Pseudospin-Resolved Transport Spectroscopy of the Kondo Effect in a Double Quantum Dot


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We report measurements of the Kondo effect in a double quantum dot, where the orbital states act as pseudospin states whose degeneracy contributes to Kondo screening. Standard transport spectroscopy as a function of the bias voltage on both dots shows a zero-bias peak in conductance, analogous to that observed for spin Kondo in single dots. Breaking the orbital degeneracy splits the Kondo resonance in the tunneling density of states above and below the Fermi energy of the leads, with the resonances having different pseudospin character. Using pseudospin-resolved spectroscopy, we demonstrate the pseudospin character by observing a Kondo peak at only one sign of the bias voltage. We show that even when the pseudospin states have very different tunnel rates to the leads, a Kondo temperature can be consistently defined for the double quantum dot system.

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The Kondo effect describes how itinerant electrons with a degenerate degree of freedom screen a localized state with the same degeneracy.

Nanostructures allow the realization of the Kondo effect based on orbital degeneracy. The advantage to using an orbital degeneracy is its potential to realize a fully tunable state-resolved probe of Kondo physics that does not perturb the Kondo correlations, which is not possible in spin-based Kondo systems.
AlGaAs/GaAs
\( \mu: 2 \times 10^6 \text{ cm}^2/\text{V s} \)
\( n: 2 \times 10^{11} \text{ cm}^{-2} \)

- Interdot tunneling negligible
- \( \Gamma_{1,2}/U \approx 0.13 \) (no Kondo)
- \( \Gamma_{1,2}/U \approx 0.24 \) (Kondo peak visible)
\[ \mu_1 = -e(\alpha_{P1}\Delta V_{P1} + \xi_{1,P2}\Delta V_{P2} + \alpha_{S1}V_{S1} + \xi_{1,S2}V_{S2}) \]

\[ \left( \frac{E}{\delta} \right) = \frac{1}{2} \left( \frac{\mu_1 + \mu_2}{\mu_1 - \mu_2} \right) \]

\[ \frac{-2}{e} \left( \frac{E}{\delta} \right) = \left( \frac{\alpha_{P1} + \xi_{2,P1}}{\alpha_{P1} - \xi_{2,P1}} \right) \left( \frac{\alpha_{P2} + \xi_{1,P2}}{\alpha_{P2} - \xi_{1,P2}} \right) \left( \frac{\Delta V_{P1}}{\Delta V_{P2}} \right) \]

\[ + \left( \frac{\alpha_{S1} + \xi_{2,S1}}{\alpha_{S1} - \xi_{2,S1}} \right) \left( \frac{\alpha_{S2} + \xi_{1,S2}}{\alpha_{S2} - \xi_{1,S2}} \right) \left( \frac{V_{S1}}{V_{S2}} \right) \]
Double Dot Coulomb Diamonds

\[ \mu_1(1,0): \]
adding one electron onto dot1 when dot2 contains 0 electron.

\[ \mu_2(1,1): \]
adding a 2nd electron onto dot2 when dot1 contains the 1st electron.
Spin-1/2 Kondo in a B field

(a) In B field, no Kondo enhancement at zero bias
(b) Kondo enhancement at $V_{S,\uparrow}=+E_Z/e$
(c) No Kondo enhancement at $V_{S,\uparrow}=(-E_Z/e)$

(d,e) Spin-dependent is not resolved in single dot spin Kondo.
Pseudospin-Resolved Bias Spectroscopy

- Pseudo-Zeeman splitting: \( E_{\text{PZ}} = 2\delta \)
- Kondo peak at \( V_{S1} = +E_{\text{PZ}} \)
- No peak at \( V_{S1} = (-E_{\text{PZ}}) \) !!
$E_{pZ}=0$ features in $V_{S2}$ scan

- An electron on dot 1 can tunnel onto the dot into D1, and an electron can tunnel onto dot 2 from D2. This maintains energy conservation and results in a pseudospin flip.

- The electron can then tunnel from dot 2 back to D2, while an electron tunnels back onto dot 1 from S1.

- This type of process (as well as higher order processes) lead to an enhanced conductance through dot 1, but does not give transport through dot 2.
Pseudospin dependent measurement

\[ \frac{\Gamma_2}{\Gamma_1} \approx 2.4 \]

- \( \Gamma_1 < \Gamma_2 \): tunneling rates are pseudospin dependent (contacting with a ferromagnetic leads)

Single T\(_K\) scale can be defined across both pseudospin components, even with very asymmetric coupling.

\[ E_1 = E + \delta \]
\[ E_2 = E - \delta \]
Summary

- Pseudospin-resolved spectroscopy of a DQD shows the pseudospin dependence of the split Kondo resonance.
- $T_K$ is well defined in the pseudospin system.
- Demonstrate the unique capabilities of DQDs to probe the many-body Kondo state.