Interplay of Ferromagnetism and Coulomb Interaction in Quantum-Dot Spin Valves

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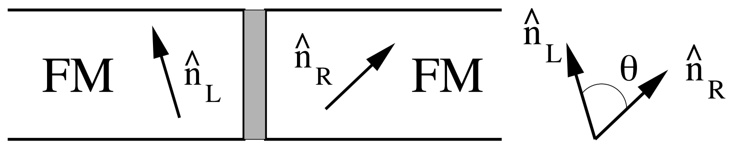
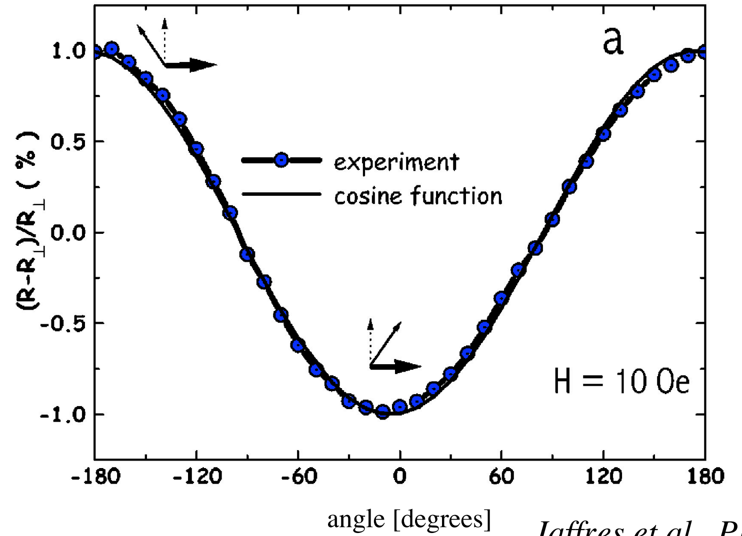
Some Concepts of Spintronics

- angular-dependent tunnel magneto resistance (TMR)

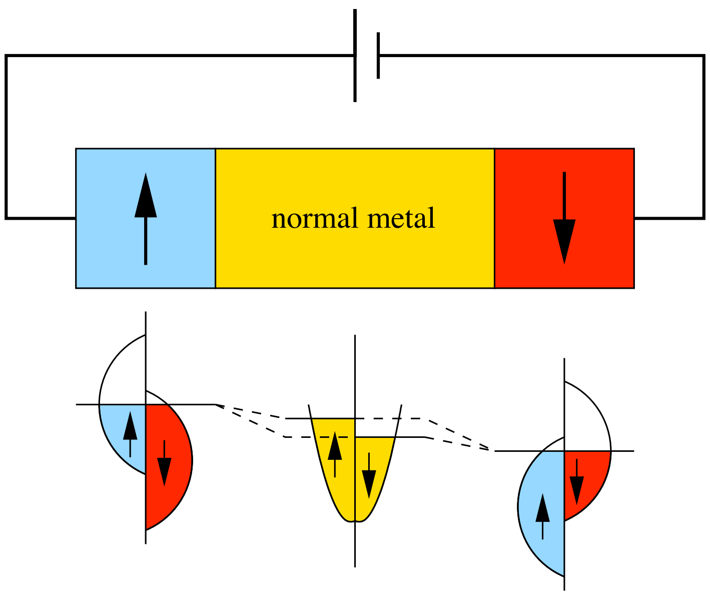


$$\mathrm{TMR}(\theta) = \frac{I^{\mathrm{P}} - I(\theta)}{I^{\mathrm{P}}} = \frac{P^2}{1+P^2}(1-\cos\theta)$$



Jaffres et al., PRB '01

- spin accumulation



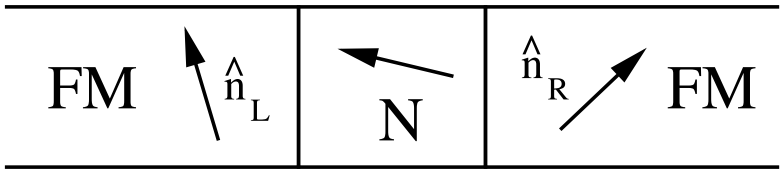
spin accumulation in normal metal

$\Downarrow$

spin-valve effect

Some Concepts of Spintronics

- non-local exchange



– imaginary part of spin-mixing conductance

(Brataas et al., '00, Phys. Rep. '06)

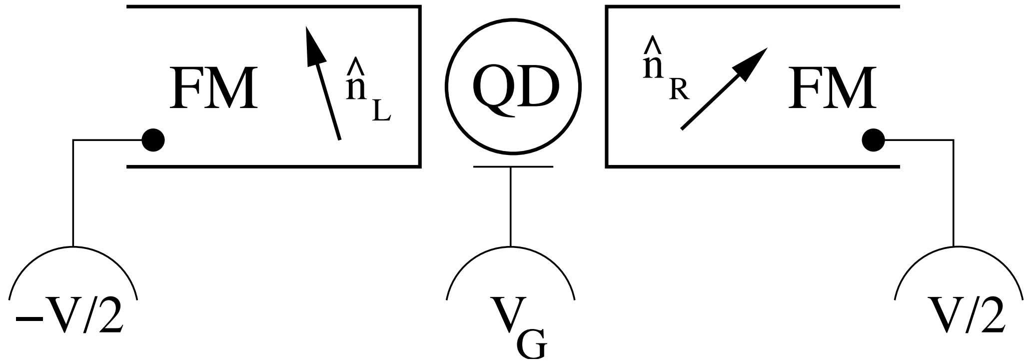
– single-particle spin-dependent interfacial phase shifts

(Brataas et al., Phys. Rep. '06, Cottet et al. '06)

– tunneling induced in FM – LL – FM

(Balents, Egger '00)

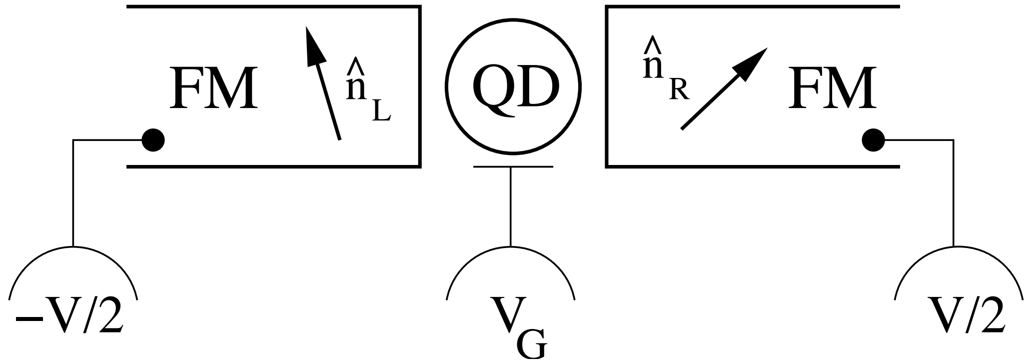
Quantum-Dot Spin Valve



model parameters:

- quantum dot with single level ϵ
- charging energy U
- tunnel coupling Γ
- spin polarization of leads $P = \frac{\nu_{\rm maj} - \nu_{\rm min}}{\nu_{\rm maj} + \nu_{\rm min}}$
- external magnetic field B
- temperature T and transport voltage V

Quantum-Dot Spin Valve



questions:

- why?

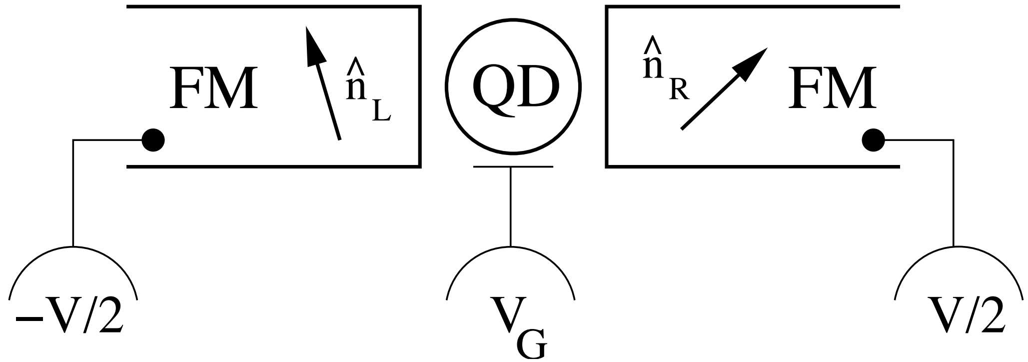
  → play with single spin degree of freedom

  → study role of Coulomb interaction

- anything new?

  → new type of many-body exchange field

Quantum-Dot Spin Valve



transport regimes:

- sequential tunneling: $\Gamma \ll k_B T$
  $\rightarrow$ spin precession for noncollinear leads
- cotunneling: order Γ^2
  $\rightarrow$ zero-bias anomaly
- strong coupling: $k_B T \leq k_B T_K \ll \Gamma$
  $\rightarrow$ Kondo effect in presence of ferromagnetism

Exchange Field

tunnel hamiltonian (dot: $|0\rangle, |\uparrow\rangle, |\downarrow\rangle, |\uparrow\downarrow\rangle$)

↓ Schrieffer-Wolff transformation ↓

effective spin model (quantum-dot spin $\vec{S}$)

↓ treat electrodes in mean field ↓

$H^{\text{eff}} = -\vec{S} \cdot \vec{B}_{\text{exch}}$ with exchange field

$$\vec{B}_{\text{exch}} = \hat{\mathbf{n}} \frac{P\Gamma}{\pi} \int' d\omega \left(\frac{1 - f(\omega)}{\omega - \epsilon} + \frac{f(\omega)}{\omega - \epsilon - U} \right)$$

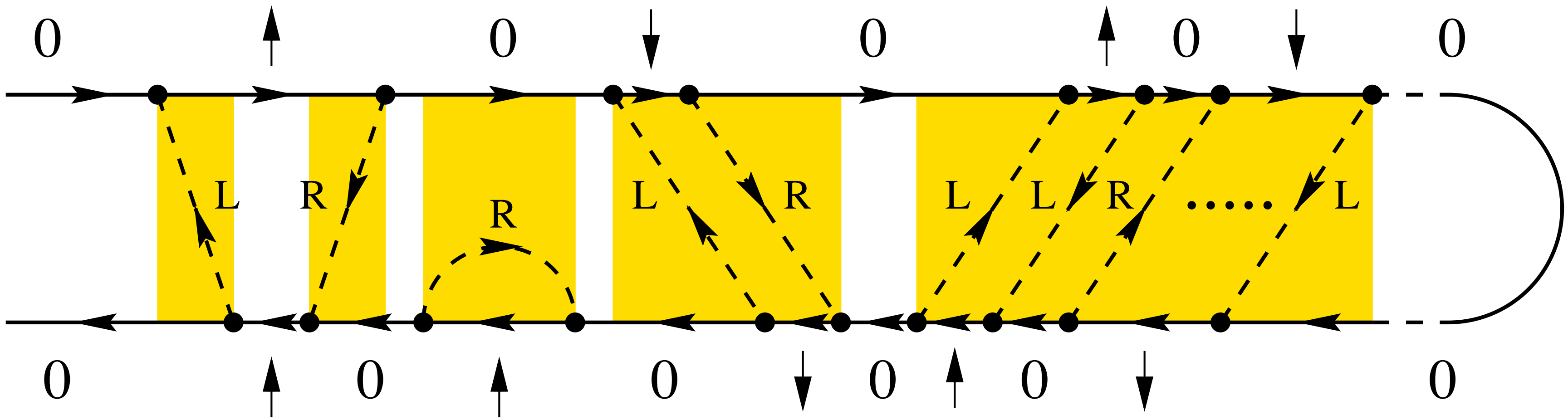
Exchange Field

$$\vec{B}_{\text{exch}} = \hat{\mathbf{n}} \frac{P\Gamma}{\pi} \int' d\omega \left(\frac{1 - f(\omega)}{\omega - \epsilon} + \frac{f(\omega)}{\omega - \epsilon - U} \right)$$

- effects
  - spin splitting (higher order in Γ)
  - spin precession (for nonequilibrium)
- magnitude and sign depends on
  - tunnel coupling Γ
  - lead spin polarization P
  - level position (gate voltage) ϵ
  - Coulomb interaction U
  - temperature T
  - transport voltage V

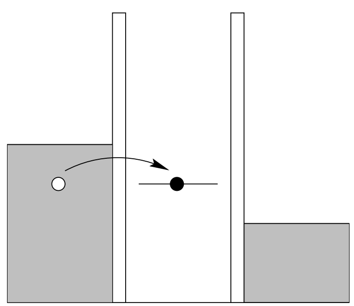
Diagrammatic Transport Theory

J.K., Schoeller, Schön, PRL '96; J.K., Schmid, Schoeller, Schön, PRB '96



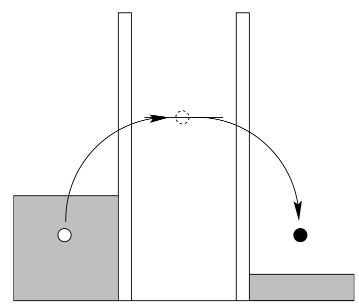
sequential tunneling

1^{st} order



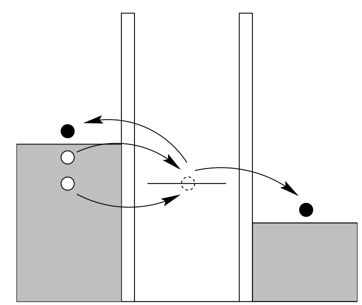
cotunneling

2^{nd} order



resonant tunneling

infinite order



Weak Coupling (Linear Response)

rate equations for dot spin: $\frac{d\vec{S}}{dt} = 0$

- spin accumulation due to spin-polarized electrodes:

$$\left(\frac{d\vec{S}}{dt}\right)_{\mathrm{acc}} \sim eVP\Gamma\left(\hat{\mathbf{n}}_{\mathrm{L}} - \hat{\mathbf{n}}_{\mathrm{R}}\right)$$

- spin relaxation due to tunneling out:

$$\left(\frac{d\vec{S}}{dt}\right)_{\mathrm{rel}} \sim -\Gamma\vec{S}$$

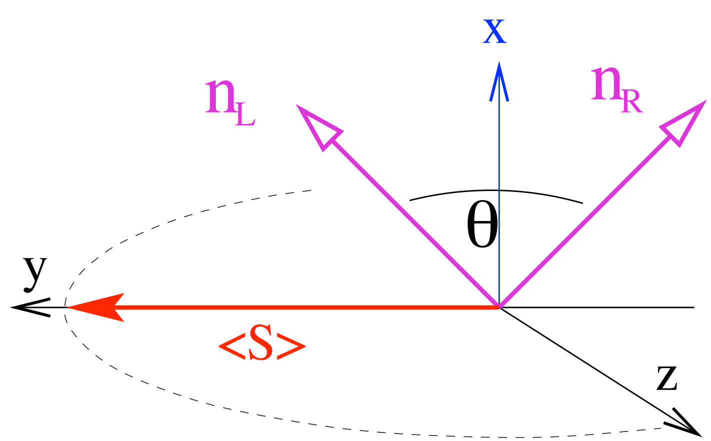
- spin precession due to exchange field:

$$\left(\frac{d\vec{S}}{dt}\right)_{\mathrm{rot}} = \vec{S} \times \underbrace{AP\Gamma\frac{\hat{\mathbf{n}}_{\mathrm{L}} + \hat{\mathbf{n}}_{\mathrm{R}}}{2}}_{\vec{B}_{\mathrm{exch}}}$$

Spin Accumulation and Precession

J.K., Martinek, PRL '03; Braun, J.K., Martinek, PRB '04

- transport voltage $\rightarrow$ spin accumulation in y-direction



Spin Accumulation and Precession

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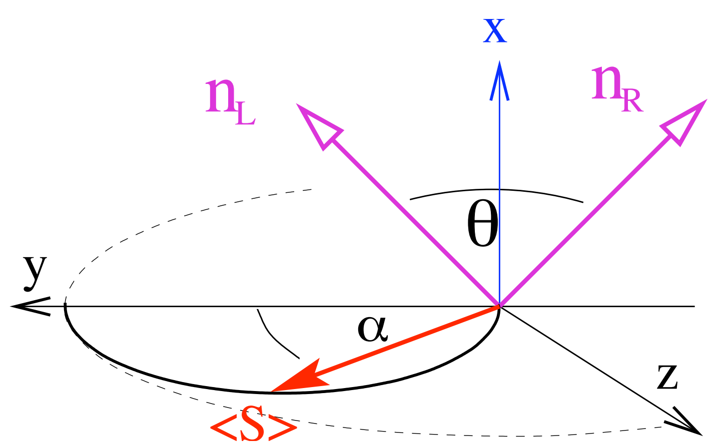
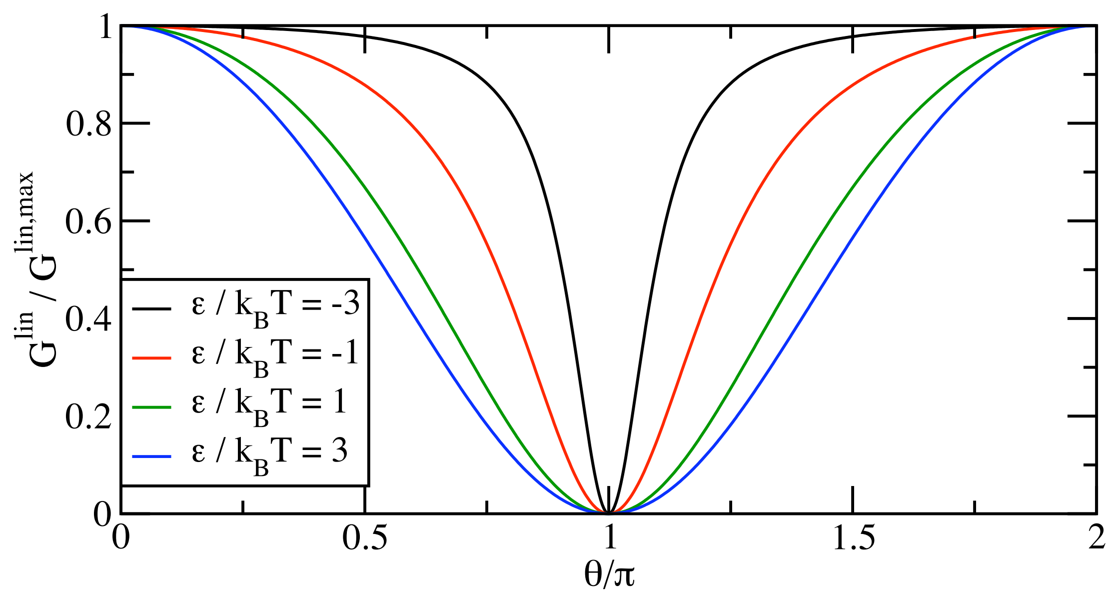


- exchange field → spin precession in $y - z$-plane

Linear Response

J.K., Martinek, PRL '03; Braun, J.K., Martinek, PRB '04

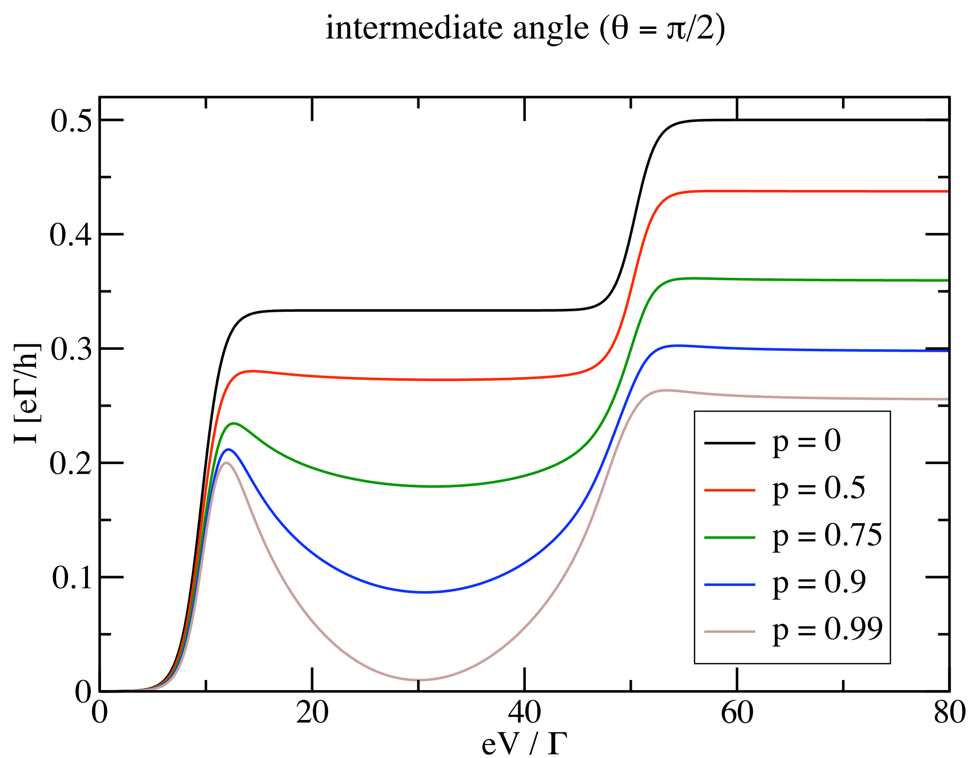
$$G^{\rm lin} = G^{\rm lin,max}\left(1 - \cos^2\alpha(\theta)\sin^2(\theta/2)\right)$$



- spin rotation reduces spin-valve effect
- gate-voltage dependence of exchange field

Nonlinear Response

Braun, J.K., Martinek, PRB ’04



$\epsilon = 10\Gamma$

$U = 20\Gamma$

$k_B T = 2\Gamma$

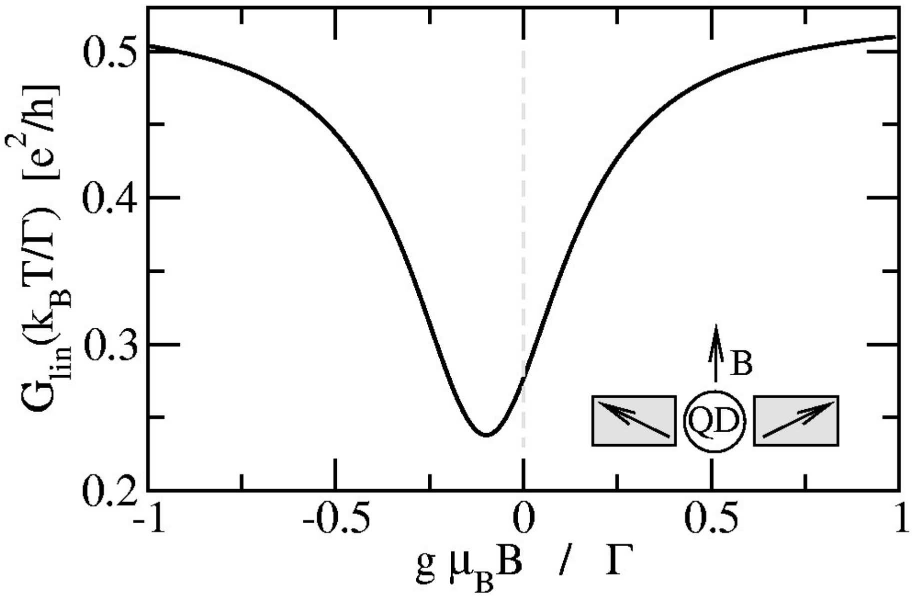
- spin blockade increases spin-valve effect
- lifted by exchange field
- bias-voltage dependence of exchange field

Hanle Effect in Transport

Braun, J.K., Martinek, EPL '05

external magnetic field rotates dot spin

⟶ decrease of spin accumulation



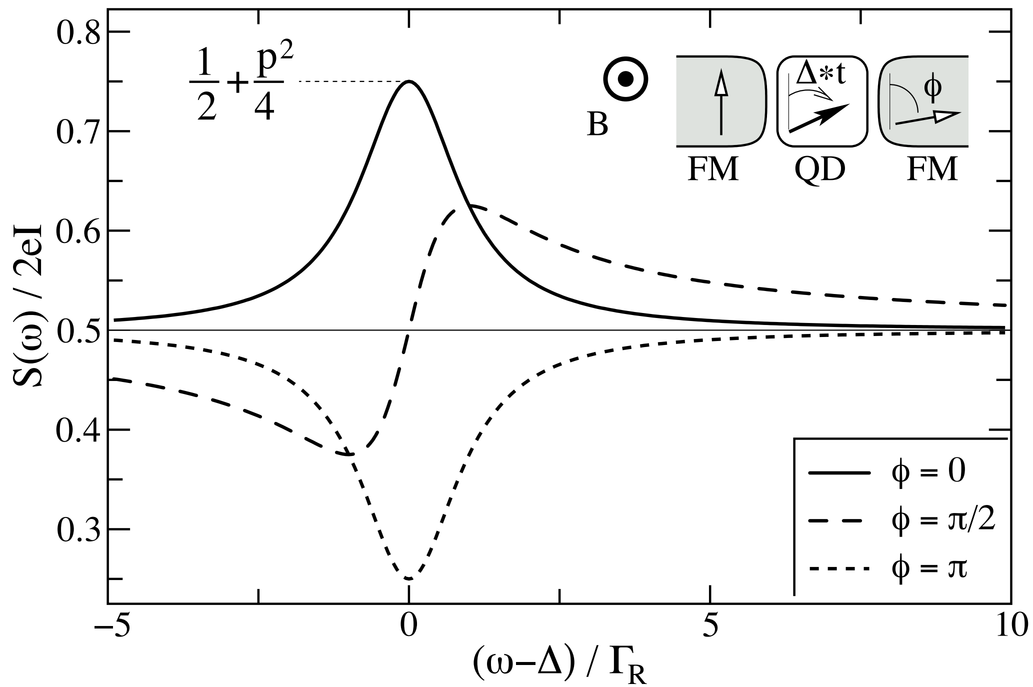
Hanle signal:

- width ⟶ inverse spin lifetime
- position ⟶ exchange field
- depth ⟶ spin accumulation

Frequency-Dependent Current Noise

Braun, J.K., Martinek, cond-mat/0601366

current noise: $S(\omega) = \int_{-\infty}^{\infty} dt \langle \delta I(0)\delta I(t) + \delta I(t)\delta I(0)\rangle e^{i\omega t}$



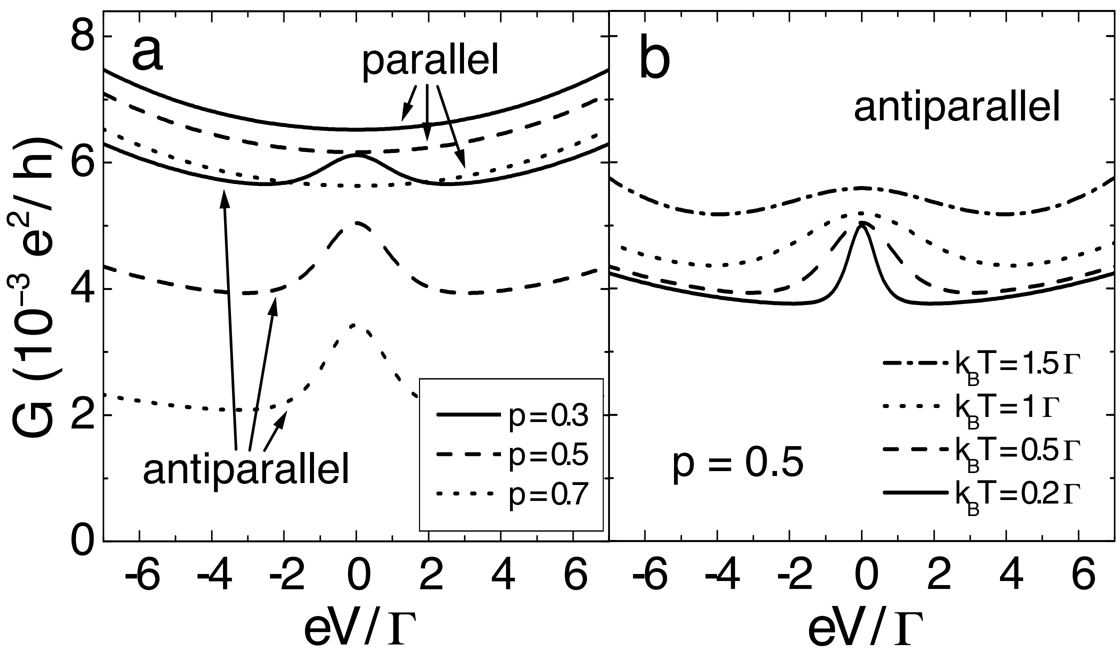
- resonance at Larmor frequency
- lineshape depends on leads' magnetization

$\longrightarrow$ current noise probes spin dynamics

Zero-Bias-Anomaly in Cotunneling

Weymann, Barnas, J.K., Martinek, Schön, PRB '05

interplay of single- and double-barrier spin-flip cotunneling affects spin accumulation



$\varepsilon = -13\Gamma, U = 30\Gamma$

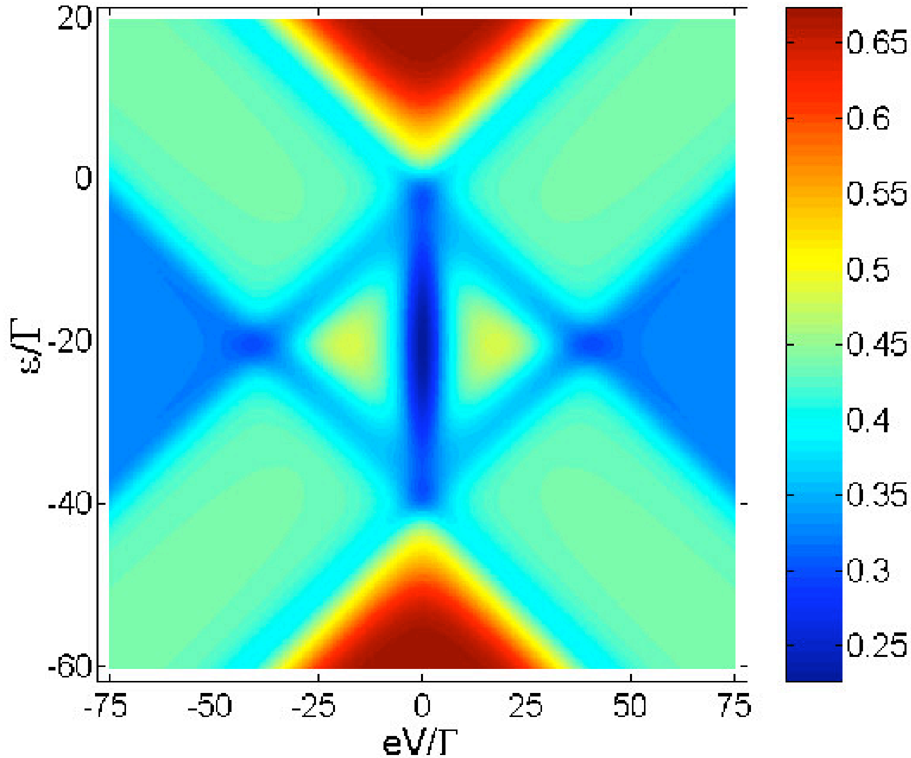
$\longrightarrow$ zero-bias anomaly of width $k_{\mathrm{B}}T$

Tunnel Magneto Resistance

Weymann, J.K., Martinek, Barnas, Schön, PRB '05

$$\mathrm{TMR} = \frac{I^{\mathrm{p}} - I^{\mathrm{ap}}}{I^{\mathrm{ap}}}$$

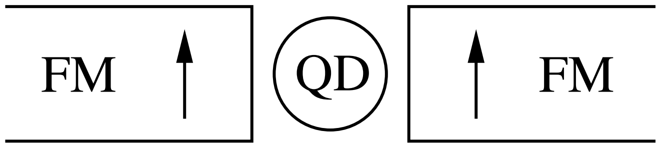
$$k_{\mathrm{B}}T = 1.5\Gamma, \quad U = 40\Gamma, \; P = 0.5$$



- single junction: $\mathrm{TMR}^{\mathrm{Jull}} = 2P^2/(1-P^2)$
- sequential tunneling: $\mathrm{TMR} < \mathrm{TMR}^{\mathrm{Jull}}$
- cotunneling: TMR reduced due to spin-flip, partially compensated by spin accumulation

Kondo Effect for Strong Coupling

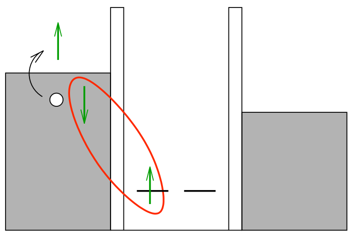
Martinek et al., PRL '03, PRL '03



strong coupling $k_{\rm B}T \leq k_{\rm B}T_{\rm K} \ll \Gamma$

parallel magnetization $\theta = 0$

- $P = 0$: Kondo effect for $T < T_{\rm K}$ and $\epsilon_\uparrow = \epsilon_\downarrow$



screening of local spin in dot

$\rightarrow$ increased conductance

- $0 < P < 1$: exchange field $\rightarrow$ splitting $\epsilon_\uparrow - \epsilon_\downarrow \neq 0$

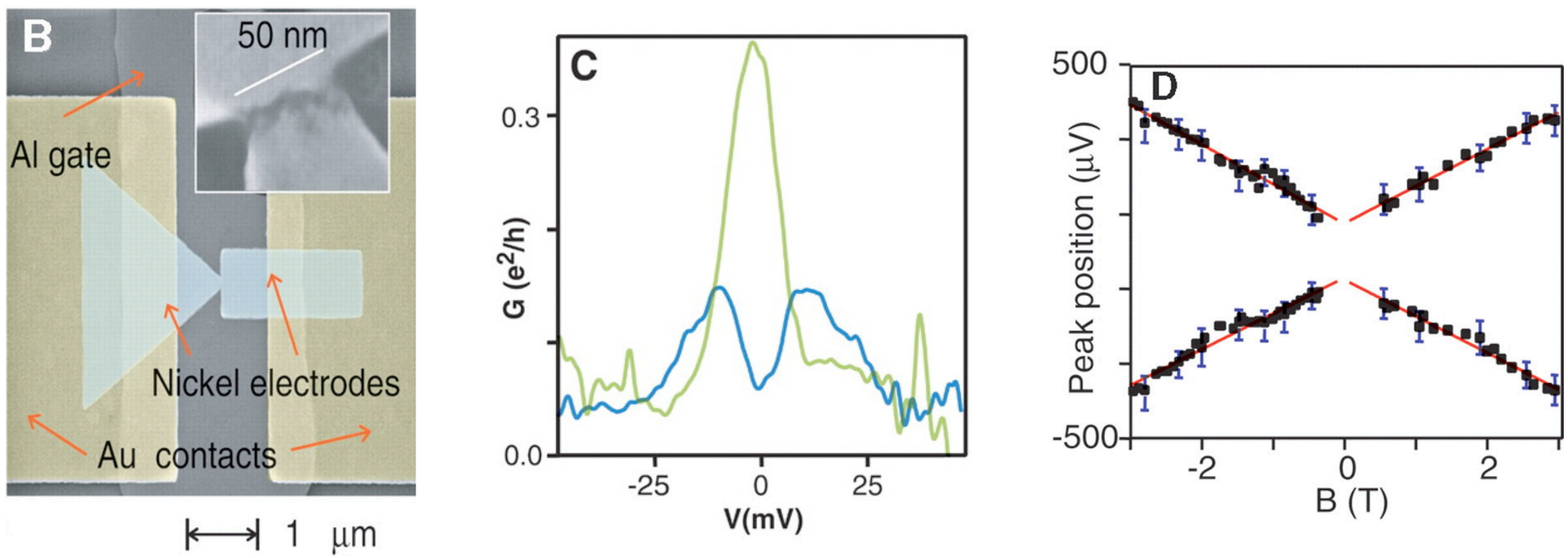
  screening harder $\rightarrow$ P-dependent $T_{\rm K}(P)$

- $P = 1$: no screening possible $\rightarrow$ no Kondo effect

Experiment: Observation of Spin Splitting

Pasupathy, Ralph et al., Science '04

system: C_{60} between Ni electrodes



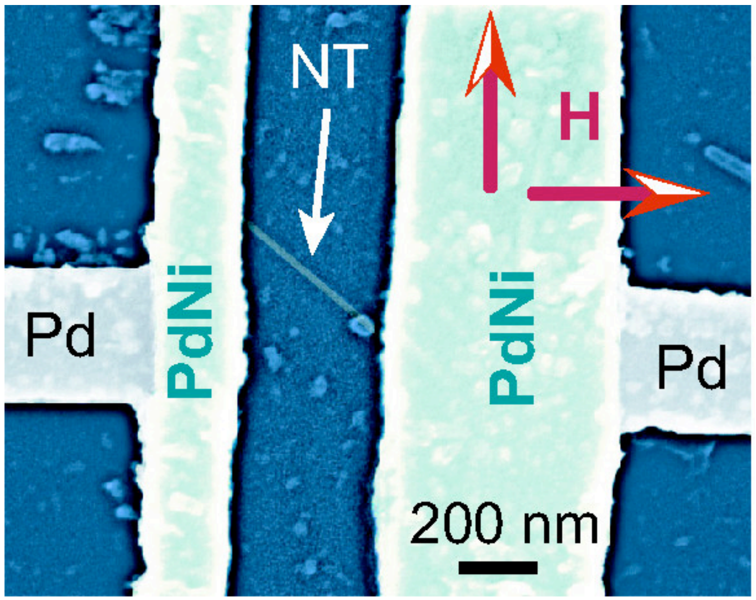
- antiparallel leads: no splitting
- parallel leads: splitting

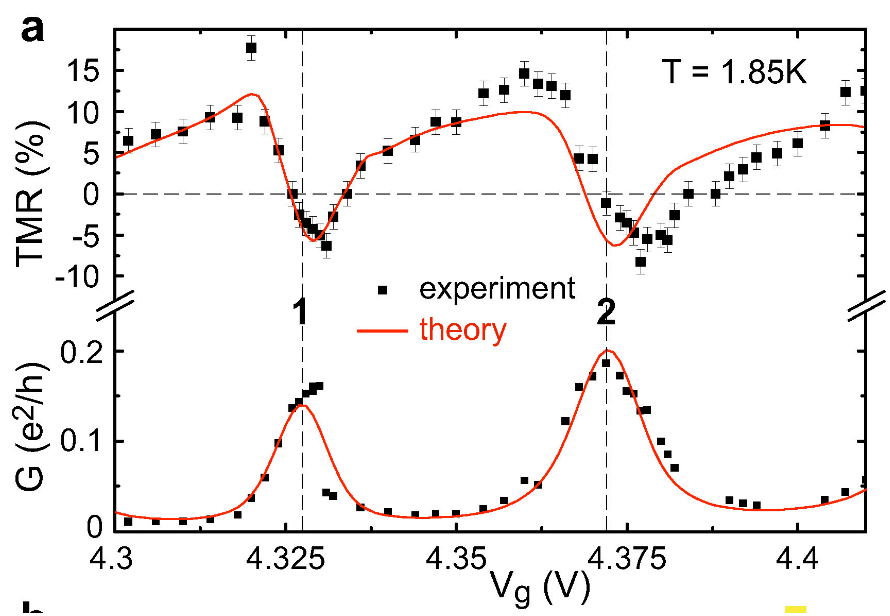
→ zero-field splitting due to exchange field

Experiment: Electric Field Control

Sahoo, Schönenberger et al., Nature Physics ’05

system: carbon nanotube between PdNi electrodes





theory fit: • spin-dependent Breit-Wigner transmission

• including spin splitting

→ gate-dependent tunnel magneto resistance

Conclusions

quantum-dot spin valves combine . . .

- spintronics: spin important
  - angular-dependent TMR and spin accumulation
- nanophysics: Coulomb interaction important
  - Coulomb oscillations and Kondo physics

most important new finding:

- new type of many-body exchange field
  - spin precession in weak-coupling regime
  - spin splitting in strong-coupling regime
  - tunable by gate and bias voltage

Collaborations & Support

- Bochum: M. Braun, D. Urban
- Karlsruhe: G. Schön
- München: L. Borda, M. Sindel, J. v. Delft
- Poznan: J. Barnas, J. Martinek, I. Weymann
- Sendai: H. Imamura, S. Maekawa, Y. Utsumi

Financial Support: SFB 491, GRK 726