Odd and even Kondo effects from emergent localization in quantum point contacts


Microscopic origin of the ‘0.7-anomaly’ in quantum point contacts

Florian Bauer, Jan Heyder, Enrico Schubert, David Borowsky, Daniela Taubert, Benedikt Bruognolo, Dieter Schuh, Werner Wegscheider, Jan von Delft & Stefan Ludwig
Conductance quantization in 1D

GaAs Quantum point contacts (Quantum Hall effect)

exact cancellation
1D density of states
electron velocity
vs. electron number
ballistic (no disorder)
non-interacting

2-terminal conductance

number of modes
spin degeneracy

\[ g = N \cdot \frac{2e^2}{h} \]

Landauer quantization

van Wees et al., PRL1988
Wharam et al., JPC1988
Conductance quantization in 1D

\[ E(n, k) = \frac{\hbar^2 k^2}{2m^*} + \left(n + \frac{1}{2}\right) \hbar \omega_0, \quad n = 0, 1, 2, \ldots \]

\[ I = e \sum_{n=1}^{N} \int_{\mu_d}^{\mu_s} dE \frac{1}{2} \rho_n(E) v_n(E) T_n(E) \]

\[ G = \frac{2e^2}{\hbar} \sum_{n=1}^{N} T_n(E_F) \]

if (ballistic) \[ \sum_{n=1}^{N} T_n(E_F) = 1 \]

\[ G = \frac{2e^2}{\hbar} N. \]
van Wees et al., PRL1988
Possible Spin Polarization in a One-Dimensional Electron Gas

K. J. Thomas, J. T. Nicholls, M. Y. Simmons, M. Pepper, D. R. Mace, and D. A. Ritchie

Cavendish Laboratory, Madingley Road, Cambridge CB3 OHE, United Kingdom
(Received 4 March 1996)

In zero magnetic field, conductance measurements of clean one-dimensional (1D) constrictions defined in GaAs/AlGaAs heterostructures show up to 26 quantized ballistic plateaus, as well as a structure close to 0.7(2e^2/h). In an in-plane magnetic field all the 1D subbands show linear Zeeman splitting, and in the wide channel limit the g factor is |g| = 0.4, close to that of bulk GaAs. For the last subband, spin splitting originates from the structure at 0.7(2e^2/h), indicating spin polarization at B = 0. The measured enhancement of the g factor as the subbands are depopulated suggests that the “0.7 structure” is induced by electron-electron interactions. [S0031-9007(96)00520-0]
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Low-Temperature Fate of the 0.7 Structure in a Point Contact:
A Kondo-like Correlated State in an Open System


(d) $T = 80 \text{ mK}, B_{\parallel} = 0 \text{ T}$
(e) $T = 600 \text{ mK}, B_{\parallel} = 0 \text{ T}$
(f) $T = 80 \text{ mK}, B_{\parallel} = 8 \text{ T}$
Low-Temperature Fate of the 0.7 Structure in a Point Contact:  
A Kondo-like Correlated State in an Open System

S. M. Cronenwett,¹,² H. J. Lynch,¹ D. Goldhaber-Gordon,¹,² L. P. Kouwenhoven,¹,³ C. M. Marcus,¹ K. Hirose,⁴  
N. S. Wingreen,⁵ and V. Umansky⁶

\[ g = \frac{2e^2}{h} \left[ \frac{1}{2} f \left( \frac{T}{T_K} \right) + \frac{1}{2} \right] \] 
modified Kondo scaling
Low-Temperature Fate of the 0.7 Structure in a Point Contact:
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N. S. Wingreen,5 and V. Umansky6

(a) B = 0 T

(b) |Vg| (mV)

0 80 mK
4.1 K

|T(K)|

0.08
0.21
0.43
0.82
1.6
4.1

Vsd (mV)

g(2e^2/h)

g(2e^2/h)
Microscopic origin of the ‘0.7–anomaly’ in quantum point contacts

Florian Bauer$^{1,2,*}$, Jan Heyder$^{1,2,*}$, Enrico Schubert$^1$, David Borowsky$^1$, Daniela Taubert$^1$, Benedikt Bruognolo$^{1,2}$, Dieter Schuh$^3$, Werner Wegscheider$^4$, Jan von Delft$^{1,2}$ & Stefan Ludwig$^1$

tight binding chain, lowest 1D subband:

\[ \hat{H} = \sum_{j,\sigma} \left[ E_{j,\sigma} \hat{n}_{j,\sigma} - \tau_j \left( d_{j+1,\sigma}^\dagger d_{j,\sigma} + \text{h.c.} \right) \right] + \sum_j U_j \hat{n}_{j,\uparrow} \hat{n}_{j,\downarrow} \]

central constriction region: N sites around j=0.

second order perturbation theory
functional renormalization group (FRG)
spin density functional theory (SDFT)
Van Hove singularity becomes a "ridge"

van Hove singularity smeared out on scale $\Omega_x$ (QPC curvature) followed by Friedel oscillations.
Friedel oscillations (2D)

Coulomb scatterer

\[ V_{ext}(r) = -\frac{Z e}{r} = -\frac{Z e^2}{(2\pi)^3} \int \frac{4\pi}{q^2} e^{i\vec{q}\vec{r}} d\vec{q} \]

induces oscillatory, decaying charge density
(due to superposition of incoming and reflected waves)

\[ V_{eff}(r) = \frac{Ze}{\varepsilon \varepsilon_0} \frac{4k_T F k_F^2}{(2k_F + k_{TF})^2} \frac{\sin(2k_F r)}{2k_F r^2} \]

1D: \( \sin(2k_F r)/r \)
Amplification of interaction effects

saddle point: electrons very slow ($E_{kin}$ small), electron interactions dominant amplifies van Hove ridge, and vice versa
this is the most important effect, and will suffice to explain 0.7 structure

FRG
von Hove ridge: consequences

1. Minimal density \( n_j \) at barrier
2. No magnetization \( m_j \) at \( B=0 \) (assumption: no spontaneous spin pol.)
3. Magnetization for nonzero \( B \)
4. Enhances spin susceptibility \( \chi_j \) (interaction enhances field)
Four predictions of the model, confirmed by exp.

1. \[ \frac{g_{nl}(\tilde{B}, \tilde{T}, \tilde{V}_{sd})}{g_{nl}(0, 0, 0)} \approx 1 - \frac{\tilde{B}^2}{\tilde{B}^2_*} - \frac{\tilde{T}^2}{\tilde{T}^2_*} - \frac{\tilde{V}_{sd}^2}{\tilde{V}_{sd*}^2} \]

2. \( \tilde{B}_*, \tilde{T}_*, \tilde{V}_{sd*} \propto \exp\left( -\pi \tilde{V}_c / \Omega_x \right) \) for \( g_{nl}(0, 0, 0) \approx 1 \)

3. \( \tilde{B}_*/\tilde{T}_* \) and \( \tilde{V}_{sd*}/\tilde{T}_* \) independent of \( \tilde{V}_c \)

4. \( 1/\tilde{B}_* \) roughly proportional to \( \chi_{tot} \)
Four predictions of the model, confirmed by exp.
Van Hove ridge also produces zero bias peak temperature dependence: OK via inelastic scattering at high T (electron – hole creation) reducing transmission at high T

B dependence also OK

high bias plateau at $\frac{1}{4} (2e^2/h)$?
Similarity to Kondo effect (quantum dot)?

Kondo
(quasi) bound state with local (spin) moment
reproduces many (if not all) salient features

von Hove ridge
no discrete, localized (spontaneous) spin
no Kondo/0.7 similarity at high energies

both
similar low energy behavior
screening of localized spin vs. van Hove ridge (spin fluctuations)
this distinction not important at low E (long length scales)
both can be described in the same low E frame work
spontaneously localized spin emerging from Friedel oscillations (Meir et al.)

odd / even Kondo effects, reflecting number of localized spins

length tunable QPCs, giving odd/even oscillations
Double peak zero bias anomaly?!

relatively “short” QPCs
L = 200 nm
W = 350 nm
(expect double peaks)

double peaks
seen in ~50% of devices
consistently over cool downs

authors conclude:
generic, not disorder / impurity
QPC with tunable length
QPC with tunable length

two impurity Kondo effect:
double peak
Temperature and B-field dependence consistent with 2IK
Magnetic impurity form contacts

Tomaž Rejec & Yigal Meir

spin density functional theory including e-e interactions

predicted
2 impurity Kondo
double zero bias peaks
Local density of state

Friedel oscillations

where is van Hove?

spin up

spin down
Kondo Model for the “0.7 Anomaly” in Transport through a Quantum Point Contact

Yigal Meir,1,2,* Kenji Hirose,3 and Ned S. Wingreen1

![Graphical representation of the Kondo Model](image-url)

**Figure (a)**: Graph showing the states $T(\epsilon)$ and $\nu(\epsilon)$.

**Figure (b)**: Graph showing the density $\rho(x)$ and $\rho(x) - \rho(x)_{\parallel}$. The inset shows the potential $V_{QPC}(x,y)$. The main graph shows $\rho(x)_{\parallel}$ and $\rho(x) + \rho(x)_{\parallel}/2$. 

*Note: The image should be interpreted as a scientific diagram representing the theoretical model and its associated parameters.
<table>
<thead>
<tr>
<th>van Hove ridge (and Friedel oscillations)</th>
<th>vs</th>
<th>emergent localized state (from Friedel oscillation)</th>
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<tbody>
<tr>
<td>open, no discrete, localized state</td>
<td></td>
<td>quasi bound state</td>
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<td>enhanced spin susceptibility</td>
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<td>localized spin fluctuations</td>
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<td>Kondo: low E, not high E</td>
<td></td>
<td>Kondo physics</td>
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<tr>
<td>no magnetization</td>
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<td>spin ½ local moment</td>
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<td></td>
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<td>(initialized</td>
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<tr>
<td>consistent with experiment multi peaks?</td>
<td></td>
<td>consistent with more experiments</td>
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<td>(incl. single, double, triple peaks corresponding to # localized spins)</td>
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<tr>
<td>½ (2e2/h) bias plateau?</td>
<td></td>
<td>experimental confirmation localized spins?</td>
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<tr>
<td>1D low n + interactions: ZBA</td>
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<tr>
<td>(in absence of SO and/or SC)</td>
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