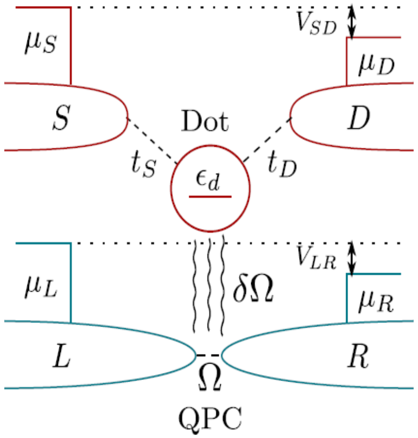
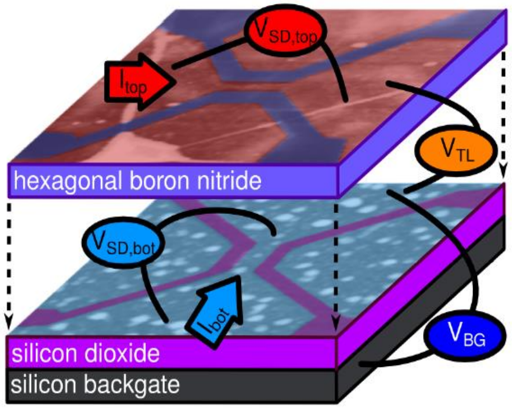
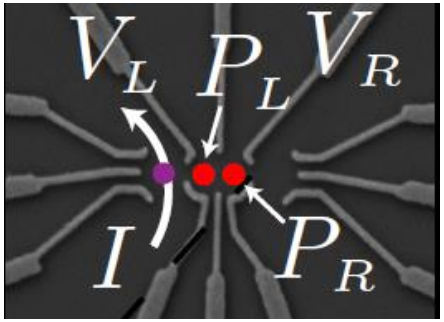
The impact of measurement backaction on many-body virtual transport



OZ, A. Carmi, and A. Romito, Phys. Rev. B **90**, 205413 (2014); Phys. Rev. B 99, 165422 (2019)



D. Bischoff, M. Eich**, OZ,** C. Rössler, T. Ihn, K. Ensslin, Nano Lett. **15**, 6003 (2015)



M. S. Ferguson, L. Camenzind, C. Mueller, B. Braunecker, **OZ**, and D. Zumbühl, in preparation

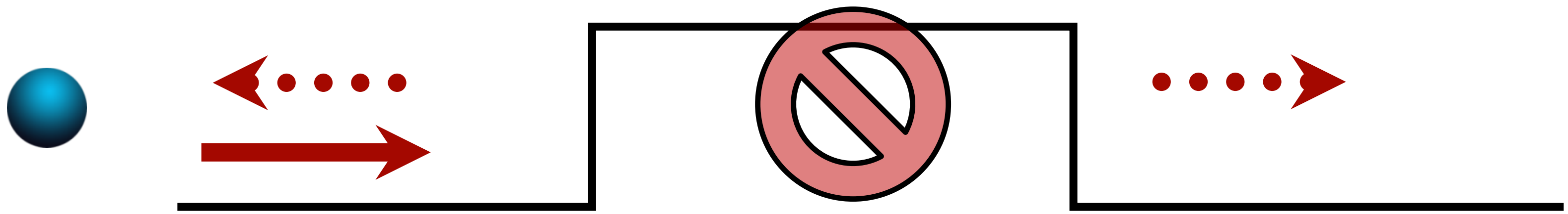
QUantum Engineered SysTems (QUEST)

Oded Zilberberg

Measurement postulate

Virtual transport

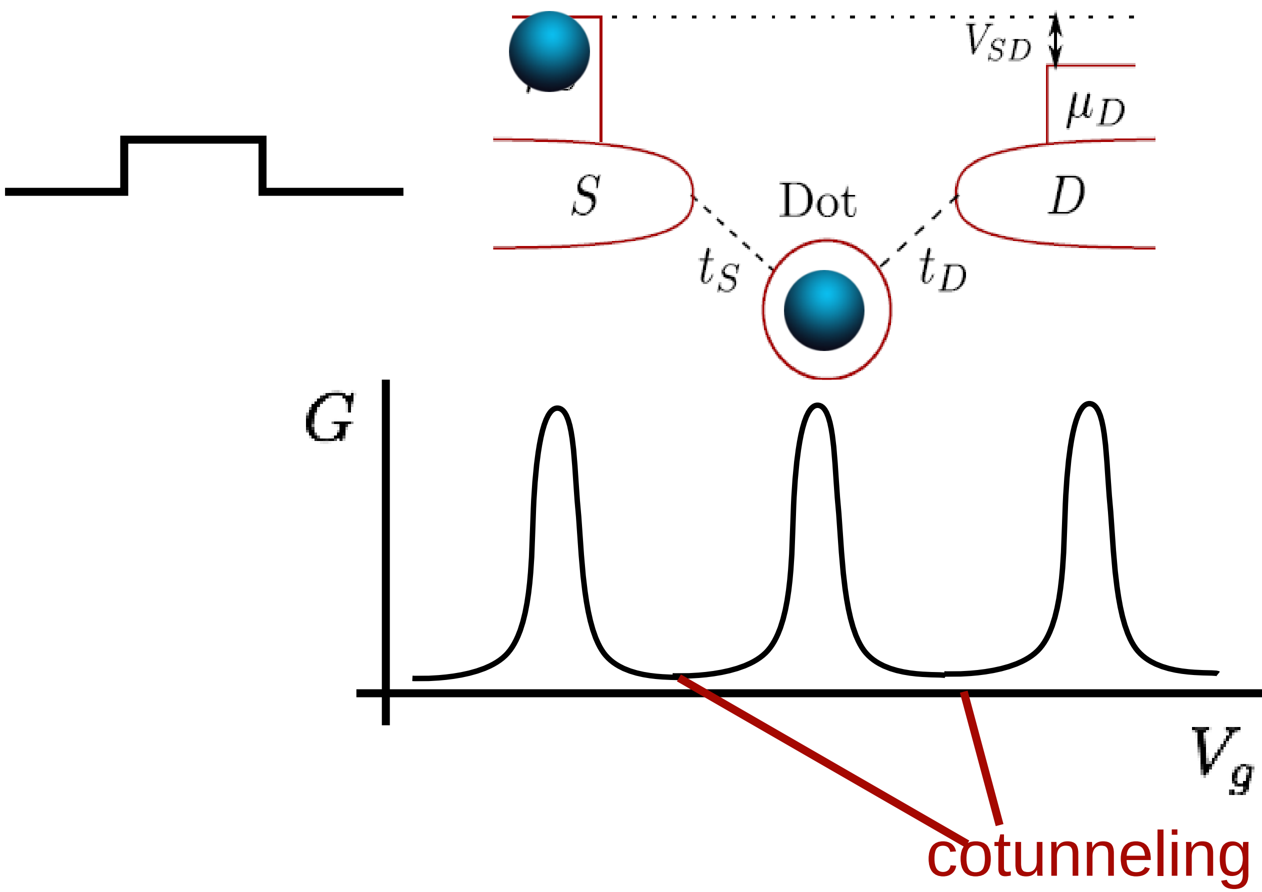
Can a particle collapse under a barrier?



See also

- E. Condon and P. Morse, RMP **3**, 43 (1931).
- E. Wigner, PR **98**, 145 (1955).
- M. Büttiker and R. Landauer, PRL **49**, 1739 1982).
- M. Büttiker, PRB **27**, 6178 (1983).
- D. Sokolovski and L. M. Baskin, PRA **36**, 4604 (1987).
- A. M. Steinberg, PRL **74**, 2405 (1995).

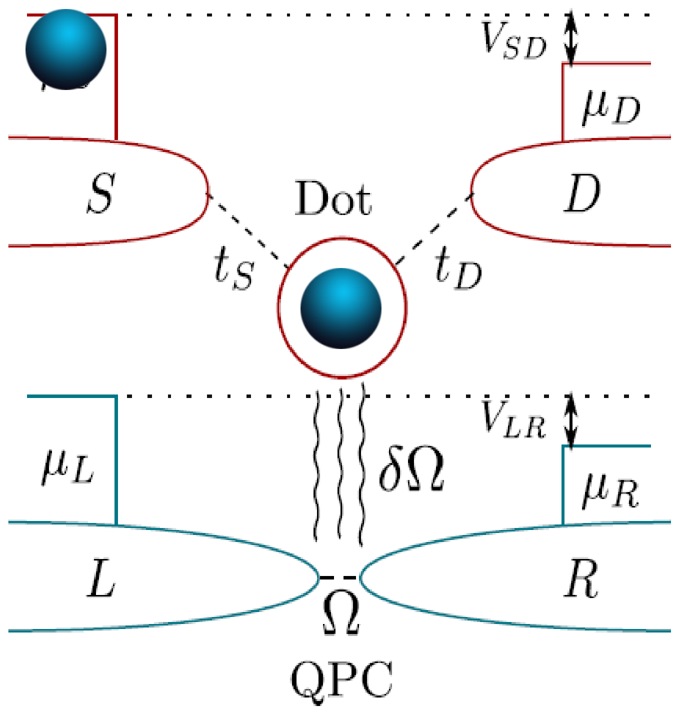
Many-body virtual transport



$$\tau \approx \hbar/\Delta E$$

OZ, A. Carmi, and A. Romito, Phys. Rev. B **90**, 205413 (2014)

Many-body virtual transport

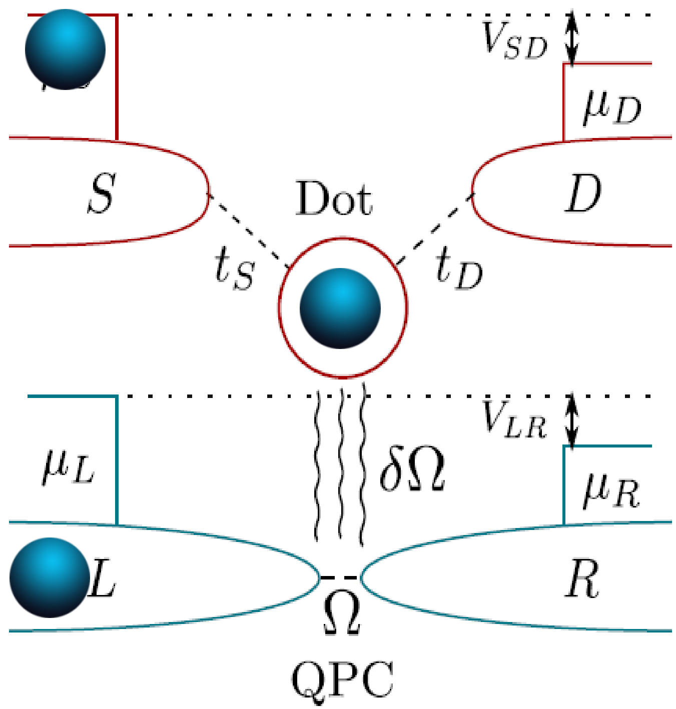


$$\tau \approx \hbar/\Delta E$$

see also, Romito and Gefen, PRB 90, 085417 (2014)
and talk by A. Steinberg

OZ, A. Carmi, and A. Romito, Phys. Rev. B **90**, 205413 (2014)

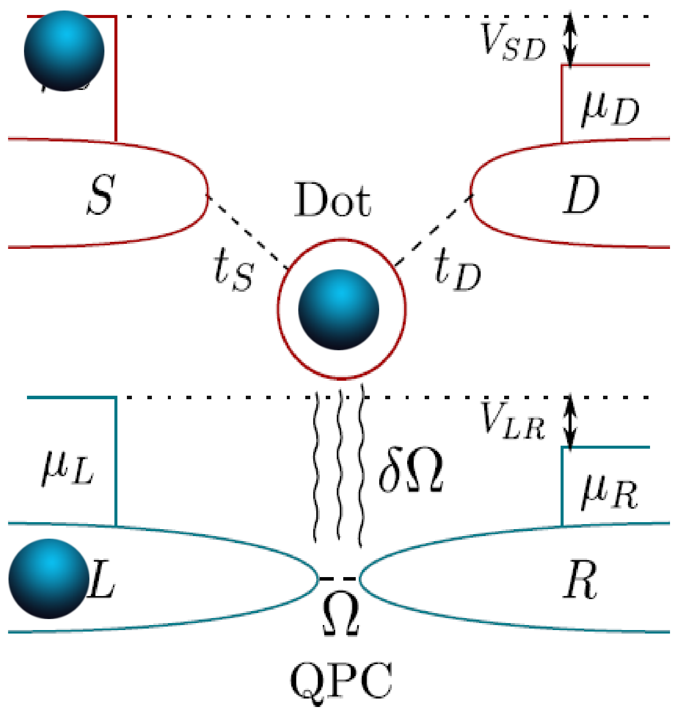
Many-body detection of virtual transport



see also, Non-barking dogs reference in talk of M. Devoret

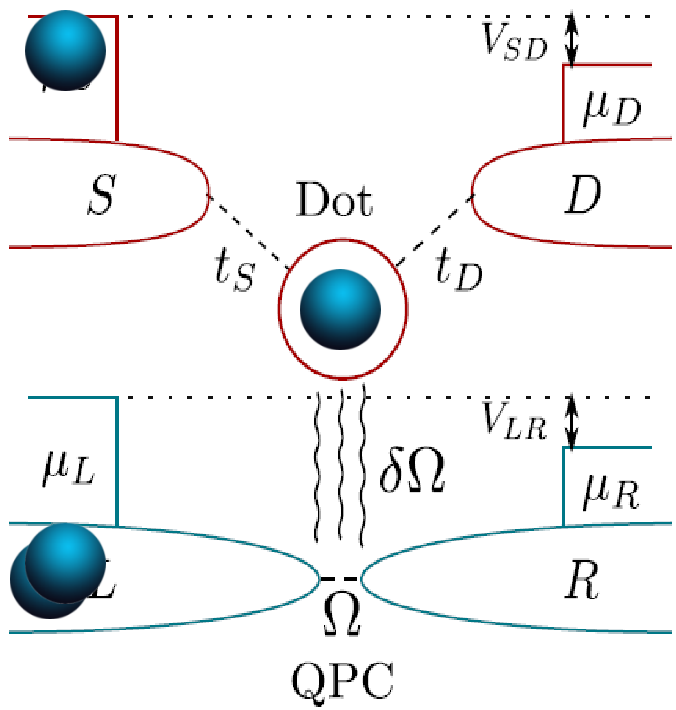
OZ, A. Carmi, and A. Romito, Phys. Rev. B **90**, 205413 (2014)

Many-body detection of virtual transport



OZ, A. Carmi, and A. Romito, Phys. Rev. B **90**, 205413 (2014)

Many-body detection of virtual transport



OZ, A. Carmi, and A. Romito, Phys. Rev. B **90**, 205413 (2014)

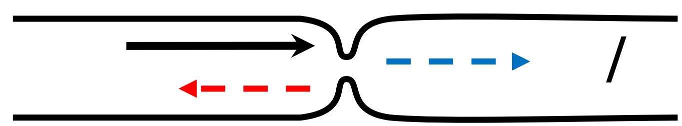
OZ, A. Carmi, and A. Romito, Phys. Rev. B **90**, 205413 (2014)

Quantum point contact (microscopic approach)

Rate equation for a QPC:

$$\mathcal{H}_{\rm PC}=\sum_l E_l a_l^\dagger a_l+\sum_r E_r a_r^\dagger a_r+\sum_{l,r}\Omega_{lr}(a_l^\dagger a_r+\text{H.c.})$$

$$|\Psi(t)\rangle=\Big[b_0(t)+\sum_{l,r}b_{lr}(t)a_r^\dagger a_l+\sum_{l<l',r<r'}b_{ll'rr'}(t)a_r^\dagger a_{r'}^\dagger a_l a_{l'}+\cdots\Big]|0\rangle$$



$$i|\dot\Psi(t)\rangle=\mathcal{H}_{\rm PC}|\Psi(t)\rangle \quad + \quad b_0(0)=1 \quad \Rightarrow \quad \tilde b(E)=\int_0^\infty e^{iEt}b(t)\,dt \quad + \quad \Omega_{lr}\equiv\Omega(E_l,E_r)=\Omega, \quad V_d\gg\Omega^2\rho$$

$$\Rightarrow\begin{cases} E\tilde b_0(E)-\sum_{l,r}\Omega_{lr}\tilde b_{lr}(E)=i\\ (E+E_l-E_r)\tilde b_{lr}(E)-\Omega_{lr}\tilde b_0(E)-\sum_{l',r'}\Omega_{l'r'}\tilde b_{ll'rr'}(E)=0\\ (E+E_l+E_{l'}-E_r-E_{r'})\tilde b_{ll'rr'}(E)-\Omega_{l'r'}\tilde b_{lr}(E)+\Omega_{lr}\tilde b_{l'r'}(E)-\sum_{l'',r''}\Omega_{l''r''}\tilde b_{ll'l''rr'r''}(E)=0\\ \cdots \end{cases}$$

S. A. Gurvitz, Phys. Rev.B 56, 15215 (1997)

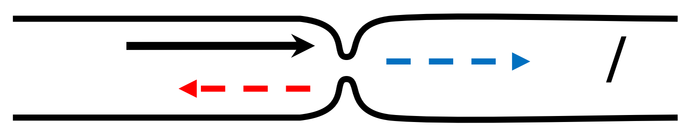
Quantum point contact (microscopic approach)

Rate equation for a QPC:

see also, works by A. Korotkov, D. Averin and A. Jordan

$$\mathcal{H}_{\rm PC}=\sum_l E_l a_l^\dagger a_l+\sum_r E_r a_r^\dagger a_r+\sum_{l,r}\Omega_{lr}(a_l^\dagger a_r+{\rm H.c.})$$

$$|\Psi(t)\rangle=\Big[b_0(t)+\sum_{l,r} b_{lr}(t)a_r^\dagger a_l + \sum_{l<l',r<r'} b_{ll'rr'}(t)a_r^\dagger a_{r'}^\dagger a_l a_{l'}+\cdots\Big]|0\rangle$$



$$i|\dot{\Psi}(t)\rangle=\mathcal{H}_{\rm PC}|\Psi(t)\rangle \quad + \quad b_0(0)=1 \quad \Rightarrow \quad \tilde{b}(E)=\int_0^\infty e^{iEt}b(t)dt \quad + \quad \begin{array}{l}\Omega_{lr}\equiv\Omega(E_l,E_r)=\Omega \\ V_d\gg\Omega^2\rho \\ D=2\pi\Omega^2\rho_L\rho_R V_d\end{array}$$

$$\Rightarrow \begin{cases}(E+iD/2)\tilde{b}_0=i \\ (E+E_l-E_r+iD/2)\tilde{b}_{lr}-\Omega\tilde{b}_0=0 \\ (E+E_l+E_{l'}-E_r-E_{r'}+iD/2)\tilde{b}_{ll'rr'}-\Omega\tilde{b}_{lr}+\Omega\tilde{b}_{l'r'}=0 \\ \cdots\end{cases}$$

S. A. Gurvitz, Phys. Rev.B 56, 15215 (1997)

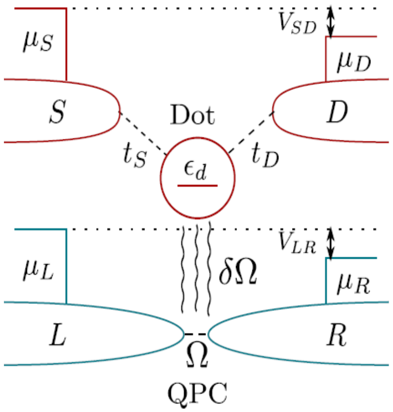
Microscopic description

Calculate the amplitudes for microscopic events

$$\langle \mathbf{l}_i, \mathbf{r}_i\,; f\,; t | 0\,; f\,; t=0\rangle^{(2)} = \left(-\frac{i}{\hbar}\right)^2 \int_0^t dt' \int_0^{t'} dt'' \langle \mathbf{l}_i, \mathbf{r}_i\,; f|\, e^{-i\frac{H_0}{\hbar}(t-t')} H_T e^{-i\frac{H_0}{\hbar}(t'-t'')} H_T e^{-i\frac{H_0}{\hbar}t''} |0\,; f\rangle$$

$$= -\frac{t_S^* t_D}{\hbar^2} \int_0^t dt' \int_0^{t'} dt'' \sum_{j,k} \int_{-\infty}^{\mu_L} d\mathbf{l}_k \int_{\mu_R}^{\infty} d\mathbf{r}_k \int_{-\infty}^{\mu_L} d\mathbf{l}_j \int_{\mu_R}^{\infty} d\mathbf{r}_j \times$$

$$e^{-i(\epsilon - E_d)t'} e^{-i(E_d - \epsilon')t''} \tilde{b}_{\mathbf{l}_i, \mathbf{r}_i | \mathbf{l}_k, \mathbf{r}_k}(t-t') b_{\mathbf{l}_k, \mathbf{r}_k | \mathbf{l}_j, \mathbf{r}_j}(t'-t'') \tilde{b}_{\mathbf{l}_j, \mathbf{r}_j}(t'').$$



Microscopic description

Calculate the amplitudes for microscopic events

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$$= -\frac{t_S^* t_D}{\hbar^2} \int_0^t dt' \int_0^{t'} dt'' \sum_{j,k} \int_{-\infty}^{\mu_L} d\mathbf{l}_k \int_{\mu_R}^{\infty} d\mathbf{r}_k \int_{-\infty}^{\mu_L} d\mathbf{l}_j \int_{\mu_R}^{\infty} d\mathbf{r}_j \times$$

$$e^{-i(\epsilon - E_d)t'} e^{-i(E_d - \epsilon')t''} \tilde{b}_{\mathbf{l}_i,\mathbf{r}_i|\mathbf{l}_k,\mathbf{r}_k}(t-t') b_{\mathbf{l}_k,\mathbf{r}_k|\mathbf{l}_j,\mathbf{r}_j}(t'-t'') \tilde{b}_{\mathbf{l}_j,\mathbf{r}_j}(t'').$$

$$|\Psi(t); e\rangle = \Big[b_0(t) + \sum_{l_1,r_1} b_{l_1 r_1}(t) a_{r_1}^\dagger a_{l_1} + \sum_{l_1<l_2, r_1<r_2} b_{l_1 l_2 r_1 r_2}(t) a_{r_1}^\dagger a_{r_2}^\dagger a_{l_1} a_{l_2} + ...\Big] |0\,; e\rangle\,,$$

$$\left|\tilde{\Psi}(t); f\right\rangle = \Big[\tilde{b}_0(t) + \sum_{l_1,r_1} \tilde{b}_{l_1 r_1}(t) a_{r_1}^\dagger a_{l_1} + \sum_{l_1<l_2, r_1<r_2} \tilde{b}_{l_1 l_2 r_1 r_2}(t) a_{r_1}^\dagger a_{r_2}^\dagger a_{l_1} a_{l_2} + ...\Big] |0\,; f\rangle\,,$$

OZ, A. Carmi, and A. Romito, Phys. Rev. B **90**, 205413 (2014)

Microscopic description – toy model

Calculate the amplitudes for microscopic events

$$\langle \mathbf{l}_i, \mathbf{r}_i ; f ; t | 0 ; f ; t = 0 \rangle^{(2)} = \left(-\frac{i}{\hbar} \right)^2 \int_0^t dt' \int_0^{t'} dt'' \langle \mathbf{l}_i, \mathbf{r}_i ; f | e^{-i \frac{H_0}{\hbar}(t-t')} H_T e^{-i \frac{H_0}{\hbar}(t'-t'')} H_T e^{-i \frac{H_0}{\hbar} t''} | 0 ; f \rangle$$

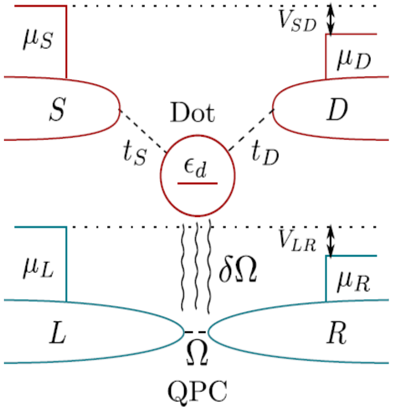
$$= -\frac{t_S^* t_D}{\hbar^2} \int_0^t dt' \int_0^{t'} dt'' \sum_{j,k} \int_{-\infty}^{\mu_L} d\mathbf{l}_k \int_{\mu_R}^{\infty} d\mathbf{r}_k \int_{-\infty}^{\mu_L} d\mathbf{l}_j \int_{\mu_R}^{\infty} d\mathbf{r}_j \times$$

$$D = 2\pi \Omega^2 \rho_L \rho_R V_d$$

$$e^{-i(\epsilon - E_d)t'} e^{-i(E_d - \epsilon')t''} \tilde{b}_{\mathbf{l}_i, \mathbf{r}_i | \mathbf{l}_k, \mathbf{r}_k}(t - t') b_{\mathbf{l}_k, \mathbf{r}_k | \mathbf{l}_j, \mathbf{r}_j}(t' - t'') \tilde{b}_{\mathbf{l}_j, \mathbf{r}_j}(t'').$$

Assumptions:

1. T=0
2. $\tilde{\Omega} = \Omega - \delta\Omega = 0$
3. $\mathcal{D}\tau_{\text{cot}} \ll 1$



OZ, A. Carmi, and A. Romito, Phys. Rev. B **90**, 205413 (2014)

Microscopic description – backaction I

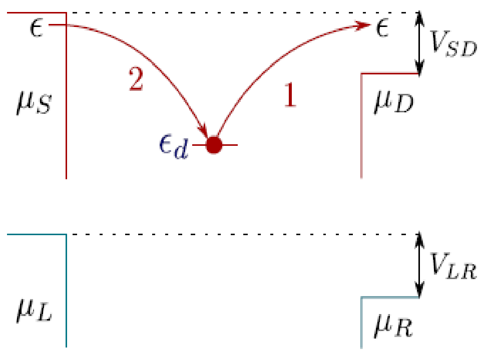
Calculate the amplitudes for microscopic events

$$\langle \mathbf{l}_i, \mathbf{r}_i ; f ; t | 0 ; f ; t=0\rangle^{(2)} = \left(-\frac{i}{\hbar}\right)^2 \int_0^t dt' \int_0^{t'} dt'' \langle \mathbf{l}_i, \mathbf{r}_i ; f | e^{-i\frac{H_0}{\hbar}(t-t')} H_T e^{-i\frac{H_0}{\hbar}(t'-t'')} H_T e^{-i\frac{H_0}{\hbar}t''} | 0 ; f\rangle$$

$$= -\frac{t_S^* t_D}{\hbar^2} \int_0^t dt' \int_0^{t'} dt'' \sum_{j,k} \int_{-\infty}^{\mu_L} d\mathbf{l}_k \int_{\mu_R}^{\infty} d\mathbf{r}_k \int_{-\infty}^{\mu_L} d\mathbf{l}_j \int_{\mu_R}^{\infty} d\mathbf{r}_j \times$$

$$e^{-i(\epsilon - E_d)t'} e^{-i(E_d - \epsilon')t''} \tilde{b}_{\mathbf{l}_i,\mathbf{r}_i|\mathbf{l}_k,\mathbf{r}_k}(t-t') b_{\mathbf{l}_k,\mathbf{r}_k|\mathbf{l}_j,\mathbf{r}_j}(t'-t'') \tilde{b}_{\mathbf{l}_j,\mathbf{r}_j}(t'').$$

$$D = 2\pi\Omega^2 \rho_L \rho_R V_d$$



$$b_0(t) = e^{-\frac{\mathcal{D}}{2}t}$$

$$W_{SD}^0 = \frac{2\pi}{\hbar} \int_{\mu_D}^{\mu_S} d\epsilon \, \rho_S \rho_D \left| \frac{t_S t_D}{\epsilon - \epsilon_d + i\hbar\mathcal{D}/2} \right|^2$$

$$= \frac{\Gamma_S \Gamma_D}{\pi \mathcal{D}} \left[\tan^{-1}\left(\frac{2(\mu_S - \epsilon_d)}{\hbar\mathcal{D}}\right) - \tan^{-1}\left(\frac{2(\mu_D - \epsilon_d)}{\hbar\mathcal{D}}\right) \right]$$

Microscopic description – backaction II

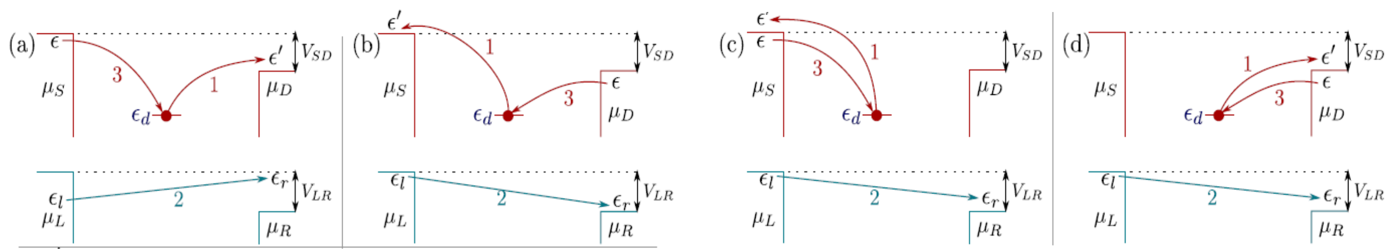
Calculate the amplitudes for microscopic events

$$\langle \mathbf{l}_i, \mathbf{r}_i\,; f\,; t | 0\,; f\,; t=0\rangle^{(2)} = \left(-\frac{i}{\hbar}\right)^2 \int_0^t dt' \int_0^{t'} dt'' \langle \mathbf{l}_i, \mathbf{r}_i\,; f| e^{-i\frac{H_0}{\hbar}(t-t')} H_T e^{-i\frac{H_0}{\hbar}(t'-t'')} H_T e^{-i\frac{H_0}{\hbar}t''} |0\,; f\rangle$$

$$= -\frac{t_S^* t_D}{\hbar^2} \int_0^t dt' \int_0^{t'} dt'' \sum_{j,k} \int_{-\infty}^{\mu_L} d\mathbf{l}_k \int_{\mu_R}^{\infty} d\mathbf{r}_k \int_{-\infty}^{\mu_L} d\mathbf{l}_j \int_{\mu_R}^{\infty} d\mathbf{r}_j \times$$

$$D = 2\pi\Omega^2 \rho_L \rho_R V_d$$

$$e^{-i(\epsilon - E_d)t'} e^{-i(E_d - \epsilon')t''} \tilde{b}_{\mathbf{l}_i,\mathbf{r}_i|\mathbf{l}_k,\mathbf{r}_k}(t-t') b_{\mathbf{l}_k,\mathbf{r}_k|\mathbf{l}_j,\mathbf{r}_j}(t'-t'') \tilde{b}_{\mathbf{l}_j,\mathbf{r}_j}(t'').$$

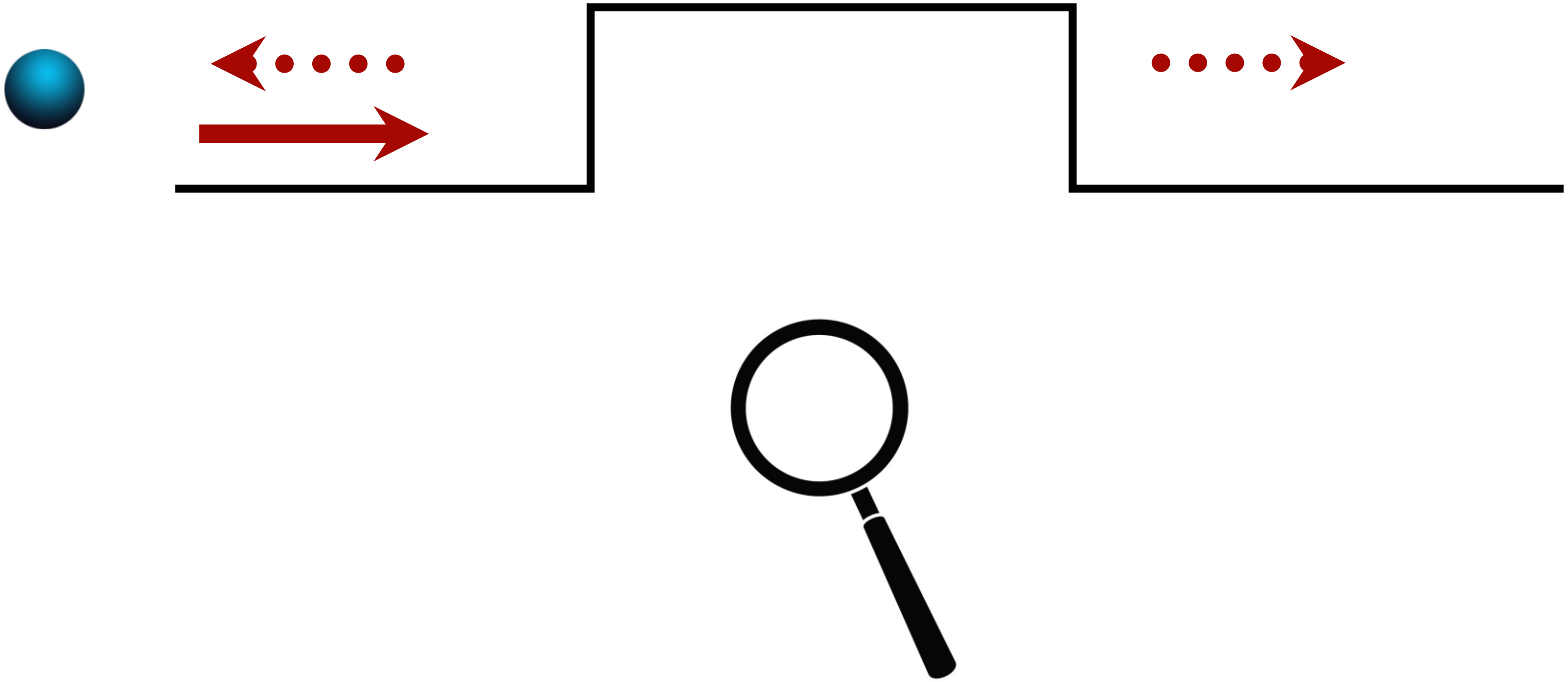


$$W^1_{\alpha\alpha'} = \quad b_{l_1 r_1}(t) = \frac{\Omega}{\mathcal{E}_{l_1} - \mathcal{E}_{r_1}} e^{-\frac{\mathcal{D}}{2}t}\left[1 - e^{i\frac{(\mathcal{E}_{l_1}-\mathcal{E}_{r_1})t}{\hbar}}\right] \quad b_{l_1 r_1 | l_1^0 r_1^0}(t) = e^{-\frac{\mathcal{D}}{2}t} e^{i\frac{(\mathcal{E}_{l_1}-\mathcal{E}_{r_1})t}{\hbar}} \delta_{l_1 l_1^0} \delta_{r_1 r_1^0} + O(\Omega^2)$$

$$= \frac{\hbar\Gamma_\alpha\Gamma_{\alpha'}\mathcal{D}}{4\pi^2 e V_{LR}} \int_{\mu_{\alpha'} - eV_{LR}} d\epsilon \int_{\mu_{\alpha'}} d\epsilon' \frac{(eV_{LR} + \epsilon - \epsilon')}{\left[(\epsilon - \epsilon_d)^2 + \frac{\hbar^2\mathcal{D}^2}{4}\right]\left[(\epsilon' - \epsilon_d)^2 + \frac{\hbar^2\mathcal{D}^2}{4}\right]}.$$

OZ, A. Carmi, and A. Romito, Phys. Rev. B **90**, 205413 (2014)

Backaction

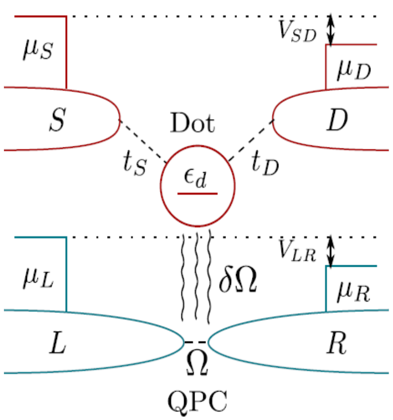


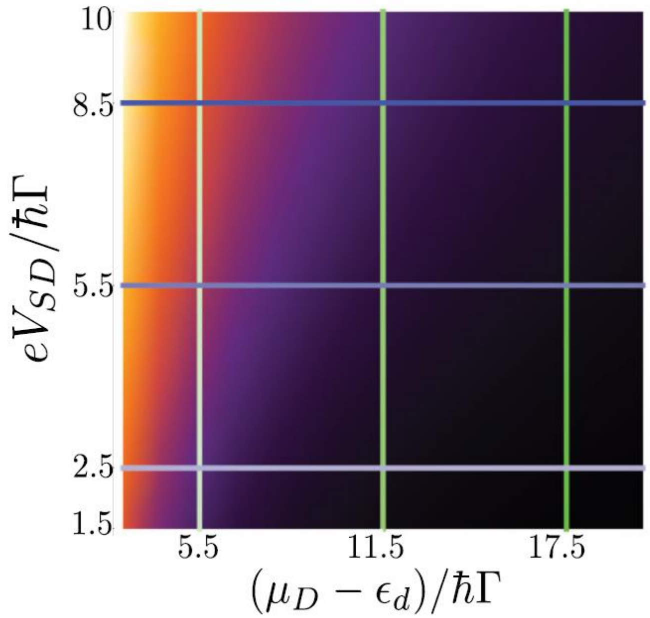
OZ, A. Carmi, and A. Romito, Phys. Rev. B **90**, 205413 (2014)

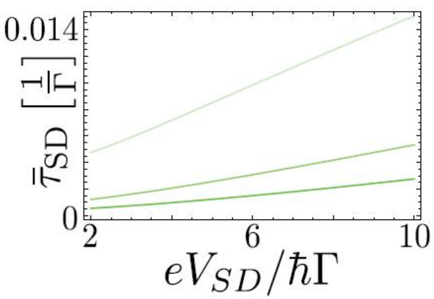
Cotunneling time

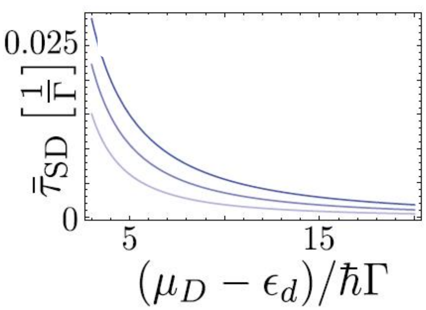
$$\bar{\tau}_{\mathrm{SD}} = \frac{\int_{-\infty}^{\infty} ds [\langle I_{\mathrm{QD}}(t) I_{\mathrm{QPC}}(t-s)\rangle - \langle I_{\mathrm{QD}}\rangle\langle I_{\mathrm{QPC}}\rangle]}{e\mathcal{D}\langle I_{\mathrm{QD}}\rangle}$$

$$= \frac{S}{2e\mathcal{D}\langle I_{\mathrm{QD}}\rangle} \approx \hbar/\Delta E$$



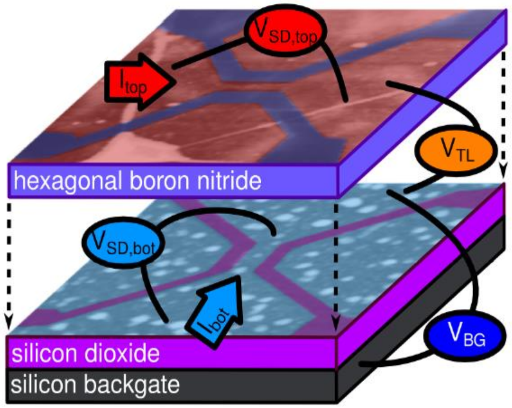


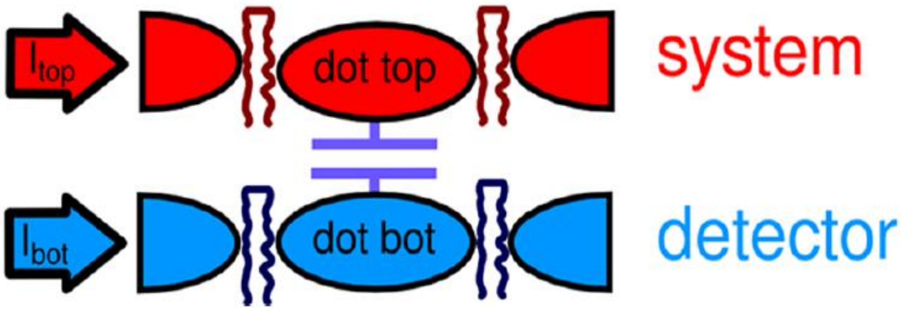


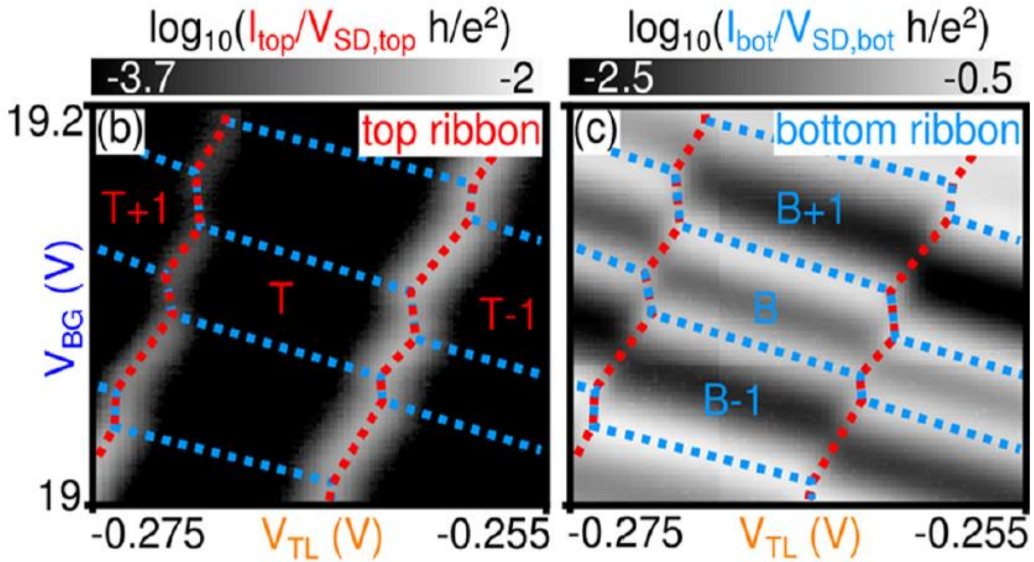


OZ, A. Carmi, and A. Romito, Phys. Rev. B **90**, 205413 (2014)

Mesoscopic drag + backaction







D. Bischoff, M. Eich, OZ, C. Rössler, T. Ihn, K. Ensslin, Nano Lett. 15, 6003 (2015)

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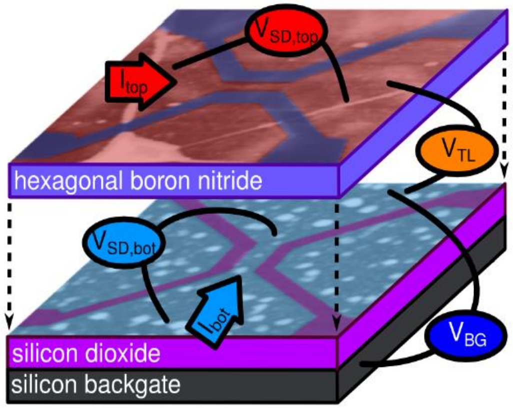

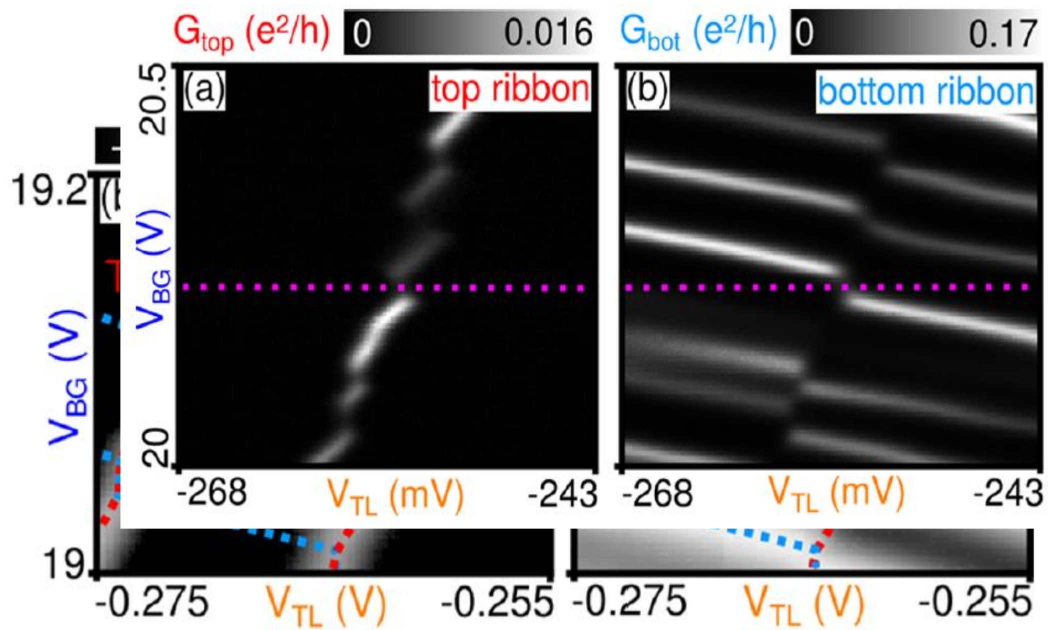

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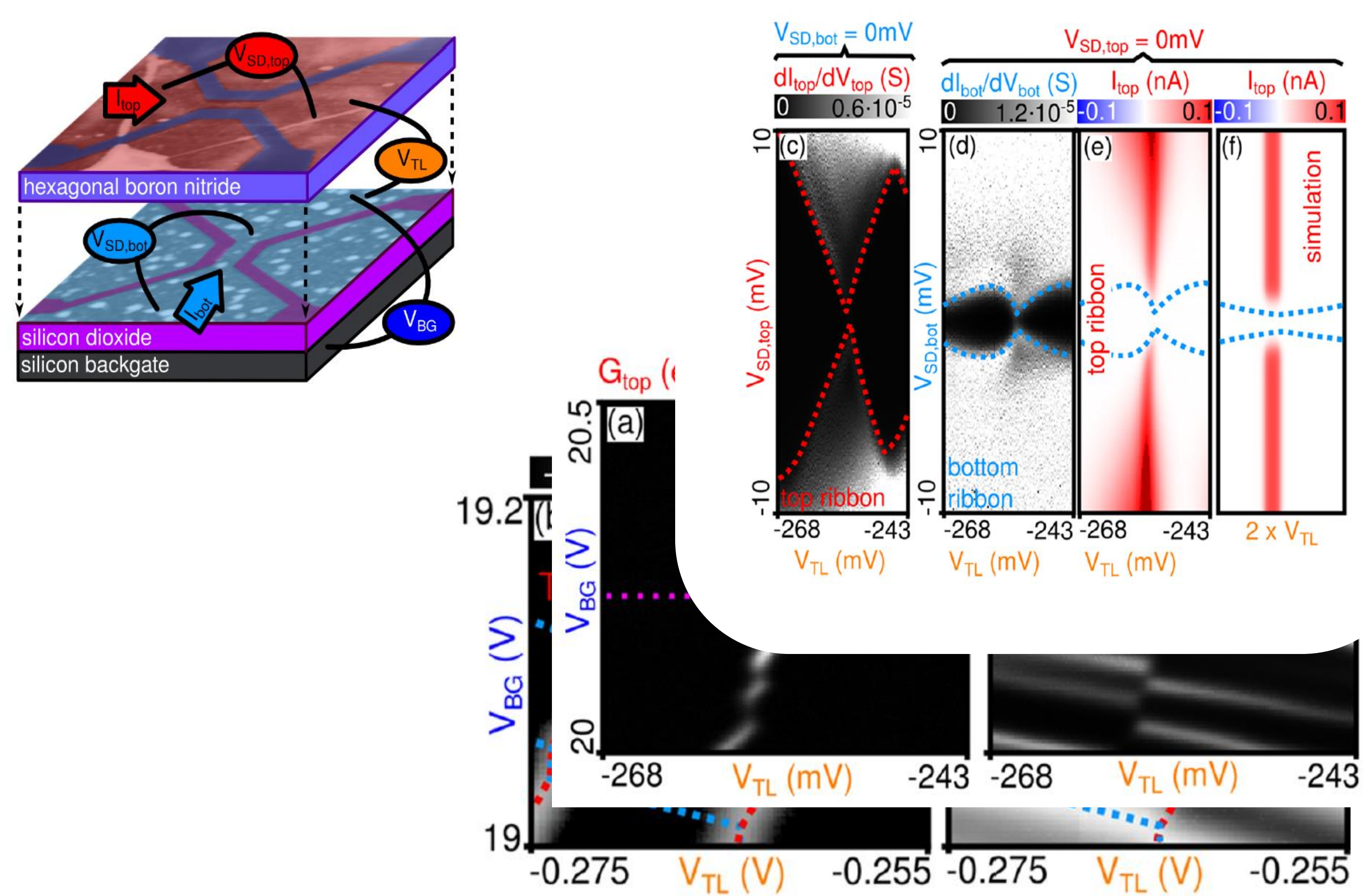

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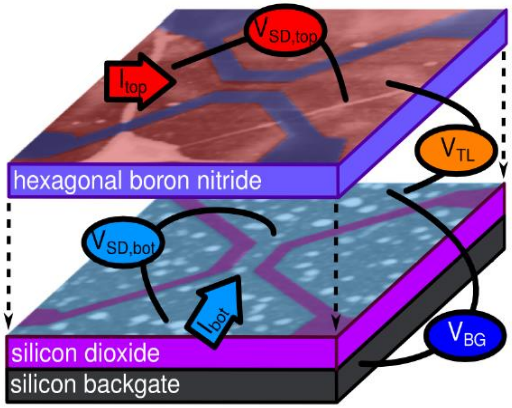
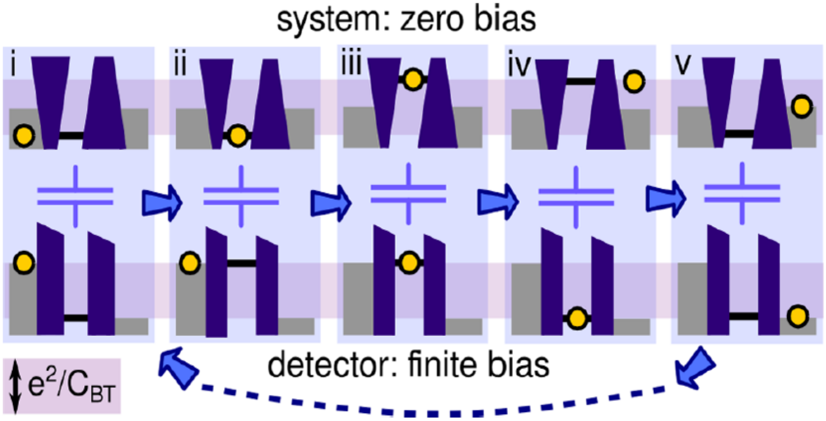
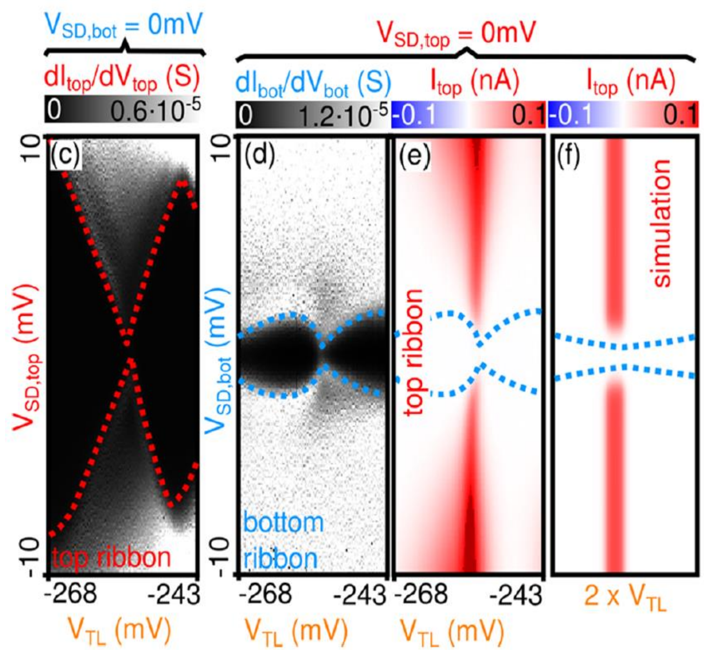




R. Sanchez, R. Lopez, D. Sanchez, M. Buttiker,

Phys. Rev. Lett. 104, 076801 (2010).



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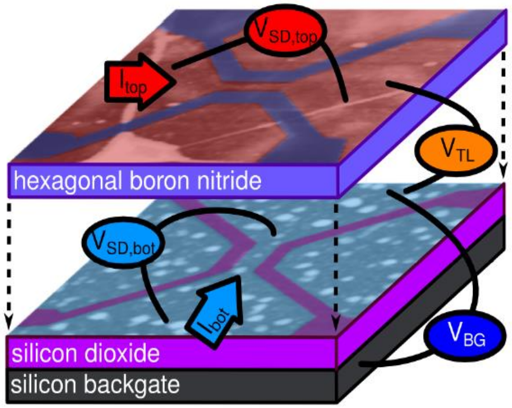

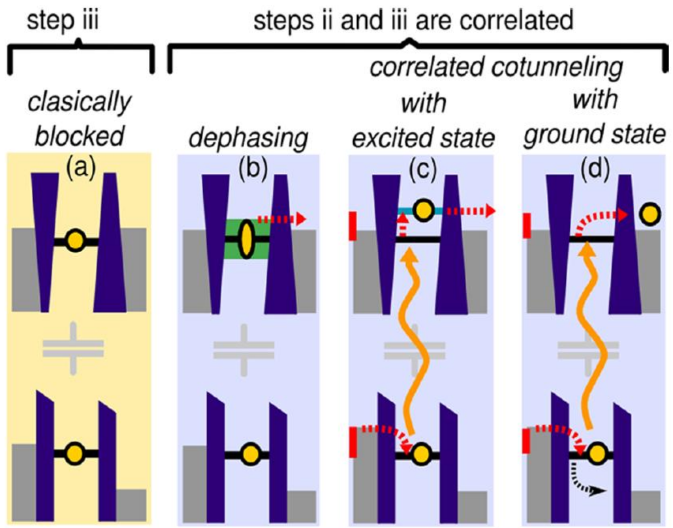

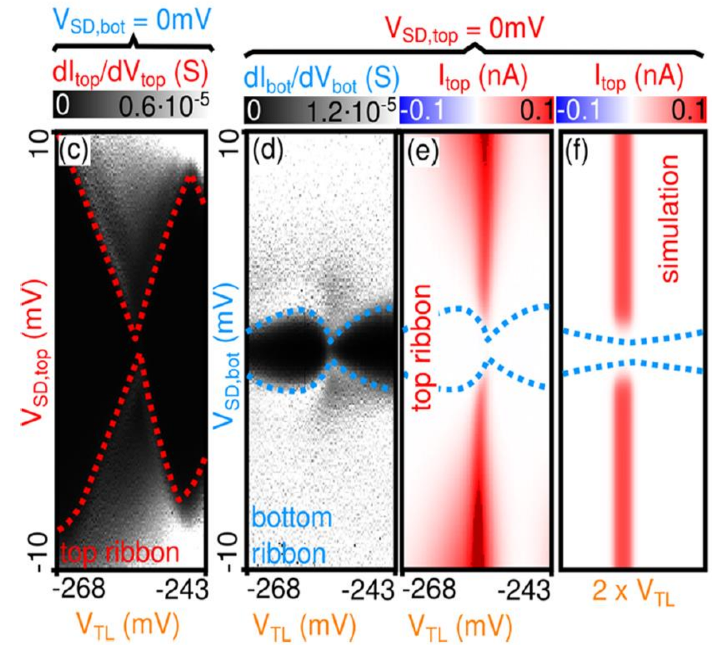

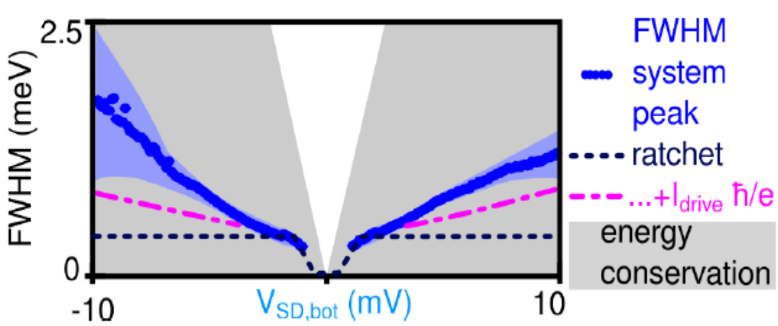

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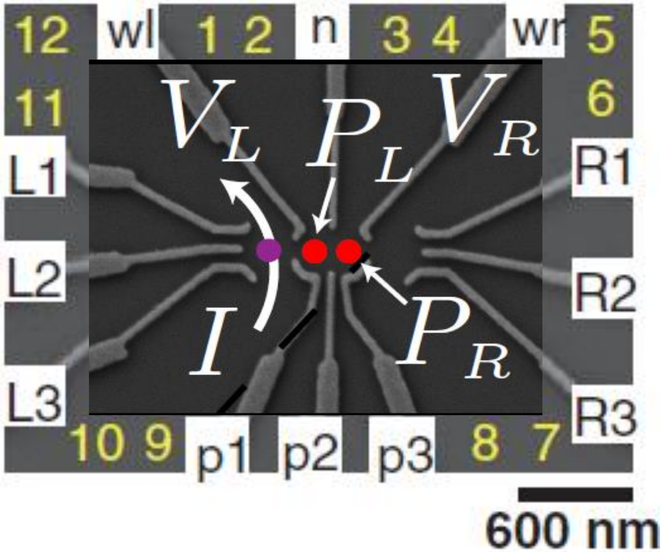
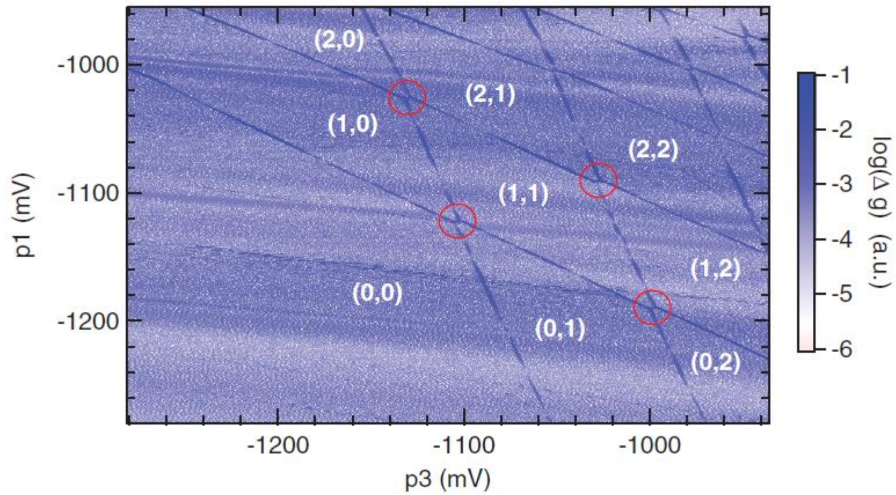
Backaction induced quantum phase transitions



Biesinger *et al.*, PRL 115, 106804 (2015)



M. S. Ferguson, L. Camenzind, C. Mueller, B. Braunecker, D. Zümbuhl, and **OZ**, in preparation

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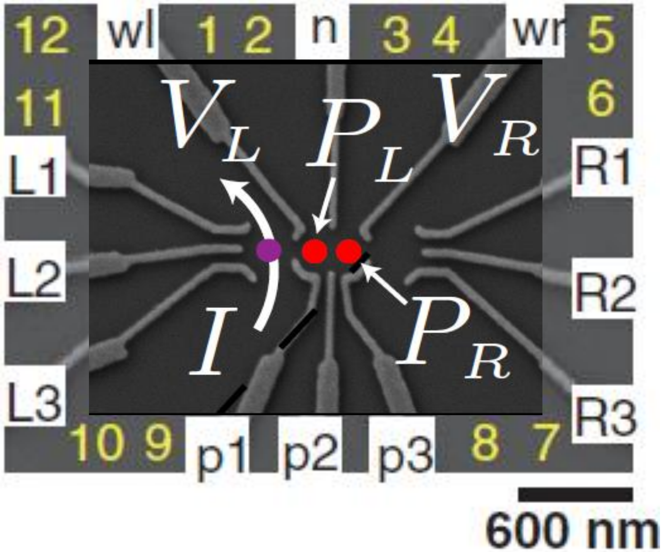

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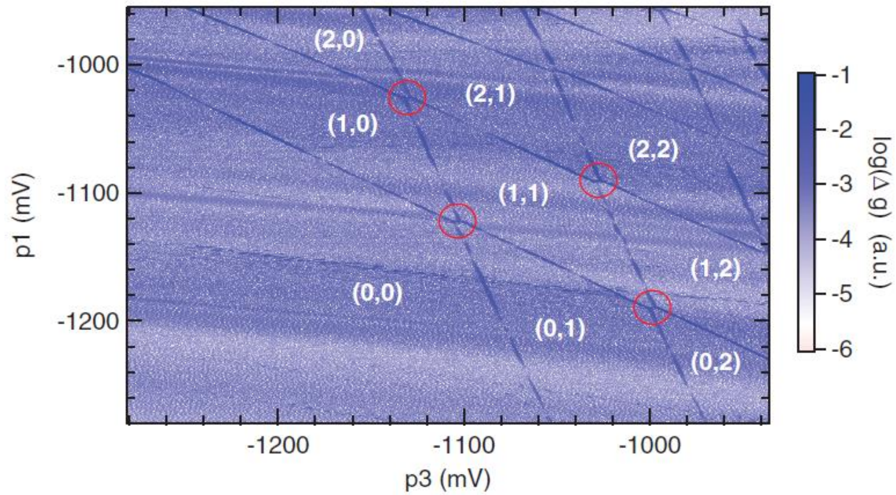

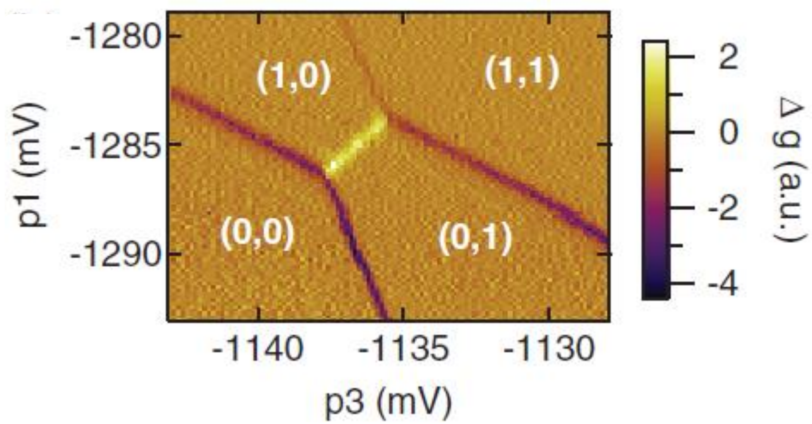

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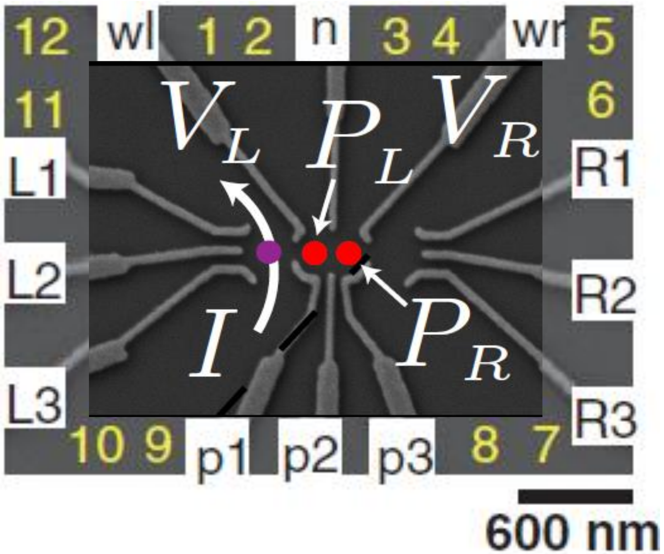

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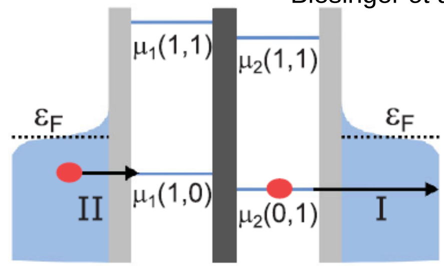

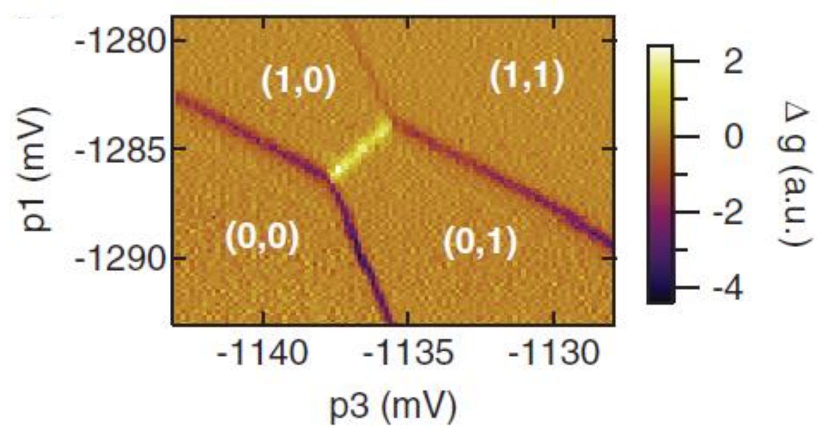

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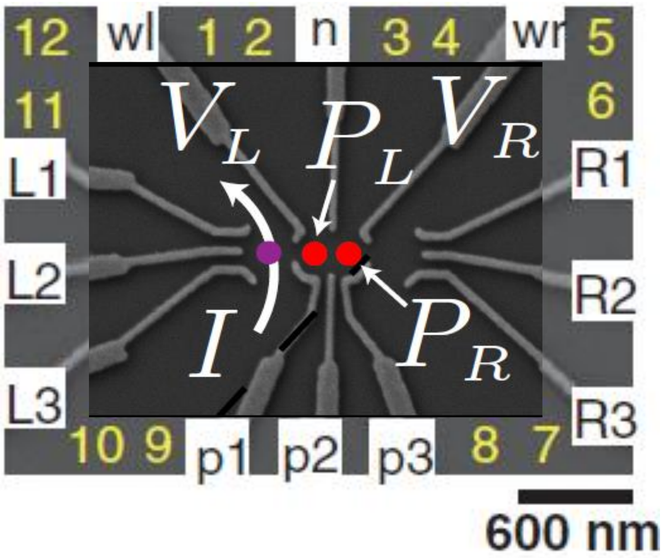
Backaction induced quantum phase transitions



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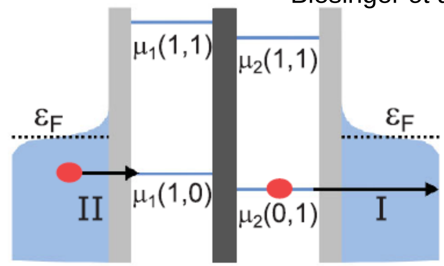

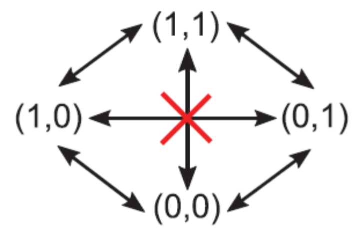

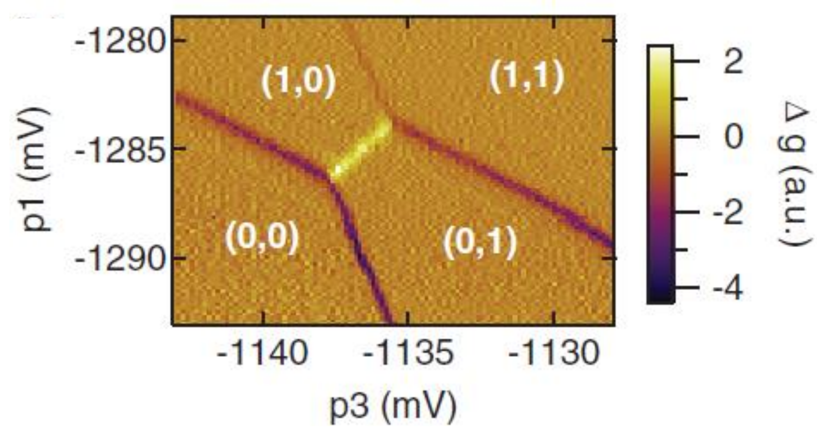

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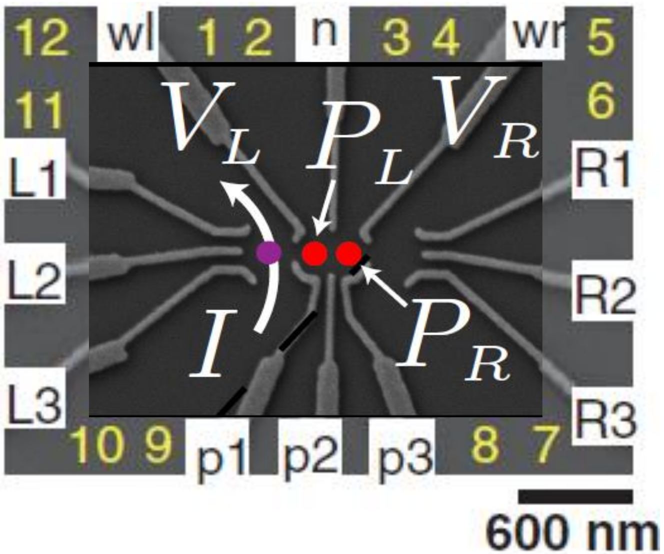

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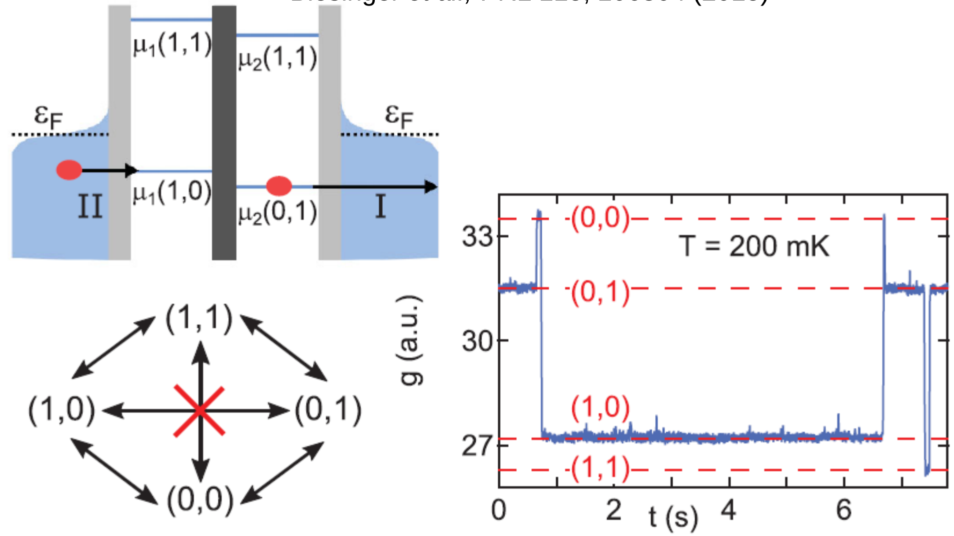

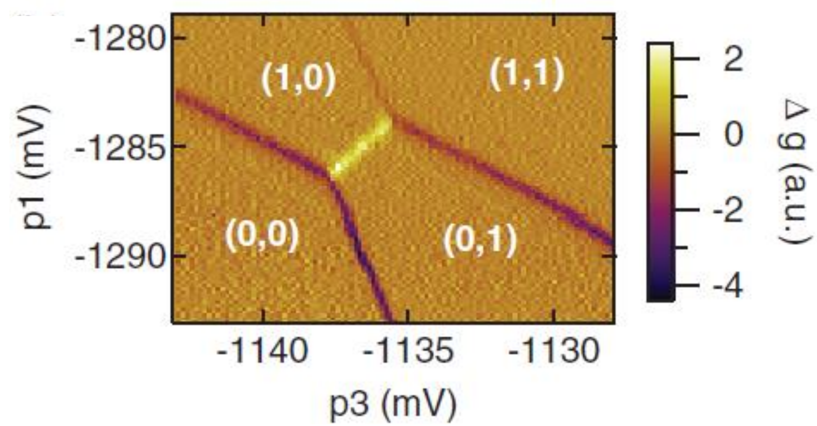

see also, talks by
M. Devoret, I. Pop,
and A. Jordan

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Backaction induced quantum phase transitions

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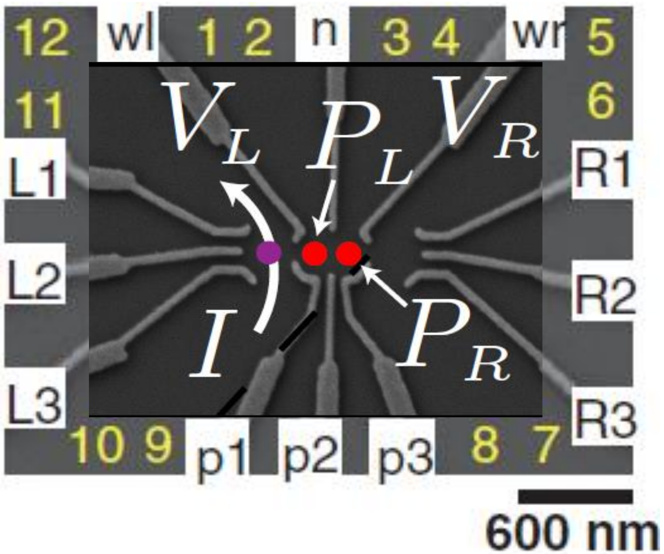

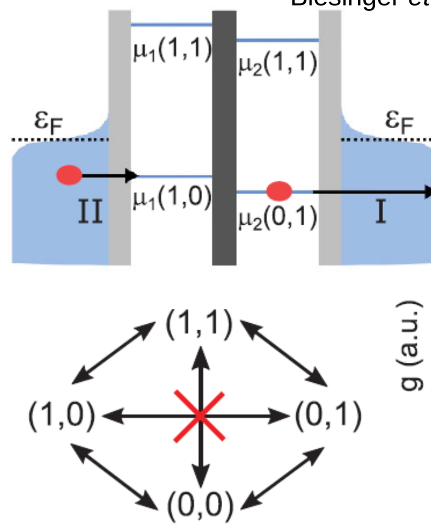

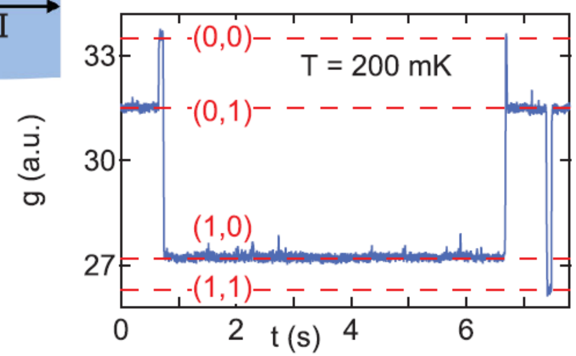

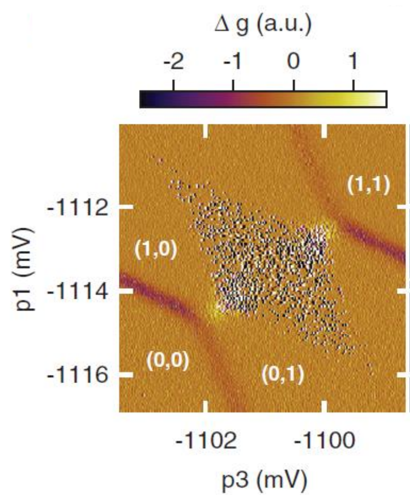

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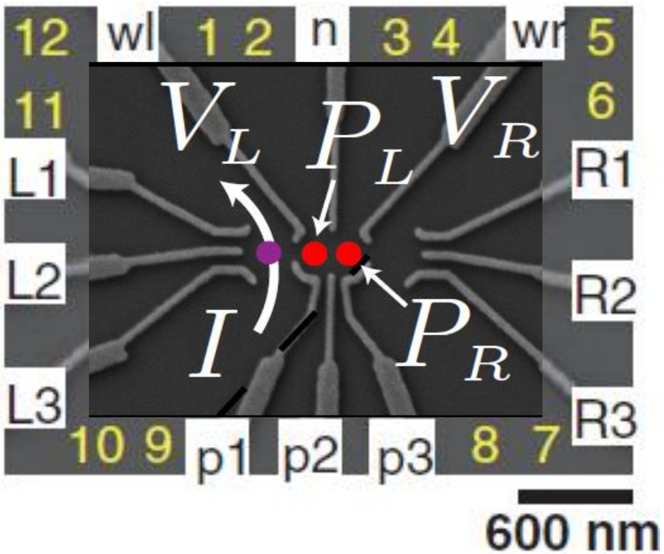

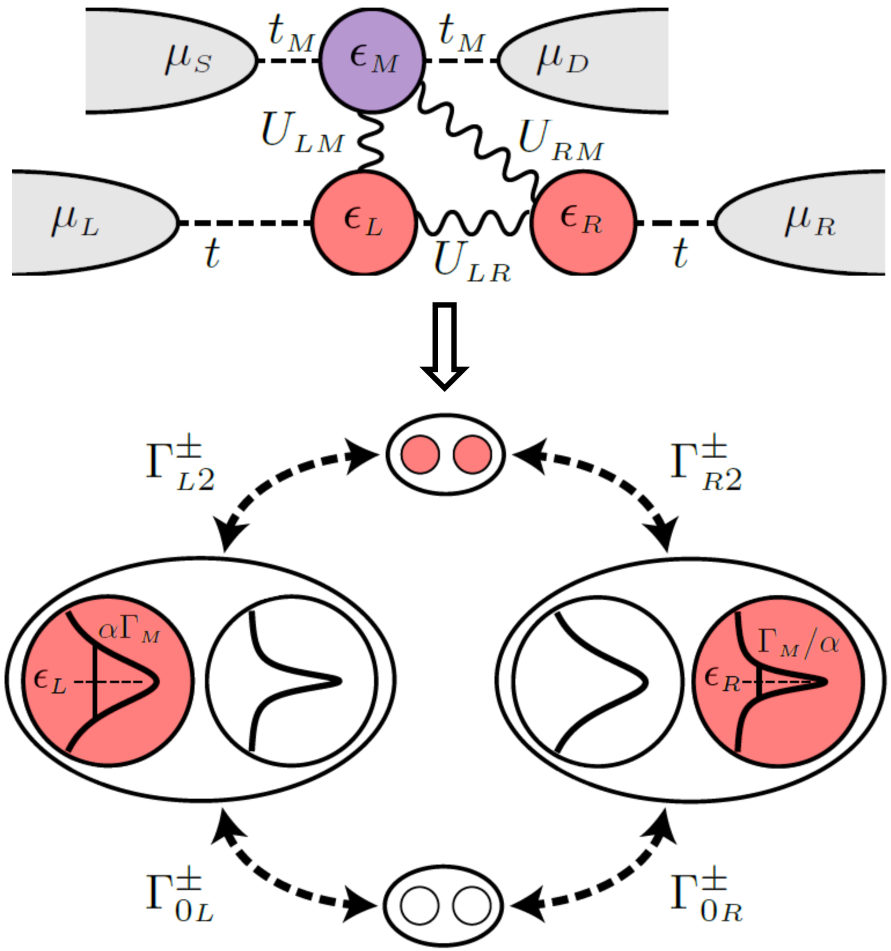

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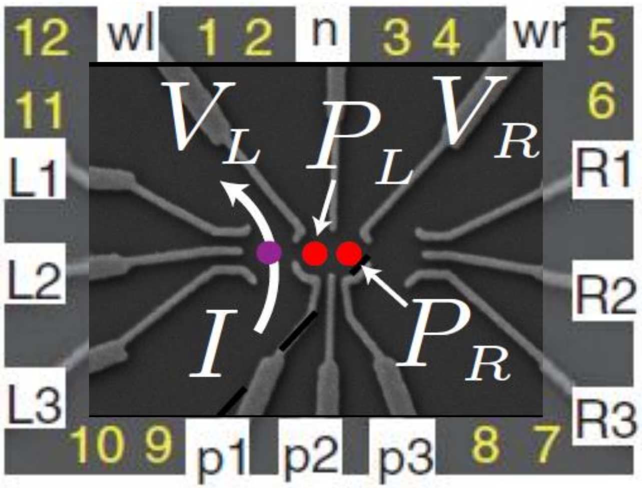

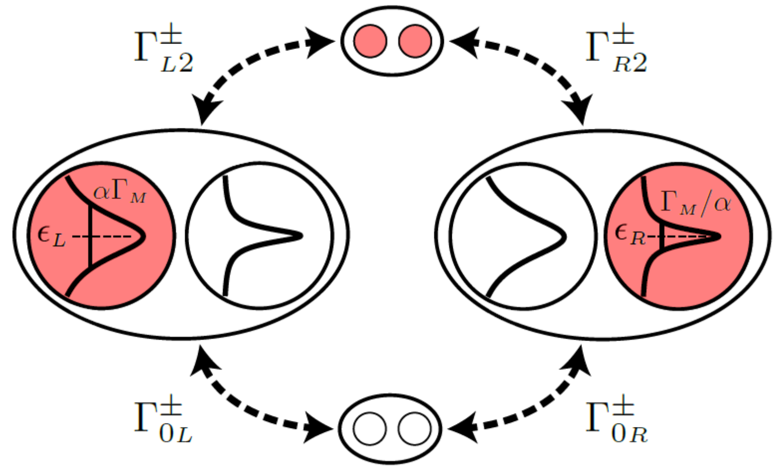

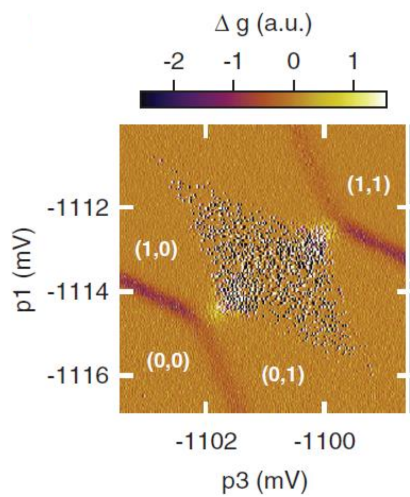

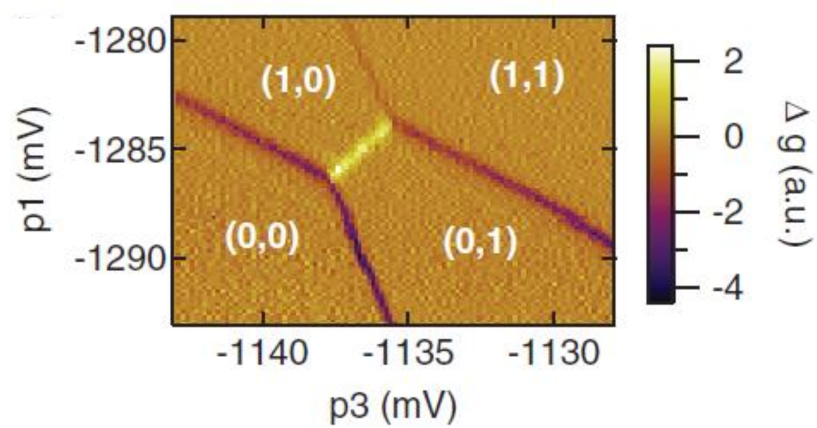

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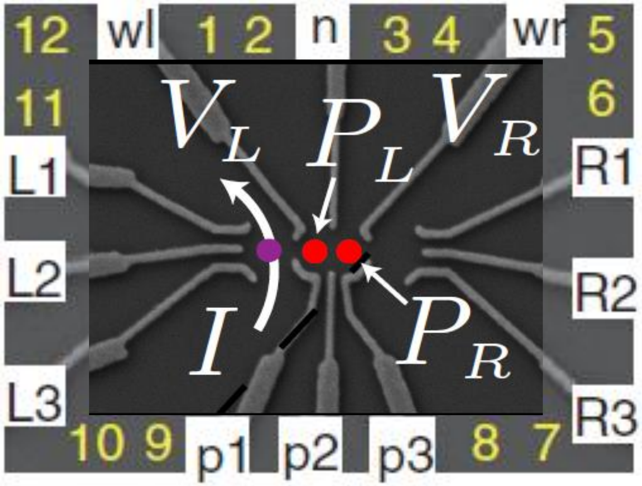

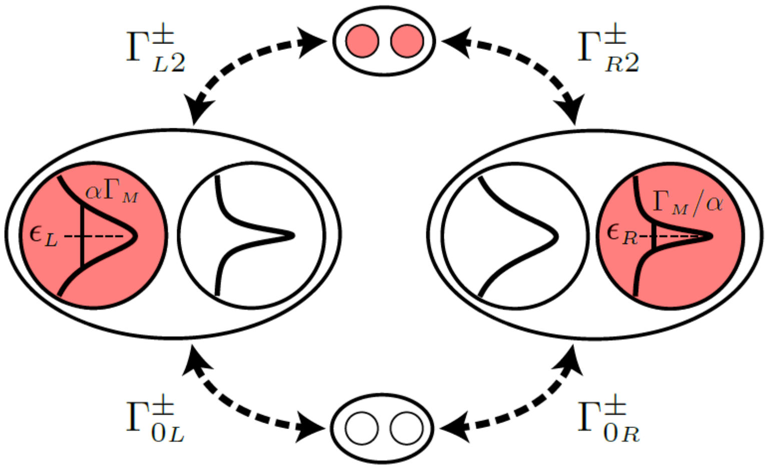

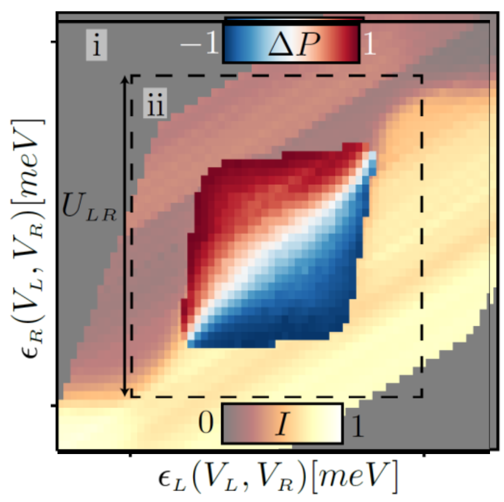

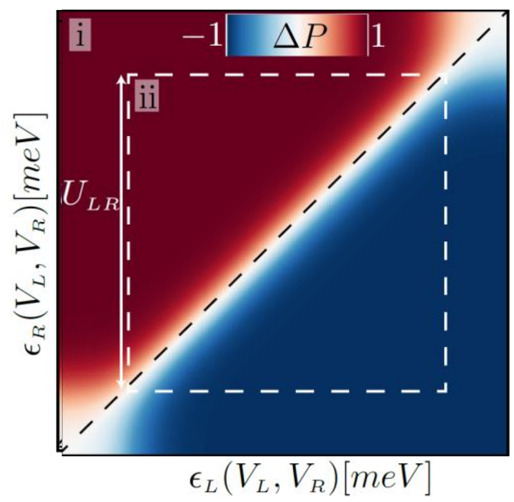

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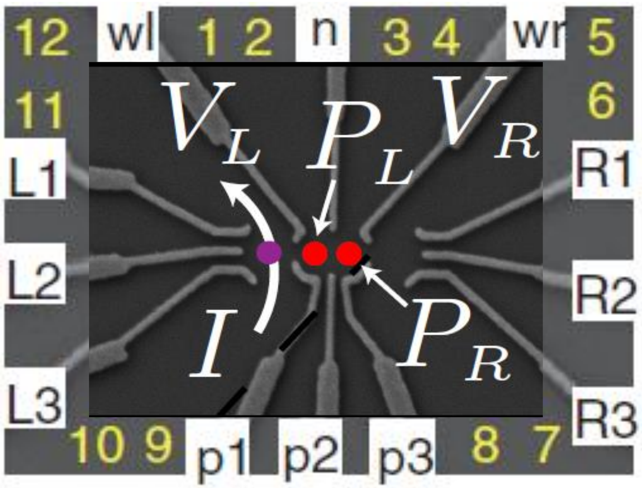
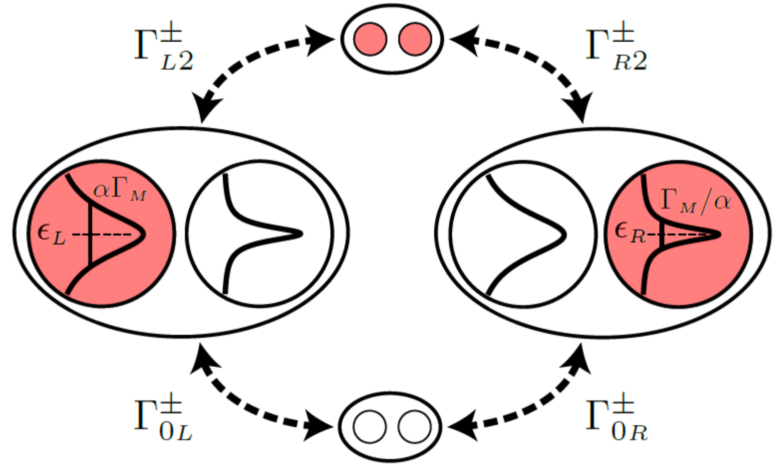
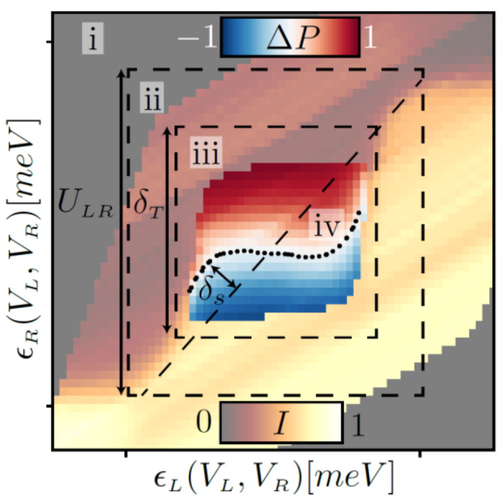
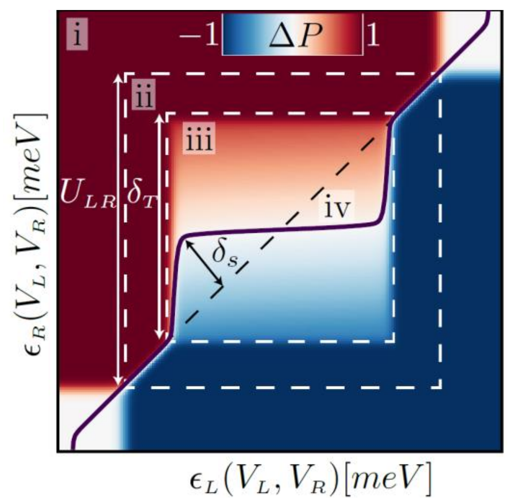








Credits

Quantum measurements

Yuval Gefen
Weizmann

Measurement backaction

Alessandro Romito
Lancaster

Assaf Carmi
Consumer physics, Inc.

Mesoscopic drag

Dominik Bischoff
Axpo group

Marius Eich
ETH

Clemens Rössler
Infenion

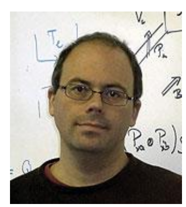
Thomas Ihn
ETH

Klaus Ensslin
ETH

Population switching

Michael S. Ferguson
ETH

Clemens Mueller
IBM Zurich



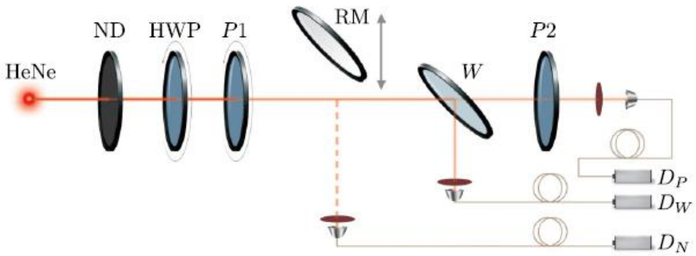
Bernd Braunecker
St. Andrews

Leon Camenzind
Basel

Dominik Zümbuhl
Basel

Summary

Quantum measurements



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OZ, A. Romito, D. J. Starling, G. A. Howland, C. J. Broadbent, J. C. Howell, and Y. Gefen, Phys. Rev. Lett. **110**, 170405 (2013);
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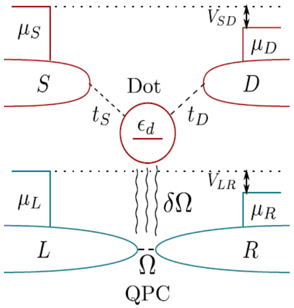
OZ, A. Romito, and Y. Gefen, Phys. Rev. B **93**, 115411 (2016);

Measurement backaction



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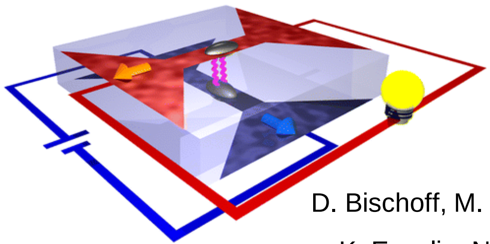
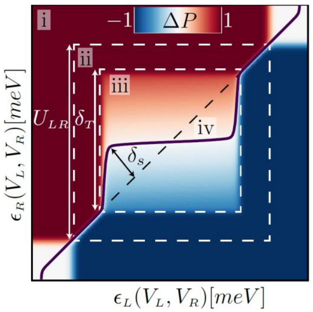
OZ and A. Romito; Phys. Rev. B 99, 165422 (2019)

Mesoscopic drag



D. Bischoff, M. Eich, OZ, C. Rössler, T. Ihn, K. Ensslin, Nano Lett. 15, 6003 (2015)

Population switching



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The QUEST continues

Thank you!