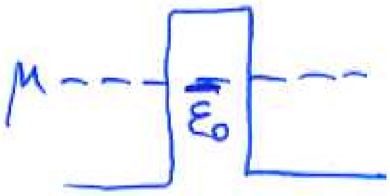
Lecture 11.

Conductivity through the quantum dot

- Kondo effect in conductivity through the quantum dot
- Splitting of the Kondo resonance in magnetic structures with quantum dots and nanoparticles
- Spin transistor

Kondo effect in conductivity through quantum dot

Resonant tunneling:



Transmission coefficient:

$$\mathcal{D}(\varepsilon) = \frac{4\Gamma_a \Gamma_b}{(\varepsilon-\varepsilon_0)^2 + (\Gamma_a+\Gamma_b)^2}$$

(Breit – Wigner)

It is one-particle formula.

Collective effects ?

Hamiltonian: tunneling + Coulomb at the localized level

$$\mathcal{H} = \sum_{k\sigma} \varepsilon_k \left(a^+_{k\sigma} a_{k\sigma} + b^+_{k\sigma} b_{k\sigma} \right) +$$

$$+ \varepsilon_0 \sum_\sigma d^+_\sigma d_\sigma + w\, d^+_\sigma d_\sigma d^+_{-\sigma} d_{-\sigma} +$$

$$+ \sum_{k\sigma} \left(V_a a^+_{k\sigma} d_\sigma + V_a^* d^+_\sigma a_{k\sigma} \right) +$$

$$+ \sum_{k\sigma} \left(V_b b^+_{k\sigma} d_\sigma + V_b^* d^+_\sigma b_{k\sigma} \right)$$

L. Glazman, M. Raikh (1988)

T. Ng, P. Lee (1988)

Reducing to the Kondo problem:

$$\alpha_{k\sigma} = u a_{k\sigma} + v b_{k\sigma}$$
$$\beta_{k\sigma} = u b_{k\sigma} - v a_{k\sigma}$$

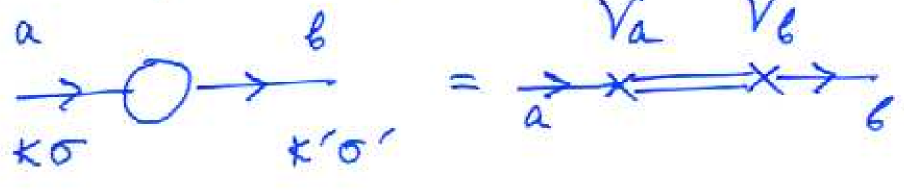
Condition: terms $\sim \beta^+_{k\sigma} d_\sigma,\ d^+_\sigma \beta_{k\sigma} = 0$

$$\Rightarrow \quad u = \frac{V_a}{V}, \quad v = \frac{V_b}{V}$$
$$V = \sqrt{|V_a|^2 + |V_b|^2}$$

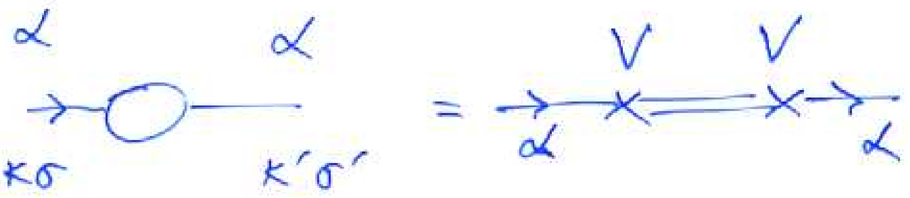
Transformed Hamiltonian:

$$\mathcal{H} = \sum_{k\sigma} \varepsilon_k \left(\alpha^+_{k\sigma}\alpha_{k\sigma} + \beta^+_{k\sigma}\beta_{k\sigma}\right) +$$
$$+ \varepsilon_0 \sum_\sigma d^+_\sigma d_\sigma + W d^+_\sigma d_\sigma d^+_{-\sigma} d_{-\sigma} +$$
$$+ V \sum_{k\sigma} \left(\alpha^+_{k\sigma} d_\sigma + d^+_\sigma \alpha_{k\sigma}\right)$$

Tunneling amplitude:



Scattering amplitude:



Relation:

$$f^{a-b}_{k\sigma\to k'\sigma'} = \frac{V_a V_b^*}{V^2} f^{\alpha-\alpha}_{k\sigma\to k'\sigma'}$$

Renormalized transparency:

$$D = D_0 \frac{4\Gamma_a\Gamma_b}{(\Gamma_a+\Gamma_b)^2} \sin^2\delta$$

$$\Gamma_{a,b} = \pi |V_{a,b}|^2 \nu$$

Kondo temperature:

$$T_K = \frac{2}{\pi}\left[2\tilde{\varepsilon}_0 (\Gamma_a+\Gamma_b)\right]^{1/2} e^{-\pi\tilde{\varepsilon}_0/2(\Gamma_a+\Gamma_b)}$$

$$\tilde{\varepsilon}_0 = \varepsilon_F - \varepsilon_0 - \frac{\Gamma_a+\Gamma_b}{\pi} \ln\frac{W}{4\tilde{\varepsilon}_0}$$

For $T \gg T_K$: perturbation theory

$$\delta \simeq \frac{\Gamma_a+\Gamma_b}{\varepsilon_F-\varepsilon_0} \ll 1$$

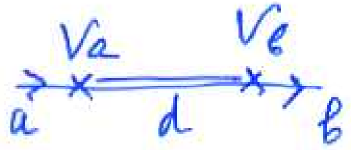
It means:

$$D \simeq D_0 \frac{4\Gamma_a\Gamma_b}{(\varepsilon_F-\varepsilon_0)^2}$$

How to calculate conductivity?

Transmittance for electron with spin σ:

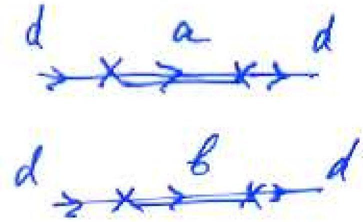
$$T_\sigma(\varepsilon) = |2i V_a V_b \nu_\sigma(\varepsilon) G_\sigma(\varepsilon)|^2$$



$$G_\sigma(\varepsilon) = \frac{1}{\varepsilon - \varepsilon_0 - \Sigma_\sigma(\varepsilon)}$$

$$\mathrm{Im}\,\Sigma_\sigma(\varepsilon) = -\pi (V_a^2 + V_b^2)\nu_\sigma(\varepsilon)$$

Occupation number:



$$\langle n_{0\sigma}\rangle = \frac{1}{\pi}\mathrm{Im}\ln G^R_\sigma(\varepsilon_F)$$

Define: $\delta_\sigma = \pi\langle n_{0\sigma}\rangle$

$\Rightarrow$ Transmittance in one spin channel:

$$T_\sigma(\varepsilon) = \frac{4V_a^2 V_b^2}{(V_a^2+V_b^2)^2}\sin^2\delta_\sigma$$

Kondo effect in QD with ferromagnetic leads

$$\mathcal{H} = \sum_{rk\sigma} \varepsilon_{rk\sigma} c^{+}_{rk\sigma} c_{rk\sigma} +$$

$r = L, R$

$$+ \varepsilon_0 \sum_{\sigma} d^{+}_{\sigma} d_{\sigma} + W d^{+}_{\uparrow} d_{\uparrow} d^{+}_{\downarrow} d_{\downarrow}$$

$$+ \sum_{rk\sigma} \left(V_{rk} d^{+}_{\sigma} c_{rk\sigma} + V^{*}_{rk} c^{+}_{k\sigma} d_{\sigma} \right) +$$

$$+ g \mu_B B \cdot \frac{1}{2} \left(d^{+}_{\uparrow} d_{\uparrow} - d^{+}_{\downarrow} d_{\downarrow} \right)$$

New elements:

- magnetic polarization in each lead
- magnetic field B
- nonequilibrium

Channels are separated – simplification

Kondo Effect in Quantum Dots Coupled to Ferromagnetic Leads

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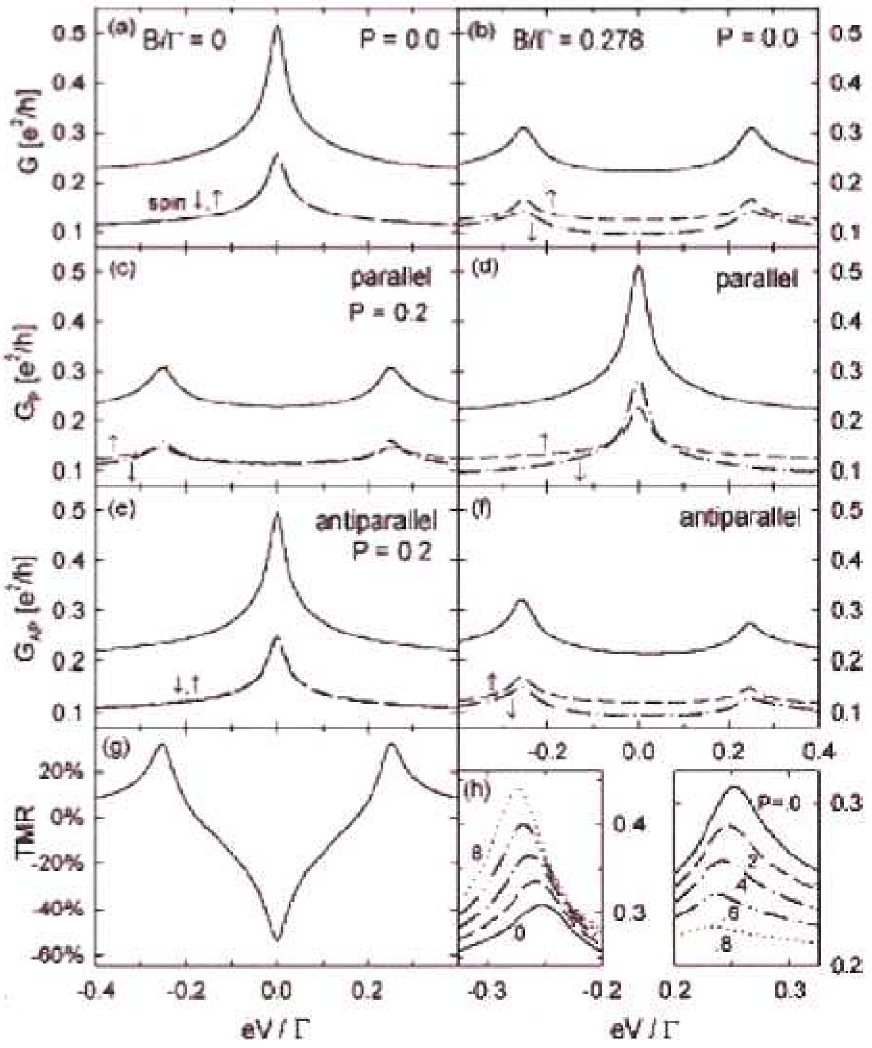

Datta-Das spin transistor

Electronic analog of the electro-optic modulator

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Appl. Phys. Lett. **56** (7), 12 February 1990

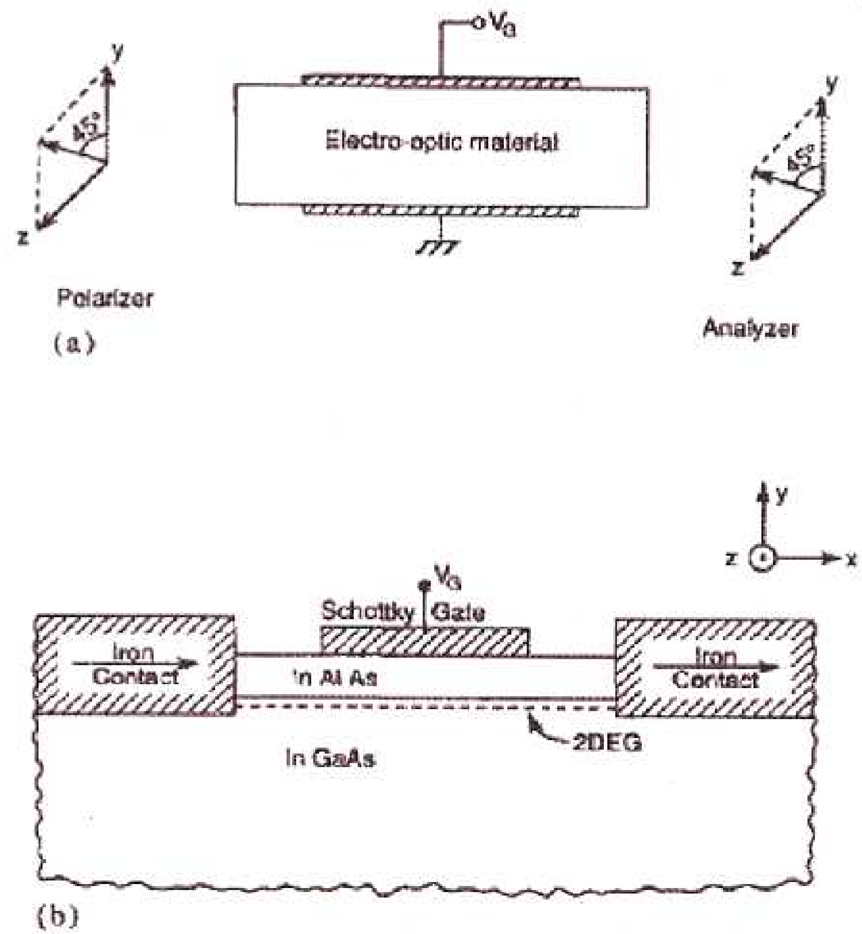

FIG. 1. (a) Electro-optic modulator; (b) proposed electron wave analog of the electro-optic modulator.

Also:

A. Voskoboynikov et al. (2000)
E. De Andrada e Silva et al. (1999)
T. Koga et al. (2002)
D. Ting et al (2002)
K. Hall et al. (2003)

Unipolar spin diodes and transistors

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(Received 12 September 2000; accepted for publication 14 December 2000)

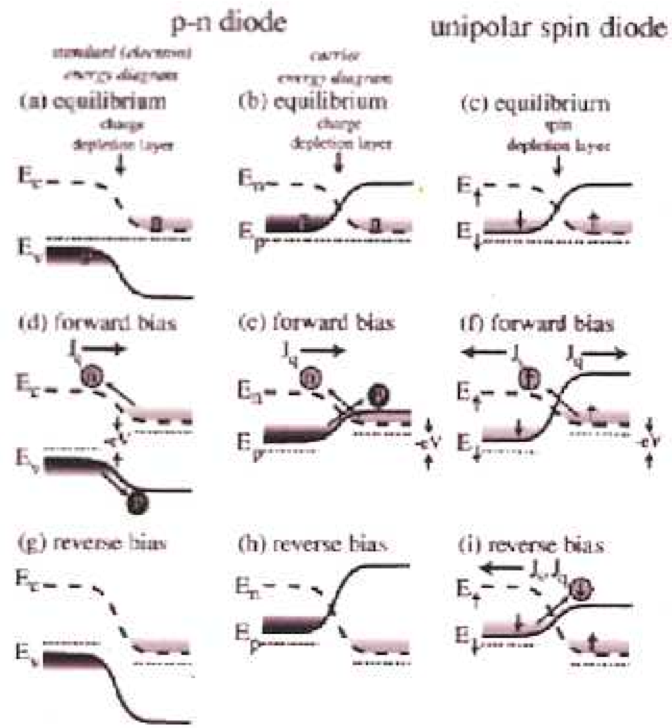

FIG. 1. Standard and carrier energy diagrams for a traditional p-n diode vs unipolar spin diode under equilibrium conditions (a)–(c), forward bias (d)–(f), and reverse bias (g)–(i).

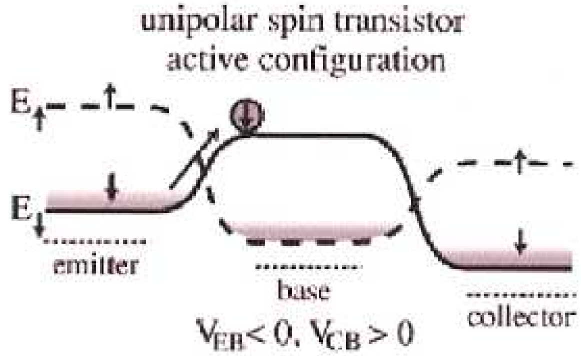

FIG. 2. Carrier energy diagram for the unipolar spin transistor in the normal active configuration.

APPLIED PHYSICS LETTERS VOLUME 84, NUMBER 1 5 JANUARY 2004

Magnetic bipolar transistor

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(Received 2 July 2003; accepted 10 November 2003)