

Interplay between proximity effect and Kondo effect in InAs self-assembled quantum dot Josephson junctions

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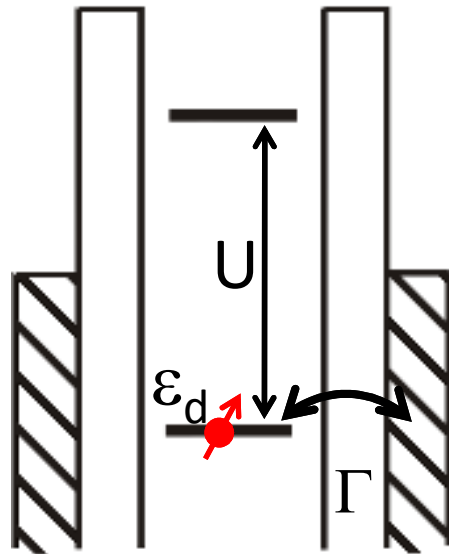
Outline

- **Introduction**
- **Interplay between proximity effect and Kondo effect**
 - **Single-level case (spin-1/2 Kondo effect)**
 - **Two-level case (Singlet-triplet Kondo effect)**
(not shown for confidential)
- **Generation of non-local entanglement**
(not shown for confidential)
- **Summary**



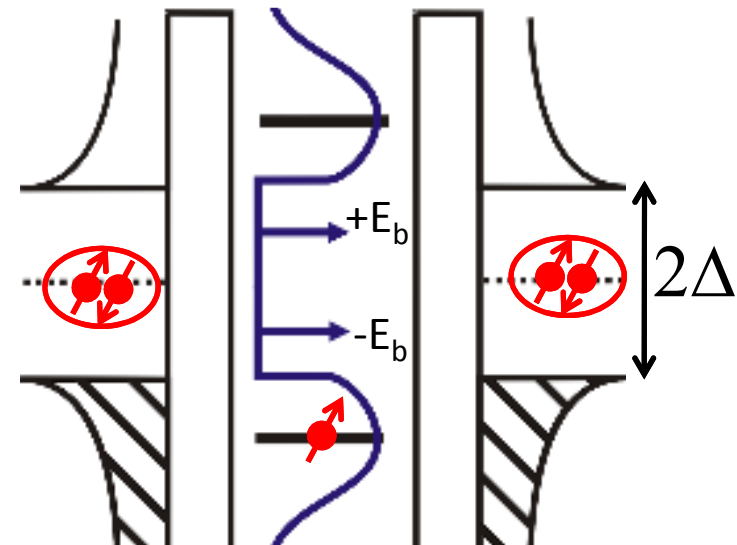
QD, QD, Josephson Junction, Kondo effect

QD



- ◆ Artificial atom
- ◆ Odd occupation : unpaired spin
single magnetic impurity
Even occupation: no unpaired spin
- ◆ Characteristic energies = U , Γ , and ϵ_d

QD Josephson junction

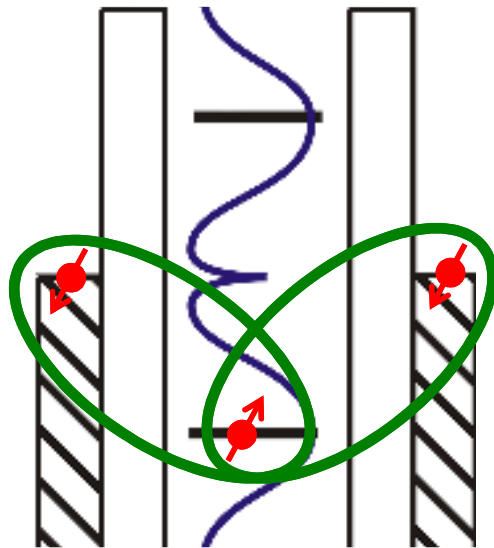


- ◆ Lack of low energy excitations in the superconducting lead suppresses Kondo effect.
- ◆ Andreev processes hybridize the energy levels of the QD – Andreev energy levels at $+E_b$ and $-E_b$.
- ◆ Characteristic energy = Δ .



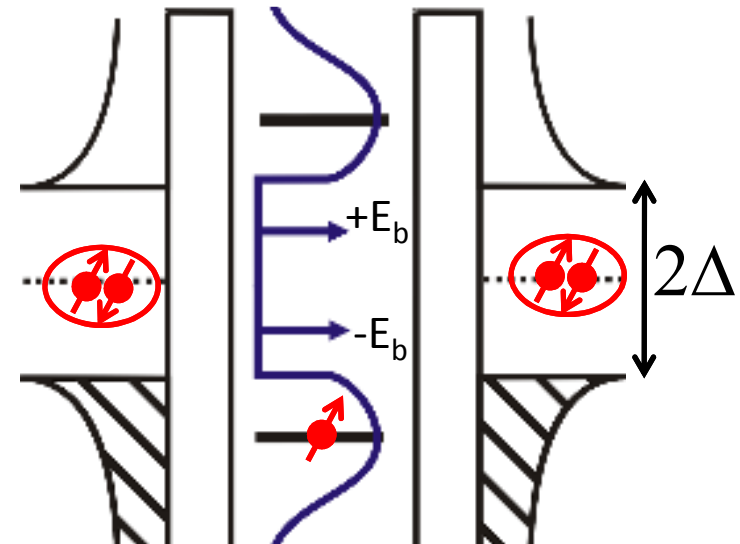
QD, QD, Josephson Junction, Kondo effect

Kondo effect



- ◆ At $T < T_K$ conduction electrons in leads screen unpaired electron spin on QD.
- ◆ Spin singlet Kondo state forms at the Fermi energy.
- ◆ Characteristic energy = $k_B T_K$.

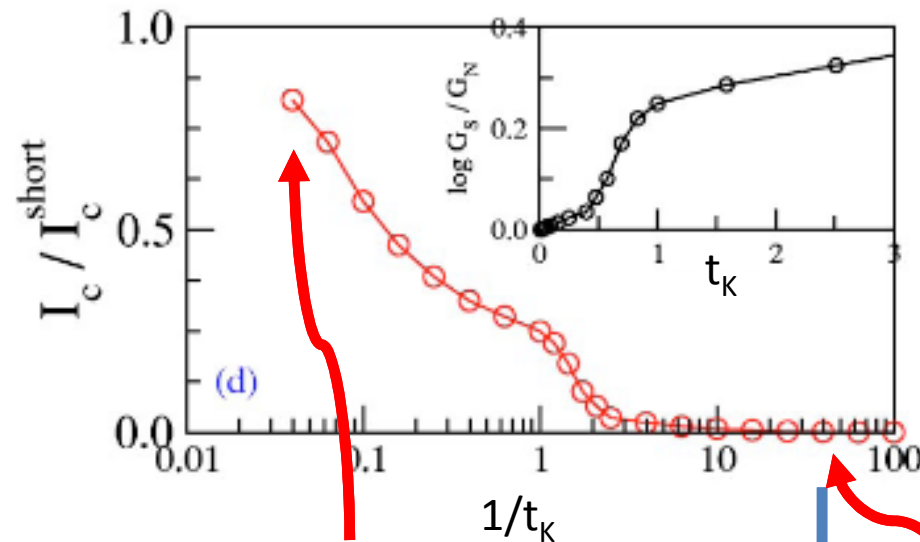
QD Josephson junction



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Interplay between proximity effect and Kondo effect



Universal scaling parameter

$$t_K = k_B T_K / \Delta$$

Numerical renormalization group (NRG)

Choi *et al.*, PRB, 70, 020502(R) (2004).

Other approaches

Glazman and Matveev, JETP **46**, 659 (1989).

Levy Yeyati *et al.*, PRL 91, 266802 (2003).

⋮

Strong Coupling ($T_K \gg \Delta$)

Kondo Resonance enhances
supercurrent.

0-junction

$$I(\phi) = I_c \sin(\phi/2)$$

$$I_c \rightarrow 2e\Delta/\hbar \quad \text{as} \quad \Delta/T_K \rightarrow 0$$

Weak Coupling ($T_K \ll \Delta$)

Coulomb Blockade dominates

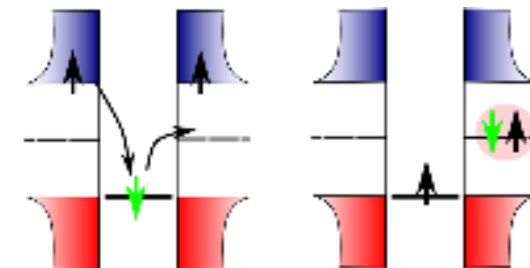
π -junction $I(\phi) = -I_c \sin(\phi)$

Experimental studies

Buitelaar *et al.*, PRL, 89, 256801 (2002).

Eichler *et al.*, PRB 79, 161407 (2009).

⋮



van Dam *et al.*, Nature, 442, 667 (2006).



Andreev entanglers

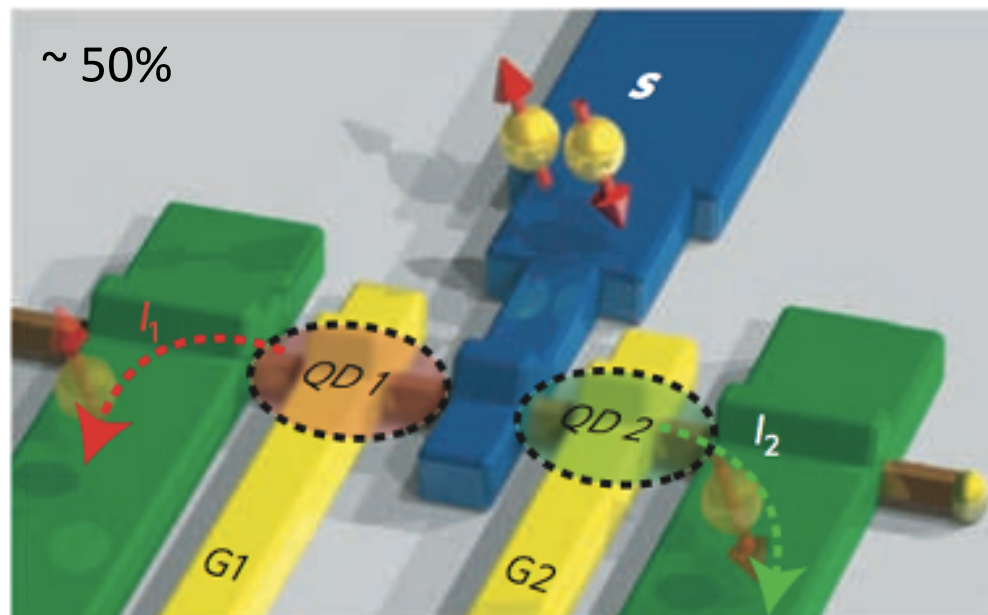
A superconducting lead provides a natural reservoir for spin entangled electron pairs

: Efficiently spatially separated onto two quantum dots because of ***the charging effect*** of individual QDs.

P. Recher and D. Loss, PRB **63**, 165314 (2001).

V. Bouchiat et al., Nanotechnology **14**, 77 (2003).

Previous measurements have identified charge correlation in the current flowing through two normal leads indicating Cooper pair splitting. **However, the non-local entanglement has not yet been confirmed.**



Cooper pair splitter

InAs nanowire QD device

L. Hofstetter et al., Nature Nano. **461**, 960 (2009).

CNT QD devices

L.G. Herrmann et al., PRL **104**, 026801 (2010).

Shot noise correlation

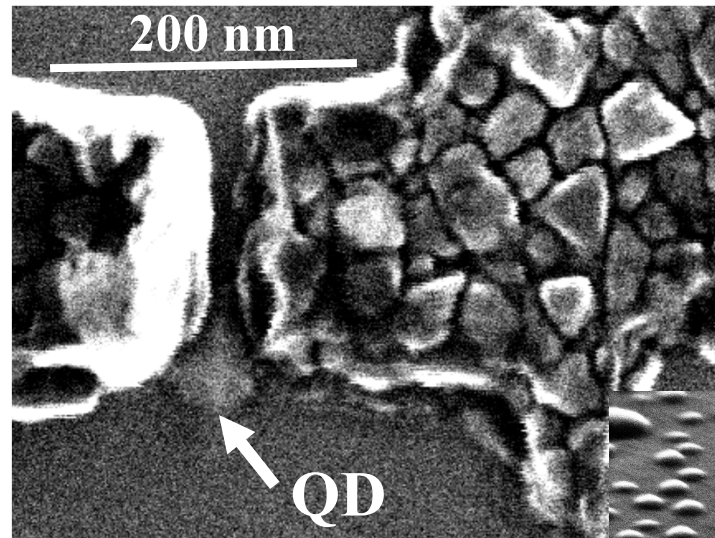
A. Das et al. arXiv:1205.2455v1



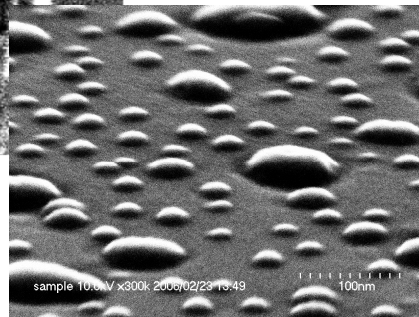
Uncapped self-assembled InAs QDs

InAs self assembled (Stranski-Krastanov) QDs

- MBE growth of InAs on GaAs substrate
- at ~1.5 ML transition 2-D to 3-D growth
- Lateral contacting using 30 nm nanogap



~ 4 ML Mixed phase



Artificial atom

Coulomb oscillation and Coulomb diamond

M. Jung *et al.*, *APL* **86**, (2005).

Shell structure and anisotropic confinement

M. Jung *et al.*, *APL* **87**, (2005).

Kondo effect

Kondo Effect

Y. Igarashi *et al.*, *PRB* **76**, (2007).

g-factor

g-tensor modulation

R. S. Deacon *et al.*, *Phys. Rev. B* **84**, 041302 (2011).

Ferromagnetic leads

Ferromagnetic leads – TMR with gate control

K. Hamaya *et al.*, *APL* **91** (2007).

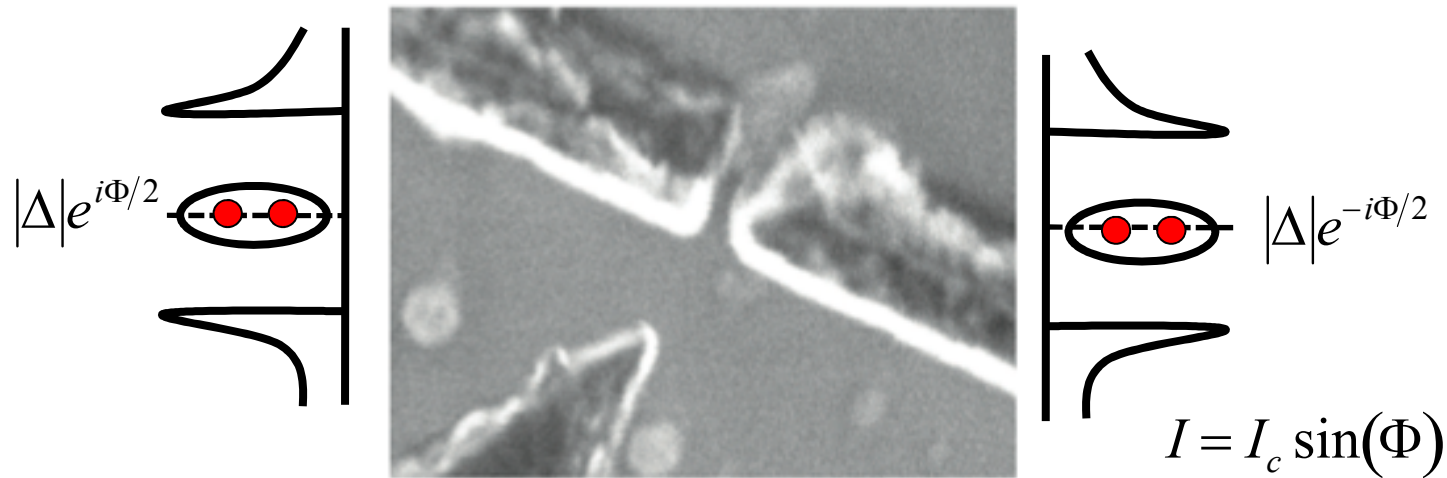
Spin-orbit interaction

Quantitative evaluation and anisotropy

S. Takahashi, *Phys. Rev. Lett.* (2010).

Electrical control

Y. Kanai *et al.*, *Nature Nanotech.* (2010).

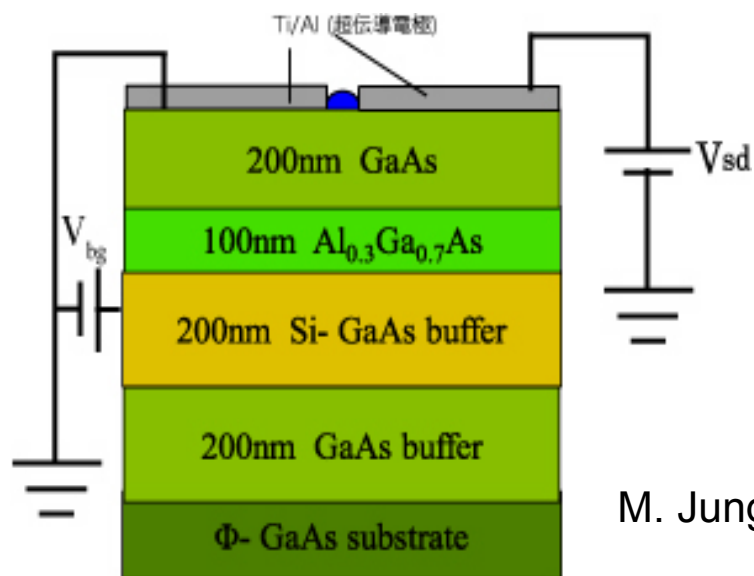
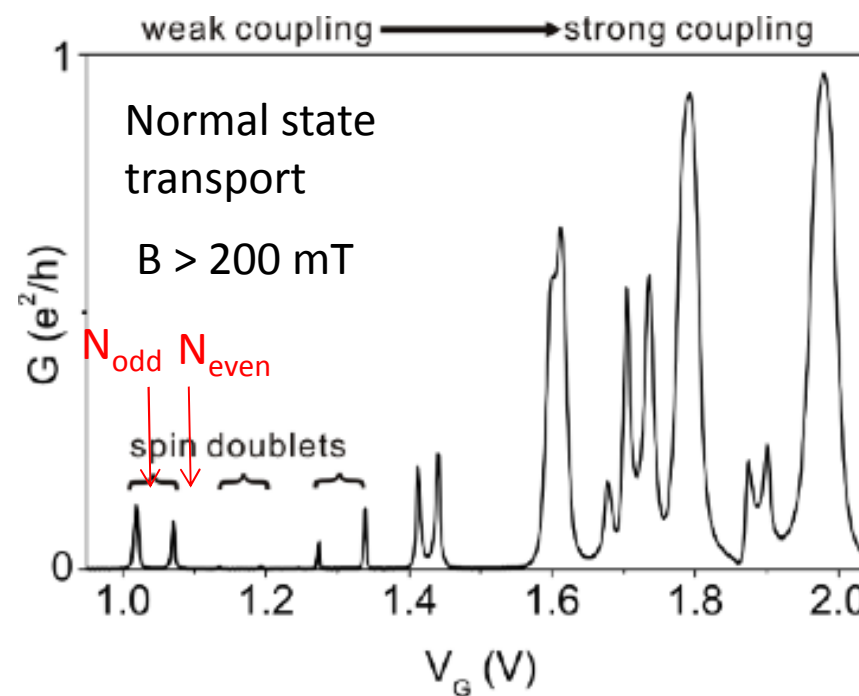
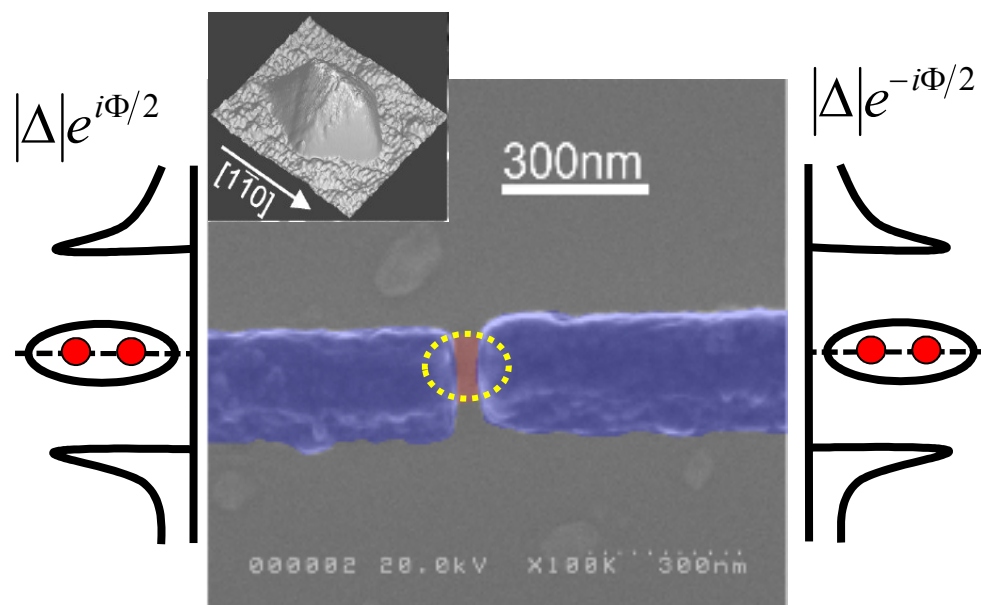


Y. Kanai et al., Phys. Rev. B **82**, 054512 (2010).

**Interplay between proximity effect
and Kondo effect
~ single-level case ~**



InAs SAQD Nanogap Junctions



g-factor = 4 to 8
 $E_c = 1$ to 2 meV
 $\delta\varepsilon = 0.5$ to 1 meV

← Pair tunneling supercurrent
 for $\Gamma < U$ in the second order
 process

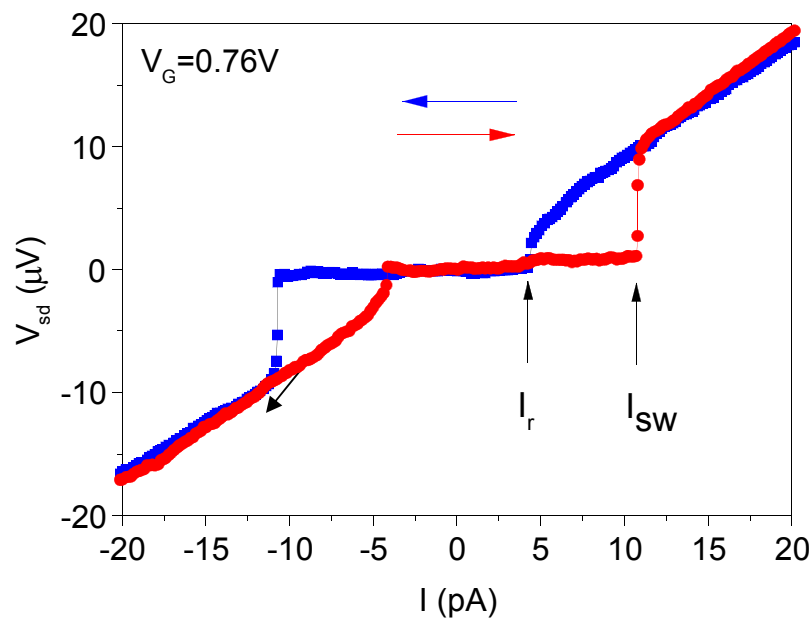
M. Jung et al., APL 86 (2005).



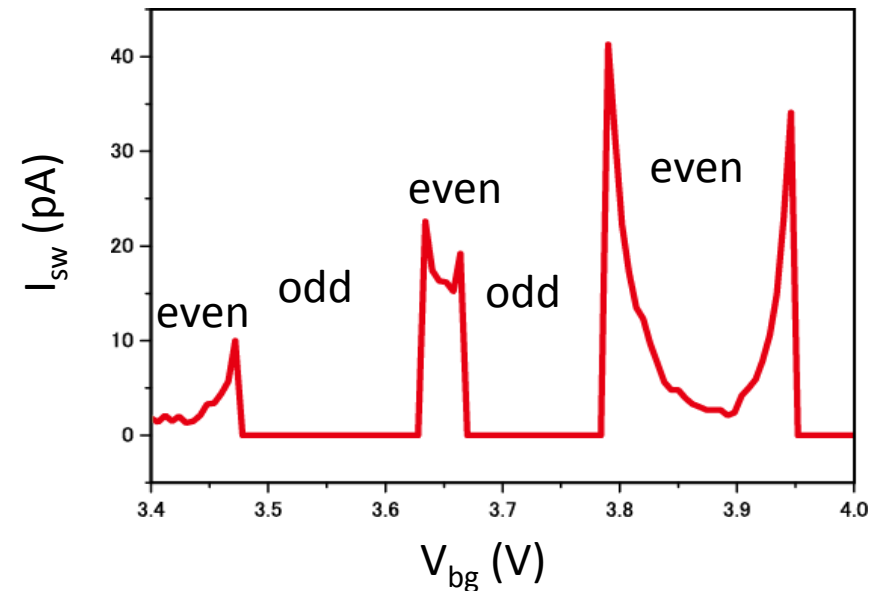
Single InAs QD Josephson Junction

Supercurrent due to pair tunneling observed when $\Gamma \geq U$.

Underdamped J current



Supercurrent is positive, or negative (or reduced) for N_{even} , or N_{odd} electrons, reflecting the 0, or π junction character, respectively.



Y. Kanai et al. J. Phys. Conf. Ser. (2009)

CNT: Jarillo-Herrero et al. Nature (2006);
Cleuziou et al., Nature (2006),..

InAs NW: van Dam et al., Nature (2006),..

InAs dot: Kim et al., APL (2011),..

$$I = I_c \sin(\Delta\phi + \delta) \quad \delta = 0 \text{ (} N_{\text{even}} \text{)} \\ = \pi \text{ (} N_{\text{odd}} \text{)}$$

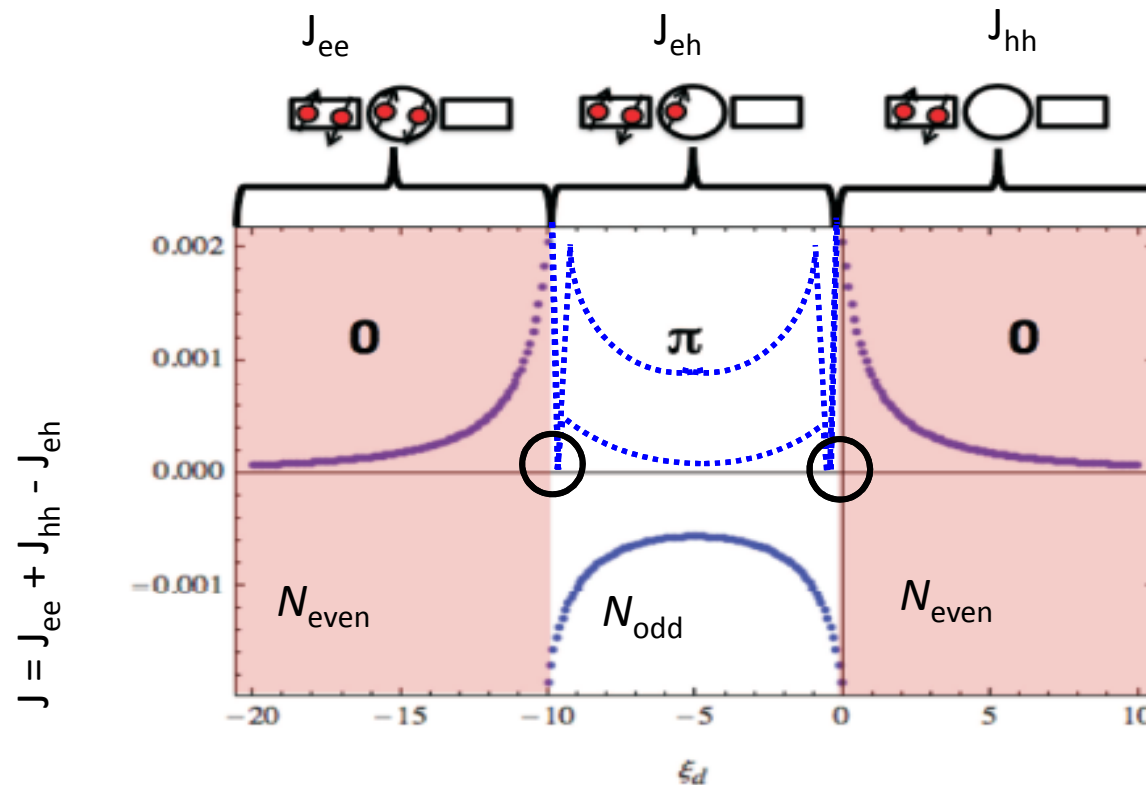
Kulik ('66)

Shiba & Soda ('69)

Glazman & Matveev ('89)



0, π -junction



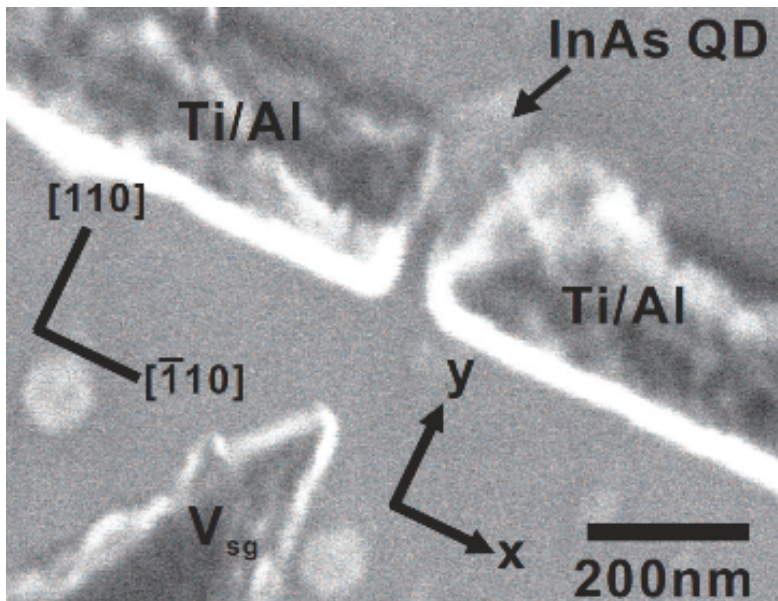
4th order perturbation theory

$$E_J = \frac{\Delta^2}{4} \int_{-\infty}^{\infty} \frac{d\xi_L}{\varepsilon_L} \int_{-\infty}^{\infty} \frac{d\xi_R}{\varepsilon_R} [J_{ee}(\xi_L, \xi_R, \xi_d) + J_{hh}(\xi_L, \xi_R, \xi_d) - J_{eh}(\xi_L, \xi_R, \xi_d)]$$

$$\varepsilon_{L/R} = \sqrt{\Delta^2 + \xi_{L,R}^2} \quad \text{superconducting energy gap of the left/right lead}$$

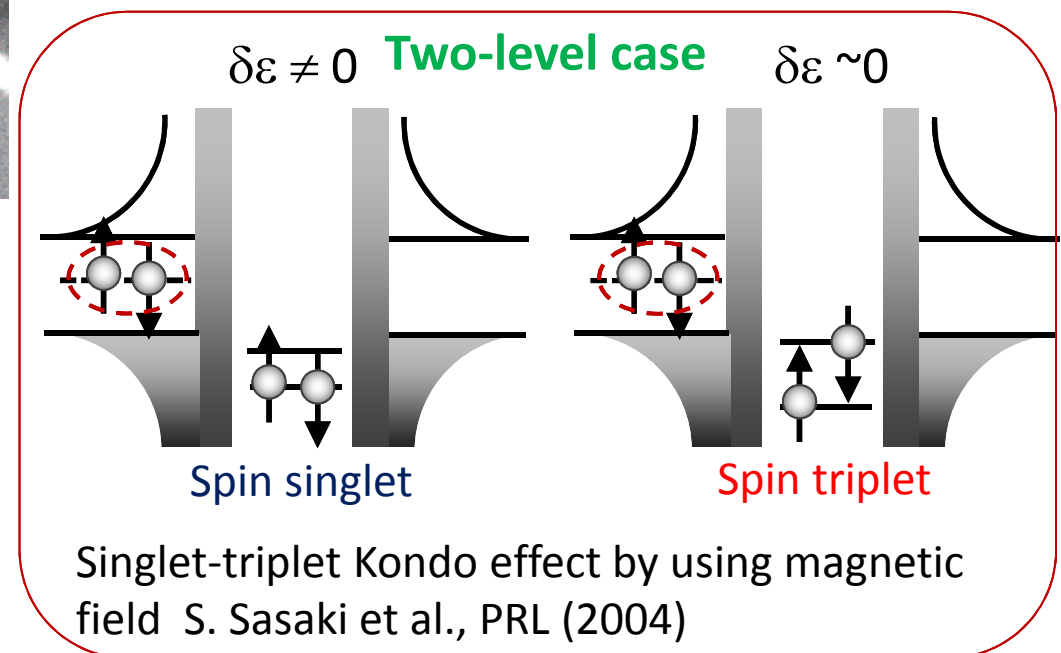
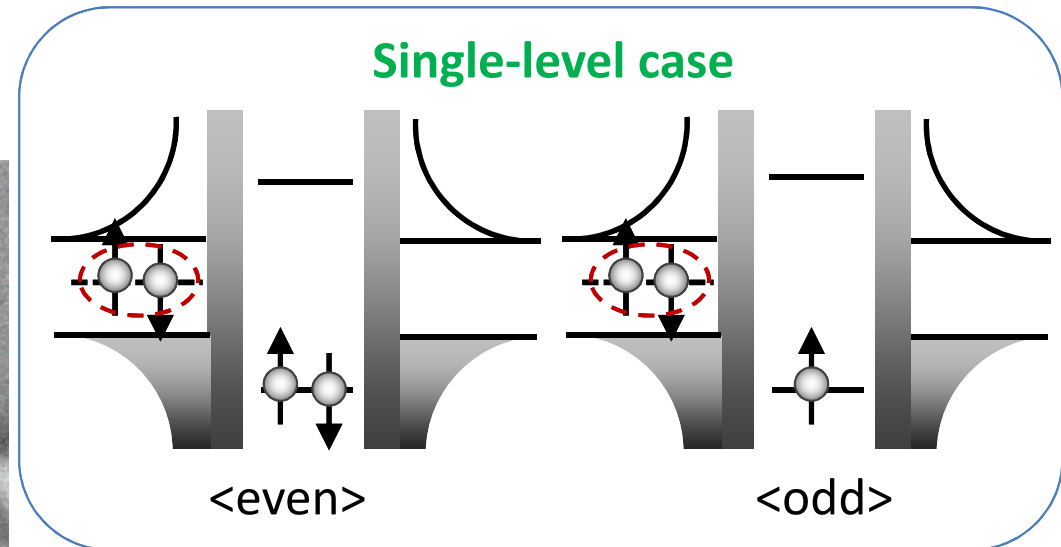


Device



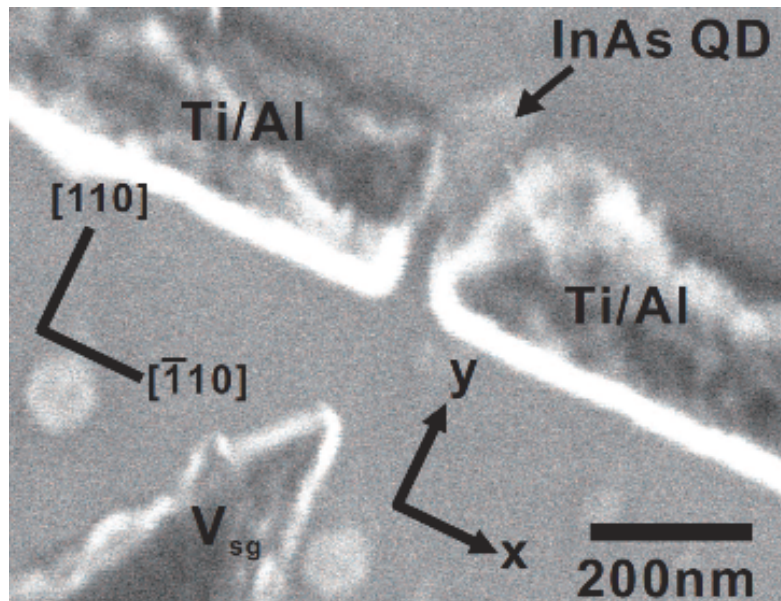
Sidegate

- Backgate 300nm from surface
- Ti/Al: $T_C \sim 1.2$ K, $B_C \sim 200$ mT





Device



Sidegate

- Backgate 300nm from surface
- Ti/Al: $T_C \sim 1.2$ K, $B_C \sim 200$ mT

Sidegate

Lateral asymmetric electric field

Modify the wavefunctions

Tunnel rate

[Y. Kanai et al., PRB (2010).]

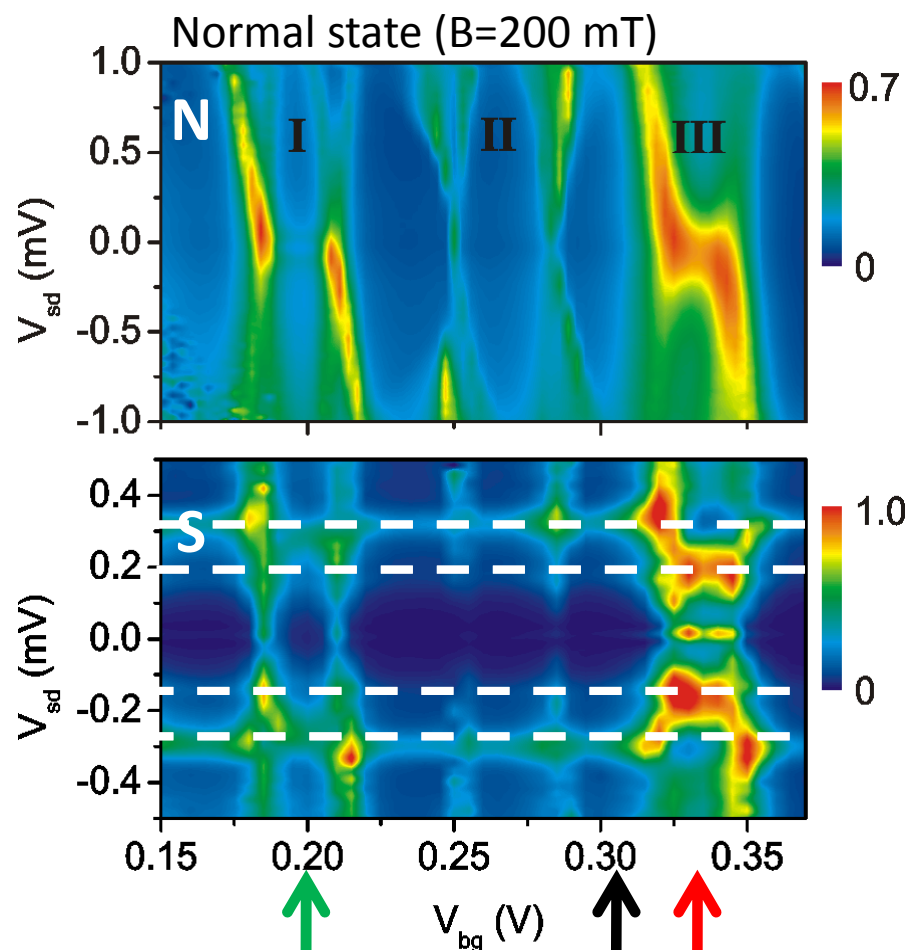
Energy level spacing

Charging energy etc.

Electrical tuning of Kondo effect and singlet-triplet degeneracy



Multiple Andreev Reflections (MAR)



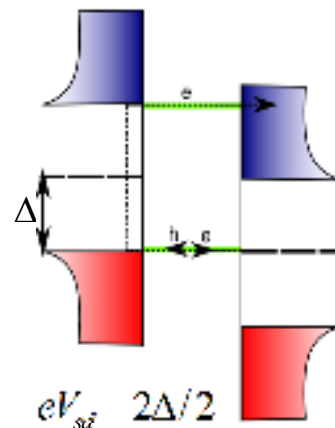
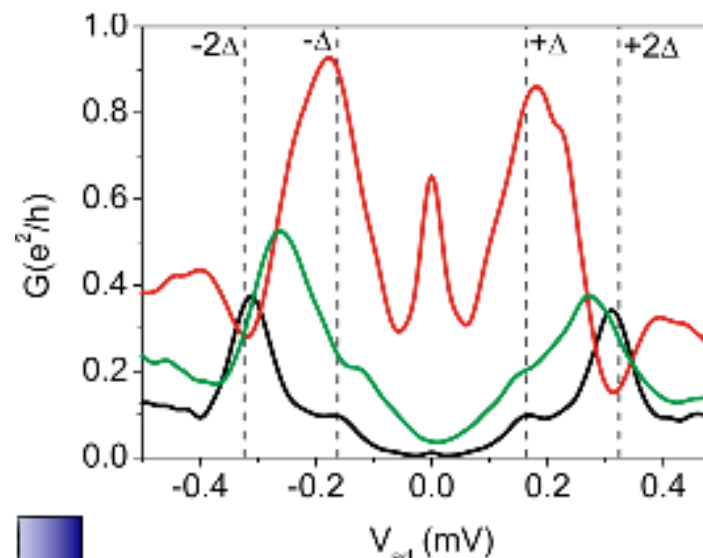
$$T_K < 0.82K$$

$$t_K < 0.44$$

$$T_K \sim 2.6K \text{ 1st order Andreev reflection}$$

$$t_K \sim 1.4$$

Spin-1/2 Kondo effect (Region I, II, and III)



MAR in Kondo regime

Δ peaks enhanced relative to 2Δ

Eichler *et al.*, PRB 75, 126602 (2007).

Sand-Jespersen *et al.*, PRL 93, 126603 (2004).

Buizert *et al.*, PRL 99, 136805 (2007).

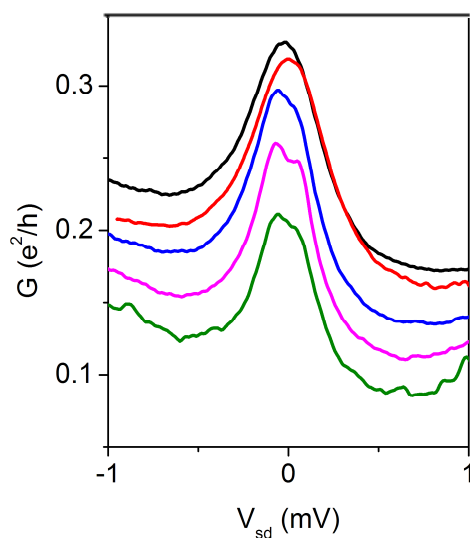
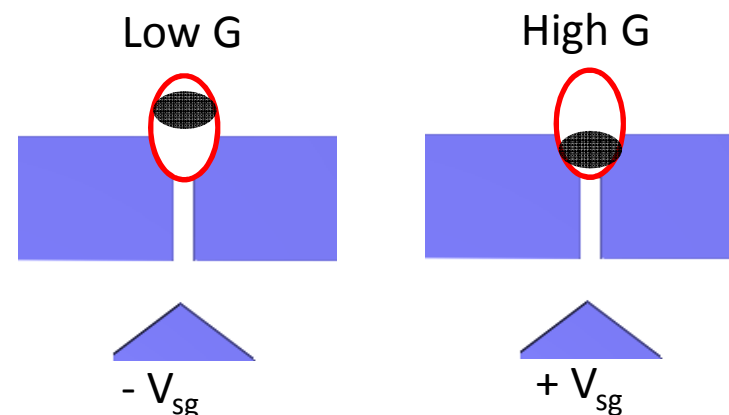
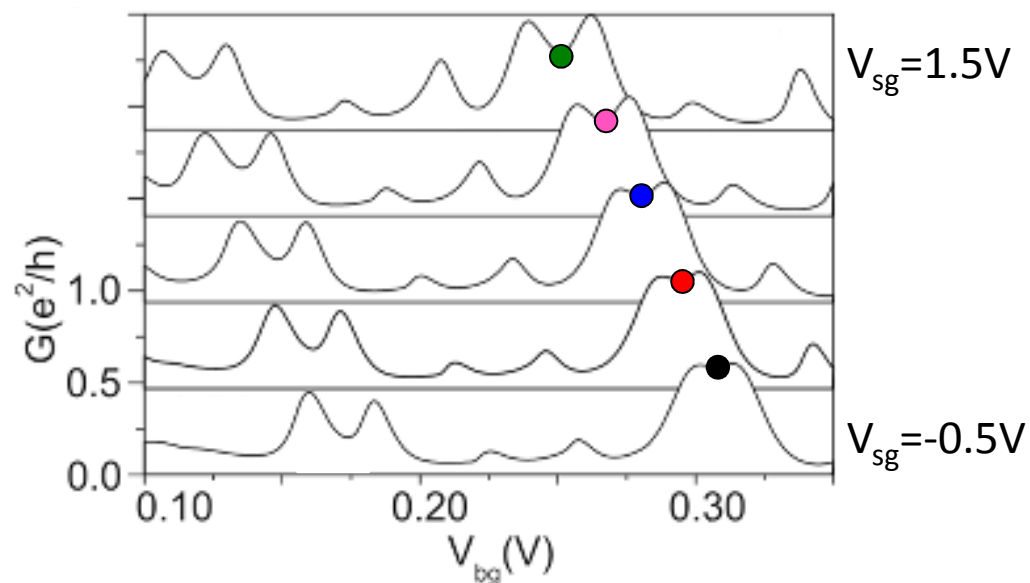
Kanai, RSD *et al.*, PRB 82, 054512 (2010).

Shimizu *et al.*, JJA 50, 035102 (2006).

Quasi-particle tunneling



Electrical tuning of Kondo effect

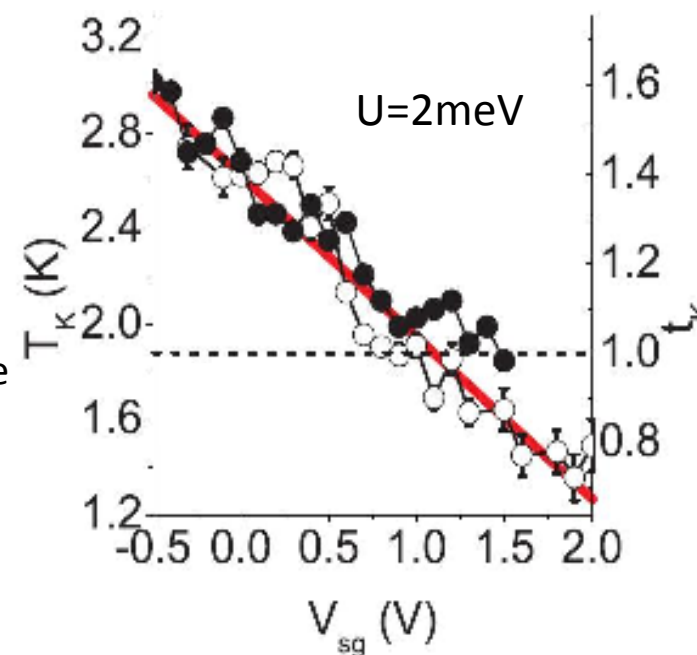


$$\alpha_{sg} = 0.025\alpha_{bg}$$

$$\alpha_{bg} = 0.09 \text{ eV/V}$$

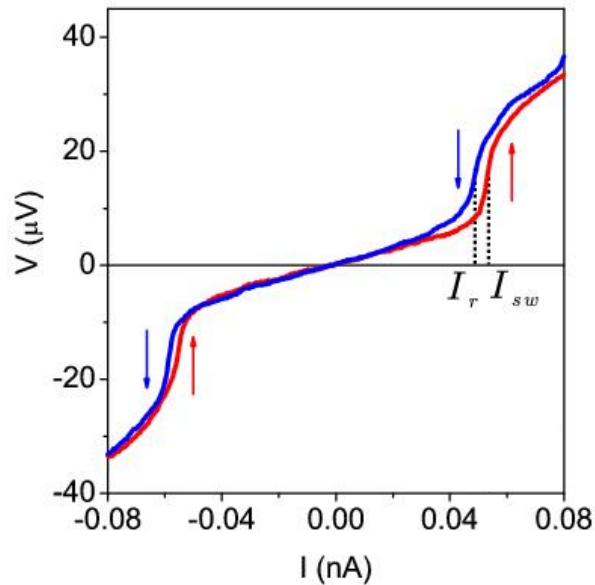
Kondo temperature T_K estimated from half-width of the zero-bias conductance anomaly and using the relation

$$T_K \sim \frac{1}{2} \sqrt{U\Gamma} \exp\left(\frac{-\pi U}{4\Gamma}\right)$$

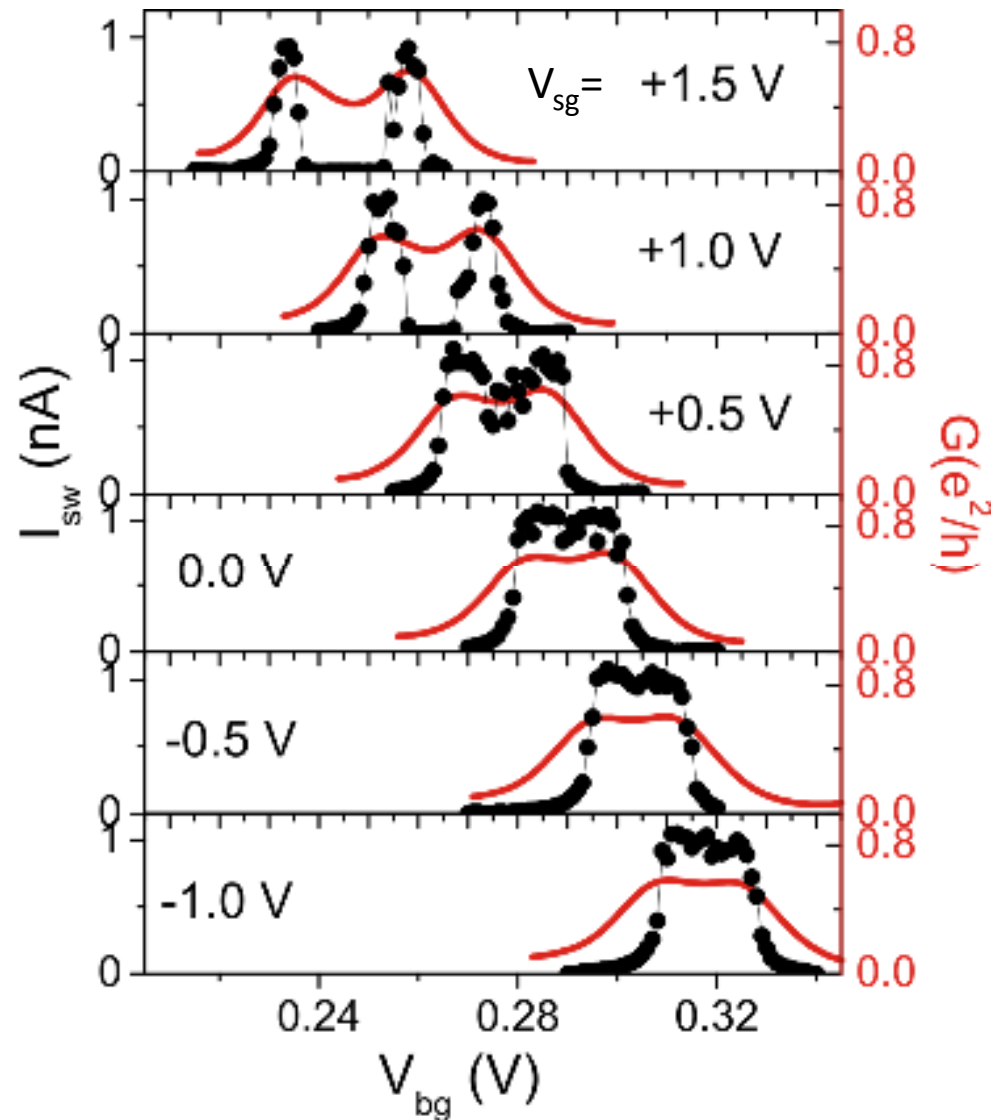




Supercurrent

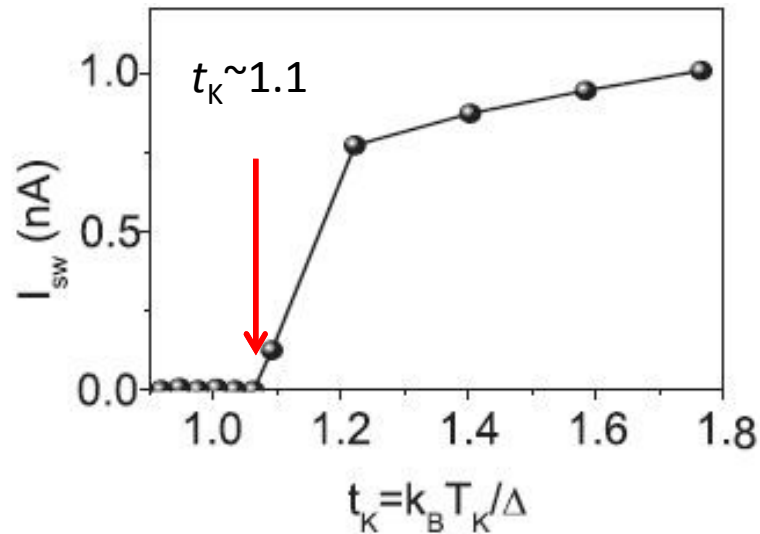


- ◆ Supercurrent is suppressed when $t_K = k_B T_K / \Delta$ is tuned below unity.
- ◆ This result is consistent with the low supercurrents predicted for the doublet groundstate (π -junction) regime.





Supercurrent

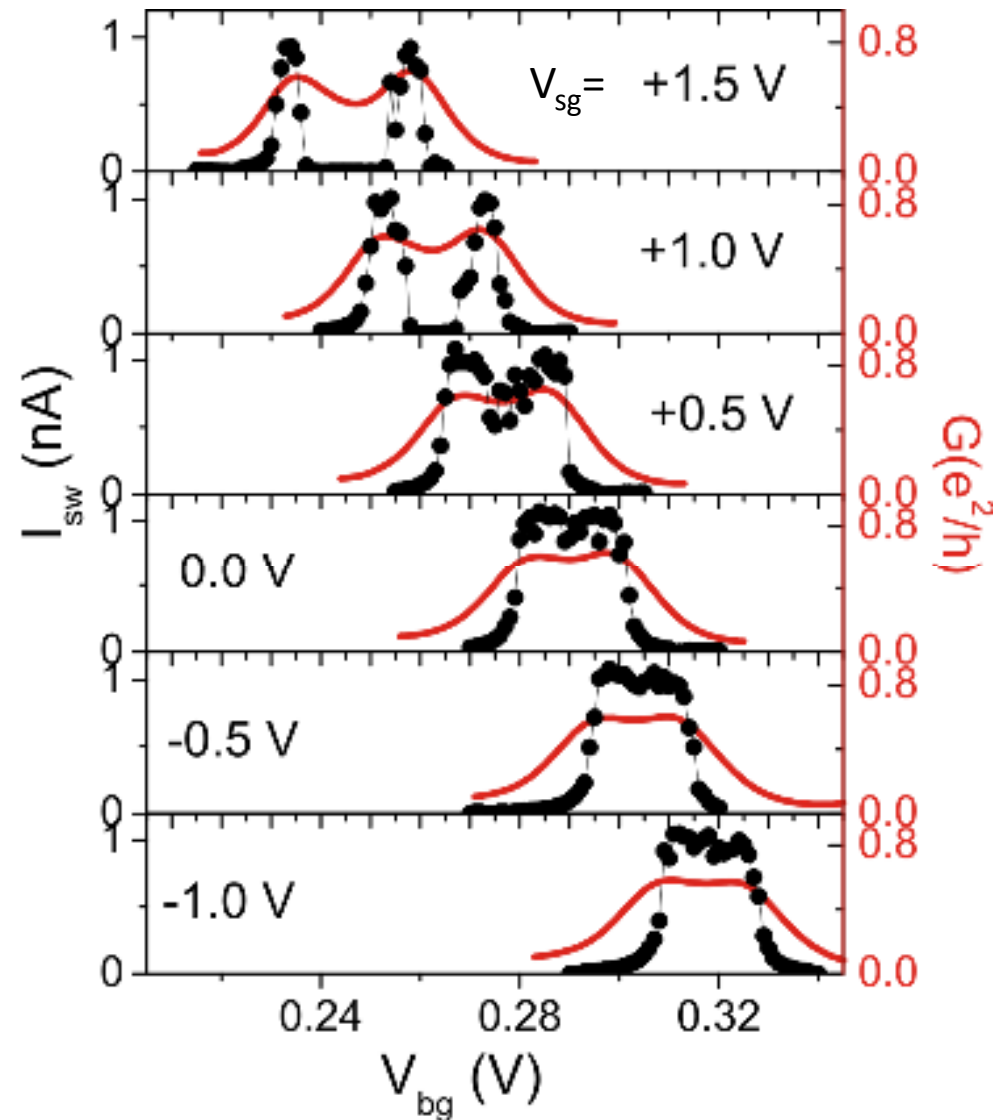


Good agreement with theoretical predictions

Choi et al., PRB 2004 –
NRG $t_K \sim 0.7$

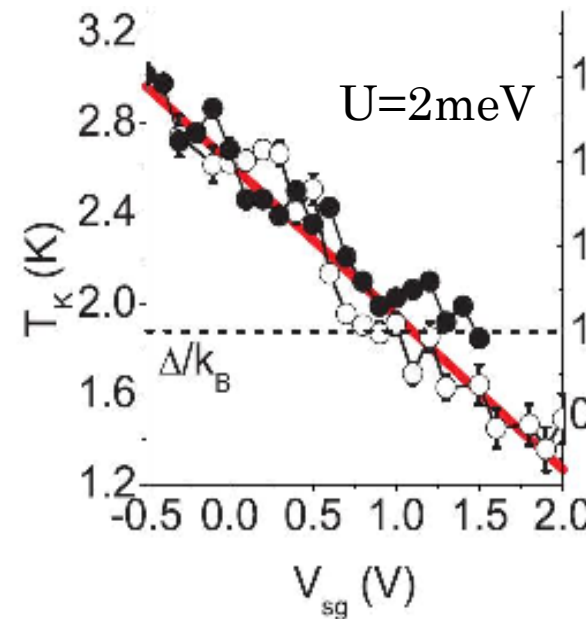
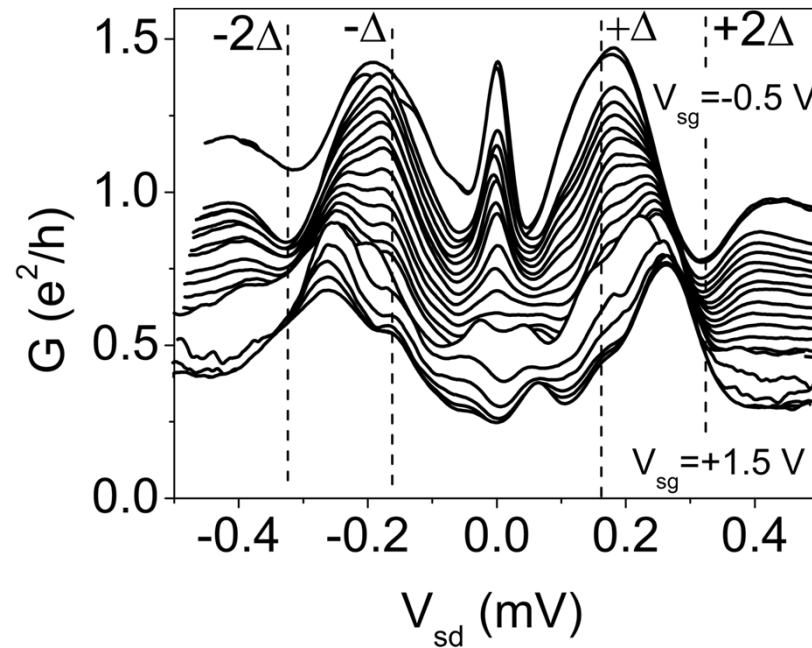
Sianno and Egger, PRL 2004 –
Quantum Monte Carlo $t_K \sim 1.1$

Similar experiment has been performed.
R. Maurand, et al., PRX 2, 011009 (2012)





Side-gate effect on MAR spectrum



$$t_K = \frac{k_B T_K}{\Delta}$$

The tuning of T_K arises from tuning of G . Asymmetry change is $<10\%$

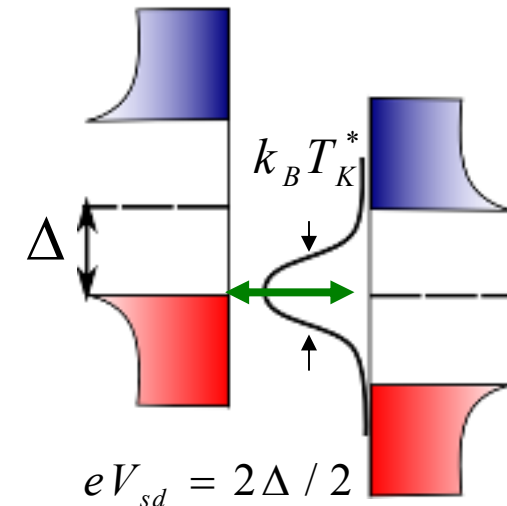
Candidates for the mechanism:

- ◆ Due to asymmetry a Kondo feature is pinned to one lead and enhances the 1st order MAR

Eichler et al., PRL 99,126602 (2007).

- ◆ ABS formed by strong coupling to one lead are probed by the weakly coupled 2nd lead.

Andersen et al., arXiv:1109.1383





Summary

- We have realized quantum dot Josephson junctions using uncapped InAs self-assembled quantum dots.
- We observed even-odd parity for superconducting transport. In some odd regions, the non-dissipative supercurrent is strongly suppressed, indicating π -junction, while it is 0-junction in even regions.
- We have demonstrated the electrical tuning of Kondo temperature via the tuning of tunnel coupling using a side-gate electrode.
- Using the tuning of Kondo temperature, we have systematically studied the behavior of the switching current and have observed the phase transition between magnetic doublet and (Kondo) singlet accompanied by 0- π junction phase change.
- The transition was observed at the scaling parameter $t_K(=k_B T_K/\Delta) \sim 1.1$.
- These observations offers ingredients for realizing non-local entangler using double quantum dot.