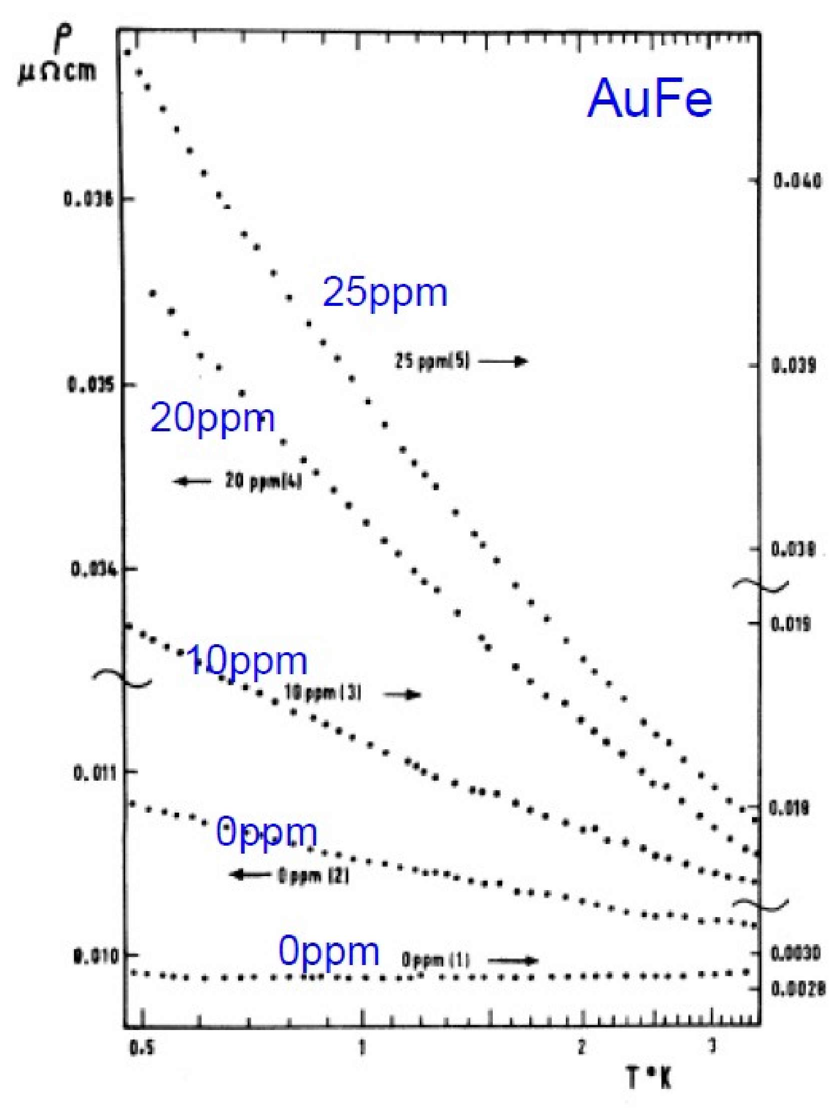
低温物理学

2009年５月28日

物性研究所
勝本信吾

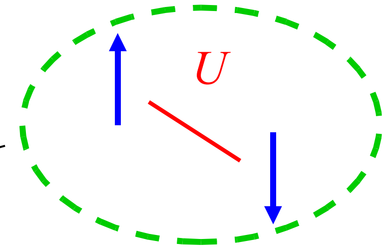
The Kondo effect in dilute magnetic alloy



The Impurity Anderson Model

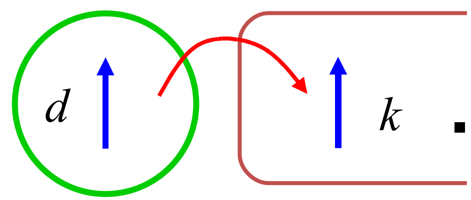
$$H = H_{\rm leads} + H_{\rm dot} + H_{\rm T} \tag{141}$$

$$H_{\rm dot} = \sum_{\sigma} \epsilon_0 d_\sigma^\dagger d_\sigma + U d_\uparrow^\dagger d_\uparrow d_\downarrow^\dagger d_\downarrow, \tag{142}$$



$$H_{\rm leads} = \sum_{\alpha=L,R} \sum_{k\sigma} \epsilon_k c_{\alpha,k\sigma}^\dagger c_{\alpha,k\sigma}, \tag{143}$$

$$H_{\rm T} = \sum_{\alpha=L,R} \sum_{k\sigma} (\gamma_\alpha c_{\alpha,k\sigma}^\dagger d_\sigma + {\rm h.c.}). \tag{144}$$



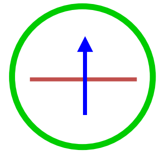
Unitary transformation

$$\begin{cases} c_{k\sigma} = (\gamma_L^* c_{L,k\sigma} + \gamma_R^* c_{R,k\sigma})/\gamma \\ \bar{c}_{k\sigma} = (-\gamma_R c_{L,k\sigma} + \gamma_L c_{R,k\sigma})/\gamma \end{cases}, \quad \gamma^2 \equiv \gamma_L^2 + \gamma_R^2 \tag{147}$$

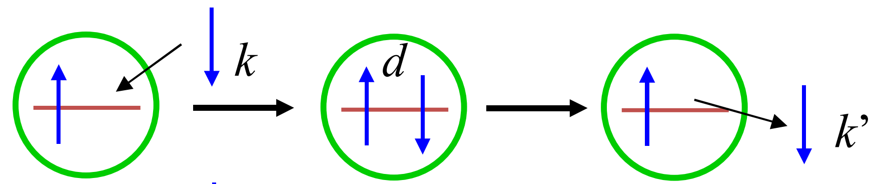
$$\begin{aligned} H_T &= \sum_{k,\sigma} [(\gamma_L c_{L,k\sigma}^\dagger + \gamma_R c_{R,k\sigma}^\dagger) d_\sigma + {\rm h.c.}] \\ &= \sum_{k,\sigma} [\gamma c_{k\sigma}^\dagger d_\sigma + {\rm h.c.}] \end{aligned} \tag{148}$$

Co-tunneling process and 2nd order perturbation

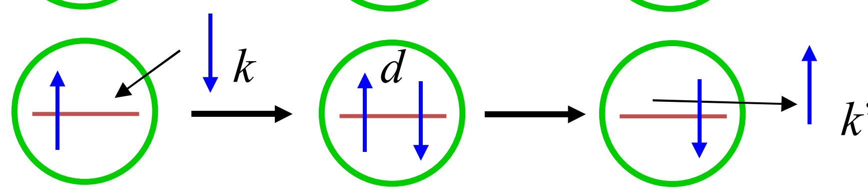
$$H = \sum_{k\sigma} \epsilon_k c^\dagger_{k\sigma} c_{k\sigma} + \sum_{\sigma} \epsilon_d d^\dagger_\sigma d_\sigma + \sum_{k\sigma} (\gamma c^\dagger_{k\sigma} d_\sigma + \text{h.c.}) + U d^\dagger_\uparrow d_\uparrow d^\dagger_\downarrow d_\downarrow \tag{149}$$

Four co-tunneling processes from 

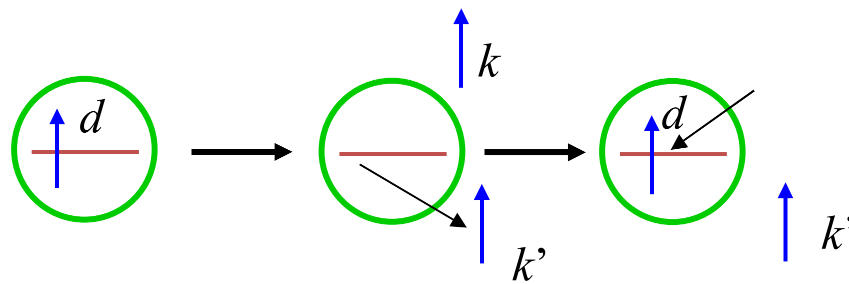
$$-\frac{\gamma^2}{\Delta E^+} c^\dagger_{k'\downarrow} d_\downarrow d^\dagger_\downarrow c_{k\downarrow}$$



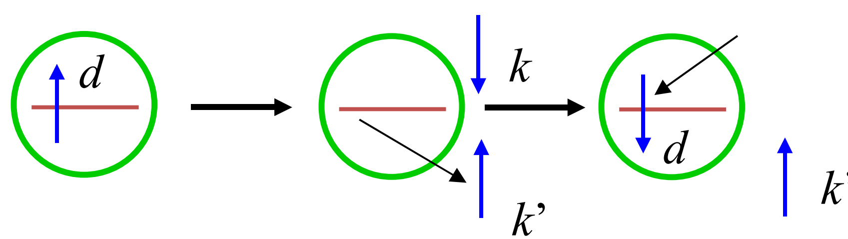
$$-\frac{\gamma^2}{\Delta E^+} c^\dagger_{k'\uparrow} d_\uparrow d^\dagger_\downarrow c_{k\downarrow}$$



$$\frac{\gamma^2}{\Delta E^-} d^\dagger_\uparrow c_{k\uparrow} c^\dagger_{k'\uparrow} d^\dagger_\uparrow$$



$$\frac{\gamma^2}{\Delta E^-} d^\dagger_\downarrow c_{k\downarrow} c^\dagger_{k'\uparrow} d_\uparrow$$



s-d Hamiltonian

$$\sum_{k\sigma} \frac{\gamma^2}{\Delta E^-} d^\dagger_\sigma d_\sigma + \sum_{kk'\sigma} \frac{\gamma^2}{\Delta E^+} c^\dagger_{k'\sigma} c_{k\sigma}$$

$$+ \sum_{kk'} \gamma^2 \left(\frac{1}{\Delta E^+} + \frac{1}{\Delta E^-} \right) (c^\dagger_{k'\uparrow} c_{k\uparrow} d^\dagger_\uparrow d_\uparrow + c^\dagger_{k'\downarrow} c_{k\downarrow} d^\dagger_\downarrow d_\downarrow + c^\dagger_{k'\uparrow} c_{k\downarrow} d^\dagger_\downarrow d_\uparrow + c^\dagger_{k'\downarrow} c_{k\uparrow} d^\dagger_\uparrow d_\downarrow).$$

$$c^\dagger_{k'\uparrow} c_{k\uparrow} d^\dagger_\uparrow d_\uparrow + c^\dagger_{k'\downarrow} c_{k\downarrow} d^\dagger_\downarrow d_\downarrow$$

$$= \frac{1}{2} (c^\dagger_{k'\uparrow} c_{k\uparrow} - c^\dagger_{k'\downarrow} c_{k\downarrow})(d^\dagger_\uparrow d_\uparrow - d^\dagger_\downarrow d_\downarrow) + \frac{1}{2} (c^\dagger_{k'\uparrow} c_{k\uparrow} + c^\dagger_{k'\downarrow} c_{k\downarrow})(d^\dagger_\uparrow d_\uparrow + d^\dagger_\downarrow d_\downarrow)$$

$$\hat{S}_z = \frac{1}{2}(d^\dagger_\uparrow d_\uparrow - d^\dagger_\downarrow d_\downarrow), \quad \hat{S}_+ = d^\dagger_\uparrow d_\downarrow, \quad \hat{S}_- = d^\dagger_\downarrow d_\uparrow$$

Dot spin operators

$$H_d = \sum_{kk'\sigma} \gamma^2 \left[\frac{1}{\Delta E^+_k} - \frac{1}{2} \left(\frac{1}{\Delta E^+_{k'}} + \frac{1}{\Delta E^-_{k'}} \right) \right] c^\dagger_{k'\sigma} c_{k\sigma}$$

$$H_{sd} = \sum_{kk'} \gamma^2 \left[\frac{1}{\Delta E^+_k} + \frac{1}{\Delta E^-_{k'}} \right] \left[\hat{S}_+ c^\dagger_{k'\downarrow} c_{k\uparrow} + \hat{S}_- c^\dagger_{k'\uparrow} c_{k\downarrow} + \hat{S}_z (c^\dagger_{k'\uparrow} c_{k\uparrow} - c^\dagger_{k'\downarrow} c_{k\downarrow}) \right]$$

s-d Hamiltonian (2)

$$J = \gamma^2 \left(\frac{1}{\Delta E^+} + \frac{1}{\Delta E^-} \right)$$

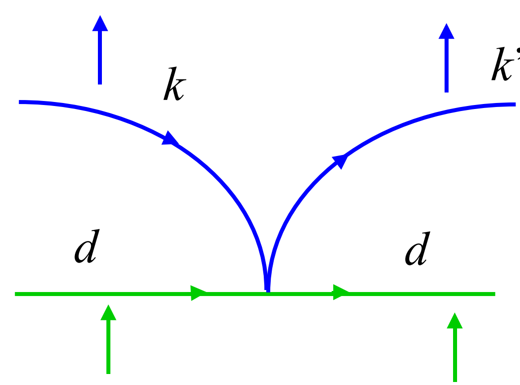
$$H_d = \sum_{kk'} \left(-\frac{J}{2} \right) c^\dagger_{k'\sigma} c_{k\sigma}$$

$$\begin{aligned} H_{sd} &= J \sum_{kk'} \left[\hat{S}_+ c^\dagger_{k'\downarrow} c_{k\uparrow} + \hat{S}_- c^\dagger_{k'\uparrow} c_{k\downarrow} + \hat{S}_z (c^\dagger_{k'\uparrow} c_{k\uparrow} - c^\dagger_{k'\downarrow} c_{k\downarrow}) \right] \\ &= J \sum_j \left[(\hat{S}_x + i\hat{S}_y)(\hat{s}_{xj} - i\hat{s}_{yj}) + (\hat{S}_x - i\hat{S}_y)(\hat{s}_{xj} + i\hat{s}_{yj}) + 2\hat{s}_{zj}\hat{S}_z \right] \\ &= 2J \sum_j \hat{\boldsymbol{s}}_j \cdot \hat{\boldsymbol{S}} \end{aligned}$$

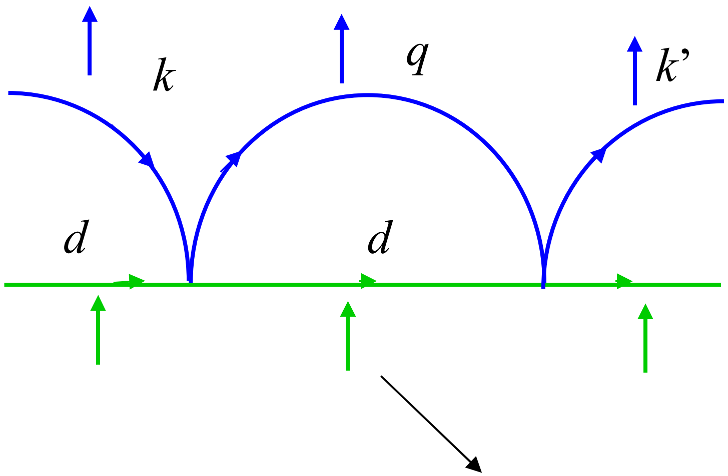
anti-ferromagnetic interaction

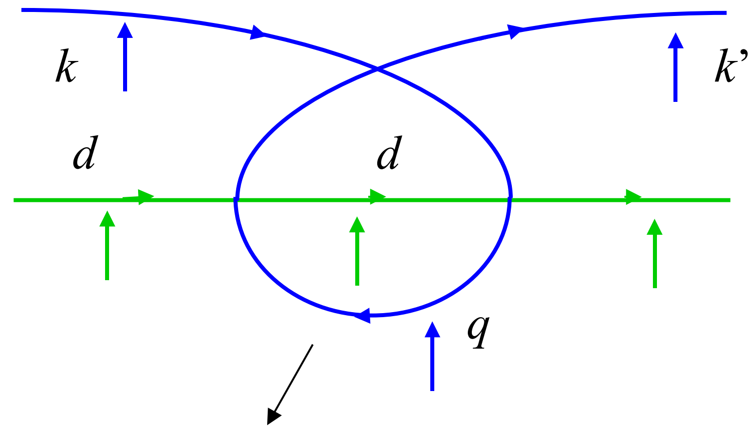
$$\hat{T} = \underline{H_T} + H_T \frac{1}{\epsilon - H_0 + i\delta} H_T + \cdots$$

$$\langle d \uparrow; k' \uparrow | \hat{T}^{(1)} | d \uparrow; k \uparrow \rangle = J/2$$



No spin-flip process





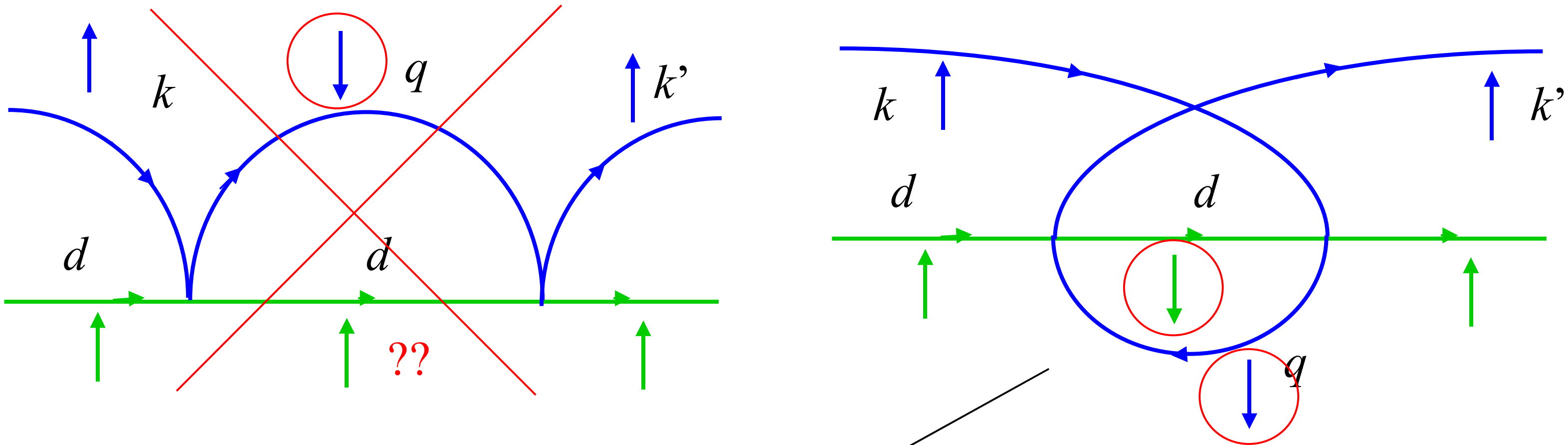
$$\sum_q \left(\frac{J}{2}\right)^2 \frac{1}{\epsilon - \epsilon_q + i\delta}[1 - f(\epsilon_q)] + \sum_q \left(\frac{J}{2}\right)^2 \frac{-1}{\epsilon - (2\epsilon - \epsilon_q) + i\delta} f(\epsilon_q)$$

$$= \sum_q \left(\frac{J}{2}\right)^2 \frac{1}{\epsilon - \epsilon_q + i\delta}$$

$$= \left(\frac{J}{2}\right)^2 \int_{-D}^{D} d\epsilon' \nu \frac{1}{\epsilon - \epsilon' + i\delta} \qquad \nu : \text{Density of states}$$

$$= \left(\frac{J}{2}\right)^2 \nu \left[\ln\left|\frac{D + \epsilon}{D - \epsilon}\right| - i\pi\right].$$

Spin flip process: Kondo anomaly



S_+とS_-の非可換性

$$\sum_q J^2 \frac{1}{\epsilon - \epsilon_q + i\delta} f(\epsilon_q) = J^2 \nu \int_{-D}^{D} \frac{1}{\epsilon - \epsilon' + i\delta} f(\epsilon') d\epsilon$$

$$\approx \begin{cases} -J^2 \nu \ln |\epsilon|/D & |\epsilon| \gg k_{\mathrm{B}} T \\ -J^2 \nu \ln k_{\mathrm{B}} T/D & |\epsilon| \ll k_{\mathrm{B}} T \end{cases}$$

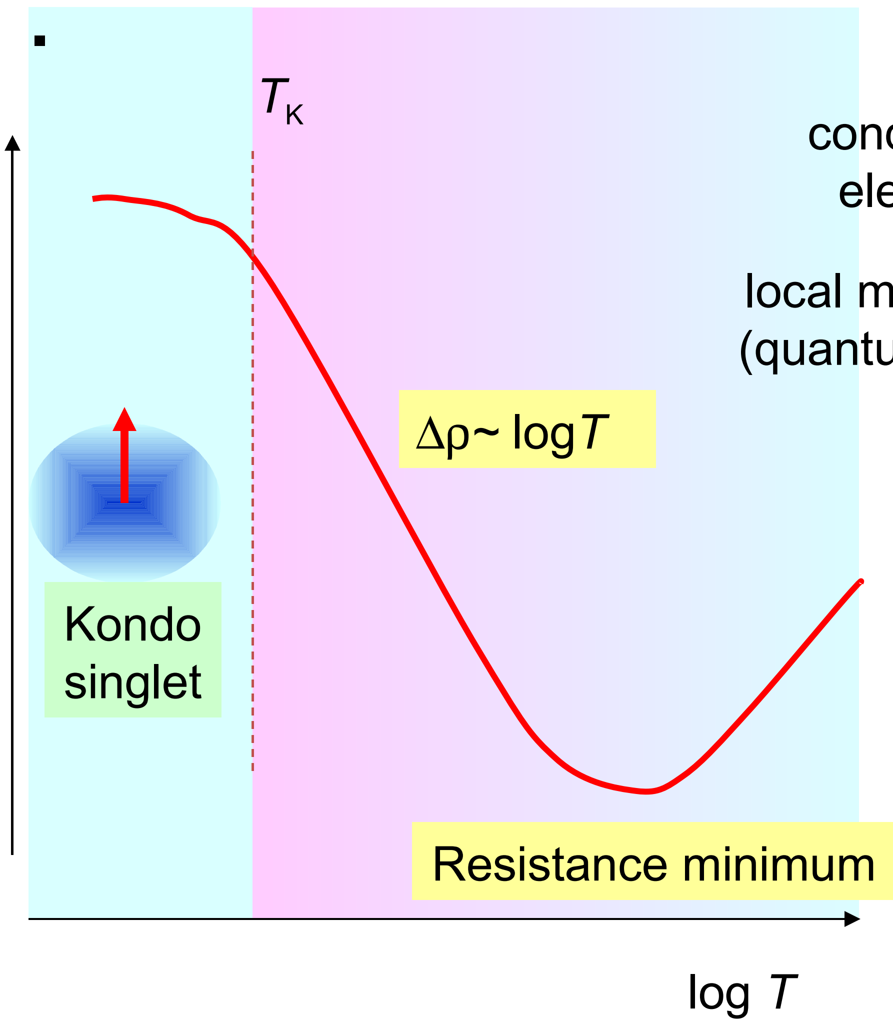
対数異常

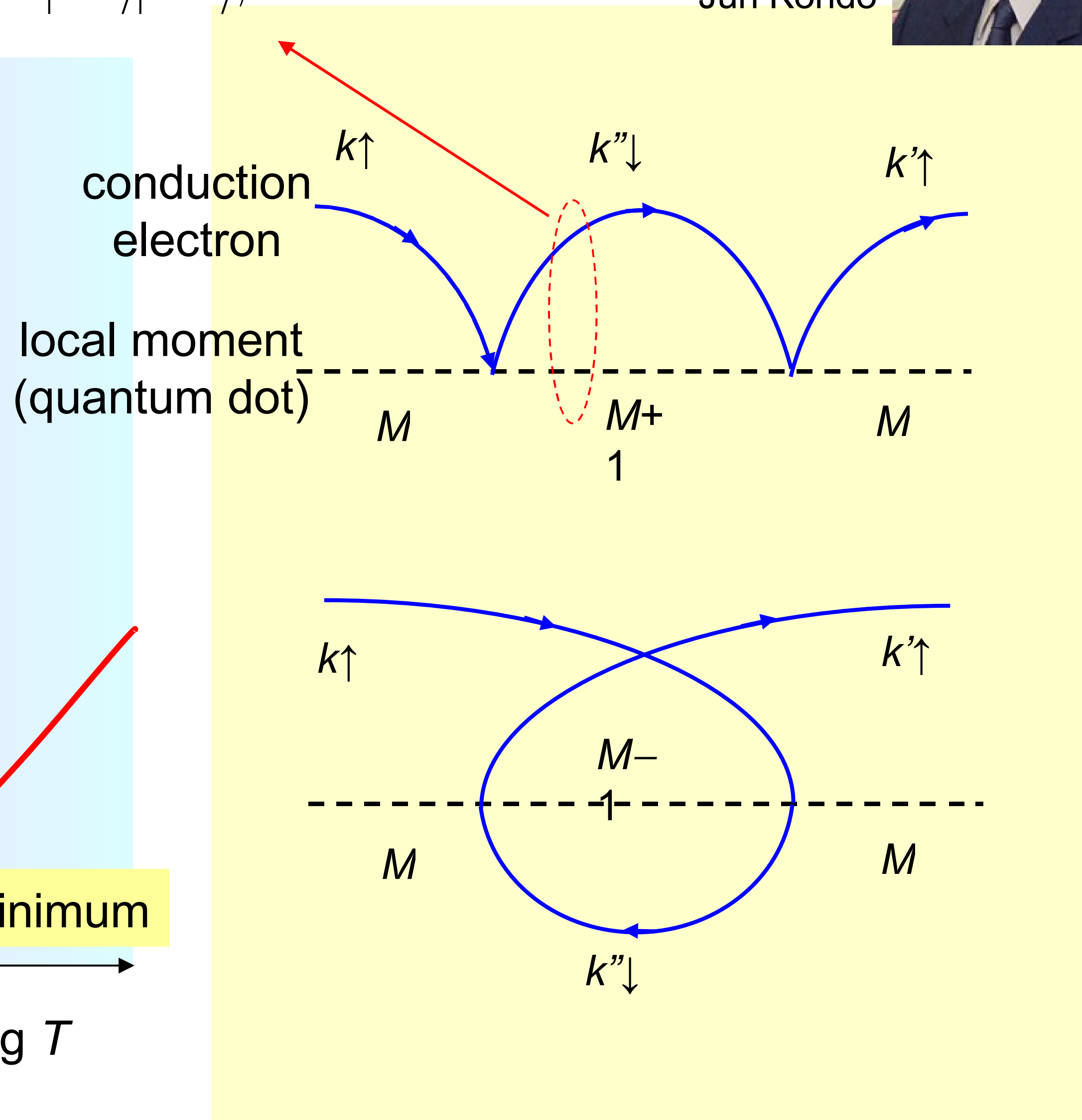
Fermi面の存在による
多体共鳴効果

The Kondo effect in dilute magnetic compounds

Jun Kondo

$$\frac{1}{\sqrt{2}}\left(\left|s\uparrow\right\rangle\left|d\downarrow\right\rangle - \left|s\downarrow\right\rangle\left|d\uparrow\right\rangle\right)$$





The Kondo singlet

Yosida's variational ground state A. Yoshimori, PR168 (1967)

Kondo singlet

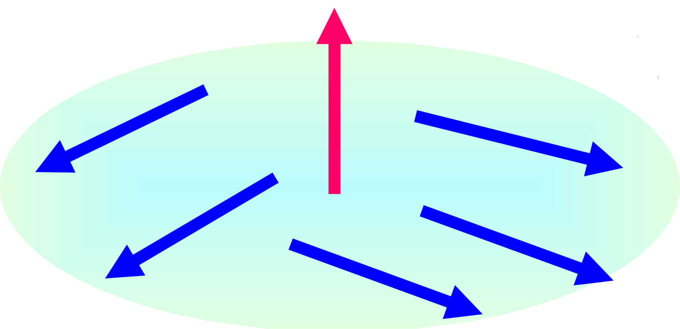
$$\psi=\{\sum_k [\Gamma_k^{\alpha} a_{k\downarrow}^{\dagger}\alpha+\Gamma_k^{\beta} a_{k\uparrow}^{\dagger}\beta] \longrightarrow \left(|s\uparrow\rangle|d\downarrow\rangle - |s\downarrow\rangle|d\uparrow\rangle\right)$$

$$+\sum_{k_1k_2k_3}[\Gamma_{k_1k_2k_3}^{\alpha\downarrow} a_{k_1\downarrow}^{\dagger} a_{k_2\downarrow}^{\dagger} a_{k_3\downarrow}\alpha+\Gamma_{k_1k_2k_3}^{\beta\uparrow} a_{k_1\uparrow}^{\dagger} a_{k_2\uparrow}^{\dagger} a_{k_3\uparrow}\beta$$

$$+\Gamma_{k_1k_2k_3}^{\alpha\uparrow} a_{k_1\downarrow}^{\dagger} a_{k_2\uparrow}^{\dagger} a_{k_3\uparrow}\alpha+\Gamma_{k_1k_2k_3}^{\beta\downarrow} a_{k_1\uparrow}^{\dagger} a_{k_2\downarrow}^{\dagger} a_{k_3\downarrow}\beta]$$

$$+\cdots\}\psi_v,$$

Fermi State

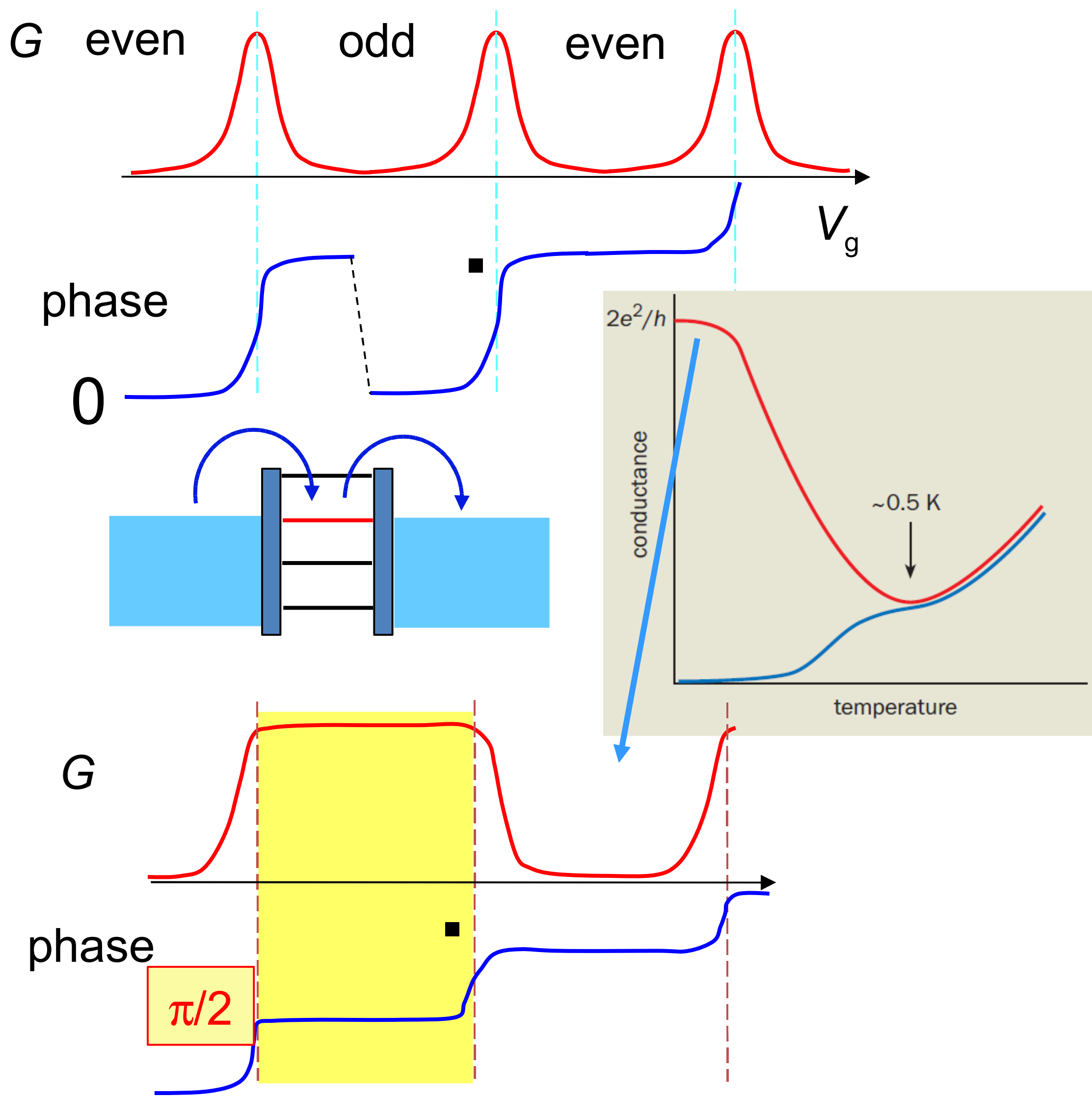


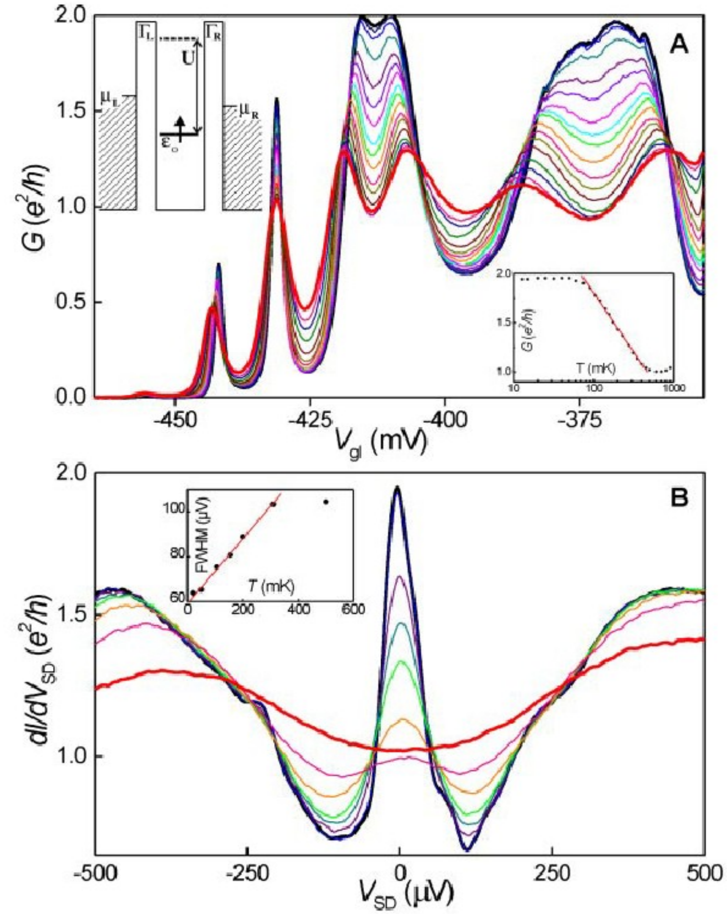
Magnetic impurity : Screened by a Kondo cloud

Single body resonance ← Quantum coherence between multiply scattered waves
→ Spatially localized state, discrete energy levels

Many body resonance ← multiple scattering with many electrons of the same energy (Fermi energy) with quantum entanglement in spin
→ Spatially localized state, energy level is the same as the Fermi energy

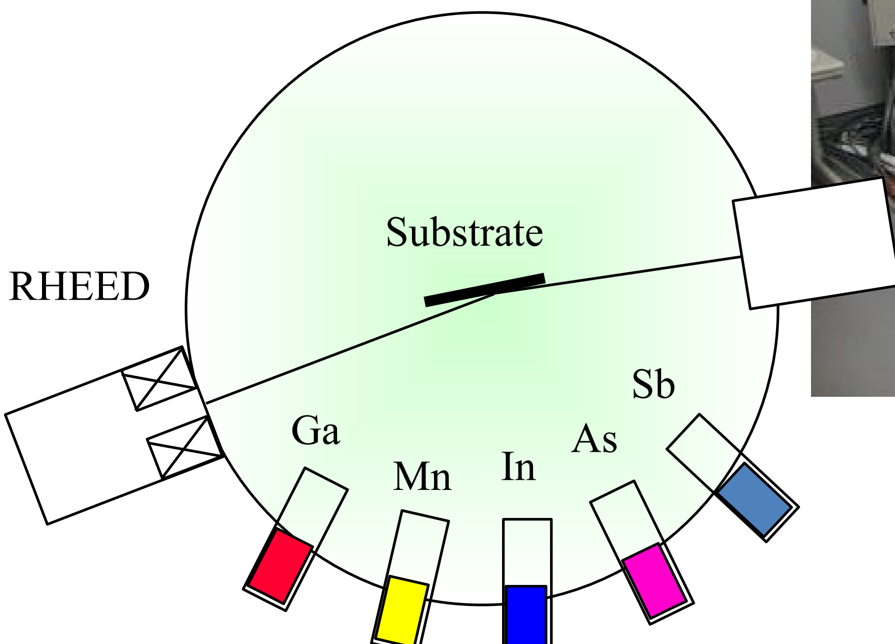
The Kondo effect in quantum dot systems





W. G. van der Wiel et al.
Science **289**, 2105 (2000).

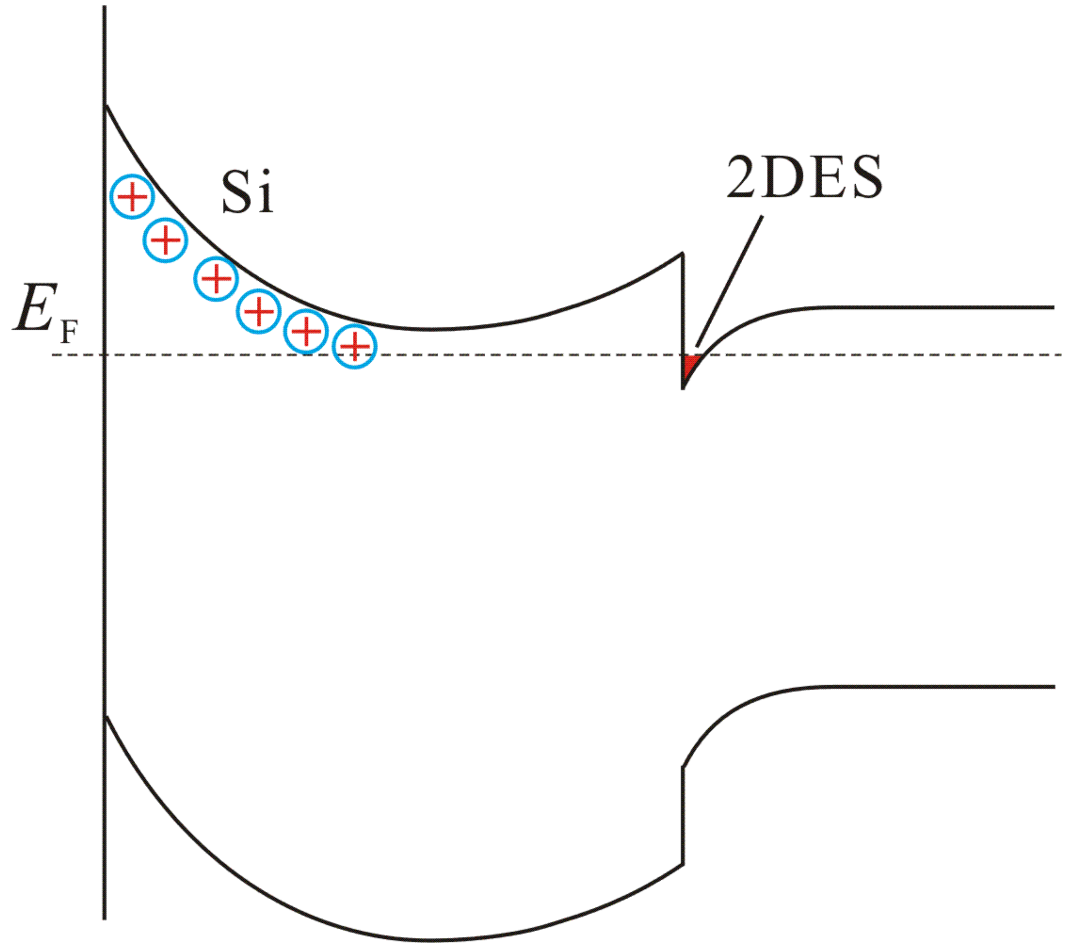
Molecular Beam Epitaxy



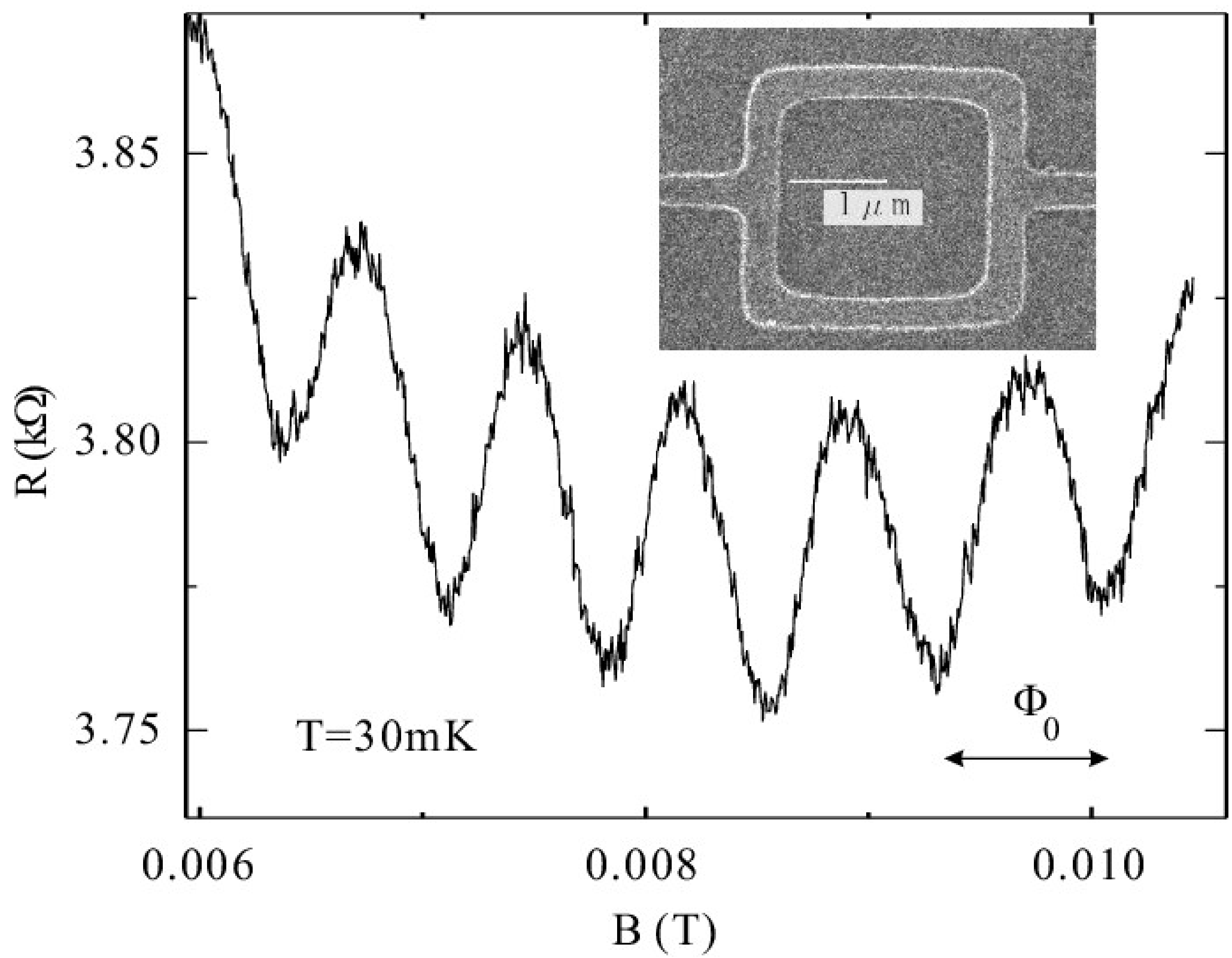
Semiconductor heterostructure

1. Long mean free path

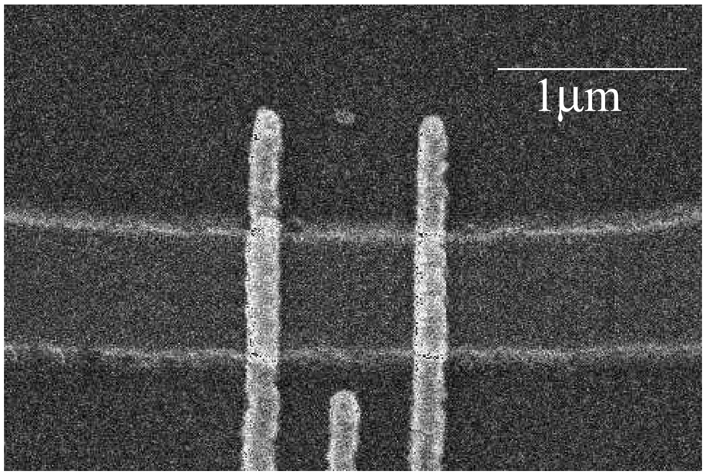
2. Low electron density (long de Broglie wave-length)

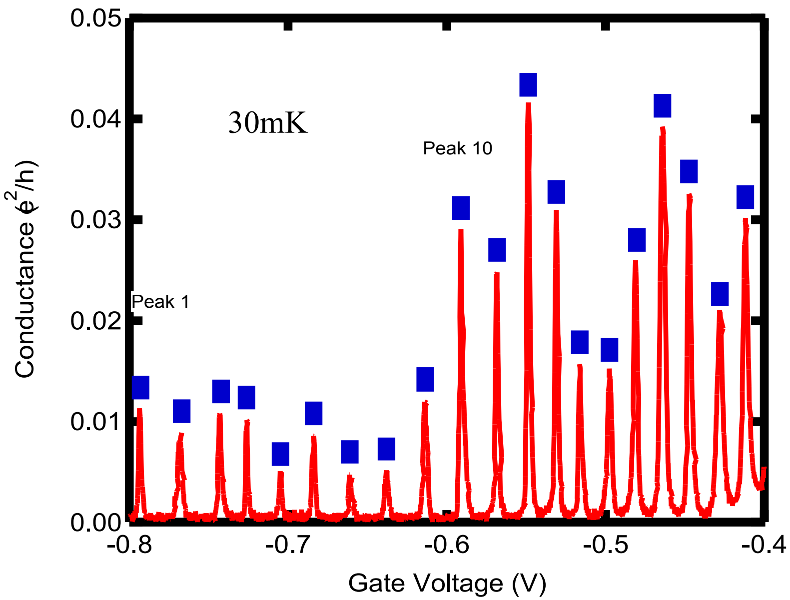


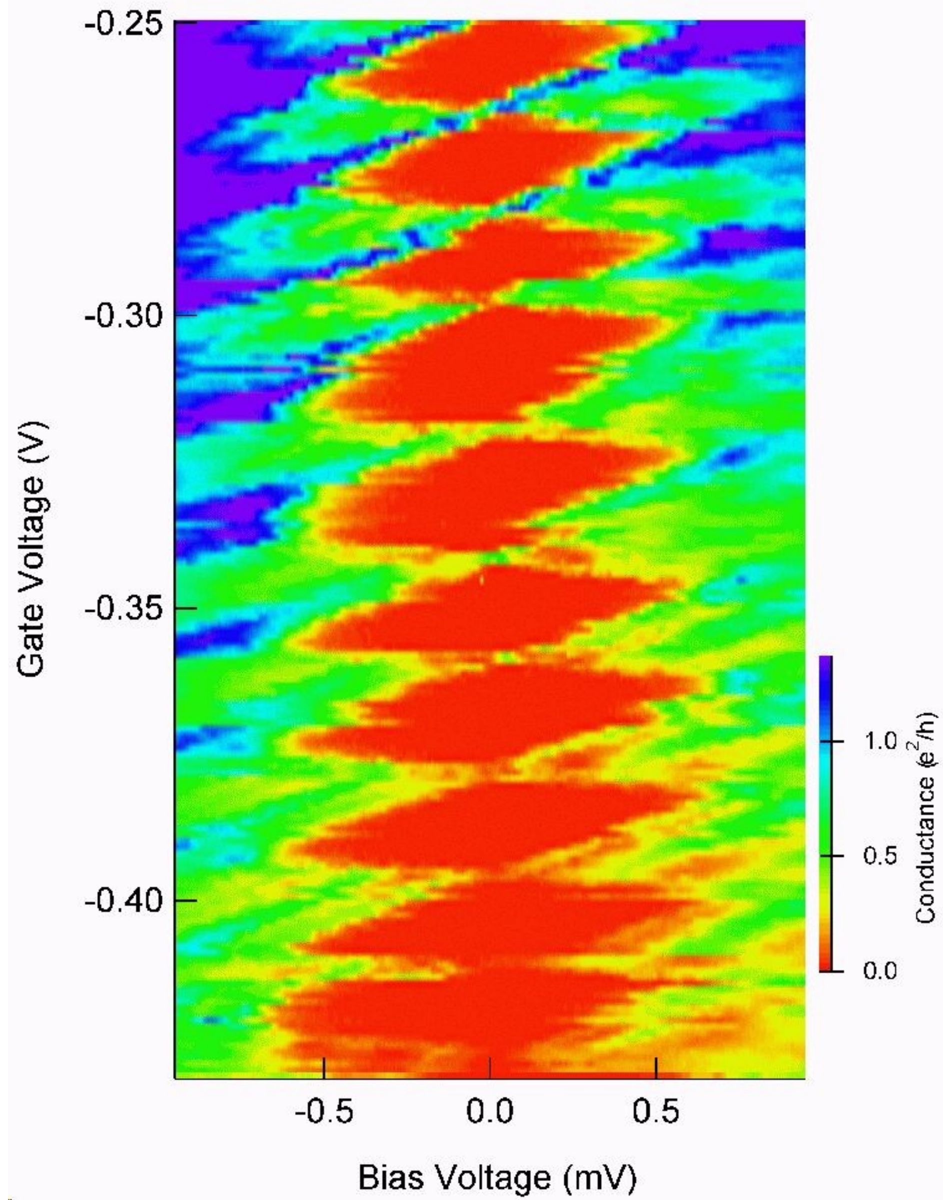
AB ring made of 2DES at a hetrointerface



Coulomb oscillation and Coulomb diamond in a semiconductor quantum dot

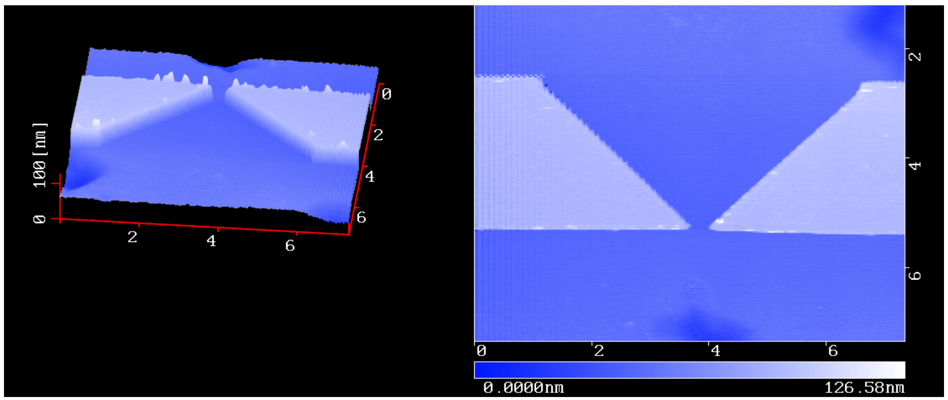


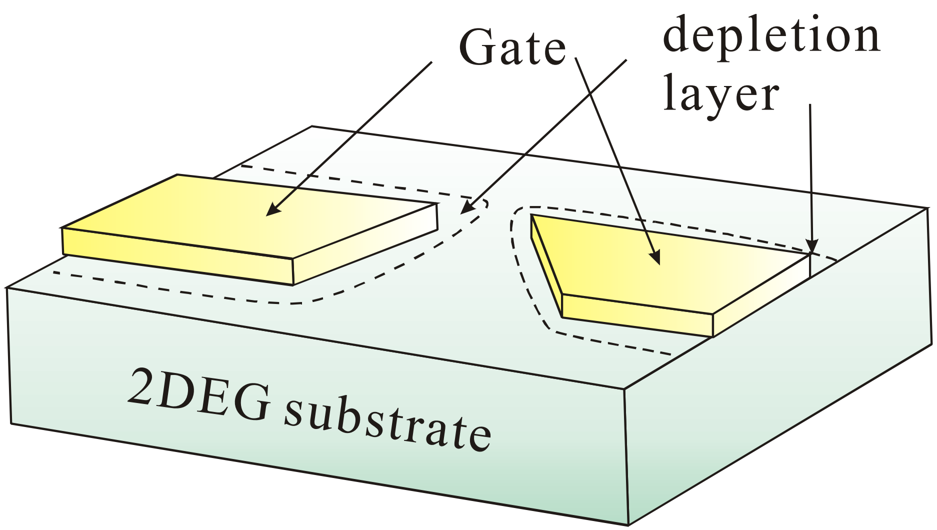


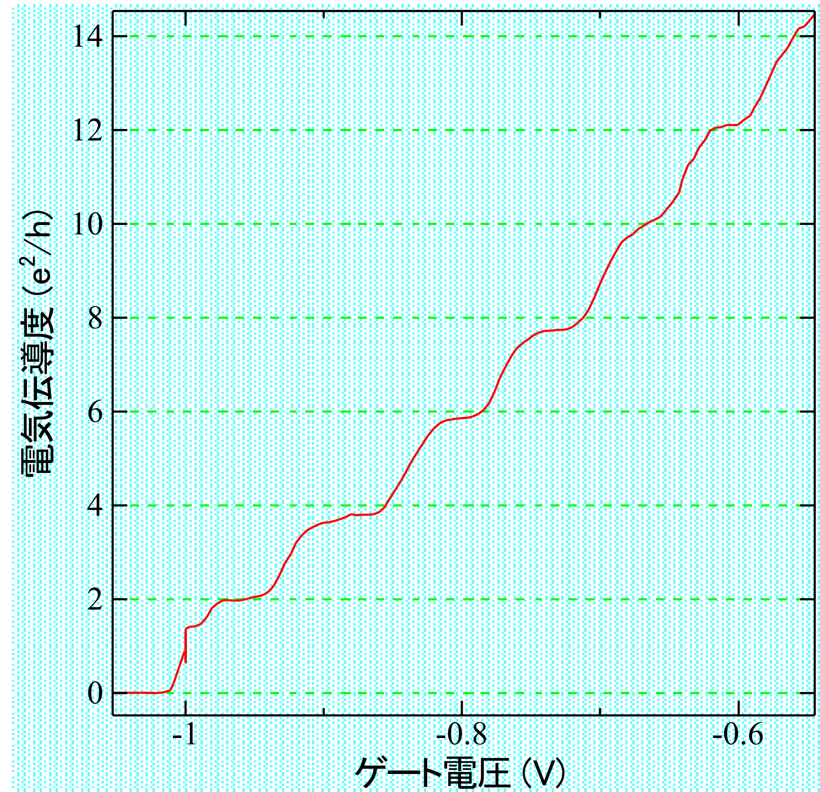


量子ポイントコンタクト

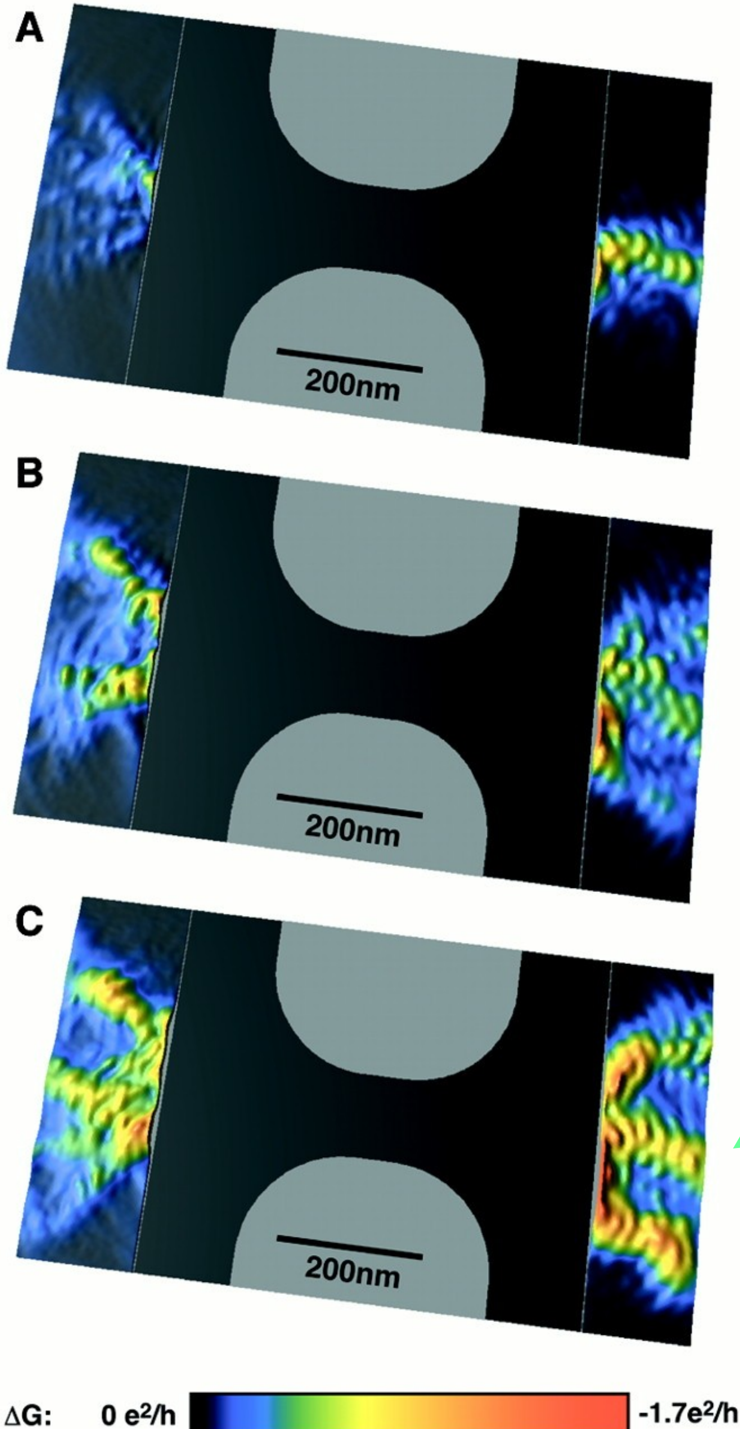
Quantum Point Contact
(QPC)

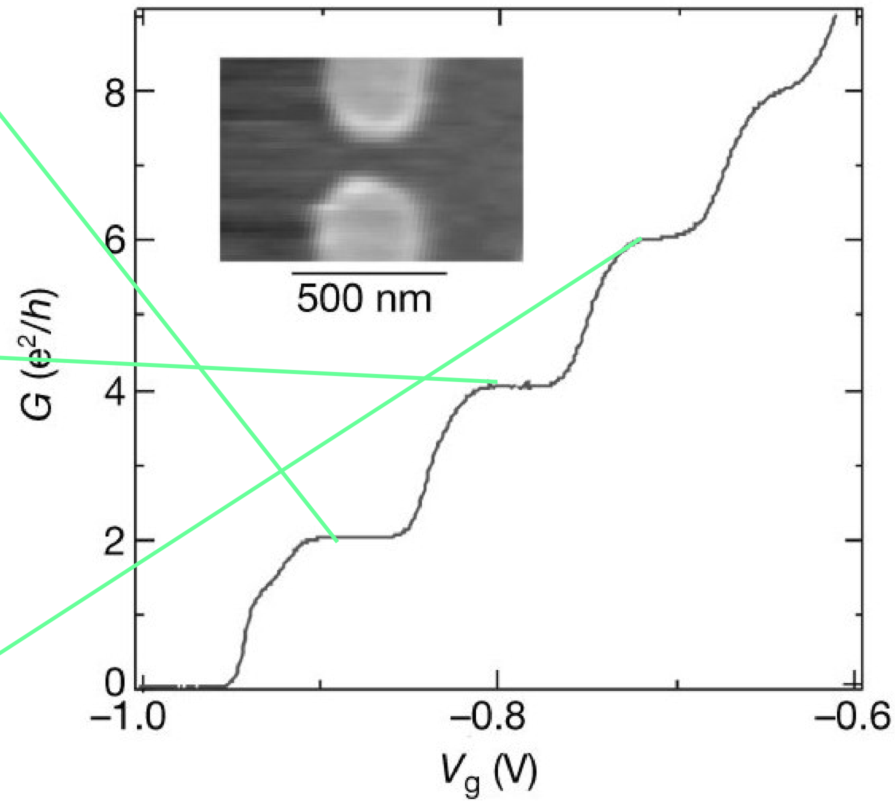






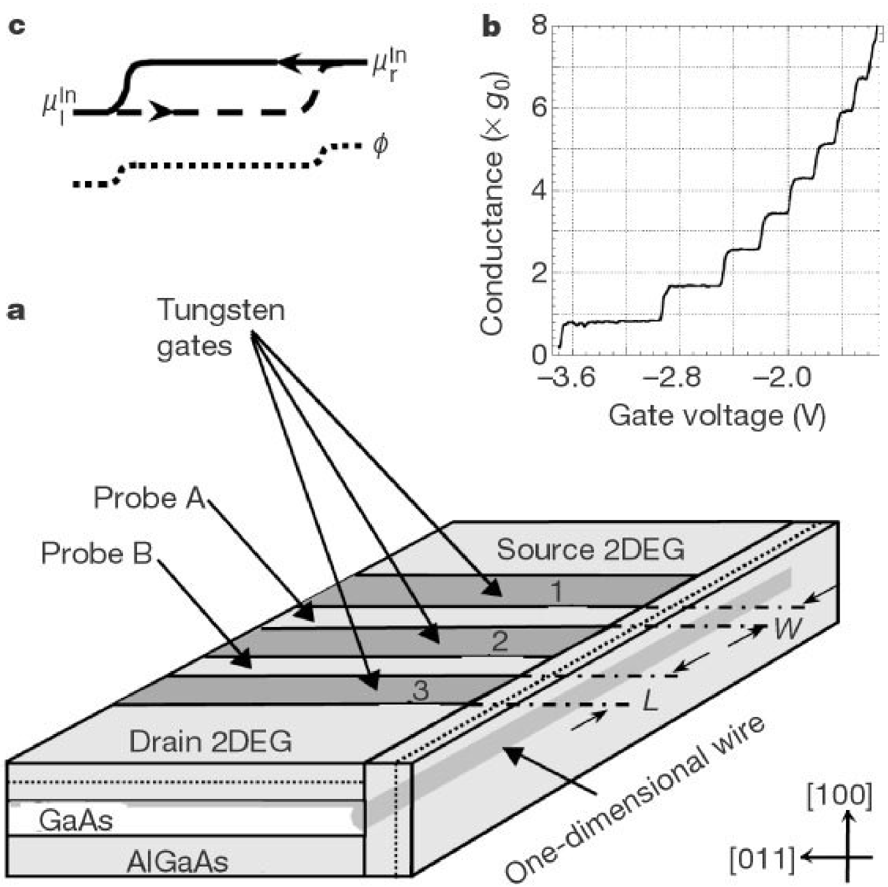
量子ポイントコンタクト
モデルは本当か？

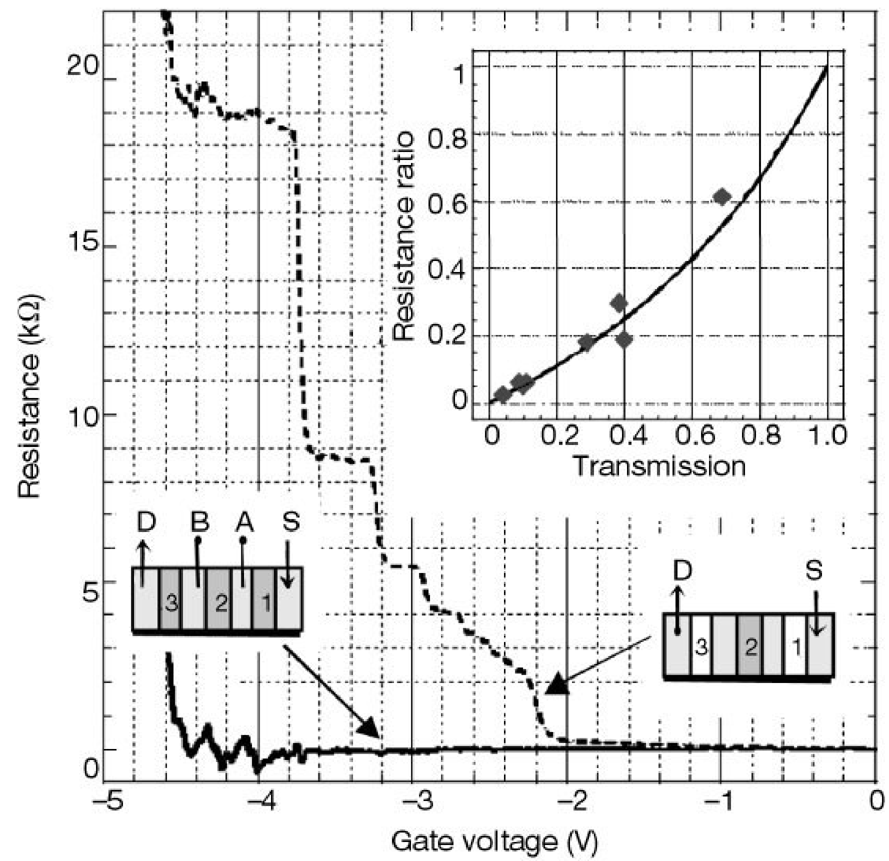




量子細線の4端子抵抗測定

R. de Picciotto et al. Nature **411**, 51 (2001)

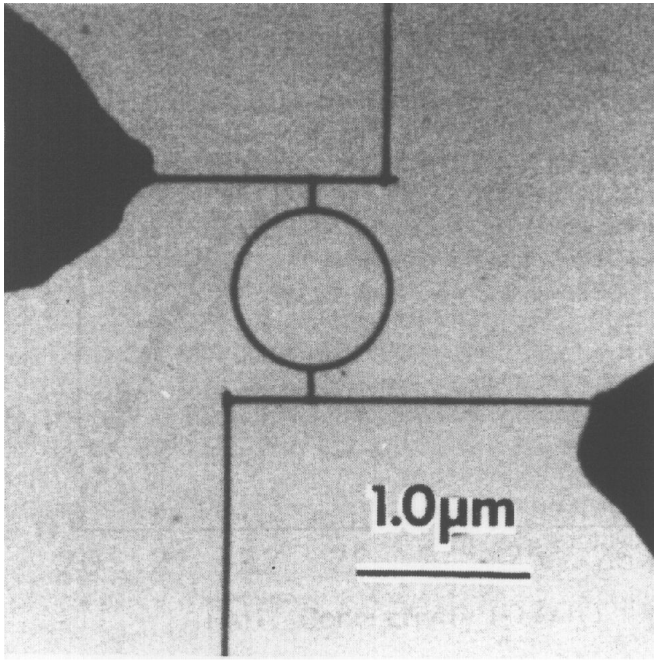


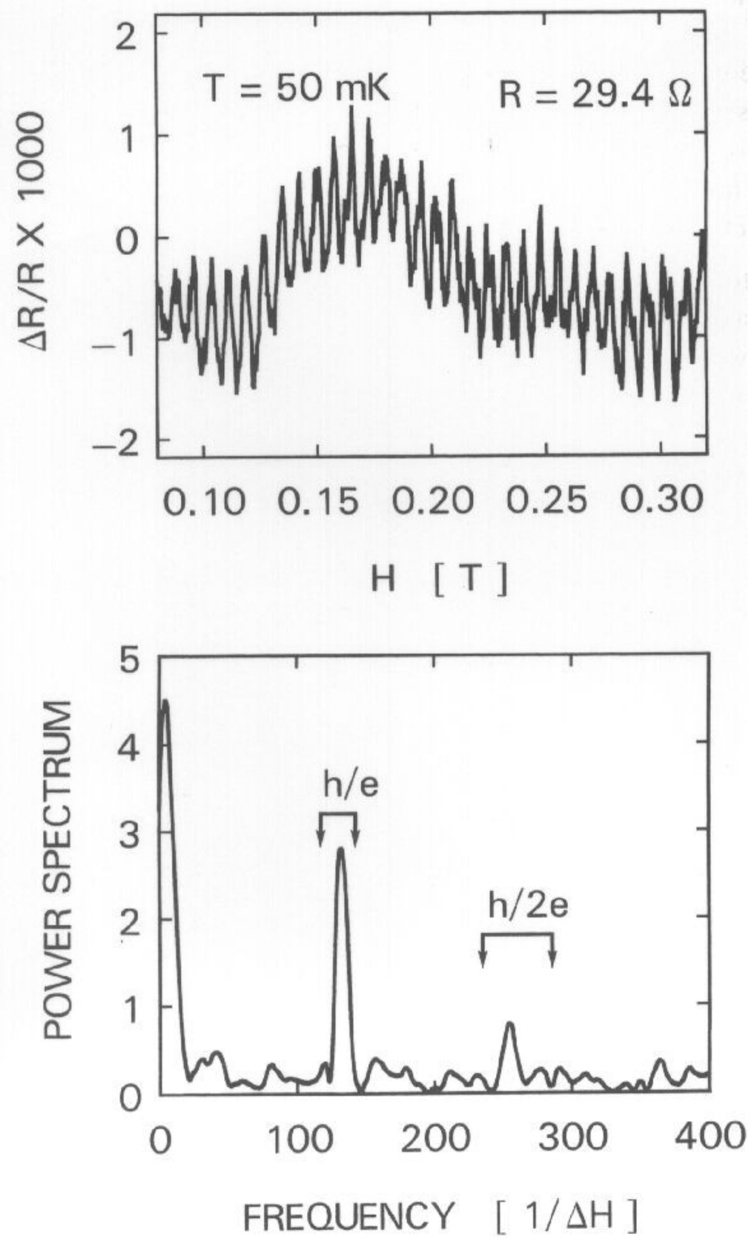


メゾスコピック物理の始まり

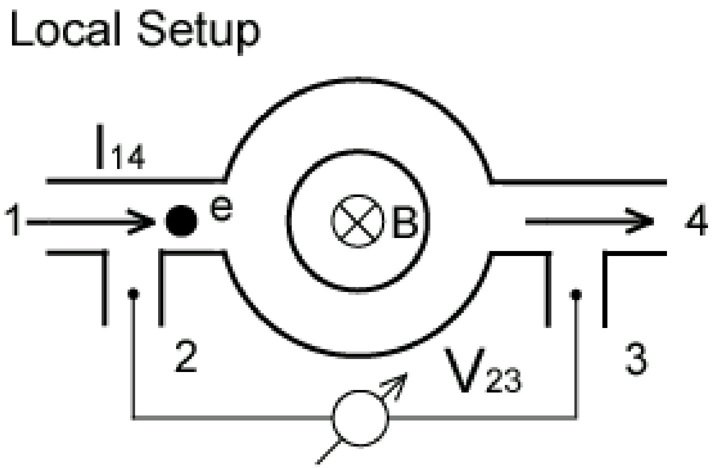
Aharonov-Bohm 効果の観測

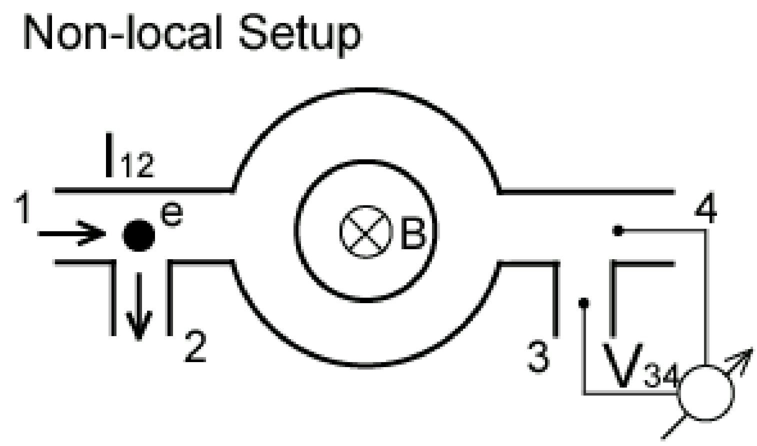
R. A. Webb et al. PRL 54, 1610 (1985).



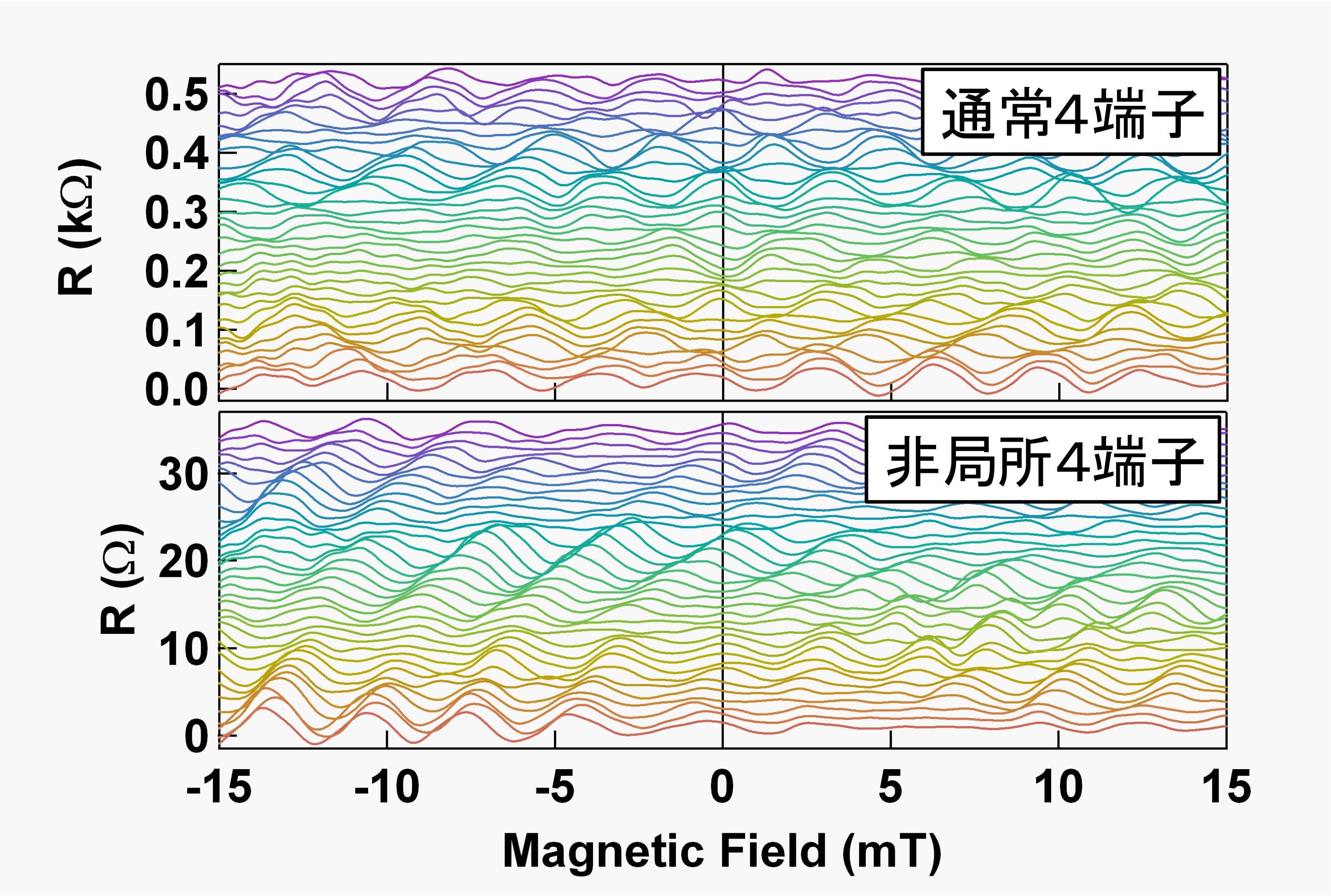


AB効果の非局所測定

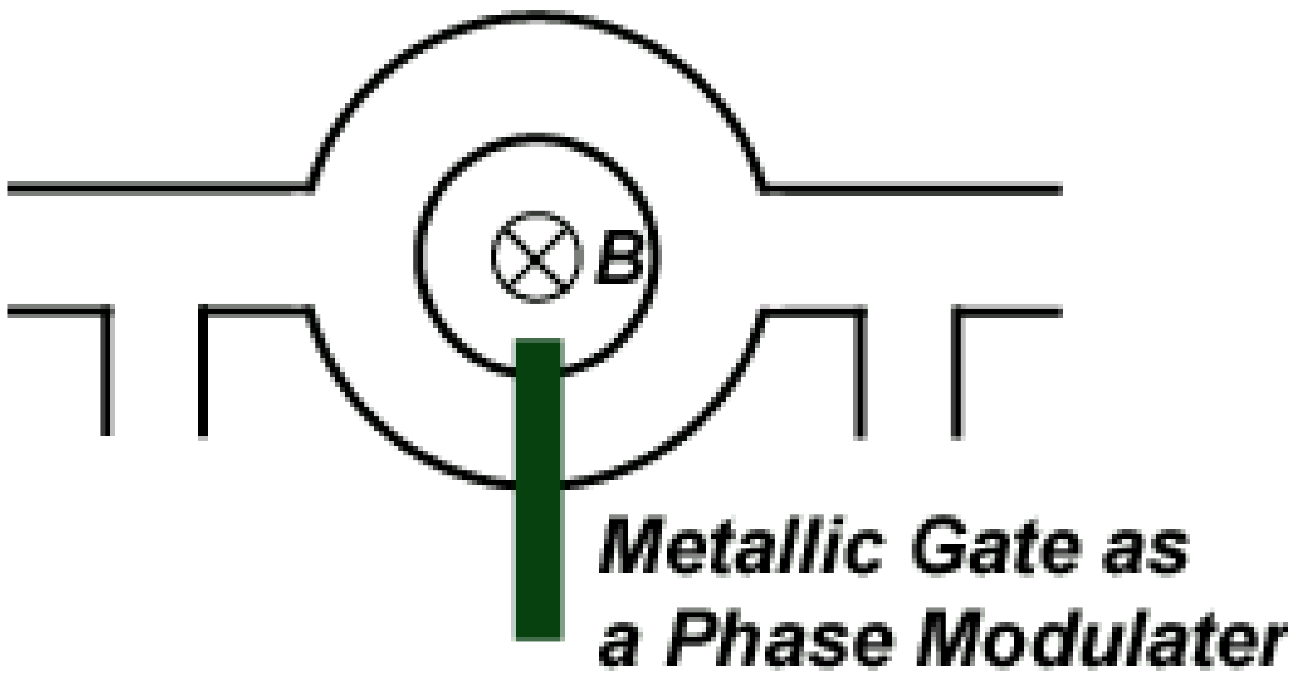




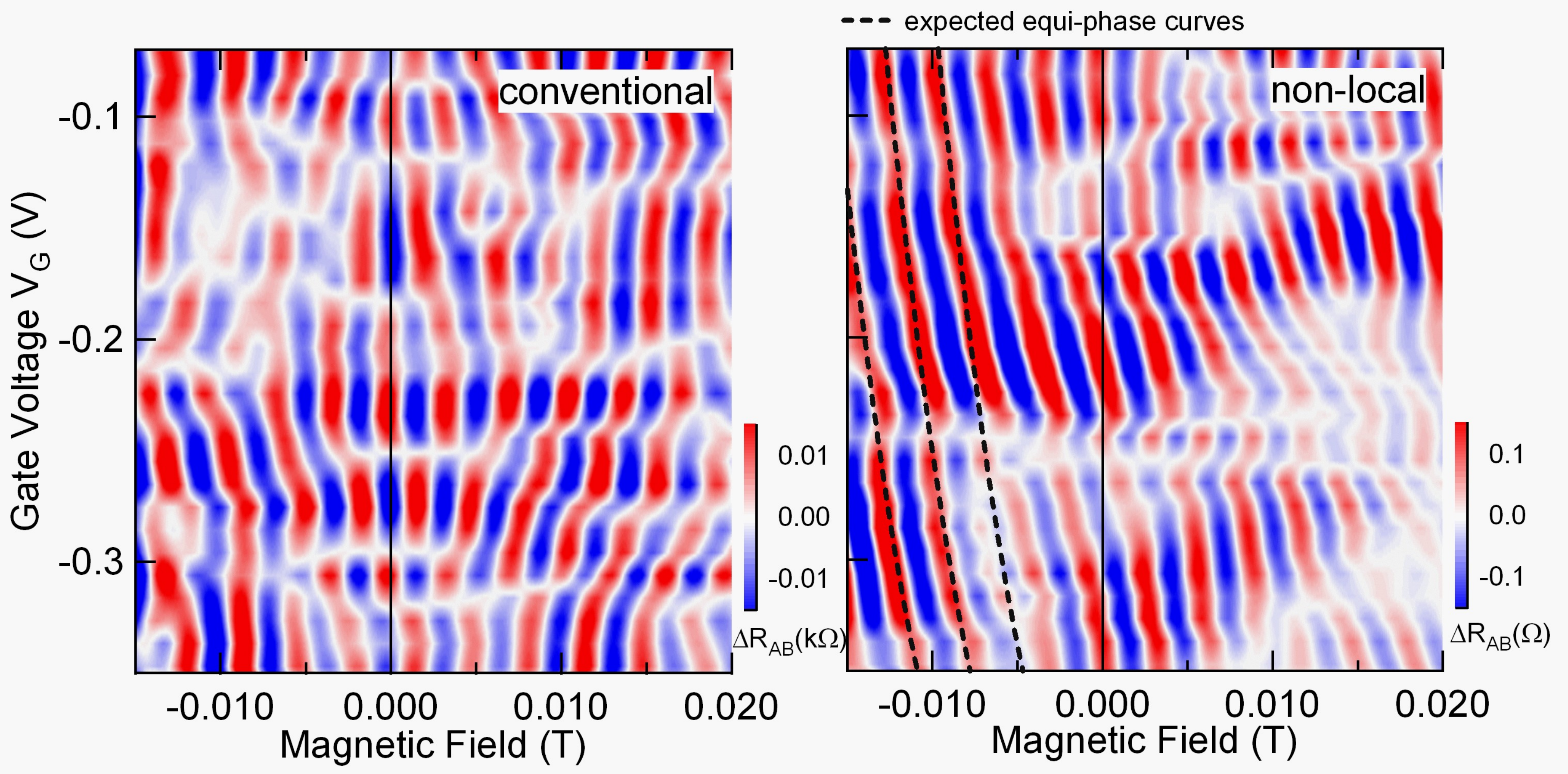
２つの端子配置での位相変化



静電的なAB位相制御



AB位相制御



expected equi-phase curves
conventional
non-local
Gate Voltage V_G (V)
-0.1
-0.2
-0.3
0.01
0.00
-0.01
ΔR_{AB}(kΩ)
0.1
0.0
-0.1
ΔR_{AB}(Ω)
-0.010
0.000
0.010
0.020
Magnetic Field (T)
Magnetic Field (T)

非局所AB効果に対するOnsagerの相反定理