Observation of the Kondo Effect in a Spin-$\frac{3}{2}$ Hole Quantum Dot

O. Klochan, A. P. Micolich, A. R. Hamilton, K. Trunov, D. Reuter, and A. D. Wieck

1 School of Physics, University of New South Wales, Sydney NSW 2052, Australia
2 Angewandte Festkörperphysik, Ruhr-Universität Bochum, D-44780 Bochum, Germany

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We report the observation of Kondo physics in a spin-$\frac{1}{2}$ hole quantum dot. The dot is formed close to pinch-off in a hole quantum wire defined in an undoped AlGaAs/GaAs heterostructure. We clearly observe two distinctive hallmarks of quantum dot Kondo physics. First, the Zeeman spin splitting of the zero-bias peak in the differential conductance is independent of the gate voltage. Second, this splitting is twice as large as the splitting for the lowest one-dimensional subband. We show that the Zeeman splitting of the zero-bias peak is highly anisotropic and attribute this to the strong spin-orbit interaction for holes in GaAs.
Introduction: Kondo

Low temperature resistivity of Au

(from W.J. de Haas and G.J. van den Berg, Physica vol. 3, page 440, 1936)
Kondo in QDs

SCIENCE VOL 281 24 JULY 1998

S. Cronenwett et. al
Unresolved QPC Features

- 0.7 anomaly
- Bound states $G < 2e^2/h$
- ZBP, but no bound state

References:
- Y. Komijani et al., EPL, 91 (2010) 67010
- Liu et al., PHYSICAL REVIEW B 84, 075320 (2011)
Kondo effect in 2DHS

- Most existing Kondo experiments conducted with electrons (spin 1/2)

- Same experiments achievable with holes
  - Behave like spin 3/2 particles due to strong spin-orbit coupling:
    - Conduction band: \( l = 0, s = 1/2 \) \( \rightarrow j = 1/2 \)
    - Valence band: \( l = 1, s = 1/2 \) \( \rightarrow j = 3/2 \) & \( j = 1/2 \)

- Better model system for strongly correlated (bulk) systems
GaAs Hole Quantum Dot

- Non-modulation doped heterostructure
- Holes induced by applying a voltage on the carbon doped top layer
  - $p = 2 \times 10^{11} \text{cm}^{-2}$, $\mu = 450'000 \text{ cm}^2/\text{Vs}$ for $V_{\text{TG}} = -0.67 \text{ V}$
- 300x300 nm quantum wire
- Defined by etching of the doped layer
- Two side gates to control the width/position of the channel
- Quantum dot formation for $V_{\text{TG}}$ near pinch-off due to wall roughness
Ballistic channel closed by applying side gate voltage

For $G<2e^2/h$: QD formation due to edge roughness/microscopic deviations in confinement potential

Bound state regime -> singlet Kondo
ZBP Stability

- ZBP stable under channel displacement (~120 nm)
  - No random impurity effect
ZBP due to Kondo?

- Zero-bias peak clearly visible for \( G < 2e^2/h \), disappearing for higher \( G \)

- Temperature dependence: ZBP vanishing for increasing \( T \)
ZBP due to Kondo?

- $B_\parallel$: splitting of the ZBP ($\Delta = 2g^*\mu_B$)
  
  $\rightarrow g^* = 0.23 \pm 0.05$

- $g^* = 0.236 \pm 0.012$

- $B_\perp$: ZBP vanishing
  
  $\rightarrow$ high anisotropy of $g^*$
ZBP due to Kondo?

- $B_{\|}$: splitting of the ZBP ($\Delta=2g^{*}\mu B$)
  \[\Rightarrow g^{*}=0.23\pm0.05\]

- $B_{\perp}$: ZBP vanishing
  \[\Rightarrow g^{*}=0.236\pm0.012\]

- High anisotropy of $g^{*}$
ZBP due to Kondo?

- “Smoking Gun” argument for Kondo:

  Kondo is a Spin effect -> splitting in B-field independent of gate voltage

![Graph showing G vs V_{SD} for different B_{ll} values. The graph shows multiple traces for different B_{ll} values, with B_{ll}=8T highlighted.]
Summary

- Stable electrostatic hole quantum dot formed in a quantum point contact on a GaAs/AlGaAs heterostructure
- QPC shows same behavior like electron systems
- Gate independent ZBP observed, in agreement with QD formation (Kondo singlet formation)
- Extraction of $g^*$ from ZBP splitting with $B_{\parallel}$
- $g^*$ measurement of 1d channels
  - ZBP splitting 2x larger than subband splitting
  - Large $g^*$ anisotropy
- No connection to 0.7 structure found