uparrow}\hat{n}_{d\downarrow}$

From eqs. A.10, A.11, A.12 and A.13, we write

$$\Delta U = \Delta\epsilon_2 + \Delta\epsilon_0 - 2\Delta\epsilon_1 = -\frac{4V^2 n_j}{\omega + \frac{U_b}{2} - \frac{D}{2} - U/2} + \frac{4V^2 n_j}{\omega + \frac{U_b}{2} - \frac{D}{2} + U/2 + \frac{J}{4}} - \frac{J^2 n_j}{\omega + \frac{U_b}{2} - \frac{D}{2} + \frac{J}{4}}, \quad (\text{A.14})$$

where we have restored the contribution from U_b in the denominator.

4. Renormalisation of the hybridisation V

Renormalisation of V happens through two kinds of processes: VJ and VU_b . Within the first kind, the scattering can be either via S_d^z or through S_d^\pm . For the first kind, we have the following contribution in the particle sector:

$$\sum_{q\beta} V c_{q\beta}^\dagger c_{d\beta} \frac{1}{\omega - H_D} \frac{1}{4} J \sum_k (\hat{n}_{d\beta} - \hat{n}_{d\bar{\beta}}) c_{k\beta}^\dagger c_{q\beta} = \frac{1}{4} V J n_j \frac{1}{2} \left(\frac{1}{\omega'_1 - E} + \frac{1}{\omega'_2 - E} \right) \sum_{k\beta} (1 - \hat{n}_{d\bar{\beta}}) c_{d\beta} c_{k\beta}^\dagger \quad (\text{A.15})$$

The transformation from $\frac{1}{\omega - H_D}$ to $\frac{1}{2} \left(\frac{1}{\omega'_1 - E} + \frac{1}{\omega'_2 - E} \right)$ is made so that we can account for both the initial state and the final state energies through the two fluctuation scales ω'_1 and ω'_2 respectively; we calculate the denominators for both the initial and final states, and then take the mean of the two (hence the factor of half in front). This was not required previously because in the earlier scattering processes, the impurity returned to its initial state at the end, at least in terms of $\epsilon_d (\hat{n}_{d\uparrow} - \hat{n}_{d\downarrow})^2$, and so we had $\omega'_1 = \omega'_2 = \omega'$.

Note that the $c_{d\beta}$ in front of the Greens function resulted in $(\hat{n}_{d\beta} - \hat{n}_{d\bar{\beta}}) \rightarrow (1 - \hat{n}_{d\bar{\beta}})$. The intermediate state is characterised by $\hat{n}_{d\beta} = 1 - \hat{n}_{d\bar{\beta}} = 1$, which means that $E = \frac{D}{2} + \epsilon_d - \frac{J}{4}$. Moreover, the initial state gives $\omega'_1 = \omega + \epsilon_d$ while the final state gives $\omega'_2 = \omega$. Therefore, the renormalisation becomes

$$-\frac{n_j}{4} V J \frac{1}{2} \left(\frac{1}{\omega - \frac{D}{2} + \frac{J}{4}} + \frac{1}{\omega - \frac{D}{2} - \epsilon_d + \frac{J}{4}} \right) \sum_{k\beta} (1 - \hat{n}_{d\bar{\beta}}) c_{k\beta}^\dagger c_{d\beta} \quad (\text{A.16})$$

One can generate another such process by exchanging the single-particle process and the spin-exchange process:

$$\sum_{q\beta} \frac{1}{4} J \sum_k (\hat{n}_{d\beta} - \hat{n}_{d\bar{\beta}}) c_{q\beta}^\dagger c_{k\beta} \frac{1}{\omega - H_D} V c_{d\beta}^\dagger c_{q\beta} \quad (\text{A.17})$$

This is simply the Hermitian conjugate of the previous contribution. Combining this with the previous then gives

$$-\frac{n_j}{8} V J \left(\frac{1}{\omega - \frac{D}{2} + \frac{J}{4}} + \frac{1}{\omega - \frac{D}{2} - \epsilon_d + \frac{J}{4}} \right) \sum_{k\beta} (1 - \hat{n}_{d\bar{\beta}}) (c_{d\beta}^\dagger c_{k\beta} + \text{h.c.}) \quad (\text{A.18})$$

We now consider the spin-exchange processes involving S_d^\pm :

$$\sum_{q\beta} V c_{q\beta}^\dagger c_{d\beta} \frac{1}{\omega - H_D} \frac{1}{2} J \sum_k c_{d\beta}^\dagger c_{d\bar{\beta}} c_{k\bar{\beta}}^\dagger c_{q\beta} = \frac{1}{2} V J n_j \frac{1}{2} \left(\frac{1}{\omega'_1 - E} + \frac{1}{\omega'_2 - E} \right) \sum_{k\beta} (1 - \hat{n}_{d\beta}) c_{d\bar{\beta}} c_{k\bar{\beta}}^\dagger \quad (\text{A.19})$$

We again have $E = \frac{D}{2} + \epsilon_d - \frac{J}{4}$, $\omega'_1 = \omega + \epsilon_d$ and $\omega'_2 = \omega$, which gives

$$-\frac{1}{4} V J n_j \left(\frac{1}{\omega - \frac{D}{2} + \frac{J}{4}} + \frac{1}{\omega - \frac{D}{2} - \epsilon_d + \frac{J}{4}} \right) \sum_{k\beta} (1 - \hat{n}_{d\beta}) c_{k\bar{\beta}}^\dagger c_{d\bar{\beta}} \quad (\text{A.20})$$

Combining this with the Hermitian conjugate obtained from exchanging the processes gives

$$-\frac{1}{4} V J n_j \left(\frac{1}{\omega - \frac{D}{2} + \frac{J}{4}} + \frac{1}{\omega - \frac{D}{2} - \epsilon_d + \frac{J}{4}} \right) \sum_{k\beta} (1 - \hat{n}_{d\beta}) (c_{k\bar{\beta}}^\dagger c_{d\bar{\beta}} + \text{h.c.}) \quad (\text{A.21})$$

The contributions from the hole sector are obtained making the transformation $\hat{n}_{d\bar{\beta}} \rightarrow 1 - \hat{n}_{d\bar{\beta}}$ on the particle sector contributions. The total renormalisation to V from VJ processes are

$$-\frac{3n_j}{8} V J \left(\frac{1}{\omega + U_b/4 - \frac{D}{2} + \frac{J}{4}} + \frac{1}{\omega + U_b/4 - \frac{D}{2} + U/2 + \frac{J}{4}} \right) \sum_{k\beta} (c_{d\beta}^\dagger c_{k\beta} + \text{h.c.}) \quad (\text{A.22})$$

The renormalisation in V from U_b arises through terms of VU_b and U_bV kind. The first term gives

$$\begin{aligned} & \sum_{q\beta} \sum_k U_b V c_{q\beta}^\dagger c_{k\beta} \hat{n}_{q\bar{\beta}} \frac{1}{\omega - H_D} c_{d\beta}^\dagger c_{q\beta} \\ &= n_j U_b V \sum_{k\beta} c_{k\beta} \left[\frac{\hat{n}_{d\bar{\beta}}}{2} \left(\frac{1}{\omega_1 - E_1} + \frac{1}{\omega'_1 - E_1} \right) + \frac{1 - \hat{n}_{d\bar{\beta}}}{2} \left(\frac{1}{\omega_0 - E_0} + \frac{1}{\omega'_0 - E_0} \right) \right] c_{d\beta}^\dagger \end{aligned} \quad (\text{A.23})$$

E_1 and E_0 are the intermediate state energies for $\hat{n}_{d\bar{\beta}} = 1$ and 0 respectively. $\omega_{1,0}$ are the quantum fluctuation scales for the corresponding initial states. $\omega'_{1,0}$ are the fluctuation scales for the corresponding final states. The

intermediate energies are $E_1 = D/2 - U_b/4 - K/4$, $E_0 = D/2 - U_b/4 - U/2 - J/4$. The fluctuation scales are $\omega_1 = \omega - U/2 = \omega'_0$, $\omega'_1 = \omega = \omega_0$. Substituting these gives

$$-n_j U_b V \sum_{k\beta} c_{d\beta}^\dagger c_{k\beta} \left[\frac{\hat{n}_{d\bar{\beta}}}{2} \left(\frac{1}{\omega - \frac{D}{2} - \frac{U}{2} + \frac{U_b}{4} + \frac{K}{4}} + \frac{1}{\omega - \frac{D}{2} + \frac{U_b}{4} + \frac{K}{4}} \right) + \frac{1 - \hat{n}_{d\bar{\beta}}}{2} \left(\frac{1}{\omega - \frac{D}{2} + \frac{U_b}{4} + \frac{U}{2} + \frac{J}{4}} + \frac{1}{\omega - \frac{D}{2} + \frac{U_b}{4} + \frac{J}{4}} \right) \right] \quad (\text{A.24})$$

The second term is of the form

$$\sum_{q\bar{\beta}} \sum_k U_b V c_{q\bar{\beta}}^\dagger c_{d\beta} \frac{1}{\omega - H_D} \hat{n}_{q\bar{\beta}} c_{k\beta}^\dagger c_{q\beta} \quad (\text{A.25})$$

and this is just the Hermitian conjugate of the previous term, so these two terms together lead to

$$-n_j U_b V \sum_{k\beta} (c_{d\beta}^\dagger c_{k\beta} + \text{h.c.}) \left[\frac{\hat{n}_{d\bar{\beta}}}{2} \left(\frac{1}{\omega - \frac{D}{2} - \frac{U}{2} + \frac{U_b}{4} + \frac{K}{4}} + \frac{1}{\omega - \frac{D}{2} + \frac{U_b}{4} + \frac{K}{4}} \right) + \frac{1 - \hat{n}_{d\bar{\beta}}}{2} \left(\frac{1}{\omega - \frac{D}{2} + \frac{U_b}{4} + \frac{U}{2} + \frac{J}{4}} + \frac{1}{\omega - \frac{D}{2} + \frac{U_b}{4} + \frac{J}{4}} \right) \right] \quad (\text{A.26})$$

In the hole sector, we have

$$\begin{aligned} & \sum_{q\bar{\beta}} \sum_k U_b V \hat{n}_{q\bar{\beta}} c_{k\beta}^\dagger c_{q\beta} \frac{1}{\omega - H_D} c_{q\beta}^\dagger c_{d\beta} \\ & - \sum_{q\bar{\beta}} \sum_k U_b V (1 - \hat{n}_{q\bar{\beta}}) c_{k\beta}^\dagger c_{q\beta} \frac{1}{\omega - H_D} c_{q\beta}^\dagger c_{d\beta} \\ & = -n_j U_b V \sum_{k\beta} c_{k\beta}^\dagger \left[\frac{\hat{n}_{d\bar{\beta}}}{2} \left(\frac{1}{\omega_1 - E_1} + \frac{1}{\omega'_1 - E_1} \right) + \frac{1 - \hat{n}_{d\bar{\beta}}}{2} \left(\frac{1}{\omega_0 - E_0} + \frac{1}{\omega'_0 - E_0} \right) \right] c_{d\beta} \end{aligned} \quad (\text{A.27})$$

$E_1 = D/2 - U_b/4 - U/2 - J/4$, $E_0 = D/2 - U_b/4 - K/4$. The fluctuation scales are $\omega_1 = \omega = \omega'_0$, $\omega'_1 = \omega - U/2 = \omega_0$. Substituting these gives

$$-n_j U_b V \sum_{k\beta} c_{d\beta}^\dagger c_{k\beta} \left[\frac{1 - \hat{n}_{d\bar{\beta}}}{2} \left(\frac{1}{\omega - \frac{D}{2} - \frac{U}{2} + \frac{U_b}{4} + \frac{K}{4}} + \frac{1}{\omega - \frac{D}{2} + \frac{U_b}{4} + \frac{K}{4}} \right) + \frac{\hat{n}_{d\bar{\beta}}}{2} \left(\frac{1}{\omega - \frac{D}{2} + \frac{U_b}{4} + \frac{U}{2} + \frac{J}{4}} + \frac{1}{\omega - \frac{D}{2} + \frac{U_b}{4} + \frac{J}{4}} \right) \right] \quad (\text{A.28})$$

The other term, obtained by exchanging V and U_b , gives the Hermitian conjugate, so the overall contribution from the hole sector is the same as the total contribution from the particle sector, but with $\hat{n}_{d\bar{\beta}} \rightarrow 1 - \hat{n}_{d\bar{\beta}}$. Combining both the sectors, we get

$$-n_j U_b V \sum_{k\beta} (c_{d\beta}^\dagger c_{k\beta} + \text{h.c.}) \frac{1}{2} \left[\left(\frac{1}{\omega - \frac{D}{2} - \frac{U}{2} + \frac{U_b}{4} + \frac{K}{4}} + \frac{1}{\omega - \frac{D}{2} + \frac{U_b}{4} + \frac{K}{4}} \right) + \left(\frac{1}{\omega - \frac{D}{2} + \frac{U_b}{4} + \frac{U}{2} + \frac{J}{4}} + \frac{1}{\omega - \frac{D}{2} + \frac{U_b}{4} + \frac{J}{4}} \right) \right] \quad (\text{A.29})$$

Combining with the renormalisation from J , the complete RG equation for V becomes

$$\begin{aligned} \Delta V = & -\frac{3n_j V}{8} \left[\left(\frac{J}{\omega - \frac{D}{2} + \frac{U_b}{4} + \frac{J}{4}} + \frac{J}{\omega - \frac{D}{2} + \frac{U_b}{4} + \frac{U}{2} + \frac{J}{4}} \right) + K \left(\frac{K}{\omega - \frac{D}{2} + \frac{U_b}{4} + \frac{K}{4}} + \frac{K}{\omega - \frac{D}{2} + \frac{U_b}{4} - \frac{U}{2} + \frac{K}{4}} \right) \right] \\ & - \frac{n_j U_b}{2} \left[\left(\frac{V}{\omega - \frac{D}{2} - \frac{U}{2} + \frac{U_b}{4} + \frac{K}{4}} + \frac{V}{\omega - \frac{D}{2} + \frac{U_b}{4} + \frac{K}{4}} \right) + \left(\frac{V}{\omega - \frac{D}{2} + \frac{U_b}{4} + \frac{U}{2} + \frac{J}{4}} + \frac{V}{\omega - \frac{D}{2} + \frac{U_b}{4} + \frac{J}{4}} \right) \right] \\ = & -\frac{n_j V}{8} \left[\left(\frac{3J + 4U_b}{\omega - \frac{D}{2} + \frac{U_b}{4} + \frac{J}{4}} + \frac{3J + 4U_b}{\omega - \frac{D}{2} + \frac{U_b}{4} + \frac{U}{2} + \frac{J}{4}} \right) + \left(\frac{3K + 4U_b}{\omega - \frac{D}{2} + \frac{U_b}{4} + \frac{K}{4}} + \frac{3K + 4U_b}{\omega - \frac{D}{2} + \frac{U_b}{4} - \frac{U}{2} + \frac{K}{4}} \right) \right] \end{aligned} \quad (\text{A.30})$$

The RG equation for V is

$$\Delta V = -\frac{3n_j V}{8} \left[J \left(\frac{1}{\omega - \frac{D}{2} + \frac{J}{4}} + \frac{1}{\omega - \frac{D}{2} - \epsilon_d + \frac{J}{4}} \right) + K \left(\frac{1}{\omega - \frac{D}{2} + \frac{K}{4}} + \frac{1}{\omega - \frac{D}{2} + \epsilon_d + \frac{K}{4}} \right) \right] \quad (\text{A.31})$$

5. Renormalisation of the spin-exchange coupling J

The term $J \vec{S}_d \cdot \vec{S}_0$ can be split into three parts: $J^z S_d^z, \frac{1}{2} J^+ S_d^+ S_0^-$ and $\frac{1}{2} J^- S_d^- S_0^+$. We will only calculate the renormalisation in J^+ , which will be equal to that of J^- , J^z due to spin-rotation symmetry. The terms that renormalise J^+ are of the form $S_d^+ S_d^z$ and $S_d^z S_d^+$. In the particle sector, we have

$$\begin{aligned} -\sum_q \sum_{kk'} \frac{1}{4} J^2 S_d^+ c_{q\downarrow}^\dagger c_{k'\uparrow} \frac{1}{\omega - H_D} S_d^z c_{k\downarrow}^\dagger c_{q\downarrow} &= n_j \frac{1}{4} J^2 \left(-\frac{1}{2} S_d^+ \right) \sum_{kk'} c_{k\downarrow}^\dagger c_{k'\uparrow} \frac{1}{\omega + \frac{U_b}{2} - \frac{D}{2} + \frac{J}{4}}, \\ \sum_q \sum_{kk'} \frac{1}{4} J^2 S_d^z c_{q\uparrow}^\dagger c_{k'\uparrow} \frac{1}{\omega - H_D} S_d^+ c_{k\downarrow}^\dagger c_{q\uparrow} &= -n_j \frac{1}{4} J^2 \left(\frac{1}{2} S_d^+ \right) \sum_{kk'} c_{k\downarrow}^\dagger c_{k'\uparrow} \frac{1}{\omega + \frac{U_b}{2} - \frac{D}{2} + \frac{J}{4}}. \end{aligned} \quad (\text{A.32})$$

The denominator is determined using $E = \frac{D}{2} + \epsilon_d - \frac{J}{4}$ and $\omega' = \omega + \epsilon_d$. In the hole sector, we similarly have

$$\begin{aligned} \sum_q \sum_{kk'} \frac{1}{4} J^2 S_d^+ c_{k\downarrow}^\dagger c_{q\uparrow} \frac{1}{\omega - H_D} S_d^z c_{q\uparrow}^\dagger c_{k'\uparrow} &= n_j \frac{1}{4} J^2 \left(-\frac{1}{2} S_d^+ \right) \sum_{kk'} c_{k\downarrow}^\dagger c_{k'\uparrow} \frac{1}{\omega + \frac{U_b}{2} - \frac{D}{2} + \frac{J}{4}}, \\ -\sum_q \sum_{kk'} \frac{1}{4} J^2 S_d^z c_{k\downarrow}^\dagger c_{q\downarrow} \frac{1}{\omega - H_D} S_d^+ c_{q\downarrow}^\dagger c_{k'\uparrow} &= -n_j \frac{1}{4} J^2 \left(\frac{1}{2} S_d^+ \right) \sum_{kk'} c_{k\downarrow}^\dagger c_{k'\uparrow} \frac{1}{\omega + \frac{U_b}{2} - \frac{D}{2} + \frac{J}{4}}. \end{aligned} \quad (\text{A.33})$$

The renormalisation due to U_b also happens through multiple terms. One of the terms is

$$\frac{1}{2} J U_b \sum_q \sum_{k,k'} S_d^+ c_{q\downarrow}^\dagger c_{k\uparrow} \frac{1}{\omega - H_D} \hat{n}_{q\uparrow} c_{k'\downarrow}^\dagger c_{q\downarrow} = -\frac{1}{2} \frac{J U_b n_j}{\omega - \frac{D}{2} + \frac{U_b}{2} + \frac{J}{4}} \sum_{k,k'} S_d^+ c_{k'\downarrow}^\dagger c_{k\uparrow} \quad (\text{A.34})$$

The factor of half in front is the same half factor that appears in front of the $S_1^+ S_2^-, S_1^- S_2^+$ terms when we rewrite $\vec{S}_1 \cdot \vec{S}_2$ in terms of S^z, S^\pm . Another term is obtained by switching J and U_b :

$$\frac{1}{2} J U_b \sum_q \sum_{k,k'} \hat{n}_{q\downarrow} c_{q\uparrow}^\dagger c_{k\uparrow} \frac{1}{\omega - H_D} S_d^+ c_{k'\downarrow}^\dagger c_{q\uparrow} = -\frac{1}{2} \frac{J U_b n_j}{\omega - \frac{D}{2} + \frac{U_b}{2} + \frac{J}{4}} \sum_{k,k'} S_d^+ c_{k'\downarrow}^\dagger c_{k\uparrow} \quad (\text{A.35})$$

The corresponding terms in the hole sector are

$$\frac{1}{2} J U_b \sum_q \sum_{k,k'} S_d^+ c_{k'\downarrow}^\dagger c_{q\uparrow} \frac{1}{\omega - H_D} \hat{n}_{q\downarrow} c_{q\uparrow}^\dagger c_{k\uparrow} = -\frac{1}{2} \frac{J U_b n_j}{\omega - \frac{D}{2} + \frac{U_b}{2} + \frac{J}{4}} \sum_{k,k'} S_d^+ c_{k'\downarrow}^\dagger c_{k\uparrow} \quad (\text{A.36})$$

$$\frac{1}{2} J U_b \sum_q \sum_{k,k'} \hat{n}_{q\uparrow} c_{k'\downarrow}^\dagger c_{q\downarrow} \frac{1}{\omega - H_D} S_d^+ c_{q\downarrow}^\dagger c_{k\uparrow} = -\frac{1}{2} \frac{J U_b n_j}{\omega - \frac{D}{2} + \frac{U_b}{2} + \frac{J}{4}} \sum_{k,k'} S_d^+ c_{k'\downarrow}^\dagger c_{k\uparrow} \quad (\text{A.37})$$

Combining all these terms, we get the updated RG equation for J :

$$\Delta J = -J n_j \frac{4U_b + J}{\omega - \frac{D}{2} + \frac{U_b}{2} + \frac{J}{4}} \tag{A.38}$$
