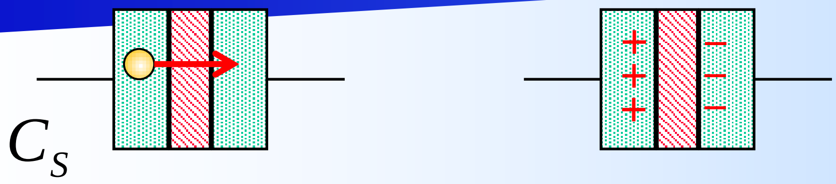
Physics of Semiconductors (14)

Shingo Katsumoto
Institute for Solid State Physics,
University of Tokyo

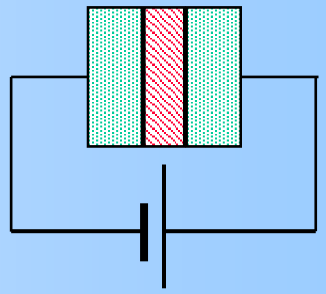
2013/7/22

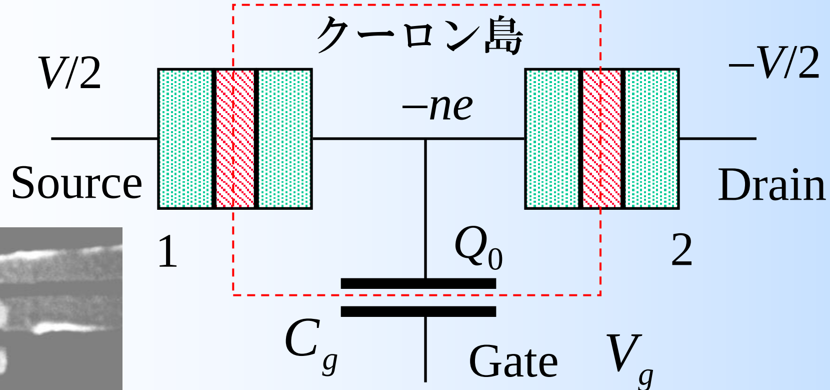
Quantum dot as a single-electron transistor



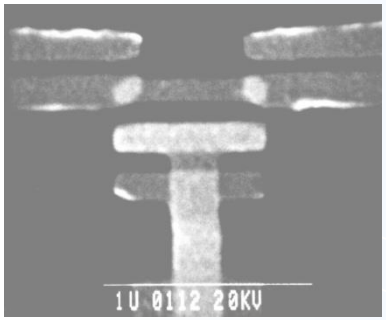
$$E_c = \frac{e^2}{2C_s}$$

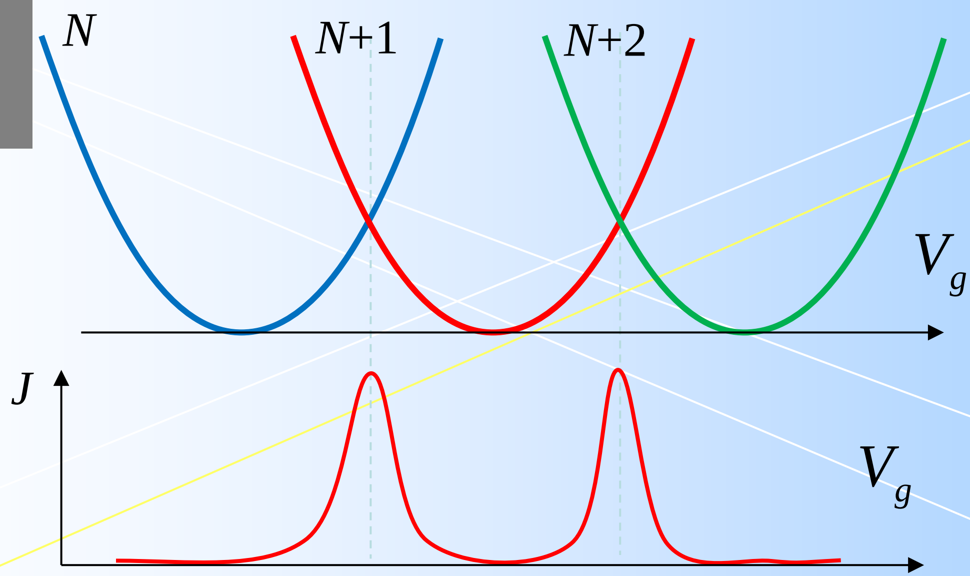
Coulomb blockade?

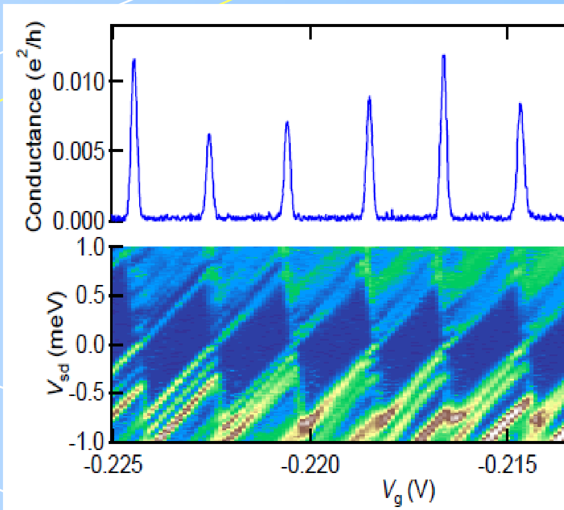




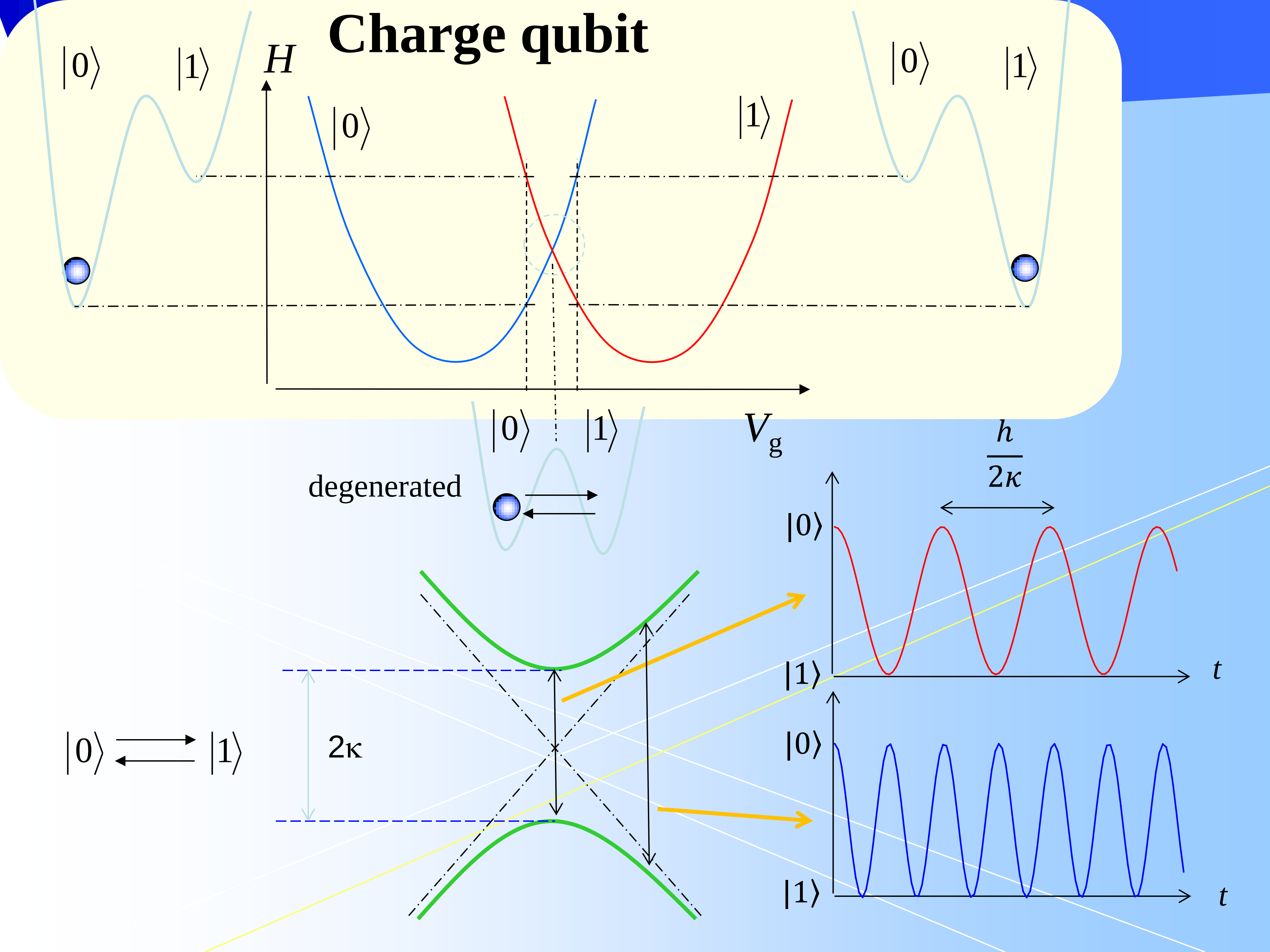
$$H = \frac{1}{2C_S}(C_g V_g - ne)^2$$





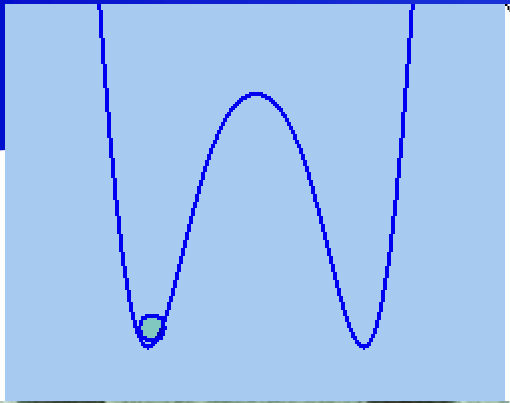


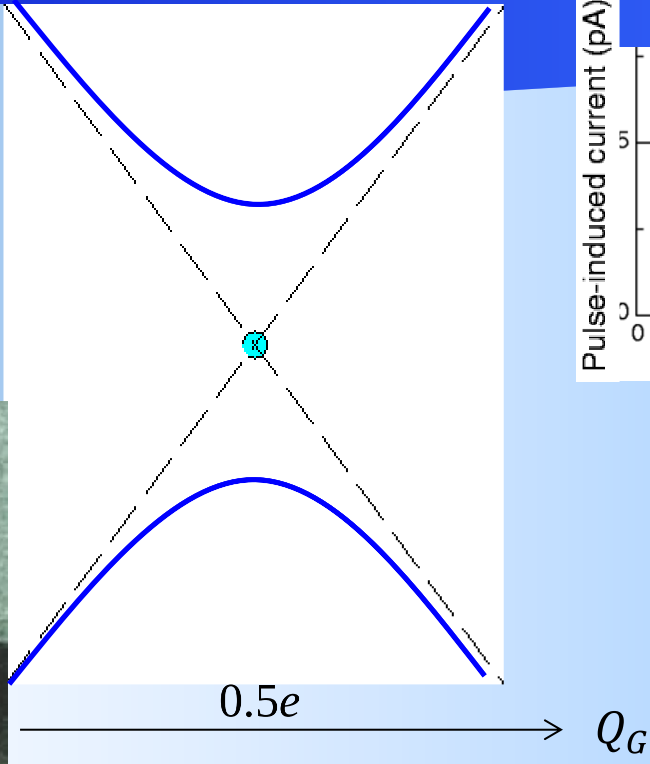
Charge qubit

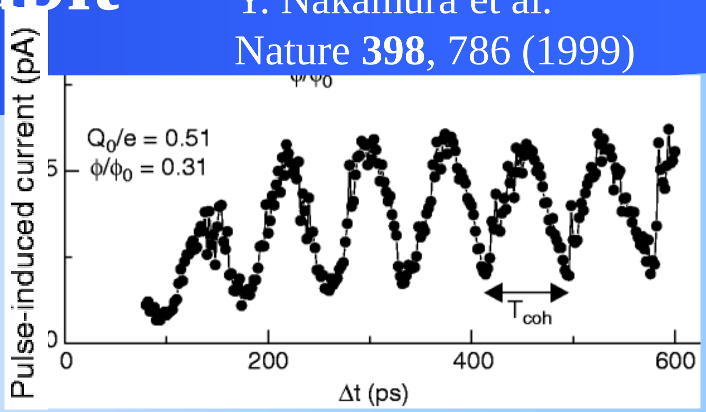


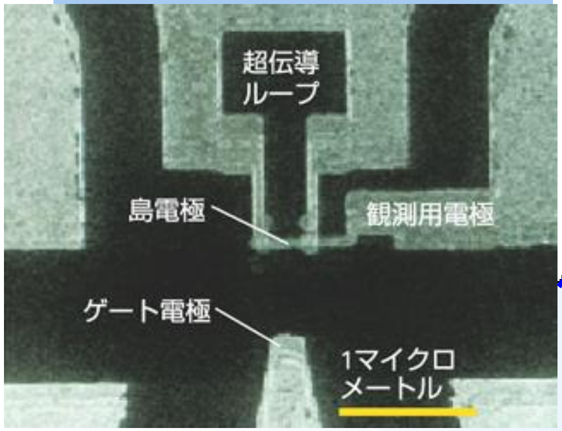
Superconducting charge qubit

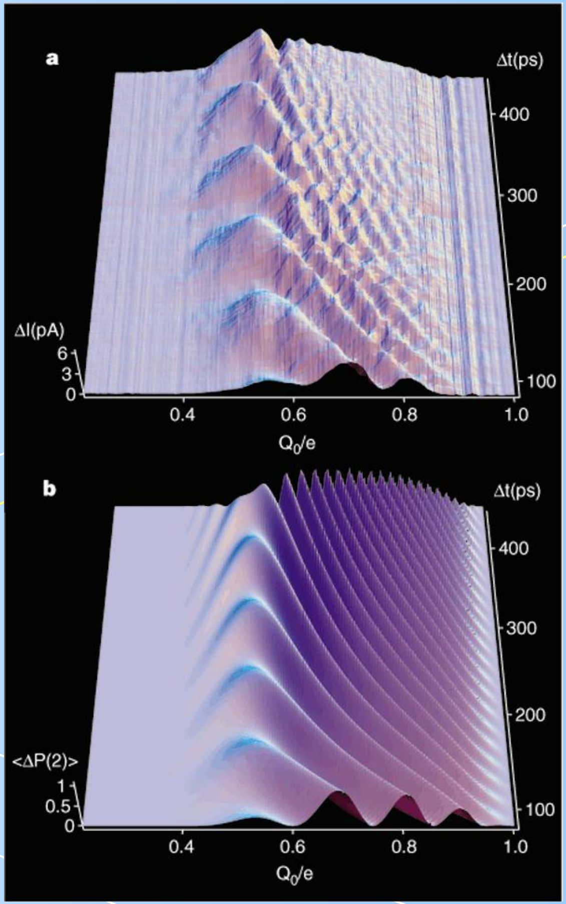
Y. Nakamura et al.
Nature **398**, 786 (1999)

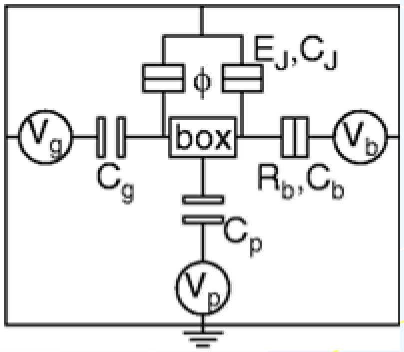


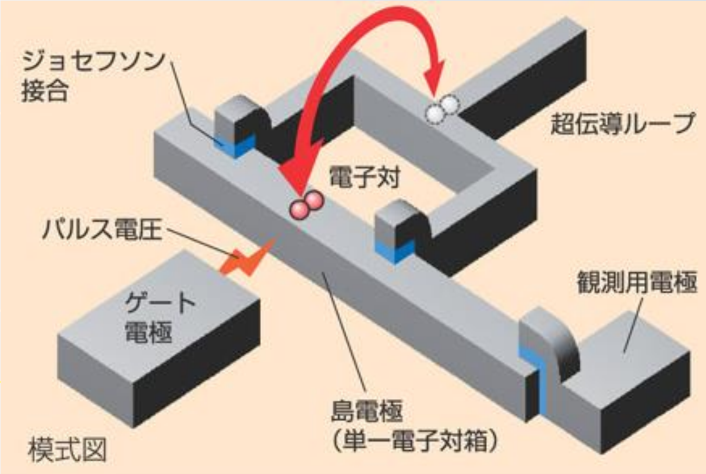




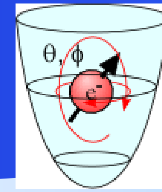








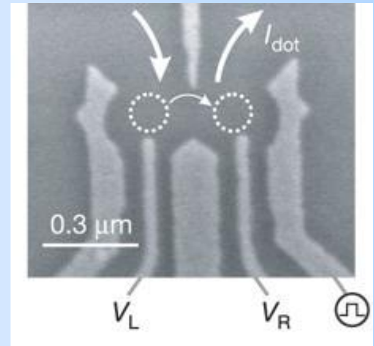
Spin qubit

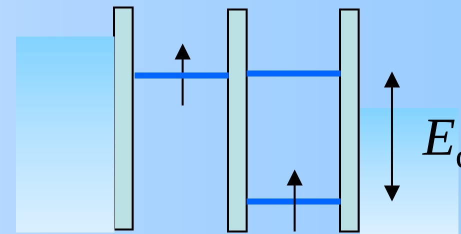


F. H. Koppens et al. Nature 442, 766 (2006)

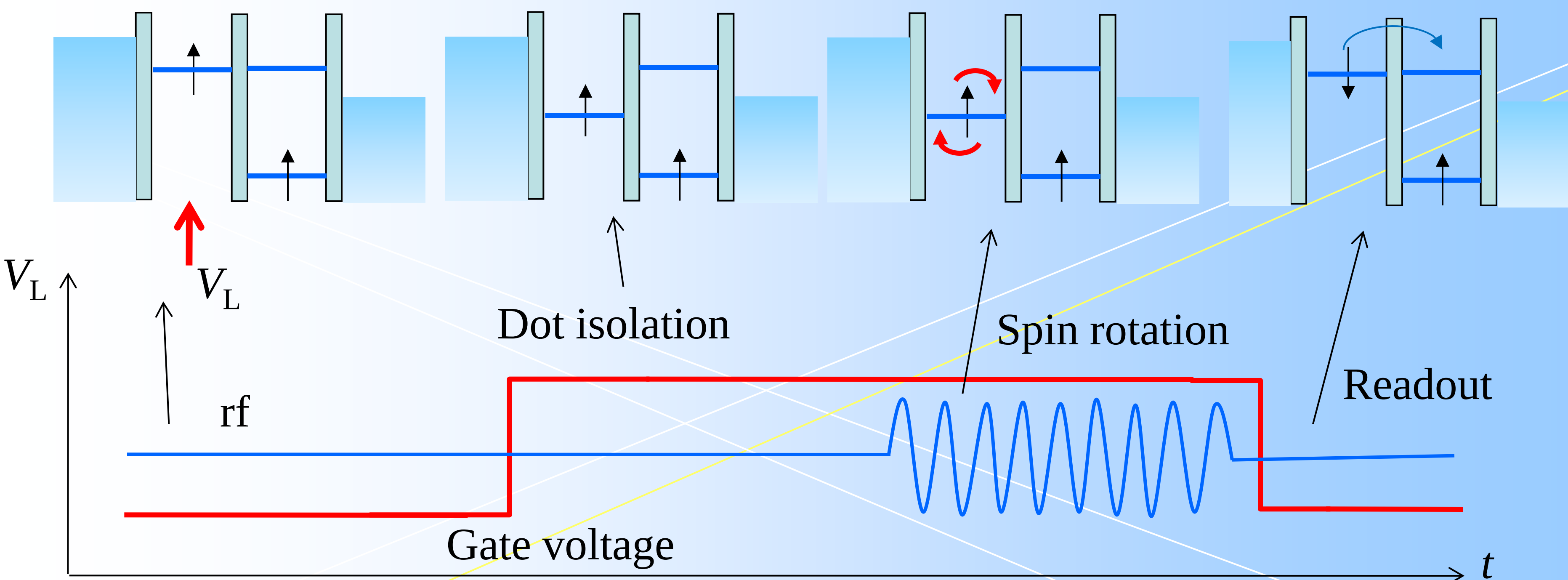
even electrons
no spin

odd electrons
spin 1/2

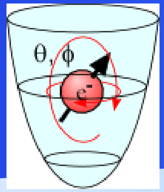




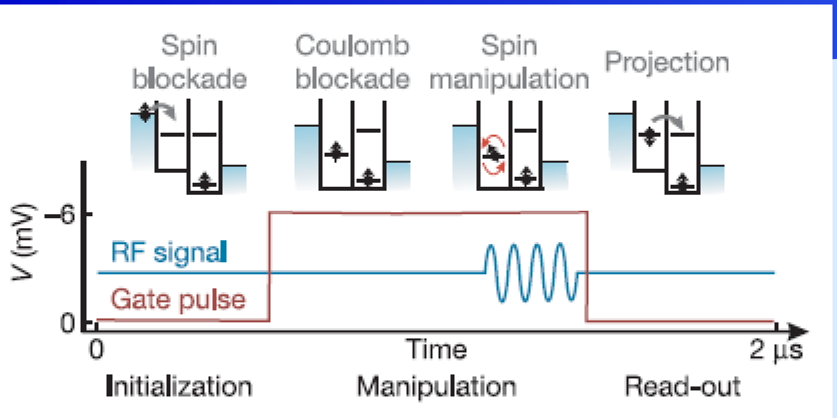
Spin blockade

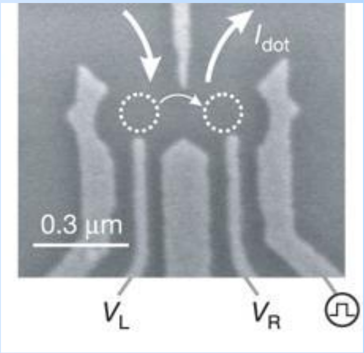


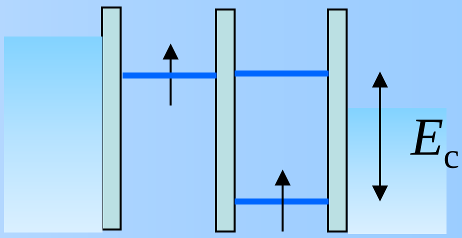
Spin qubit



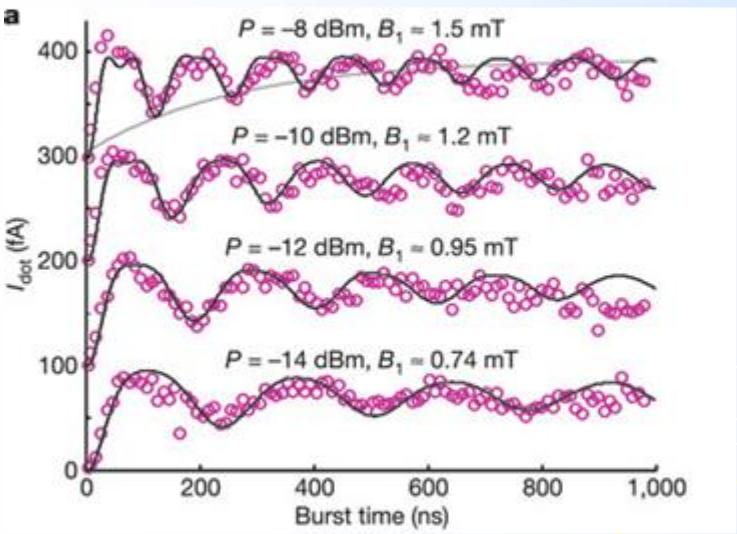
F. H. Koppens et al. Nature 442, 766 (2006)

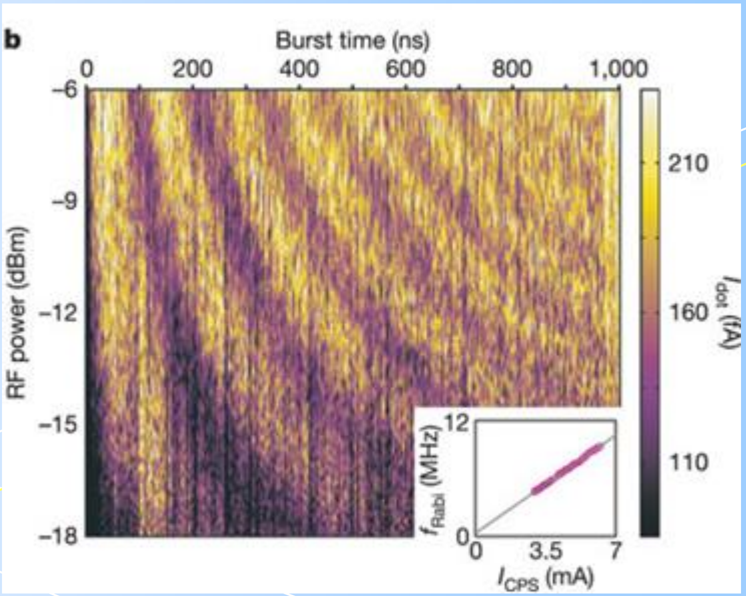






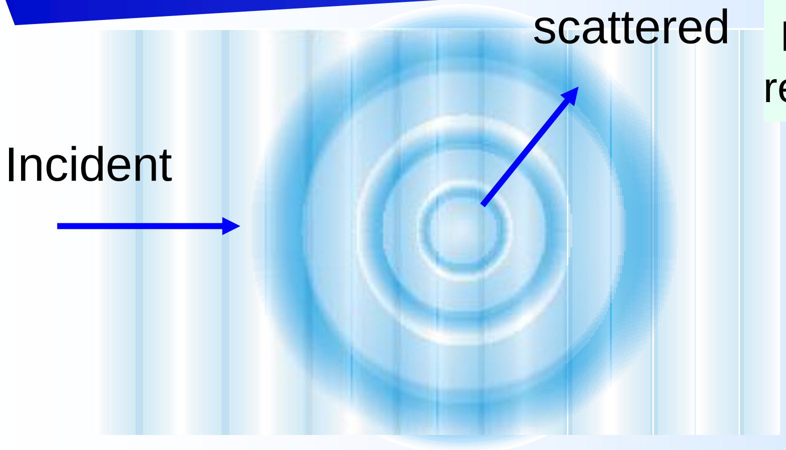
Spin blockade

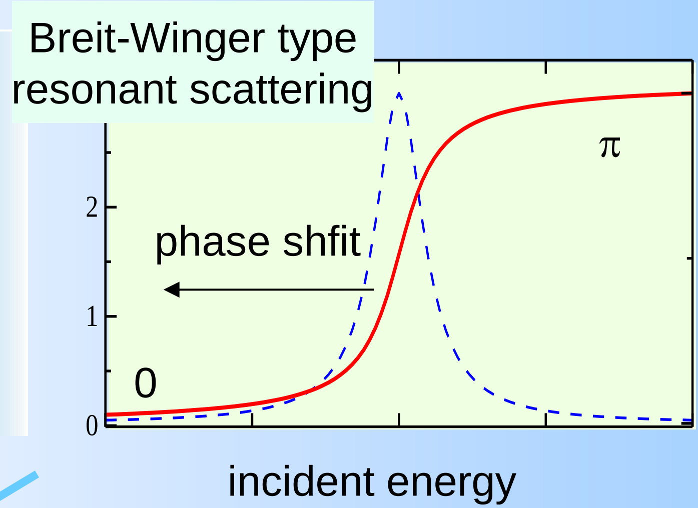




The Fano effect

Ugo Fano



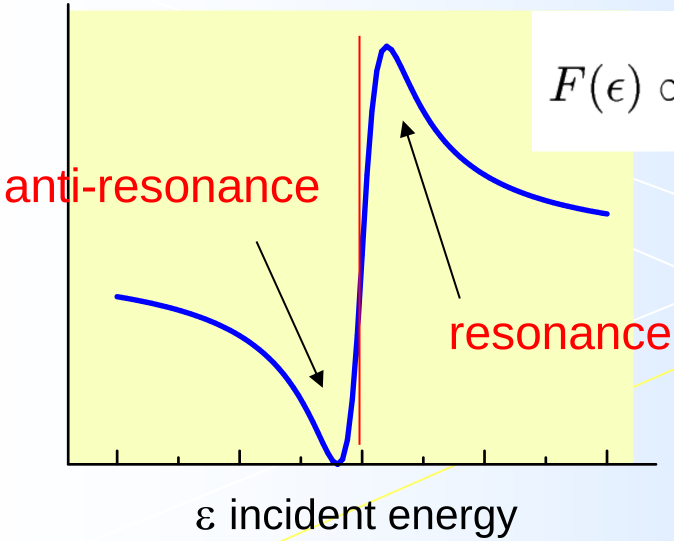


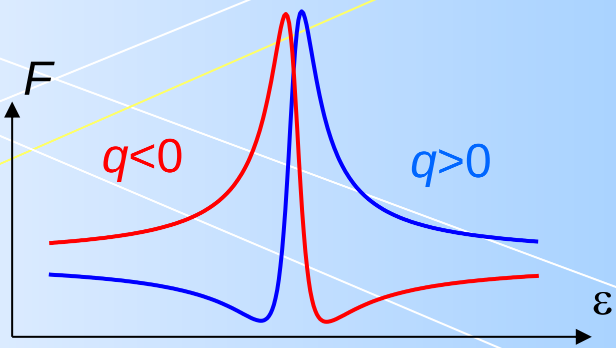
interference

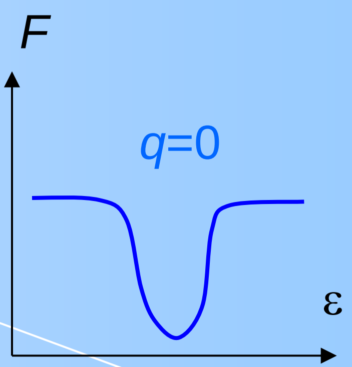
F (ε) : transition probability

Fano parameter

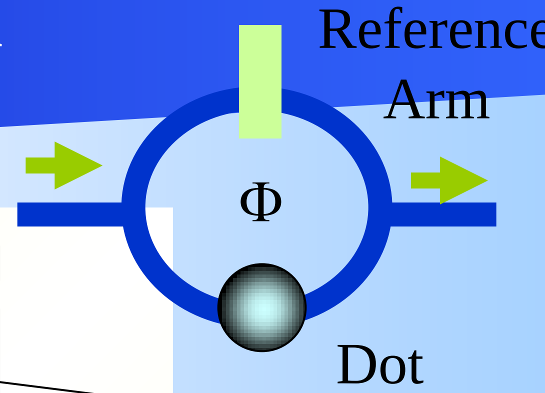
$$F(\epsilon) \propto \frac{(\tilde{\epsilon} + q)^2}{(\tilde{\epsilon}^2 + 1)}, \quad \tilde{\epsilon} = \frac{\epsilon - \epsilon_c}{\Gamma/2}$$

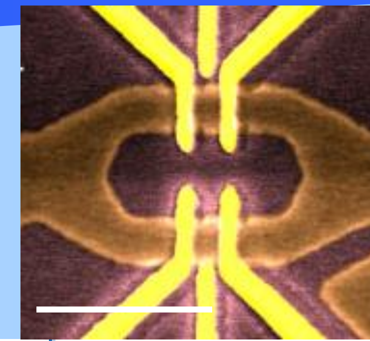


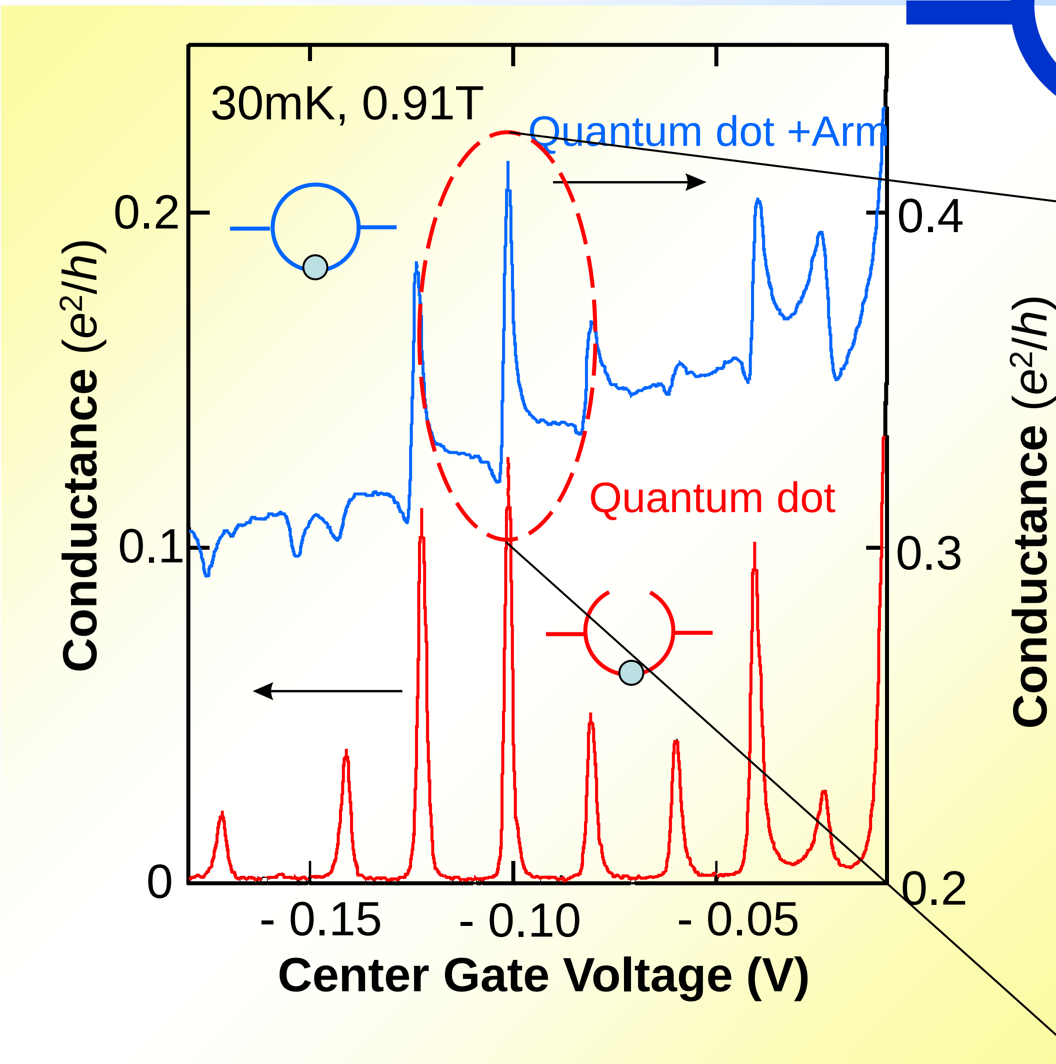


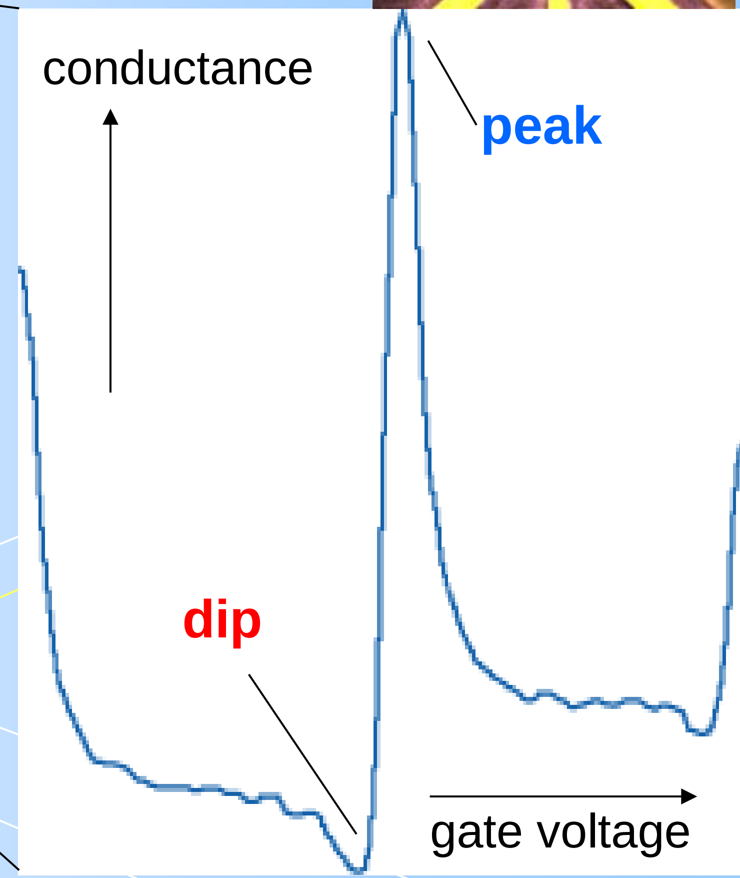


Distortion of Coulomb Oscillation

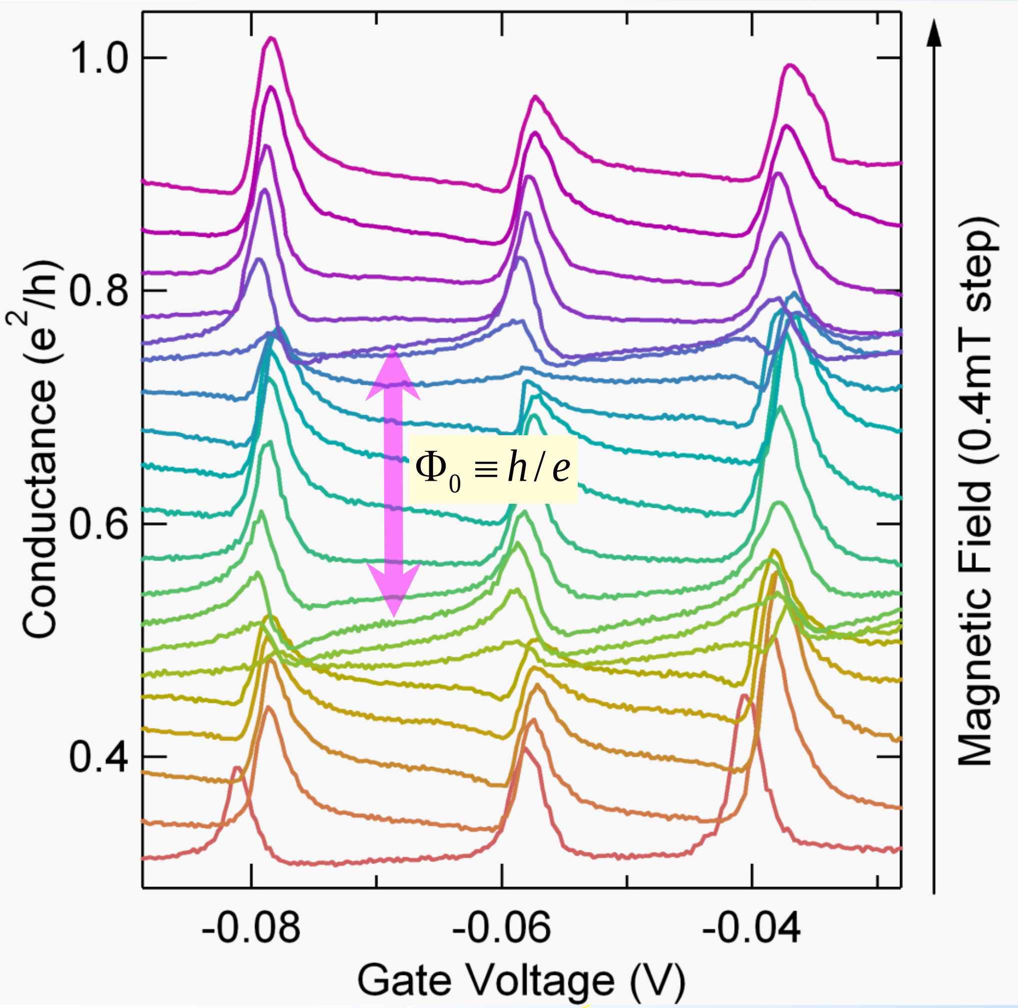


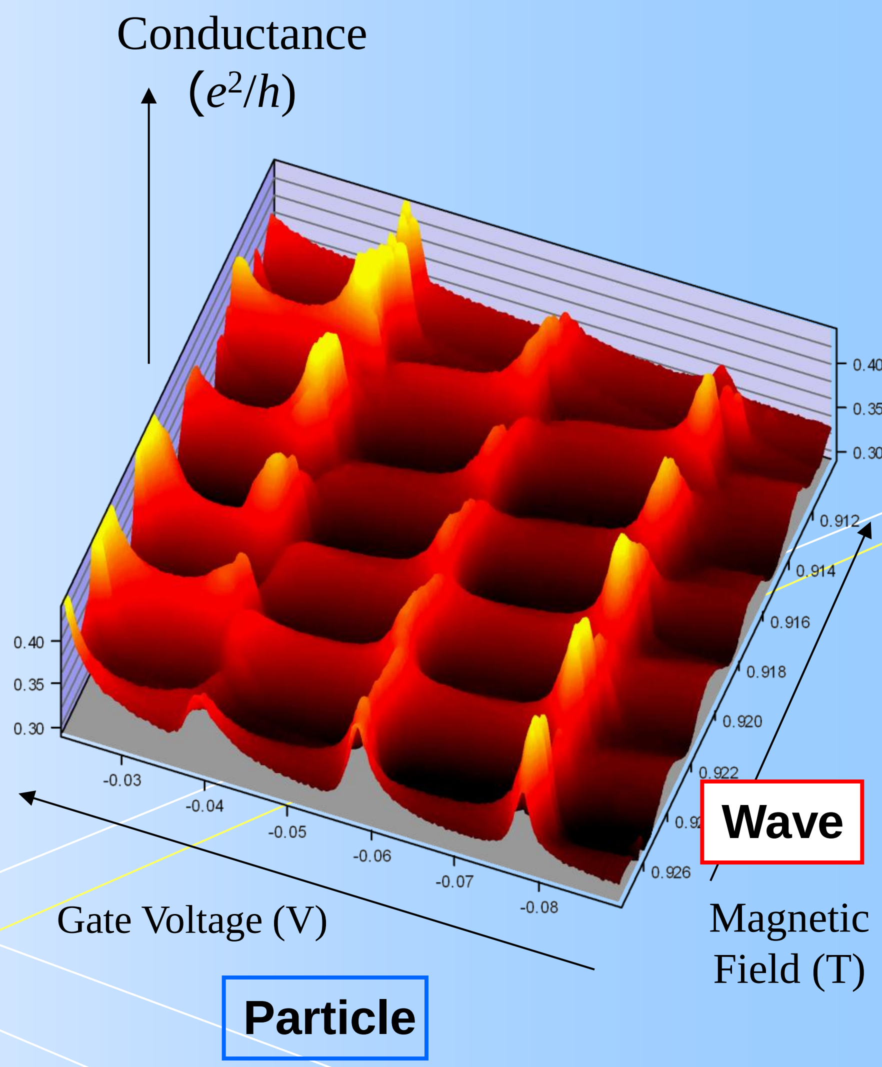






Effect of magnetic flux





K. Kobayashi et al. PRL 88, 256806 (`02)

Spin state and quantum decoherence

Akera PRB **59**, 9802(`99), König & Gefen PRB**65**, 045316 (`02)

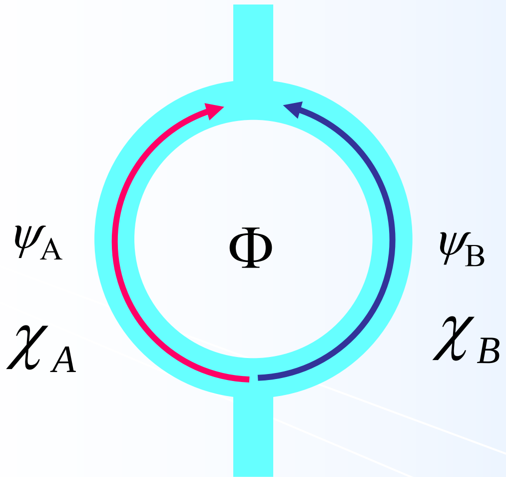
χ_A:spin-up χ_B:spin-down

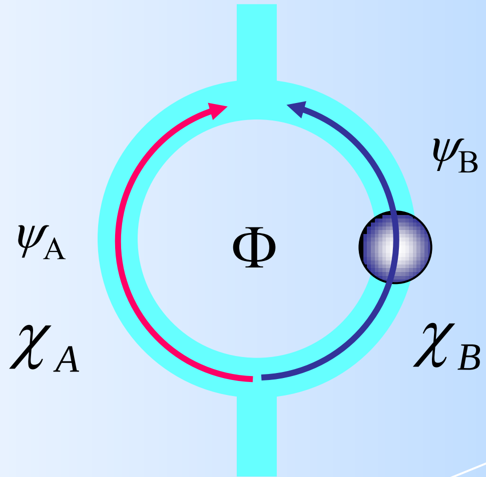
interference term : 0

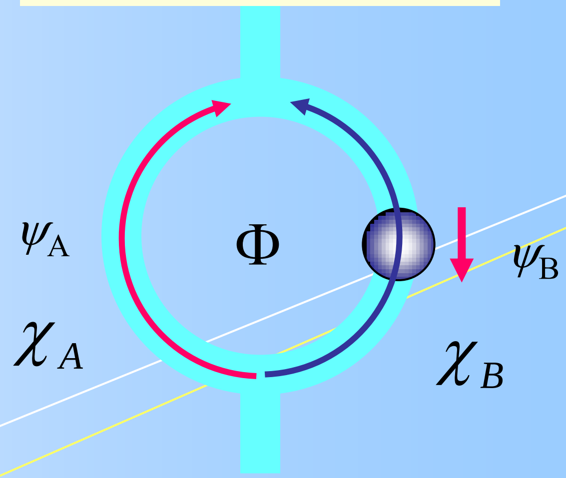
$$2|\psi_A||\psi_B|\cos\theta\int d\xi\chi_A(\xi)\chi_B^*(\xi)$$

$$2|\psi_A||\psi_B|\cos\theta$$

Partial coherence





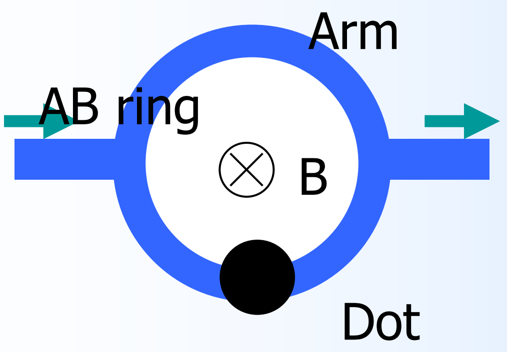


N:even
no spin-flip scattering

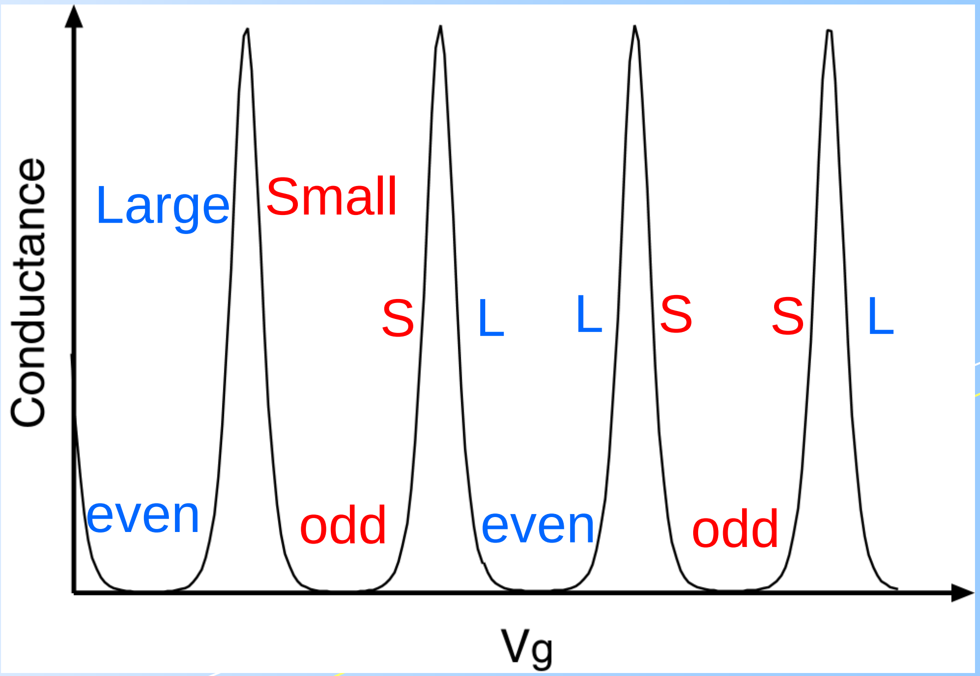
N:odd
spin-flip scattering
exists

Spin-flip process reduces quantum coherence

Coulomb oscillation and AB oscillation

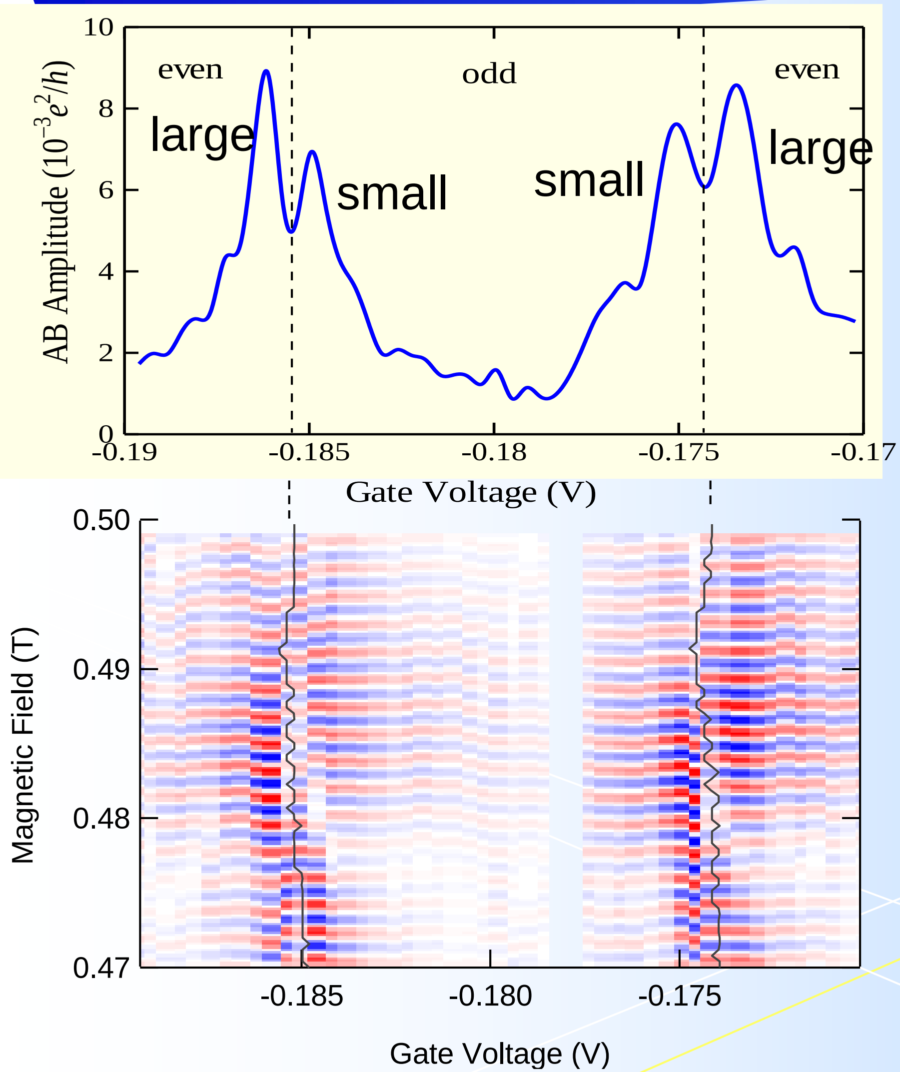


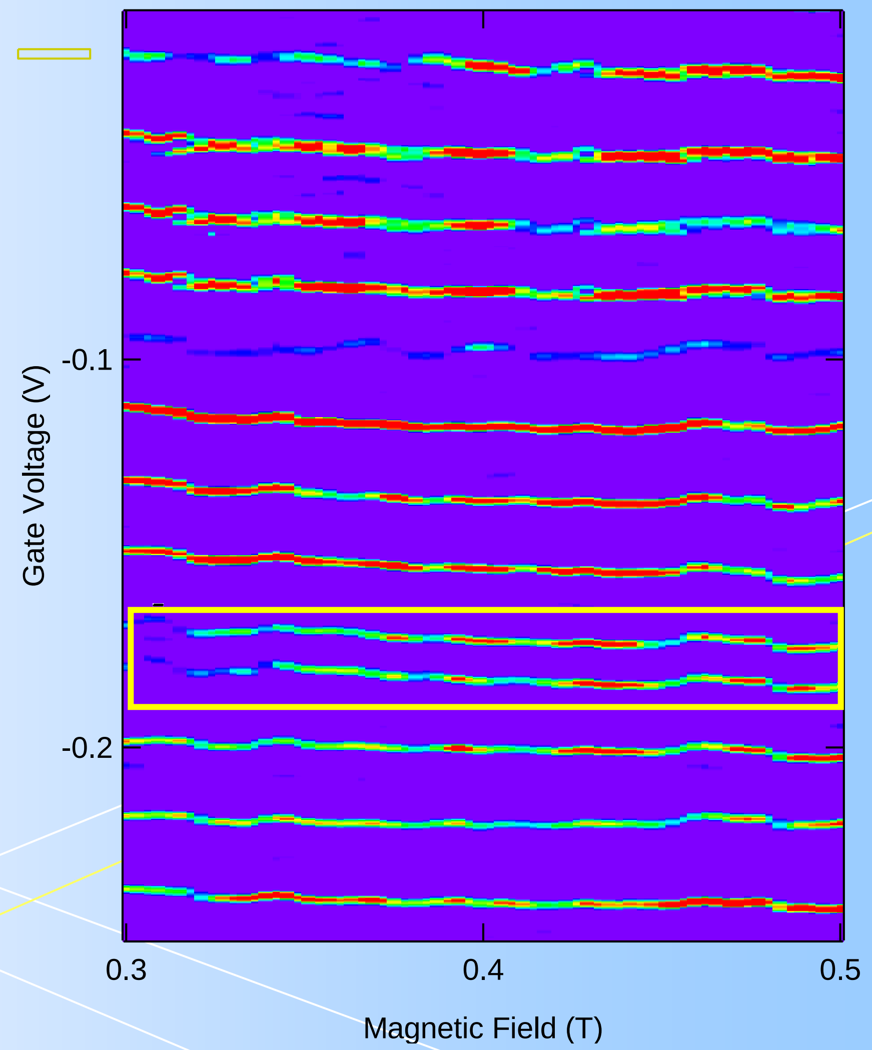
difference of coherence due to
the parity of electron number



- Asymmetry of AB amplitude
- The asymmetry reflects the parity of electron number

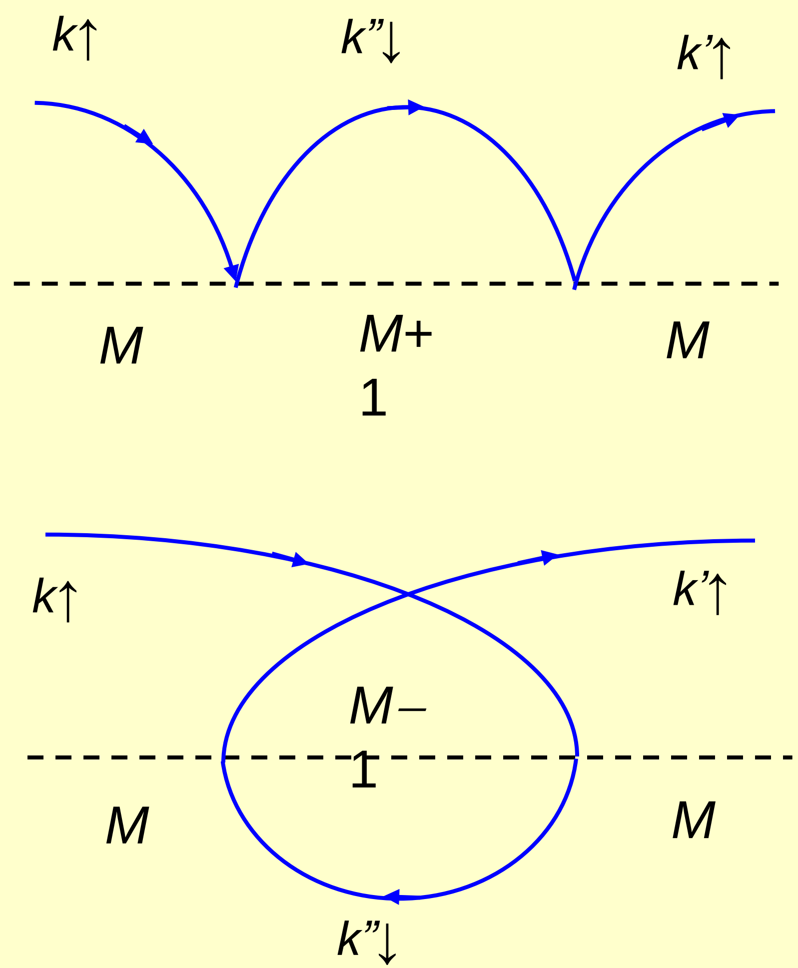
AB amplitude for a spin-pair

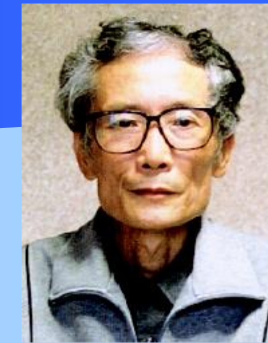




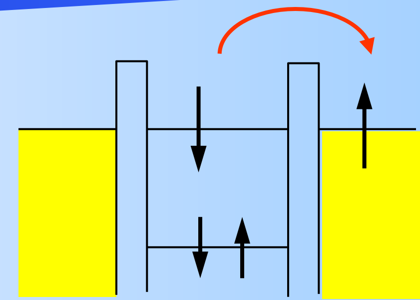
H. Aikawa et al. PRL **92**, 176802 (`04)

The Kondo Effect



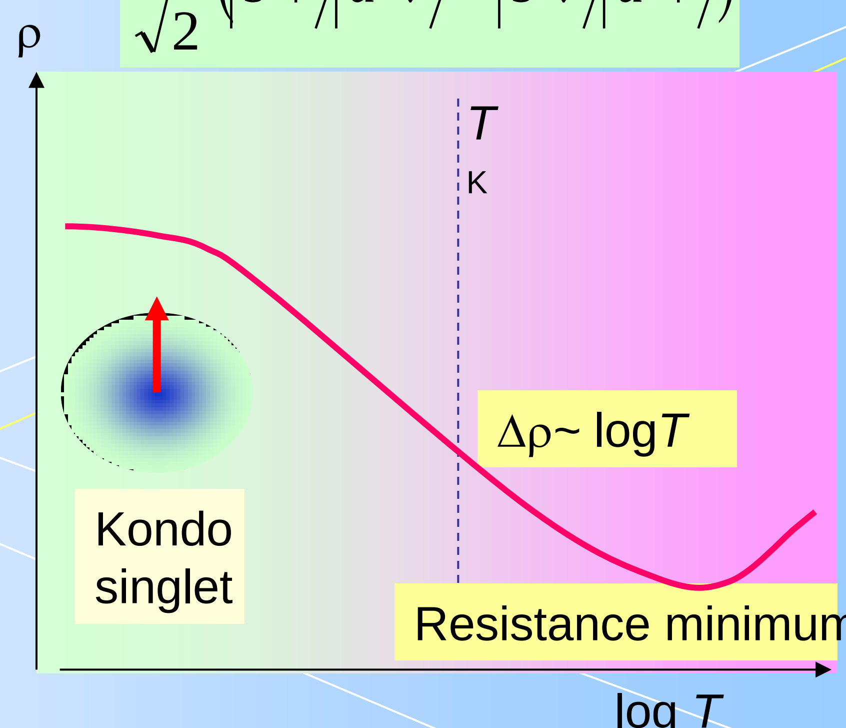


Jun Kondo



What is happening ?

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



PHYSICAL REVIEW VOLUME 168, NUMBER 2 10 APRIL 1968

Closed-Form Solution for the Collective Bound State due to the *s-d* Exchange Interaction

AKIO YOSHIMORI
Institute for Solid State Physics, University of Tokyo, Tokyo, Japan

(Received 6 September 1967)

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

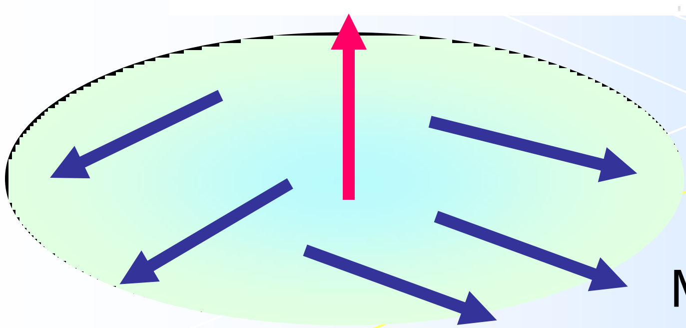
$$+ \sum_{k_1k_2k_3} \left[\Gamma_{k_1k_2k_3}{}^{\alpha\downarrow} a_{k_1\downarrow}{}^{\dagger} a_{k_2\downarrow}{}^{\dagger} a_{k_3\downarrow} \alpha + \Gamma_{k_1k_2k_3}{}^{\beta\uparrow} a_{k_1\uparrow}{}^{\dagger} a_{k_2\uparrow}{}^{\dagger} a_{k_3\uparrow} \beta \right.$$

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

$$+ \cdots \Big\} \psi_v, \quad (1)$$

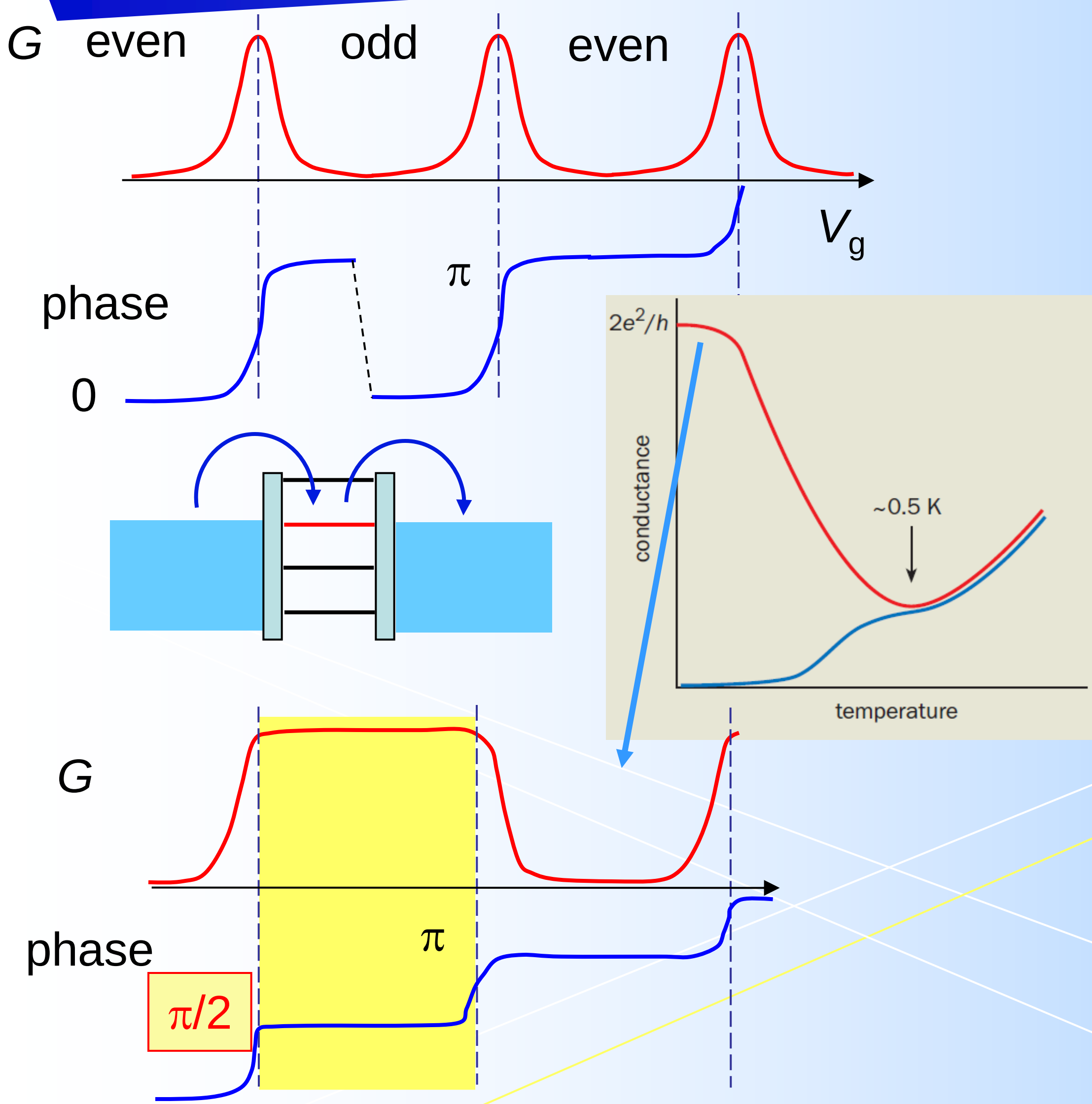
Kondo singlet

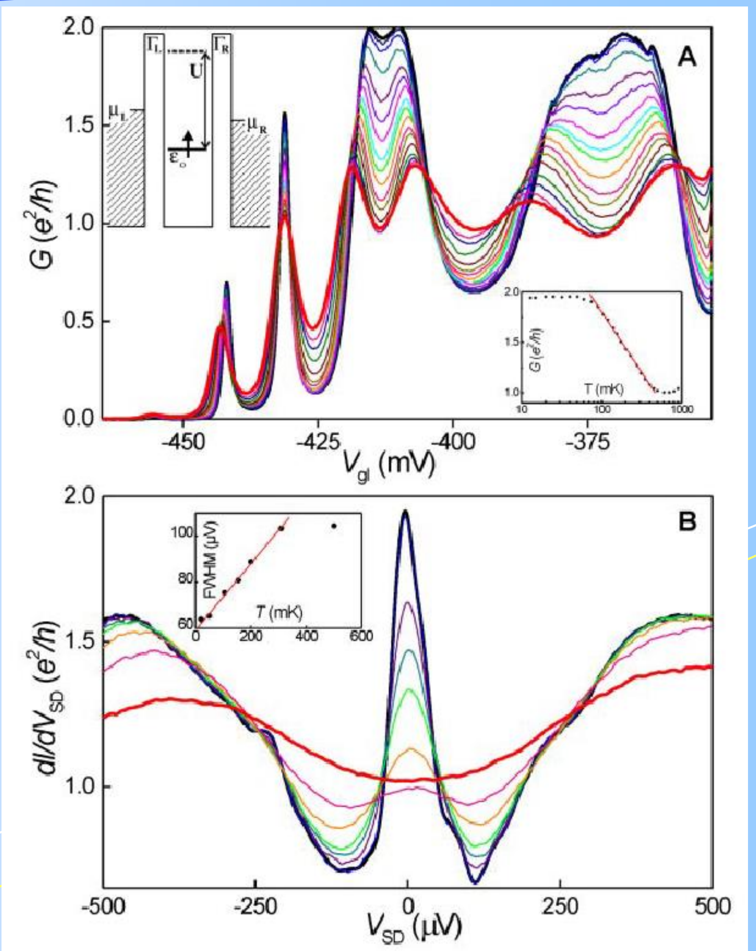
Fermi State



Magnetic impurity : Screened by a Kondo cloud

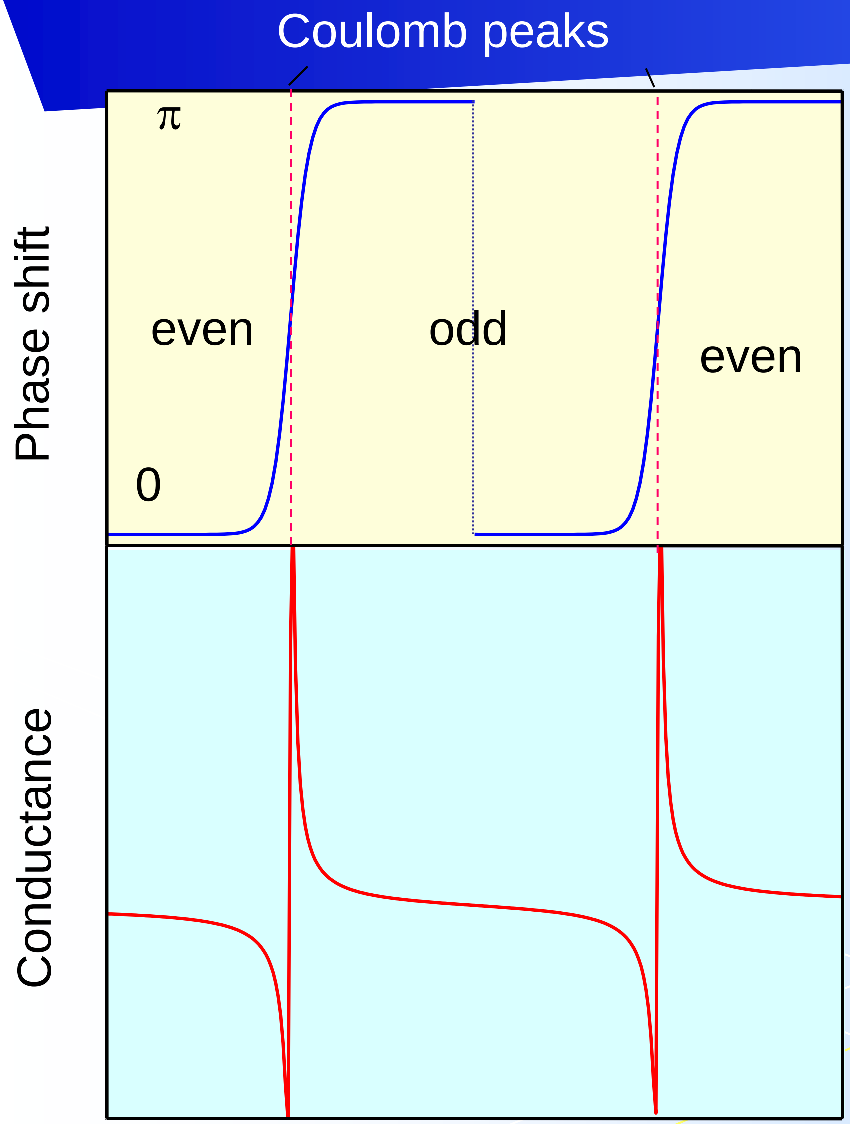
The Kondo Effect in a Quantum Dot System

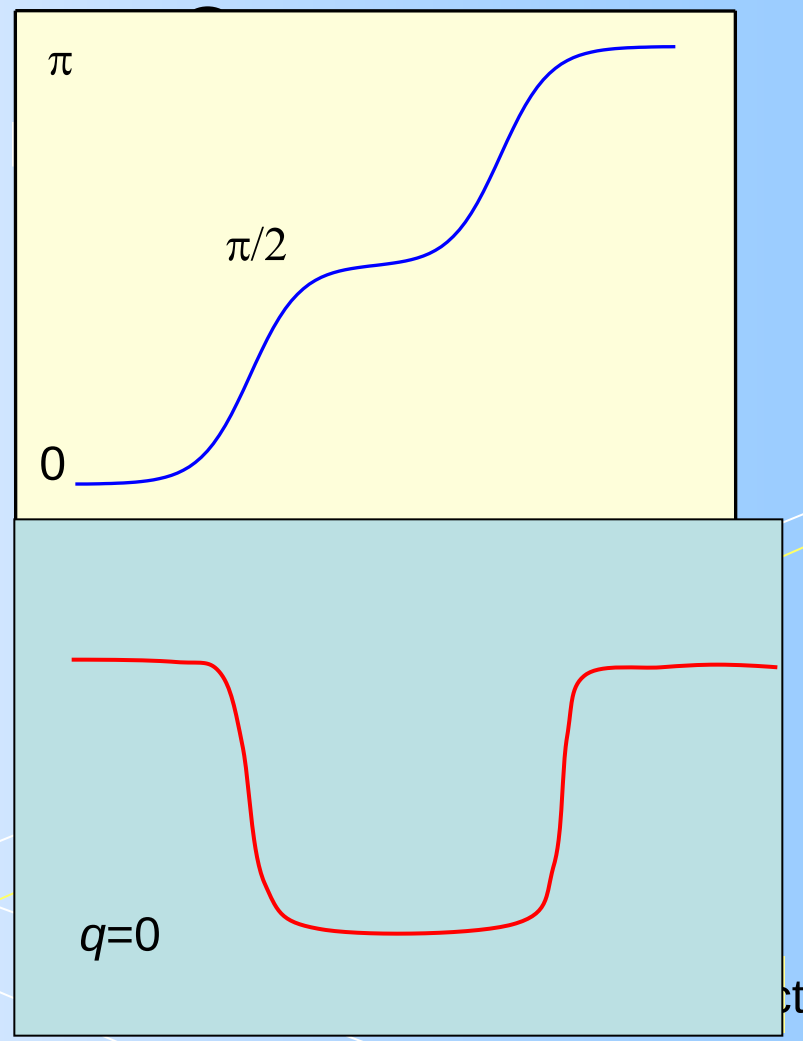




W. G. van der Wiel et al.
Science **289**, 2105 (2000).

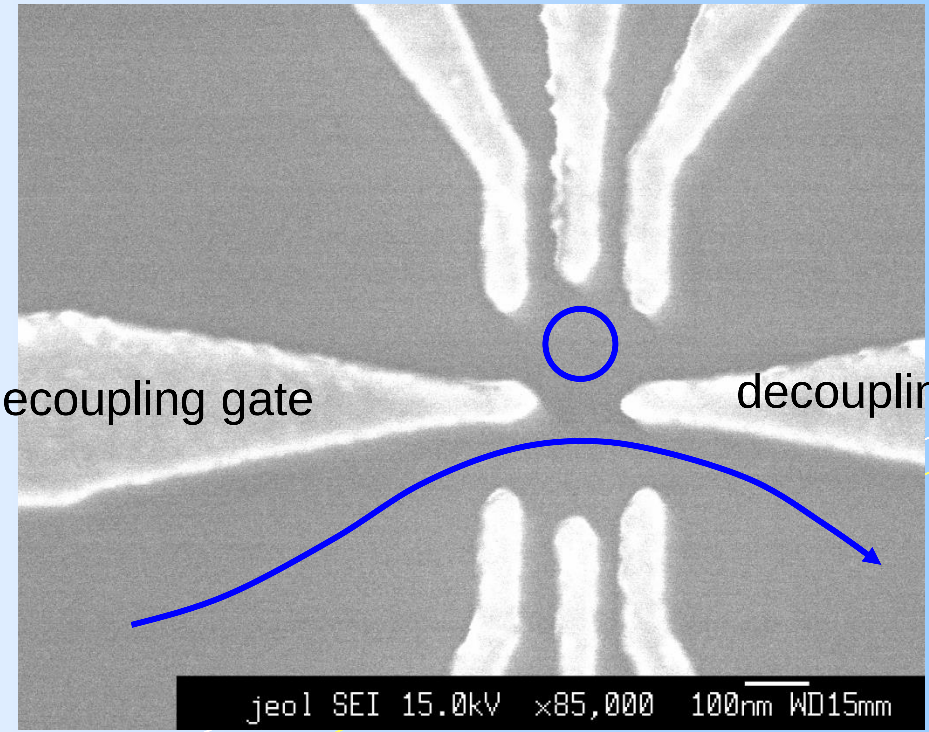
The Fano-Kondo Effect in Transport





T-coupled Quantum Dot-Wire Hybrid

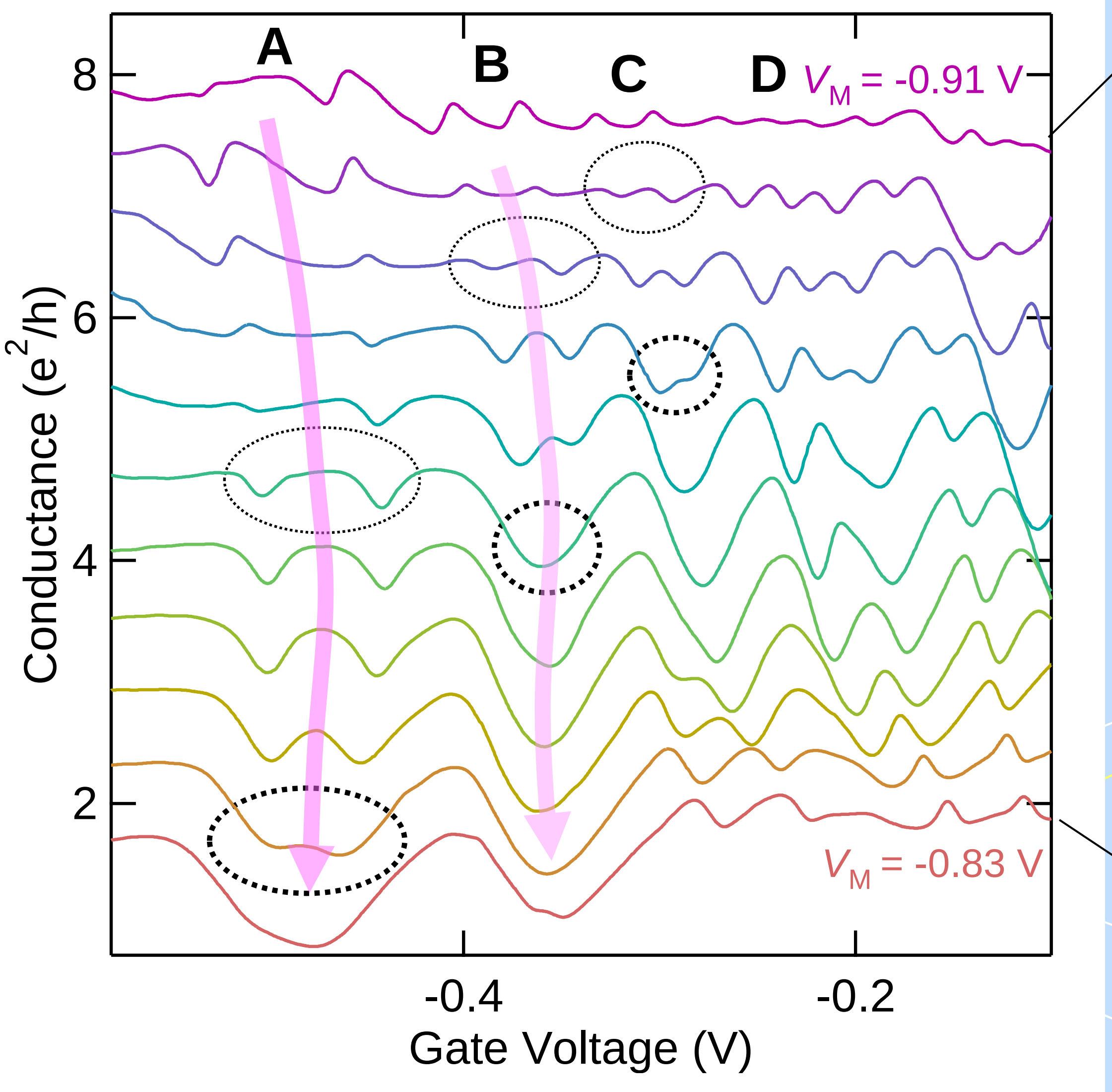
- U = 0.3 - 0.7meV
- Δ = 0.3 - 0.5meV
- Dot diameter ~ 50nm



Spatially compact
-> high coherence

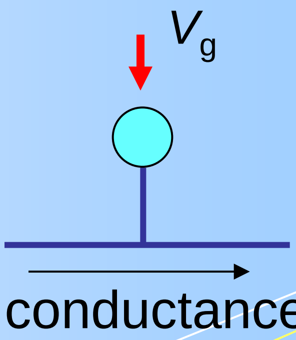
Single connection point
-> small dot size is available

Coupling strength dependence of anti-resonance



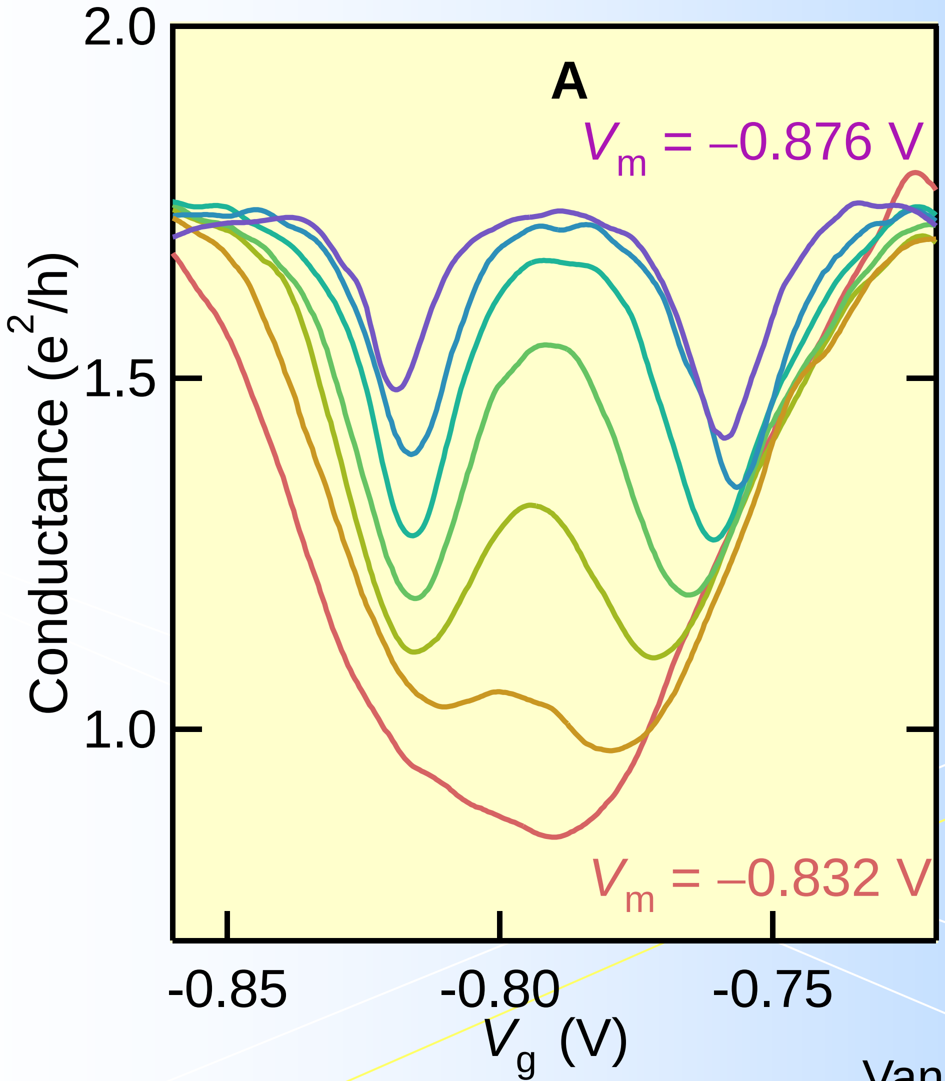
coupling : weak

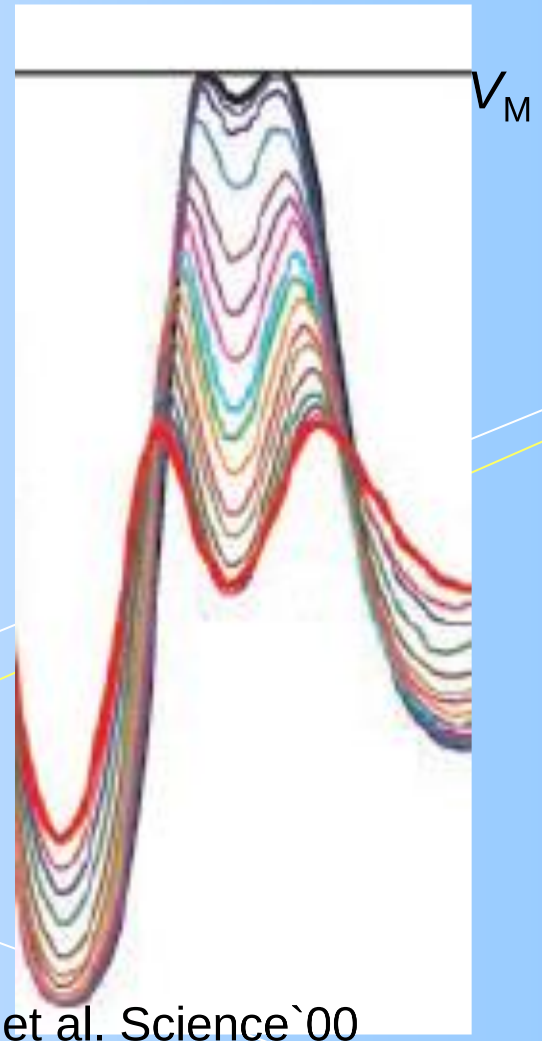
Decoupling gate V_M
: 8mV pitch



coupling : strong

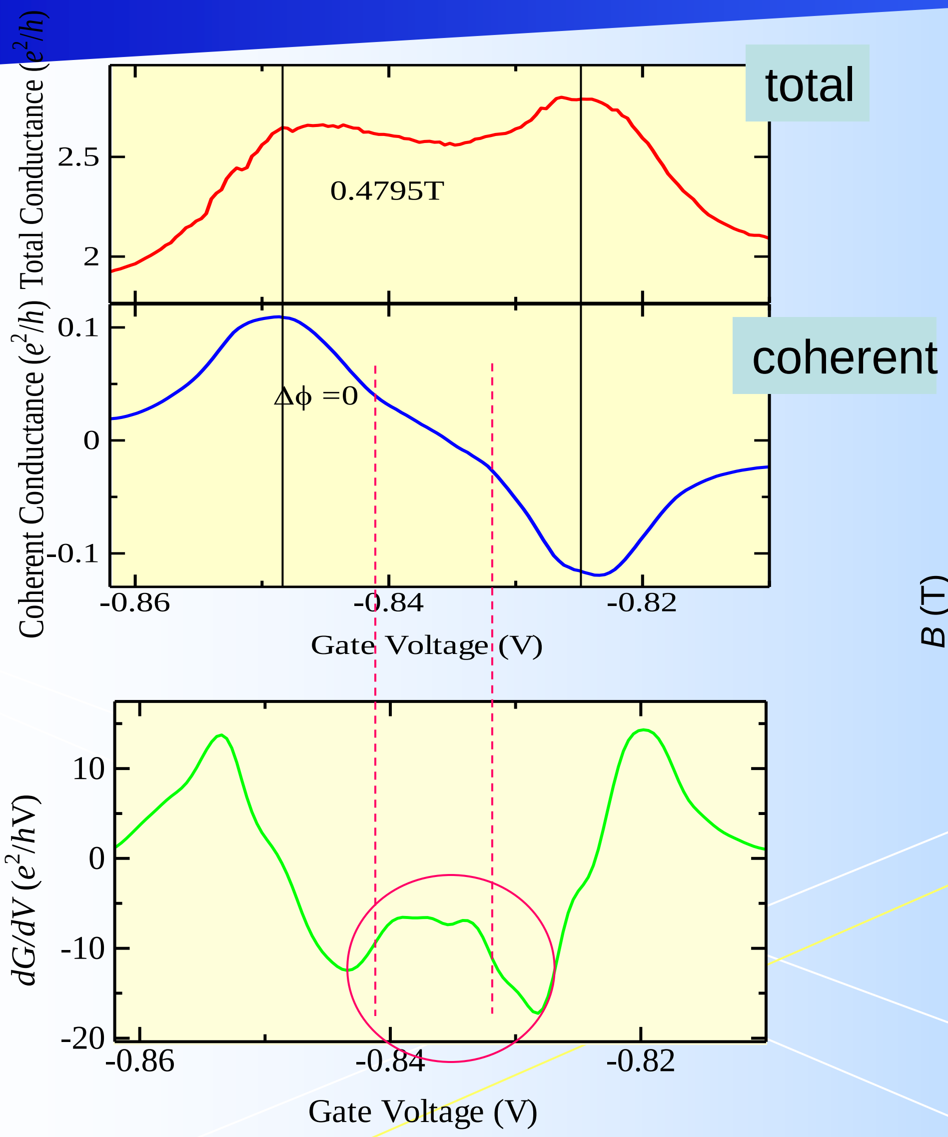
Coupling strength dependence of anti-resonance

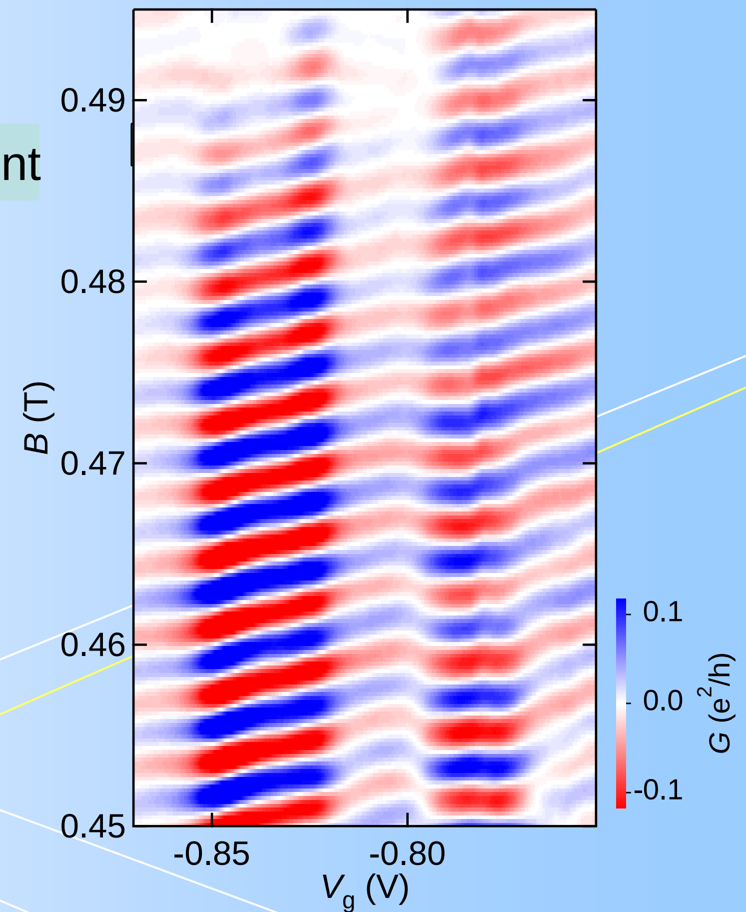




Van der Wiel et al. Science`00

“Coherent” component and the Fano-Kondo Effect





Problems for your report

http://kats.issp.u-tokyo.ac.jp/kats/

勝本信吾

Shingo Katsumoto

自己紹介

現在の研究テーマ

論文リスト

「ポケットに電磁気を」が単行本になりました

出版された書籍

「半導体」講義ノート (2013 Apr.-July.)

研究紹介
メンバー
実験装置
投稿
出版リスト
アルバム
物性研トップ

http://kats.issp.u-tokyo.ac.jp/kats/semiconII/

「半導体」講義ノート

English

2013年前期，再び「半導体」の講義を担当することになりました．今回は一応半年間で，非常に
導体」と全く同じではありませんが，当然オーバーラップはあります．黒板で喋りながら書いた
間違いを見つけられた方，お教えいただくのは大歓迎です．

4/15より英語での講義となります．Broken Englishでごめんなさい．まあ，国際会議等ではこの
英文のレジュメも用意する予定です．

1.	第1回 2013年4月8日		プロジェクタ用資料		
2.	第2回 2013年4月15日	英文レジュメ	プロジェクタ用資料	練習問題	英文
3.	第3回 2013年4月22日	英文レジュメ			
4.	第4回 2013年5月7日	英文レジュメ	プロジェクタ用資料		
5.	第5回 2013年5月13日	英文レジュメ	プロジェクタ用資料		
6.	第6回 2013年5月20日	英文レジュメ	プロジェクタ用資料		
7.	第7回 2013年5月27日	英文レジュメ	プロジェクタ用資料		
8.	第8回 2013年6月3日	英文レジュメ	プロジェクタ用資料		
9.	第9回 2013年6月10日	英文レジュメ	プロジェクタ用資料		
10.	第10回 2013年6月17日	英文レジュメ	プロジェクタ用資料		
11.	第11回 2013年6月24日	英文レジュメ	プロジェクタ用資料		
12.	第12回 2013年7月1日	英文レジュメ	プロジェクタ用資料		
13.	第13回 2013年7月8日	英文レジュメ	プロジェクタ用資料		
14.	第14回 2013年7月22日	英文レジュメ	プロジェクタ用資料		

2013年度レポート問題

まだ完成版ではありませんが，レポート問題もアップしました．英文版は近々アップロード予定．

Problems for your report

Select two from the following eight problems and answer them.

Submission:
Format: Adobe pdf, MSWord, RTF or print on real papers.
Either in Japanese or English (readable and understandable)

Attachment to email
Send it to kats plus @issp.u-tokyo.ac.jp
(Confirm the receipt within two days.)
Papers: Intra-university mail to 勝本信吾 at 物性研究所
or drop box at administration office (物理教務)

Dead line: End of August, 2013

I. Fundamentals in band theory

(i) Show that tight-binding approximation to the simple cubit lattice gives the dispersion as

$$E_n(\boldsymbol{k}) = E_n - \alpha_n - 2t \sum_{j=x,y,x} \cos k_j a.$$

Apply the same to the body-centered cubic and the face-centered cubit structures.

I. Fundamentals in band theory

(ii) Wavefunctions at the top of valence band (Γ-point) in sp3-bonding diamond structure semiconductors can be written to the second order of $k \cdot p$ approximation as

$$\text{Heavy hole band: } \left|\frac{3}{2}, \pm\frac{1}{2}\right\rangle = \frac{1}{\sqrt{6}}\left\{2|z\rangle \begin{pmatrix}\alpha \\ \beta\end{pmatrix} - (|x\rangle \pm i|y\rangle)\begin{pmatrix}\beta \\ \alpha\end{pmatrix}\right\},$$

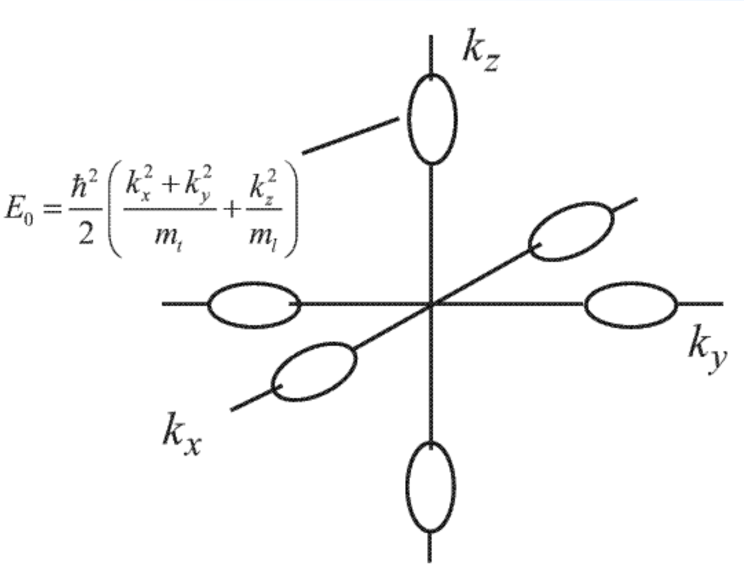
$$\text{Light hole band: } \left|\frac{3}{2} \pm \frac{3}{2}\right\rangle = \frac{1}{\sqrt{2}}(|x\rangle \pm i|y\rangle)\begin{pmatrix}\alpha \\ \beta\end{pmatrix},$$

$$\text{Spin split-off band: } \left|\frac{1}{2}, \pm\frac{1}{2}\right\rangle = \frac{1}{\sqrt{3}}\left\{|z\rangle \begin{pmatrix}\alpha \\ \beta\end{pmatrix} + (|x\rangle + i|y\rangle)\begin{pmatrix}\beta \\ \alpha\end{pmatrix}\right\},$$

where α and β are spin part of the wavefunction, and $|x\rangle$, $|y\rangle$, $|z\rangle$ are just showing the symmetry along the axes.
Show that these functions diagonalize the spin-orbit interaction

$$H_{\text{so}} = \frac{C_{\text{so}}}{r^3}(\boldsymbol{l} \cdot \boldsymbol{\sigma})$$

II Si valley structure, carrier statistics, pn junction



(i) The conduction band bottom of Si consists of 6 equivalent valleys close to X-points (bit inside the first Brillouin zone). The effective transverse mass $m_t = 0.19 m_0$, the effective longitudinal mass $m_l = 0.97 m_0$, which were obtained from cyclotron resonance. The valence band top is at the Γ-point. It has degeneracy of heavy and light hole bands as well as strong non-parabolicity. Averaged effective mass for heavy hole is $m_{hh} = 0.49 m_0$, and for light hole $m_{lh} = 0.16 m_0$.

(1-a) Calculate the effective density of states N_c for the conduction band at temperature T.
(1-b) Also obtain the effective density of states N_v for the valence band.
(1-c) Calculate the *np* product (n_i^2) at 300K (the band gap at 300K is 1.1 eV).

(ii) Obtain 300K built-in potential of a Si pn diode, which is abruptly doped as $n = 1 \times 10^{17}$ cm^{-3}, $p = 5 \times 10^{17}$ cm^{-3}. Use the value of *np* product obtained in (1-c).

III CV characteristics of pn diodes

V_b (V)	C (pF)
0.0	408
−0.2	380
−0.4	350
−0.6	334
−0.8	313
−1.0	296
−1.2	283
−1.4	273

There is a GaAs (dielectric constant 13) p^+n diode grown with molecular beam epitaxy. Doping is abrupt and uniform for both p and n layers. We have cut the grown film to a $1mm^2$ area and measured the differential capacitance with applying the (negative) bias voltage V_b and obtained the results summarized in the table on the left.

Obtain the built-in potential in unit of V. The measured C contains some experimental errors.

Assume that the capacitance is dominated by the doping in the n layer and obtain the donor concentration in the n layer in unit cm^{-3}.

IV Various confinement potentials

Choose the material as GaAs (electron effective mass $m^* = 0.067 m_0$) and calculate energy levels for various one-dimensional confinement (along *z*).

(i) Quantum well with infinite barrier height and width a = 10nm. Obtain energy levels for ground state, 1st and 2nd excited states.

(ii) The *n*-th eigen value of triangular potential

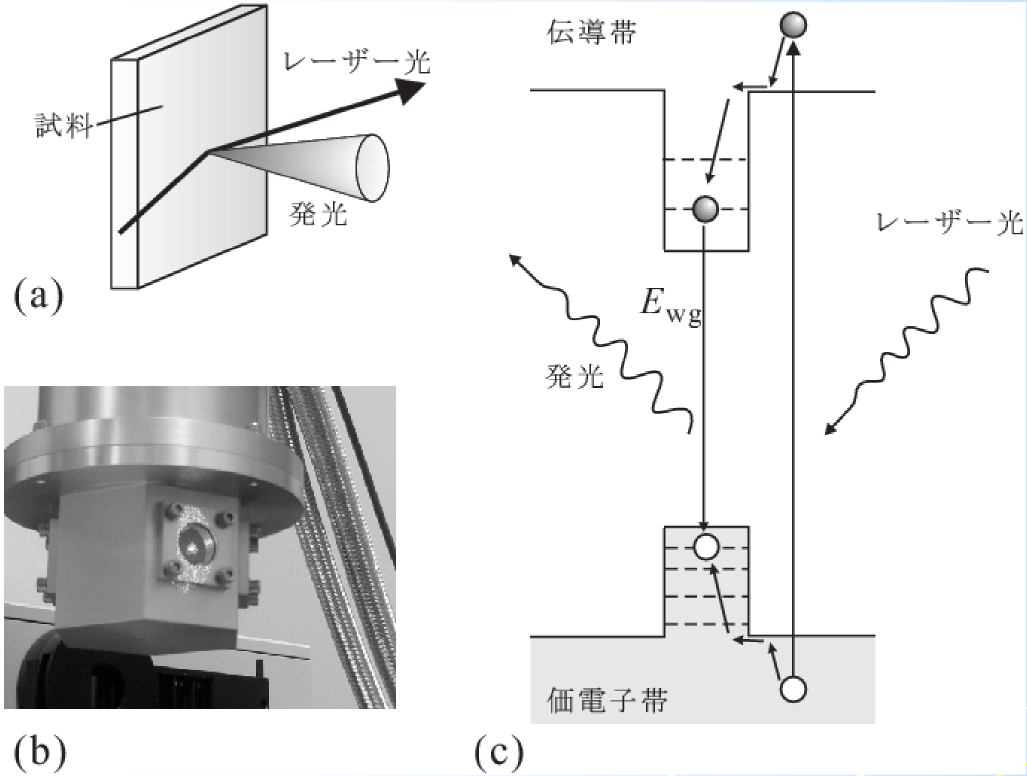
$$U(z) = \begin{cases} \infty & (z < 0) \\ e\mathcal{E}z & (z \geq 0) \end{cases}$$

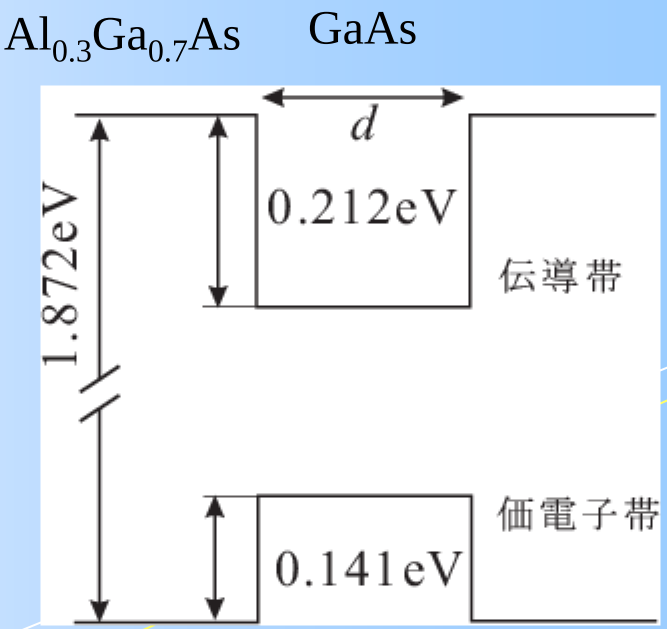
for $\mathcal{E} = 10^5$ V/cm. Refer to appendix "Eigenstates of triangular potential".

(iii) The *n*-th engenvalue of harmonic potential

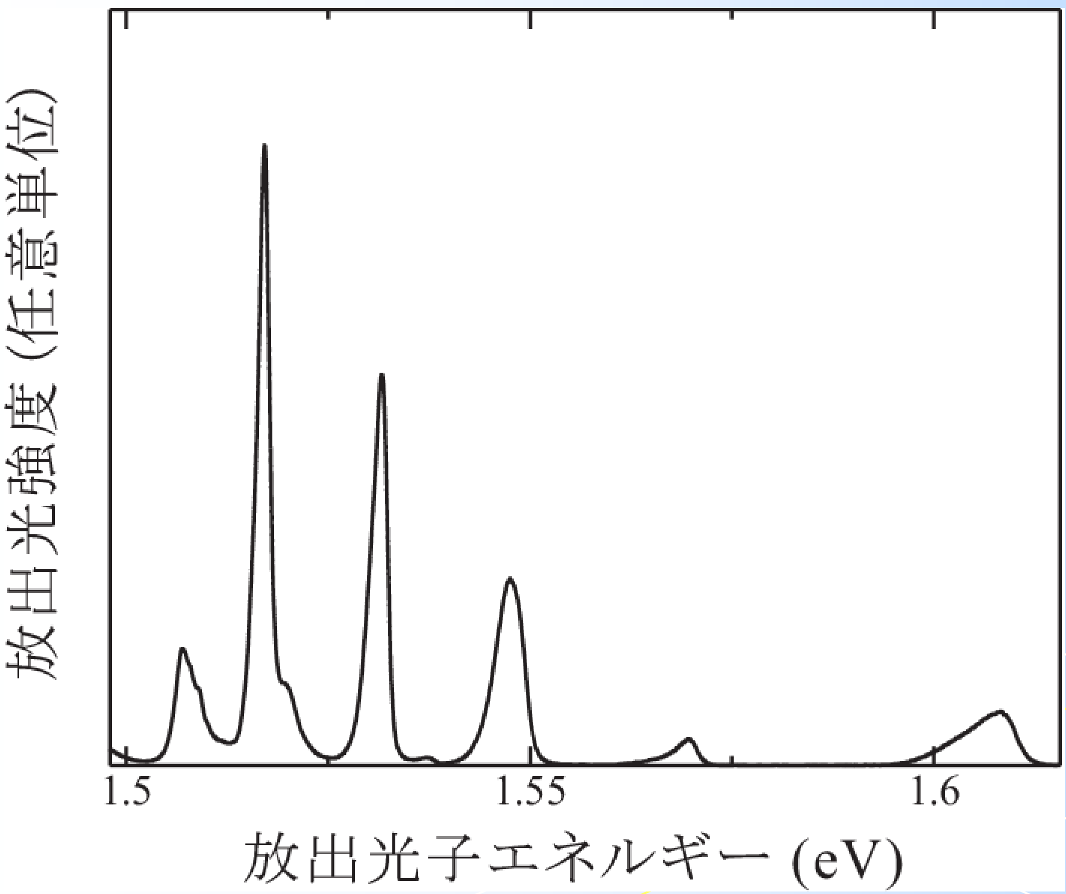
$$U(z) = \frac{m^* \omega^2}{2} z^2$$

V Photoluminescence from quantum wells





V Photoluminescence from quantum wells



Results for d =5 nm, 7.5 nm, 10 nm, 15 nm.

T = 4K.

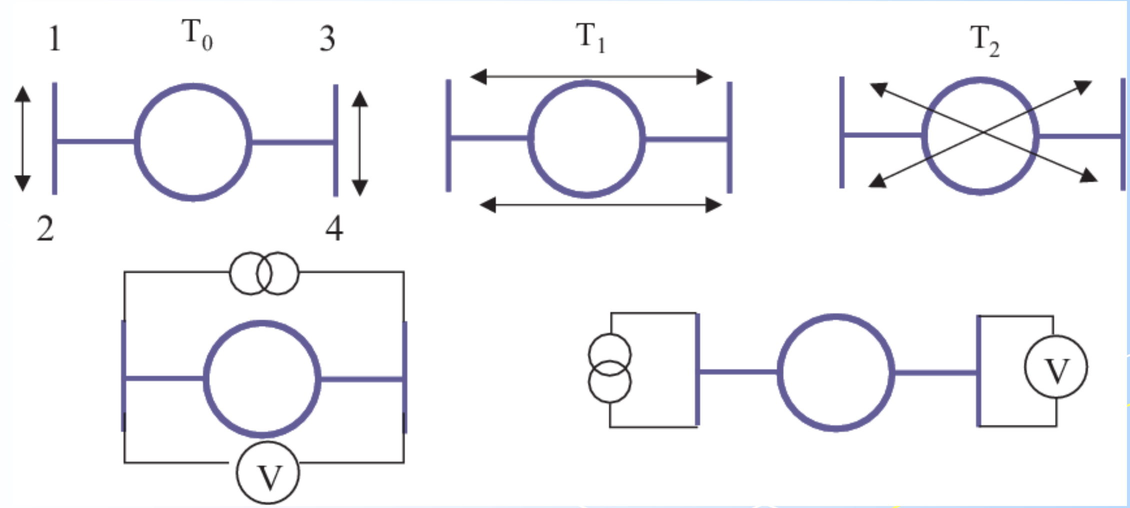
Calculated confinement energies of quantum wells.

Obtain exciton binding energies.

VI Coherent transport I

(i) Derive Landauer formula for a four terminal quantum wire with transmission coefficient *T* by using Landauer-Buettiker formalism.

(ii) Treat an AB ring as a four terminal conductor with transmission coefficients shown in the following figure.



Obtain ordinary resistance (left) and non-local resistance (right).

VII Coherent transport II

(i) Let M_T be a transfer matrix of a potential barrier with a complex transmission coefficient t and a complex reflection coefficient r. Show that MT can be expressed as follows.

$$M_T = \begin{pmatrix} 1/t^* & -r^*/t^* \\ -r/t & 1/t \end{pmatrix}.$$

(ii) If an AB ring is a double slit system, the probability amplitude of outgoing wavefunction is written as

$$|\psi|^2 = |\psi_1|^2 + |\psi_2|^2 + 2|\psi_1||\psi_2|\cos\theta,$$

which gives if we put $|\psi_1| = |\psi_2|$ and $\theta = -\pi$, zero. The result is apparently against the requirement of unitarity. Also in $\theta = \frac{e\Phi}{\hbar} + \theta_0$, if $\theta_0 \neq 0$, Onsagar reciprocity is also broken (Φ is magnetic flux piercing through the ring). Discuss what is wrong in the above "double slit model".

VIII Electric transport through edge modes