Irradiation-induced Kondo resonance in two-dimensional electron systems

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Abstract. We demonstrated theoretically that formation of the resonant scattering states in the two-dimensional (2D) electron system irradiated by a circularly polarized electromagnetic field leads to the emergence of localized magnetic moments. As a consequence, the corresponding Kondo resonances appear. For GaAs-based quantum wells and microwave fields, we estimate the Kondo temperature around 2.5 K, which can be detected in state-of-the-art measurements.

1. Introduction
In 1964 paper [1], Jun Kondo suggested the mechanism responsible for the minimum in the temperature dependence of the resistivity of noble divalent metals, the effect which had remained a mystery for more than three decades [2]. Within the model proposed by him, the conduction electrons interact antiferromagnetically with the localized magnetic impurities leading to the log(T) corrections to the relaxation time. It has been soon demonstrated that the low energy physics of the Kondo effect shows universality and is characterized by a single energy scale \(T_K\), Kondo temperature. Therefore, it can be effectively treated by the methods of the renormalization group theory [4]. Particularly, the Kondo physics is appropriate to describe the transformation of ground states when going from the high energy range to the low energy one. The concept of the Kondo resonance was later applied to the systems containing the dense arrays of magnetic impurities [5, 6] which triggered the research of the Kondo insulators and heavy fermion systems in condensed matter physics [7, 8].

The Kondo temperature is defined by the effective on-site Coulomb repulsion of impurity atoms, hybridization of the conduction and impurity electrons, and the relative position of their resonant energy with respect to the Fermi level. While these parameters are fixed in the bulk materials, they can be effectively tuned in nanodevices. Since the first demonstration of the Kondo effect in quantum dots [9], the tunable Kondo effect in nanostructures become an excited field of research [10, 11, 12]. While the tuning of Kondo temperature is usually achieved by the gate voltage, in the present research we show that the Kondo effect can be switched on and off by means of the off-resonant electromagnetic field. Manipulation of the properties of the condensed matter systems by an off-resonant electromagnetic field (the Floquet engineering) became an established research field with a plethora of illuminating fundamental effects [13], including numerous field-induced phenomena predicted and observed in various nanostructures [14, 15, 16, 17, 18]. Particularly, it has been recently shown that the irradiation
of 2D electron systems with an off-resonant circularly polarized field leads to the formation of the quasi-stationary electron states localized at repulsive impurities [19, 20, 21]. Noteworthy, the parameters of these states can be effectively controlled by the irradiation. In the following, we explore the possibility of the formation of the Kondo effect mediated by these light-induced electron states.

2. Model

![Diagram](image)

**Figure 1.** (a) Geometry of the problem: The irradiation leads to the transformation of the repulsive delta potential to the cylindrical potential barrier with the radius \( r_0 \). If the resonant electron energy \( \varepsilon_s \) lies below the Fermi level \( \mu \) and the repulsive Coulomb energy \( U \) for electrons in the localized state is large enough, the singly occupied resonant state may become the ground state which leads to the formation of localized magnetic moment and emergence of the Kondo resonance; Effect of the circularly polarized irradiation with the frequency \( \omega/2\pi = 200 \) GHz and the intensity \( I \) on (b) the effective hole and electron bandwidths \( D_{h,e} \) and (c) the Kondo temperature in a GaAs-based QW filled by 2D electron gas with the Fermi energy \( \varepsilon_F \) = 5 meV, energy broadening \( \Gamma_s = 0.1\varepsilon_s \) and the electron effective mass \( m_e = 0.067m_0 \) (\( m_0 \) is the free electron mass) for the zero temperature. The blue shadow areas mark the validity range of the model, where the applicability conditions are satisfied for both the Kondo Hamiltonian (\( \Gamma_s \ll D_{h}, D_{e} \)) and the dressed potential approach (\( \varepsilon_s \ll \hbar \omega \)).

Assuming the parabolic dispersion of electrons with the effective mass \( m_e \), let us consider the 2D electron system with repulsive impurities irradiated by a circularly polarized electromagnetic field (see Fig. 1a). Under action of the field, the repulsive delta potential of the impurities, \( u_0\delta(r) \), turns into the effective cylindrical potential barrier \( u_0\delta(r - r_0)/2\pi r_0 \) with the radius \( r_0 = eE_0/(m_0\omega^2) \), where \( E_0 \) is the field amplitude and \( \omega \) is the field frequency [19, 20]. This barrier supports the quasi-stationary electron states localized inside the barrier (\( r < r_0 \)), where the energy \( \varepsilon_s \), the broadening \( \Gamma_s \), and the wave function \( \psi_s \) of the lowest of the states read [20] \( \varepsilon_s = \hbar^2 \xi_0^2/2m_e r_0^2 \), \( \Gamma_s = 2\varepsilon_s\alpha^2/N_0(\xi_0)J_1(\xi_0) \) and \( \psi_s(r) = \theta(r_0 - r)J_0(\xi_0r/r_0)/\sqrt{\pi r_0}J_1(\xi_0) \).

Where \( J_n(\xi) \) and \( N_n(\xi) \) are the Bessel functions of the first and second kind, respectively, \( \xi_0 \) is the first zero of the Bessel function \( J_0(\xi) \), and \( \theta(r) \) is the Heaviside function. The dressing field approach which omits the time dependence of the Hamiltonian is valid when \( \hbar \omega \gg \varepsilon_s \). Due to the semi-transparent nature of the barrier, the conduction electrons with the energy \( \varepsilon_k = \hbar^2k^2/2m_e \) may tunnel in and out of the resonant state with the energy \( \varepsilon_s \). Therefore, the electron system can be described by the tunnel Hamiltonian \( H_T = \sum_{k}\varepsilon_k(\hat{c}_k^\dagger\hat{c}_k - \mu) + \sum_\sigma(\varepsilon_s - \mu)\hat{d}_\sigma\hat{d}_\sigma + \sum_{k,\sigma}T_k\hat{c}^\dagger_{k,\sigma}\hat{d}_\sigma + \text{H.c.} \), where \( \hat{c}_{k,\sigma}^\dagger \) (\( \hat{c}_{k,\sigma} \)) are the production (annihilation) operators for conduction electron states, \( \hat{d}_\sigma^\dagger (\hat{d}_\sigma) \) are the production (annihilation) operators for the light-induced localized electron states, \( \sigma = \uparrow, \downarrow \) is the spin projection, \( \mu \) is the chemical potential, \( T_k \) is the tunneling amplitude which reads \( T \approx \sqrt{\Gamma_s/\pi N_\varepsilon} \) near the tunnel resonance (\( \varepsilon_s = \varepsilon_k \)) in the case of weak tunneling, and \( N_\varepsilon = S m_e/(\pi \hbar^2) \) is the density of conduction electron states.
To access the Kondo physics, we have to take into account the Coulomb interaction of the localized electrons by adding the Hamiltonian \( H_C = U \hat{d}_\uparrow \hat{d}_\downarrow \) to the tunnel Hamiltonian \( H_T \), where \( U \approx \gamma e^2/(\epsilon r_0) \) is the effective Coulomb energy of the localized electrons, \( \epsilon \) is the static permittivity of the material, and \( \gamma \approx 0.8 \). The total Hamiltonian \( H = H_T + H_C \) describes the famous Anderson impurity model. Within this model, the Coulomb repulsion of impurity electrons lifts energy of the doubly occupied state and forms the spin-polarized singly occupied ground state (see Fig. 1a). Neglecting the interaction between the localized states and the conduction electron continuum, there are three eigenstates of the Hamiltonian \( H_T \) pictured schematically in Fig. 1a: (i) the empty state \( | \rangle \) with the energy \( \mu \); (ii) the singly occupied state \( | \uparrow \rangle + | \downarrow \rangle \) with the energy \( \varepsilon_s - \mu \); (iii) the doubly occupied state \( | \uparrow \downarrow \rangle + | \downarrow \uparrow \rangle \) with the energy \( 2(\varepsilon_s - \mu) + U \). The Kondo physics originates due to the emergence of the local magnetic moments at the localized electron state in the low energy range. This happens if the singly occupied resonant state \( \varepsilon_s \) has the lowest energy, i.e. for \( \varepsilon_s - \mu < 0 \) and \( U > \mu - \varepsilon_s \). Since \( U \) and \( \varepsilon_s \) differently depend on the irradiation intensity \( I \), there exists a range of field amplitudes for which the singly occupied state has the lowest energy. Namely, \( r_0 \) should satisfy the condition

\[
\sqrt{\frac{\hbar^2 \varepsilon_s^2}{2m_e \mu}} < r_0 < \frac{\gamma e^2}{2\epsilon r_0} + \sqrt{\frac{\varepsilon_s^2}{2\epsilon r_0} + \left( \frac{\gamma e^2}{2\epsilon r_0} \right)^2}.
\]

If the single occupied state has the lowest energy, we can use the Schreiffer-Wolff (SW) transformation to project the Anderson impurity model to the Kondo model, yielding [22] \( H_K = \sum_{k,\sigma}(\varepsilon_k - \mu) \hat{c}_{k,\sigma} \hat{c}_{k,\sigma} + J \hat{\sigma}(0) \cdot \hat{S}_s - \frac{\sqrt{\pi N_e}}{2} \hat{\psi}^{\dagger}(0) \hat{\psi}(0) \), where \( \hat{\psi}(0) = \sum_k \hat{c}_{k,\sigma}, \hat{\sigma}(0) = \hat{\psi}^{\dagger}(0) \hat{\sigma} \hat{\psi}(0), \)

\[
\hat{S}_s = \hat{d}^{\dagger} (\hat{\sigma}/2) \hat{d},
\]

and the coupling coefficients \( J \) and \( V \) read

\[
J = \frac{\Gamma_s}{\pi N_e} \left[ D_e^{-1} + D_h^{-1} \right], \quad V = \frac{\Gamma_s}{2\pi N_e} \left[ D_e^{-1} - D_h^{-1} \right].
\]

Here \( D_e = \mu - \varepsilon_s \) and \( D_h = U + \varepsilon_s - \mu \) define the energies of electron-like and hole-like excitations due to the tunnelling and, therefore, should be treated as the effective bandwidth of the model. It is essential for the following that the SW transformation is applicable only if \( \Gamma_s \ll D_e, D_h \). It should be noted also that the system under consideration corresponds to the Kondo model with the broken electron-hole symmetry.

3. Results and discussion

The dependence of the bandwidths \( D_{e,h} \) on the irradiation intensity, \( I \), is plotted in Fig. 1b for GaAs-based quantum well with the electron effective mass \( m_e = 0.067 m_0 \), where \( m_0 \) is the free electron mass. The region, where the SW transformation is applicable and the Kondo effect is expected, is marked by the shadow. Since the typical Kondo temperature is essentially smaller than the conduction bandwidth \( 2D_0 \approx 3eV \) (for GaAs), one needs to transform the initial high-energy Hamiltonian to the low-energy range in order to find the Kondo temperature. Such a transformation can be performed within the poor man’s scaling renormalization approach [24, 25], which was originally proposed by Anderson. Within this approach the higher energy excitations are integrated out which changes the effective bandwidth \( D \) and the corresponding couplings \( J(D), V(D) \). The renormalized coupling constant \( J(D) \) diverges at some critical bandwidth \( D = D_K \) associated with the Kondo temperature \( T_K = D_K \).

The only difference of the considered system from the original Kondo problem [3] is the strong electron-hole asymmetry since the typical Fermi energy in GaAs-based QWs is \( \varepsilon_F < D_0 \). As a consequence, for \( D > \varepsilon_F \) only the second order process involving a virtual electron should be taken into account. On the contrary, the both electron and hole processes contribute to the effective coupling rescaling for the case of \( D < \varepsilon_F \). Applying the known general solution of the
asymmetric electron-hole Kondo problem [26] to the considered system, we arrive at the Kondo temperature

\[ T_K = \varepsilon_F \exp \left( -\frac{1}{2\pi N_\varepsilon J'(\varepsilon_F)} \right). \]  

(3)

where

\[ J'(\varepsilon_F) = \frac{J}{\left[ 1 + \frac{\pi N_\varepsilon}{2} \ln \frac{D_0}{\varepsilon_F} (J + V) \right] \left[ 1 - \frac{\pi N_\varepsilon}{2} \ln \frac{D_0}{\varepsilon_F} (3J - V) \right]} . \]  

(4)

In Fig. 1c we plot the dependence of the Kondo temperature on the irradiation intensity for the same GaAs-based quantum well.

4. Conclusion

It is shown theoretically that the circularly polarized irradiation of two-dimensional electron systems can induce the Kondo effect. It follows from the present analysis that the Kondo temperature reaches the value of several K in semiconductor quantum wells, which allows to observe the effect experimentally in the state-of-the-art measurements.

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References

[1] Kondo J 1964 Progress of Theoretical Physics 32 37
[2] de Haas W J, de Boer J and van den Berg G J 1934 Physica 1 1115
[3] Anderson P W 1961 Physical Review 124 41
[4] Wilson K G 1973 Review of Modern Physics 47 773
[5] Steglich F, Aarts J, Bredl C D, Lieke W, Meschede D, Franz F and Schäfer H 1979 Physical Review Letters 43 1892
[6] Andres K, Graebner J E and Ott H R 1975 Physical Review Letters 35 1779
[7] Tsunetsugu H, Sigrist M and Ueda K 1993 Physical Review B 47 8345
[8] Stewart G R 1973 Review of Modern Physics 47 773
[9] Goldhaber-Gordon D, Göres J, Kastner M A., Shtrikman H, Mahalu D and Meirav U 1998 Physical Review Letters 81 5225
[10] Cronenwett S M, Oosterkamp T H and Kouwenhoven L P 1998 Science 281 540
[11] Park J, Pasupathy A N, Goldsmith J I, Chang C, Yaish Y, Petta J R, Rinkoski M, Sethna J P, Abruna H D, McEuen P L and Ralph D C 2002 Nature 417 722
[12] Itikhar Z, Anthore A, Mitchell A, Parmentier F, Gennser U, Ouerghi A, Cavanna A, Mora C, Simon P and Pierre F 2018 Science 360 1315
[13] Basov D N, Averitt R D and Hsieh D 2017 Nature Materials 16 1077
[14] Lindner N H, Refael G and Galitski V 2011 Nature Physics 7 490 (2011).
[15] Rechtsman M C, Zeuner J M, Plotnik Y, Lumer Y, Podolsky D, Dreisow F, Nolte S, Segev M and Szameit A 2013 Nature 496 196
[16] Wang Y H, Steinberg H, Jarillo-Herrero P and Gedik N 2013 Science 342 453
[17] Sie E J, McIver J W, Lee Y H, Fu L, Kong J and Gedik N 2015 Nature Materials 14 290
[18] McIver J W, Schulte B, Stein F U, Matsuyama T, Jotzu G, Meier G and Cavalleri A 2020 Nature Physics 16 38
[19] Kibis O V 2019 Physical Review B 99 235416
[20] Kibis O V, Boev M V and Kovalen V M 2020 Physical Review B 102 075412
[21] Kibis O V, Kolodyny S A and Iorsh I V 2021 Optics Letters 46 50
[22] Coleman P 2015 Introduction to many-body physics (Cambridge: Cambridge University Press)
[23] Riseborough P S and Lawrence J M 2016 Reports on Progress in Physics 79 084501
[24] Anderson P W 1970 Journal of Physics C: Solid State Physics 3 2436
[25] Anderson P W 1973 Comments on Solid State Physics 5 73
[26] Zitko R and Hovrat A 2016 Physical Review B 94 125138