Destruction of the Kondo effect by a local measurement

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(Dated: March 22, 2022)

We show that the local spin measurement which decoheres the localized spin in a Kondo system, suppresses the Abrikosov-Suhl resonance and destroys the Kondo effect. This happens due to elimination of the entanglement between the localized spin and the conduction electrons, and differs essentially from smearing of the resonance by dissipation. Considering decoherence by a spin bath, we predict that the Kondo effect disappears when the Kondo temperature becomes smaller than the coupling with a bath. This effect can be detected in experiments on “quantum corrals” or quantum dots doped by impurities with internal degrees of freedom.

PACS numbers: 03.65.Yz; 75.20.Hr; 73.21.La

The Kondo effect discovered originally as a mechanism to explain the resistivity minimum in dilute magnetic alloys [3] is one of most interesting many-body phenomena in condensed matter physics. It plays a crucial role for heavy fermion physics [2], for metallic glasses and systems with orbitally degenerate ions [3], for quantum dots [4, 5], for quantum tunneling in metals [3], etc. The key feature of the Kondo effect is the formation of the Abrikosov-Suhl resonance near the Fermi level. The STM technique allowed visualization of this resonance for magnetic impurities [6] and for orbital Kondo effect on atomically clean metal surfaces [7]. This resonance is a consequence of the strong quantum correlations between the localized magnetic moment (or other center with internal degrees of freedom) and the conduction electrons. These two subsystems form a singlet state analogous to the state of the Einstein-Podolsky-Rosen spin pair [8, 9, 10]. Such states are often fragile, since the quantum correlations can be destroyed by decoherence, as a result of quantum measurement of one of the spins (or both) either by a specially designed device or by an environment which has the same effect as a measurement apparatus.

In this paper we show that a spin measurement, which decoheres the Kondo system and destroys correlation between the localized spin and the conduction electrons, suppresses the Abrikosov-Suhl resonance and thus leads to disappearance of the Kondo effect. This effect is essentially different from the suppression of the Kondo effect by dissipation (resulting e.g. from external radiation) [11]: the crucial difference between decoherence and dissipation has been discussed in detail [10, 11, 12]. We show that for Kondo systems this leads to definite predictions, which can be tested in experiments.

One of the standard considerations of the Kondo effect is based on the $s$–$d$ exchange Hamiltonian [13]:

$$H_{sd} = \sum_{k,\alpha} \epsilon_k c^\dagger_{k\alpha} c_{k\alpha} + H_1, \quad H_1 = J_{sd} S_1 S_2$$

where $S_1$ is the impurity spin and $S_2 = (1/2N) \sum_{k\nu} \sigma_{\alpha\beta} c_{k\nu}^\dagger c_{k\nu}$ is the spin of the conduction electrons at the impurity location, $N$ is the number of sites. However, it is instructive to start first from another, exactly solvable, model of the Kondo effect. Instead of the central spin $1/2$, let us consider a central orbitally degenerate ion, whose internal electrons (“f”-electrons) are coupled with the conduction electrons, i.e. the infinite-U degenerate Anderson model with the Hamiltonian [4, 5, 13]:

$$H = P \sum_{k,\nu} \left[ \epsilon_k c^\dagger_{k\nu} c_{k\nu} + \epsilon_f d^\dagger_{\nu} d_{\nu} \right] P + H_1$$

$$H_1 = P \sum_{k,\nu} \left[ V (c^\dagger_{k\nu} + d^\dagger_{\nu}) c_{k\nu} \right] P$$

where $c_{k\nu}$, $d_{\nu}$ are the Fermi operators for conduction and localized $f$-electrons, correspondingly, $\epsilon_k$ and $\epsilon_f$ are their bare energies counted from the Fermi level, $V$ is the hybridization parameter, $\nu = 1, 2, ..., N_f$ is the “flavor” index and $P$ is the projection operator into the space with $n_f = \sum_{\nu} d^\dagger_{\nu} d_{\nu} < 2$. Both Hamiltonians [4, 5] describe essentially the same physics, so that our conclusions remain qualitatively valid for both cases, but the latter one is exactly solvable in the limit $N_f \to \infty$, assuming that $V \to 0$ and $V^2 N_f = const$. Its ground state wave function is [13]:

$$|\Psi_0\rangle = A \left( |0\rangle + |1\rangle \right)$$

$$|0\rangle = \prod_{\nu, k < k_F} \epsilon^\dagger_{k\nu} |vac\rangle$$

$$|1\rangle = \sum_{k < k_F} |k\rangle \equiv \frac{1}{\sqrt{N_f}} \sum_{\nu, k < k_F} \alpha_k d^\dagger_{\nu} c_{k\nu} |0\rangle$$

where $|vac\rangle$ is the vacuum state, $A = \sqrt{1 - \langle n_f \rangle}$ is the normalization factor, $\langle n_f \rangle$ is the average occupation of the $f$-level, $\alpha_k = V \sqrt{N_f} / (E_0 + \epsilon_k - \epsilon_f)$, and $E_0$ is the ground state energy counted from the energy of the
conduction electrons) plays the role of the Kondo temperature because of the identity Fano (anti)resonance in the conduction electron spectrum to the Abrikosov-Suhl resonance; the energy \( E^* = \rho V^2 N_f (1 - \langle n_f \rangle) / \langle n_f \rangle \) (\( \rho \) is the density of states for conduction electrons) plays the role of the Kondo temperature provided that \( Z \ll 1 \); in that regime \( Z \) is exponentially small in \( V^2 N_f \) (for more details, see, e.g., [2][3]). This Abrikosov-Suhl resonance results in the Fano (anti)resonance in the conduction electron spectrum because of the identity

\[
\langle \langle c_{k\nu} | c_{k'\nu}^\dagger \rangle \rangle E = \frac{1}{E - \epsilon_k} + \frac{G(E)}{(E - \epsilon_k)(E - \epsilon_{k'})} \tag{5}
\]

It is the Fano antiresonance that is observed in the STM experiments [2][3].

The state [2][3] describes quantum correlations between the \( f \)-electrons and the conduction electrons. These two subsystems can be considered as an “EPR pair” [10], where the state of the conduction electrons is determined by the state of the \( f \)-electrons (and vice versa). One of the most impressive features of such states is that the decohering action applied to one subsystem immediately affects the state of the other subsystem, which has not been directly subjected to decoherence. We demonstrate below that in our case, such an influence, e.g. the measurement of the number of the \( f \)-electrons \( n_f \), leads to an immediate change of the state of the conduction electrons, and suppresses the Kondo effect. This effect is similar to the situations explored recently for Anderson localization [10], in the Bose-Einstein condensate [17], and for an antiferromagnet [18]. However, the case of Kondo systems may be more easily studied in real experiments (see the discussion below).

Let us assume that the decohering influence of the apparatus is so effective that it can be described as a von Neumann’s measurement [13]. This means that the initial density matrix \( \rho_i = |\Psi_0\rangle \langle \Psi_0| \) is momentenously transformed into the final one \( \rho_f = A^2 (|0\rangle \langle 0| + |1\rangle \langle 1|) \). The Green’s function of the \( f \)-electrons after the measurement is

\[
G_f(E) = -i \int_0^{\infty} dt e^{itE} \text{Tr} \rho_f \left[ d_{\nu}(t) d_{\nu}^\dagger(t) + d_{\nu}^\dagger(t) d_{\nu}(t) \right], \tag{6}
\]

and can be evaluated similarly to Ref. [13]. One has to introduce the functions \( \exp(-iHt) |\phi\rangle \) where \( |\phi\rangle = |0, k\rangle, d_{\nu}^\dagger |0\rangle \), write the equations of motion for them with taking into account only the leading terms in \( 1/N_f \) and make the Laplace transformation. As a result, the Green’s function after the measurement becomes (in the limit of large \( N_f \)):

\[
G_f(E) = \frac{A^2}{E - \epsilon_f + \Gamma (\epsilon_f - E)} \tag{7}
\]

It has the same pole \( E^* \) as the Green’s function before the measurement, but the residue equals to \((1 - \langle n_f \rangle)^2\) instead of \( 1 - \langle n_f \rangle \). It means that the amplitude of the Abrikosov-Suhl resonance, and, consequently, the Fano antiresonance in the conduction electron spectra, diminish after the measurement by the factor of order of \( E^*/(\rho V^2 N_f) \), which is very small in the Kondo regime.

Experimentally, this effect can be checked with the “quantum corral” setup [6], by putting, e.g., a cerium atom on the metallic surface in the focus of an elliptic “quantum corral”. Due to interaction with the \( f \)-electrons of Ce, the spectrum of conduction electrons exhibits the Fano (anti)resonance which can be observed by an STM tip placed at the other focus of the elliptic corral. The charge state of the Ce atom can be measured, e.g. by a point contact, placed near the atom (as has been analyzed in Ref. [21]). Immediately after the measurement of the Ce atom, the amplitude of the Fano resonance should drop drastically. Instead of the Ce atom, a magnetic impurity can also be used, but it seems easier to measure the charge of the ion rather than its magnetic moment. Another possibility is to employ the optically induced Kondo effect, which could be generated by a circularly polarized light in a system with an impurity level located in the Fermi sea, e.g. in a Si-doped GaAs/AlGaAs superlattice with Be impurity, as has been analyzed in Ref. [21]. The state of the impurity spin can be measured by a circularly polarized probe beam: once the probe photon is absorbed, the state of the impurity is determined uniquely by the angular momentum conservation. The disappearance of the Fano resonance can be detected, e.g. by X-ray absorption.

But it might be more feasible to employ the Kondo effect in quantum dots [4][5], where the bath of environmental degrees of freedom decoheres the central spin, thus working in essentially the same manner as a measuring device. Indeed, as the results above show, the spectral weight of the Abrikosov-Suhl resonance is determined by the non-zero value of the non-diagonal element of the density matrix \( \langle 0 | \rho | 1 \rangle = \langle 0 | \Psi_0 \rangle \langle \Psi_0 | 1 \rangle \neq 0 \) (see Eq. [3]). The interaction \( \mathcal{V} \) between the dot and the bath reduces the value of \( \langle 0 | \rho | 1 \rangle \) [11][12][13], since the bath entangles with the quantum dot, and destroys the quantum correlations between the dot and the conduction electrons. When \( \mathcal{V} \) is strong enough to make \( \langle 0 | \rho | 1 \rangle \) negligible, we have \( \rho_f = a_1 |0\rangle \langle 0| + a_2 |1\rangle \langle 1| \) and, as shown above, the Kondo effect is destroyed.

In the destruction of the Kondo effect by a decohering action of an external microwave field has been considered.

“Fermi sea” state \(|0\rangle\):

\[
E_0 = \Gamma (E_0) \equiv V^2 N_f \sum_{k < k_F} \frac{1}{E_0 + \epsilon_k - \epsilon_f}. \tag{4}
\]
in Ref. [13]. However, the external radiation works similar to increasing temperature, smearing the Kondo effect, and represents an effect of dissipation. In contrast to dissipation, the decoherence caused by the measurement leads to the pure decrease of the amplitude of the resonance (in $1/Z = 1 - (n_j)$ times), without any smearing. The difference between decoherence and dissipation is one of the most important points in the modern theory of decoherence [13].

Here, we consider decoherence by a spin bath [22], which allows a clear demonstration of the dissipation-less suppression of the Kondo effect. Such a bath can be implemented in experiments by doping GaAs with manganese (so that the magnetic moments of Mn ions form the bath) or chromium impurities. The interaction between the spins of impurities is weak but not negligible: it determines the chaotic (or close to chaotic) dynamics of the bath, and our results show that this is a qualitatively important detail. Rigorous treatment of this problem is very difficult, but qualitative features of decoherence of a Kondo system can be studied by representing the spin state of the subsystem of conduction electrons by a single collective spin $1/2$. I.e., instead of the Hamiltonian (1), state of the subsystem of conduction electrons by a single Kondo system can be studied by representing the spin of the dot (so that the magnetic moments of Mn ions form the bath) or chromium impurities. The interaction between the spins of impurities is weak but not negligible: it determines the chaotic (or close to chaotic) dynamics of the bath, and our results show that this is a qualitatively important detail. Rigorous treatment of this problem is very difficult, but qualitative features of decoherence of a Kondo system can be studied by representing the spin state of the subsystem of conduction electrons by a single collective spin $1/2$. I.e., instead of the Hamiltonian (1), we consider a qualitatively similar Hamiltonian

$$H = JS_1S_2 + \sum_{j=1}^{N} A_j I_j + H_B$$

which describes essentially the same physics as (1). Here, $S_1$ is the spin of the quantum dot ($S_1 = 1/2$), $S_2$ represents the collective spin of the conduction electrons ($S_2 = 1/2$), $I_j$ are the environmental spins ($I_j = 1/2$), and $A_j$ are the coupling constants of the spin of the dot $S_1$ with the bath spins. The Hamiltonian $H_B$ describes the chaotic dynamics of the bath.

Both Hamiltonians (1) and (8) predict a singlet ground state in the absence of the bath; the energy scales of the Hamiltonians match, since the parameter $J > 0$ is the renormalized (effective) coupling of the spin of the dot with the conduction electron subsystem, i.e., $J = E^7 \sim T_K$ (so $J \ll J_{ad}$). The entanglement between $S_1$ and $S_2$ can be described using the reduced density matrix $\rho = \text{Tr}_{\{I\}} W$, where $W$ is the density matrix of of the whole system (the two central spins $S_{1,2}$ plus all the bath spins), and the trace is taken over the bath spins $\{I\}$. The entangled singlet state of the quantum dot and the conduction electrons (where the Kondo effect is maximal) corresponds to the non-diagonal element $\rho_{12} = \langle \uparrow \downarrow | | \rho | \downarrow \uparrow \rangle = -1/2$. The decay of entanglement between $S_1$ and $S_2$ is characterized by a decrease of the absolute value of $\rho_{12}$. When $\rho_{12}$ vanishes, the Kondo effect disappears.

We study this process by direct numerical solution of the compound “system-plus-bath” time-dependent Schrödinger equation with the Hamiltonian (8). Initially, the system and the bath are in an uncorrelated product state. The initial state of the Kondo system is the singlet. The initial state of the bath is a random superposition of all basis states, which corresponds to low-temperature experiments when the temperature $J \gg T \gg A_j$. The chaotic dynamics of the bath has been simulated by using the form of $H_B$ suggested in [24], the level statistics has been checked to agree with the Wigner-Dyson distribution. The number of the bath spins has been varied from $N = 12$ to $N = 6$, and different sets of $A_j$ have been used. The results of a sample run are shown in Fig. 1(a). Decoherence dynamics of the Kondo system and the decay of the element $\rho_{12}$ are clearly seen.

The simulations illustrate the dynamics of the measurement process, which starts from the singlet state of the Kondo system. For the quantum dot with magnetic impurities, this dynamics is not relevant (since the initial product state is not realistic), but the final quasi-equilibrium state is absolutely meaningful, giving the correct value of $\rho_{12}$. This value, as well as general features of the system’s evolution, is stable with respect to considerable changes in the parameters of $H_B$, number of spins, values of $A_j$, or variation of the initial conditions. Thus, the final state of the system represents the “pointer state” [10, 11] which is robust with respect to decoherence.

The equilibrium value of $\rho_{12}$ is determined by a competition between the exchange constant $J$ and the strength of the system-bath interaction. Analysis similar to [24] suggests that the relevant quantity characterizing the system-bath coupling is the mean-square exchange $b = \sqrt{\sum_j A_j^2}$, so the final value of $\rho_{12}$ is determined by the ratio $J/b$. Our results show that this is correct (see Fig. 1(b)): the results obtained with different number of the bath spins $N$, different sets of $A_j$, and different values of $J$, fall close to a universal curve $\rho_{12}(J/b)$. The scatter is moderate, stemming from the finite value of $N$ and fluctuations present in the final state (Fig. 1(a)).

The suppression of the Kondo effect as a function of
$J/b$ is gradual, and the center of the transition corresponds to $J/b \approx 0.3$. For typical quantum dots $3$, $J \approx T_K \approx 0.4$ K, and $A_i \sim I/n$ where $n \sim 10^7$ is the total number of the lattice sites inside the dot and $I \sim 1$ eV is the exchange of the impurity spin with the electron of the dot (the factor $1/n$ originates from the normalization of the wave function of the electron in the quantum dot). Thus, $b \sim \sqrt{m_1 I/n}$ where $n_i$ is the number of impurities in the dot. At large concentrations $x = n_i/n \sim 0.01$, Mn impurities in GaAs order ferromagnetically $25$, and our model becomes invalid (impurities no longer form a spin bath), but for other ions, such as Fe $26$, the critical concentration is larger, and $x \sim 0.01$ is acceptable. Therefore, in realistic systems $b \sim 0.1$-0.3 K, and the ratio $T_K/b \sim 0.3$ is easily achievable, so that an experimental check of our predictions is possible. The experiment is rather straightforward: several Fe- or Mn-doped samples with different impurities concentration should be prepared, and the Kondo-anomaly should be measured, similar to $3$. The Kondo effect can be suppressed further by reducing the size of the dot (since the ratio $J/b$ is proportional to $n$, i.e. the volume of the dot).

Note that doping of the dot with non-magnetic impurities having internal degrees of freedom, e.g. with Ce atoms, will suppress the Kondo effect in exactly the same manner. Another possibility is to use a double quantum dot system $27$, where the Kondo effect changes due to the presence of the “orbital” (right or left dot) degree of freedom, in addition to the spin of the dots. The measurement of the electron presence in a given dot $20$ will bring the Kondo effect to the single dot regime.

Summarizing, we have shown that the quantum measurement of the spin in a Kondo system suppresses the Abrikosov-Suhl resonance and destroys the Kondo effect. This suppression is caused by the decohering influence of the measuring apparatus, and does not involve dissipation, i.e. it is qualitatively different from the dissipative suppression of the Kondo effect $13$. The effect predicted here can be studied in realistic experiments on quantum dots doped with magnetic (Mn, Cr) or non-magnetic (Ce) impurities, where the bath of impurities decoheres the Kondo system in the same way as a measuring device. The estimates show that such an experiment is already achievable with today’s experimental techniques.

This work was partially carried out at the Ames Laboratory, which is operated for the U. S. Department of Energy by Iowa State University under Contract No. W-7405-82 and was supported by the Director of the Office of Science, Office of Basic Energy Research of the U. S. Department of Energy. Support from the Dutch “Stichting Nationale Computer Faciliteiten (NCF)” is gratefully acknowledged. This work was partially supported by Russian Science Support Foundation.

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