半導体中の飛行量子ビット
Flying qubits in semiconductors

Yasuhiro Tokura (NTT Basic Research Laboratories)

- Introduction -flying qubit-
- Topics
    - Effect of statistics
    - Entanglement generation and detection
    - Single electron emission and collection
    - Qubit entangler
- Conclusions

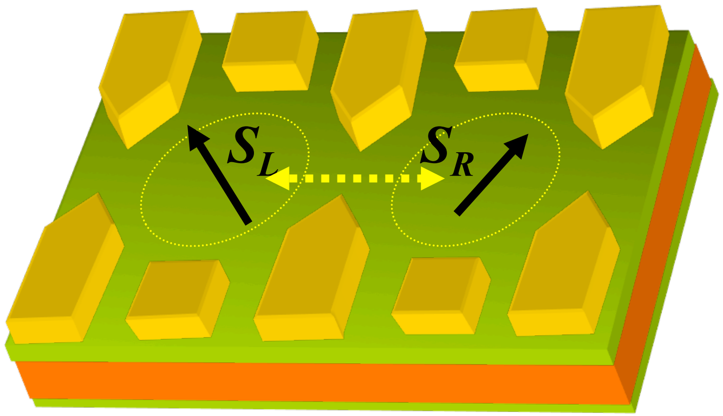
Self-introduction

- 相関理化学という分野で修士課程修了。
- 1985年　NTT入社　基礎研究所所属
- 半導体物性、メゾスコピック、ナノサイエンスに従事
- 1998年　オランダ・デルフト工科大　客員研究員
- 2004年　東京理科大　客員教授
- 2005年　量子光物性研究部　部長

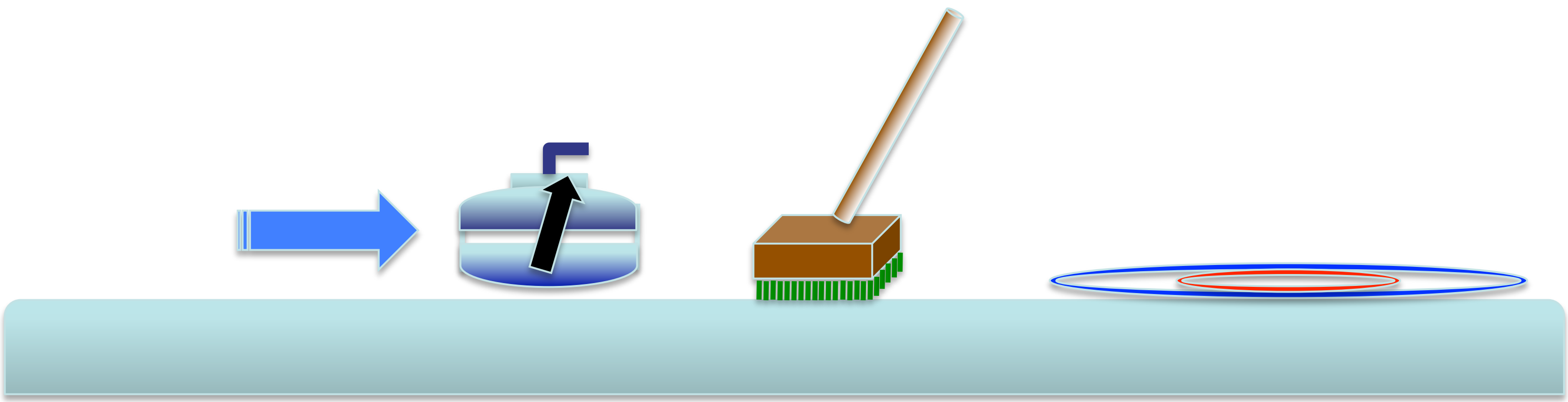
- *興味のある研究分野*
  - 量子輸送現象、非平衡現象、量子情報処理
- *趣味等*
  - *音楽、バドミントン、旅行*

Quantum Optical state control research group

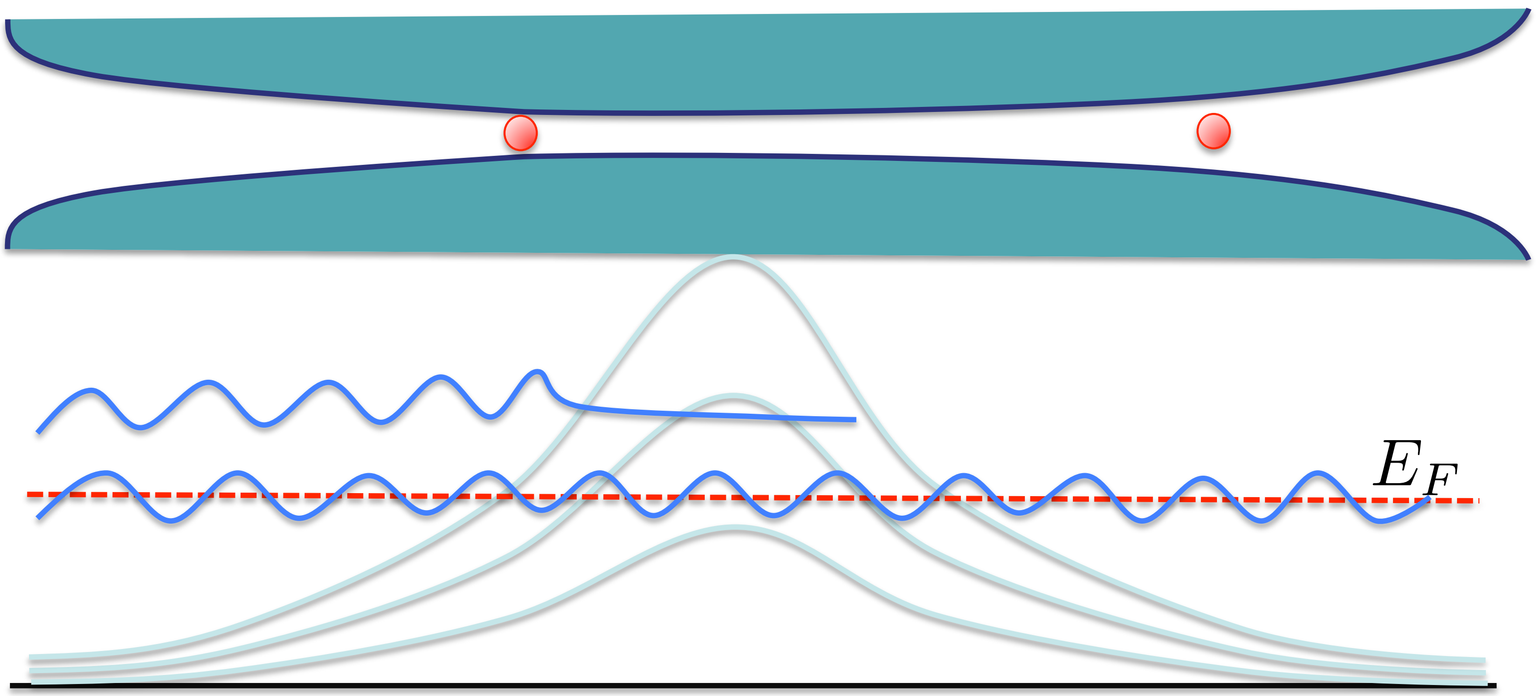
Static qubits and flying qubits



Loss and DiVincenzo PRA (98)



Quantum wire, quantum point contact



Conductance $G = \frac{2e^2}{h} \sum_n T_n$ *Transmission probability of mode n*

T_n

$T_n = 1$ *Noiseless mode*

Shot noise

For simplicity, only consider single mode, eV >> k_BT

Input occupation: $\langle n_{in} \rangle = 1$

Transmitted occupation: $\langle n_T \rangle = T$

Reflected occupation: $\langle n_R \rangle = R$

Conservation of electron #

$$n_{in} = n_T + n_R$$

$$\Rightarrow 1 = T + R$$

Electron cannot be divided

$$n_T = 0 \text{ or } 1$$

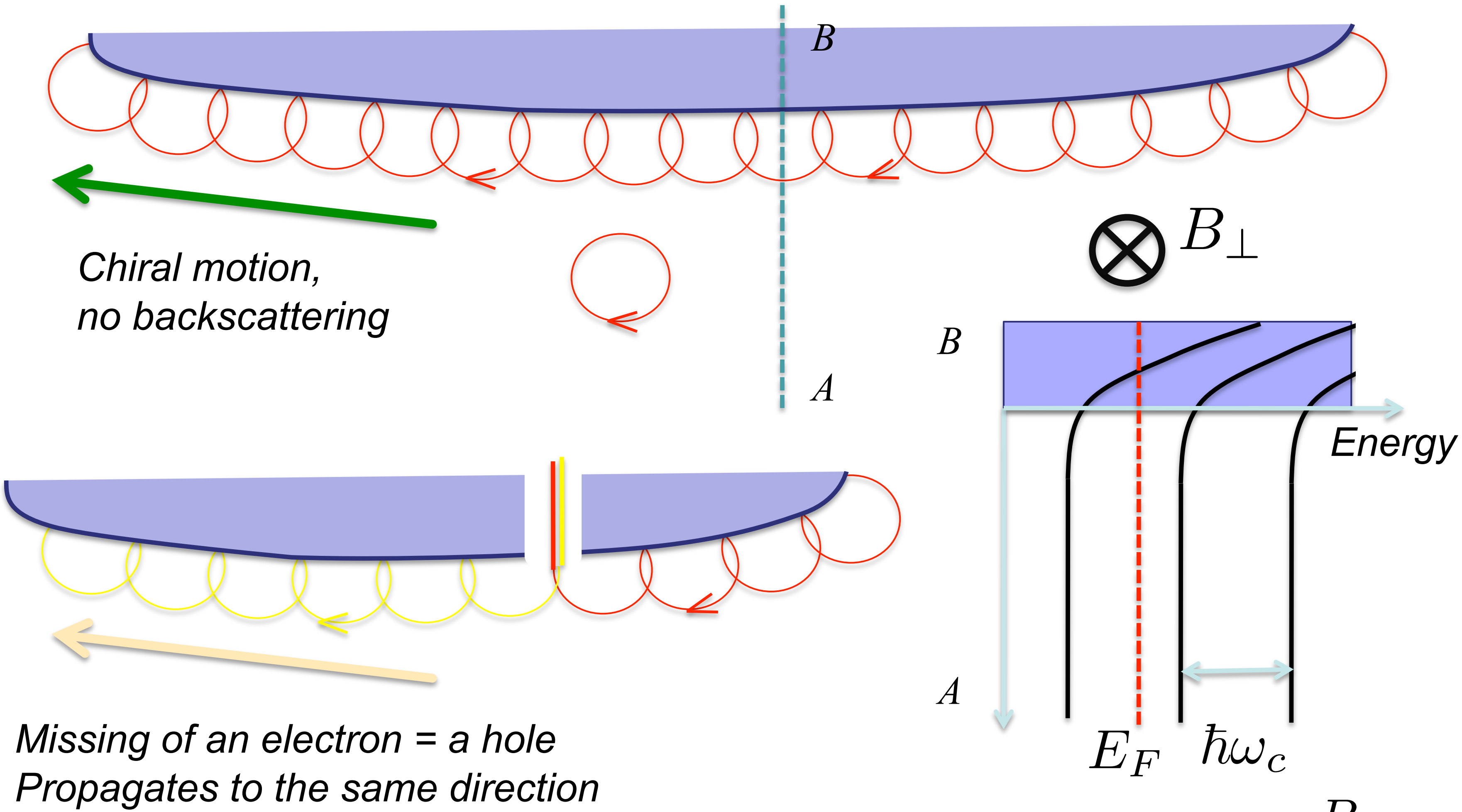
 # fluctuation from its average

$$\Delta n_T \equiv n_T - \langle n_T \rangle$$

Shot noise at zero frequency limit:

$$S_0 \propto \langle (\Delta n_T)^2 \rangle = \langle n_T^2 \rangle - \langle n_T \rangle^2$$
$$= \langle n_T \rangle - \langle n_T \rangle^2 = T(1-T)$$

An edge state

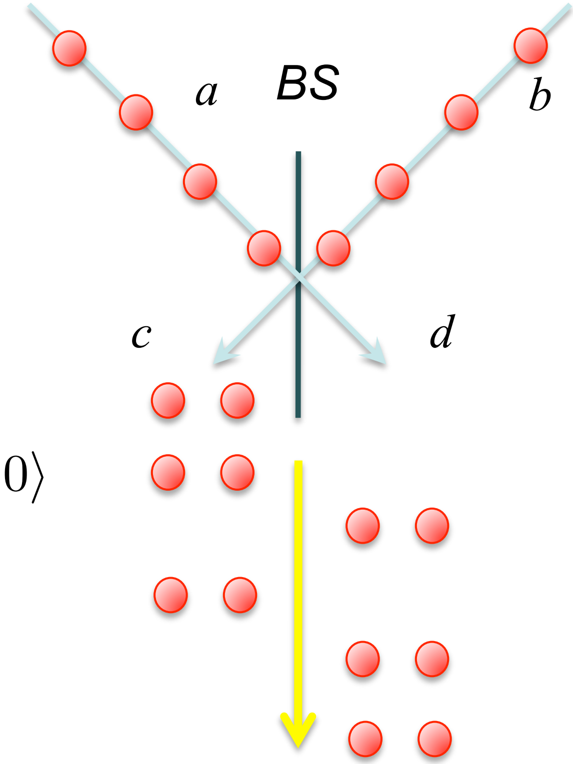


Cyclotron frequency $\omega_c = \dfrac{eB_\perp}{m^*}$

Photons - bunching

Ideal beam splitter (BS) unitary matrix (T=1/2):

$$\begin{pmatrix} a \\ b \end{pmatrix} \rightarrow \frac{1}{\sqrt{2}} \begin{pmatrix} 1 & 1 \\ 1 & -1 \end{pmatrix} \begin{pmatrix} c \\ d \end{pmatrix}$$



Collision experiment of photon (Boson)

$$\begin{aligned} a^\dagger b^\dagger |0\rangle &\rightarrow \frac{1}{\sqrt{2}}(c^\dagger + d^\dagger)\frac{1}{\sqrt{2}}(c^\dagger - d^\dagger)|0\rangle \\ &= \frac{1}{2}(c^{\dagger 2} - d^{\dagger 2})|0\rangle \end{aligned}$$

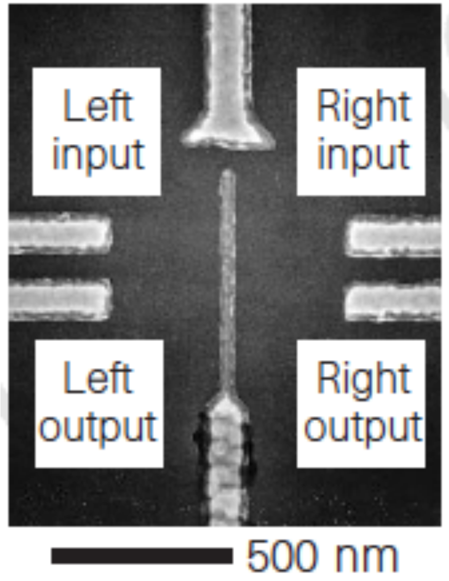
Shot noise in port c:

$$\begin{aligned} S_c &\propto \langle(\Delta n_c)^2\rangle \\ &= \langle n_c^2\rangle - (\langle n_c\rangle)^2 \\ &= 2 - 1 = 1 \end{aligned}$$

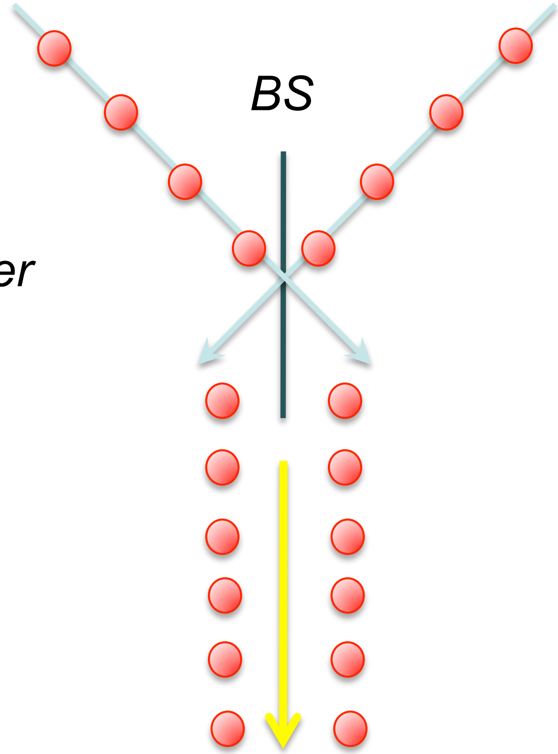
Classical limit (distinguishable particles)

$$\begin{aligned} \langle n_c\rangle &= 0 \times \frac{1}{4} + 1 \times \frac{1}{2} + 2 \times \frac{1}{4} = 1 \\ \langle n_c^2\rangle &= 0^2 \times \frac{1}{4} + 1^2 \times \frac{1}{2} + 2^2 \times \frac{1}{4} = \frac{3}{2} \\ S_c &\propto \frac{1}{2} \end{aligned}$$

Electrons - anti-bunching



Scanning electron micrograph of an electron beam splitter device



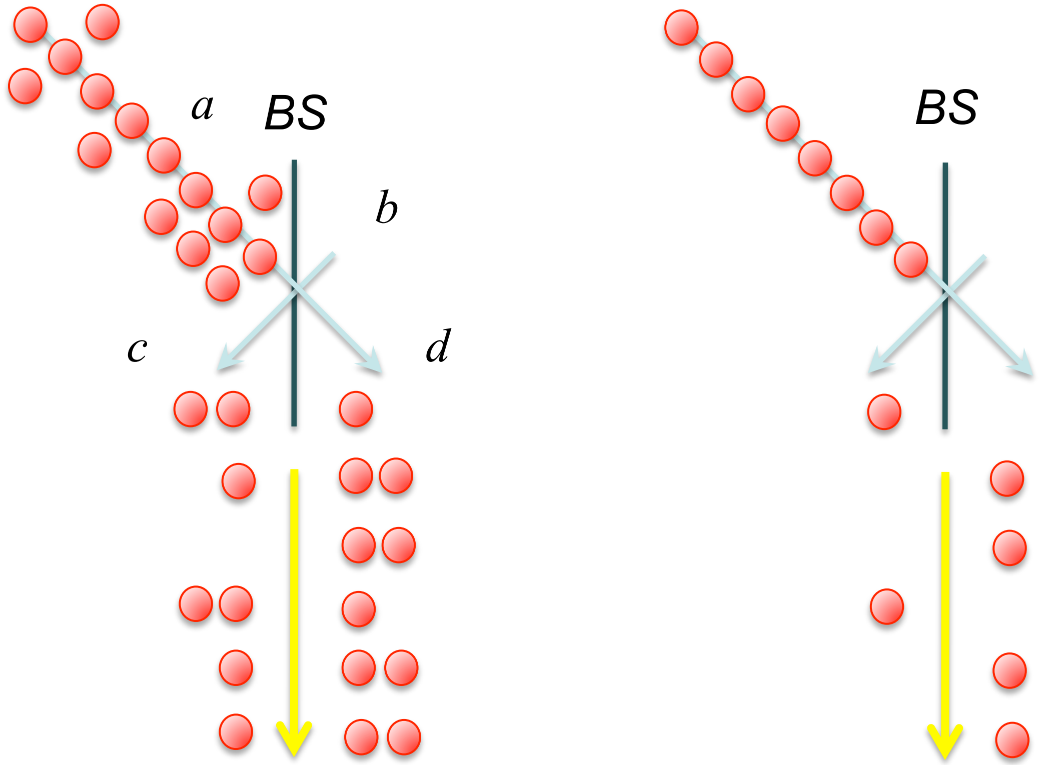
$$a^\dagger_\sigma b^\dagger_{\sigma'}|0\rangle \rightarrow \frac{1}{2}(c^\dagger_\sigma c^\dagger_{\sigma'} - d^\dagger_\sigma d^\dagger_{\sigma'} - c^\dagger_\sigma d^\dagger_{\sigma'} - c^\dagger_{\sigma'} d^\dagger_\sigma)|0\rangle$$

For $\sigma = \sigma', \quad c^\dagger_\sigma c^\dagger_{\sigma'} = 0$!

$$S_c \propto \langle(\sum_\sigma n_{c\sigma})^2\rangle - \langle\sum_\sigma n_{c\sigma}\rangle^2 = \frac{5}{4} - 1^2 = \frac{1}{4}$$

R.C. Liu, B. Odom, Y. Yamamoto, & S. Tarucha, Nature 391, 263 (1998).

Cross correlation in two ports



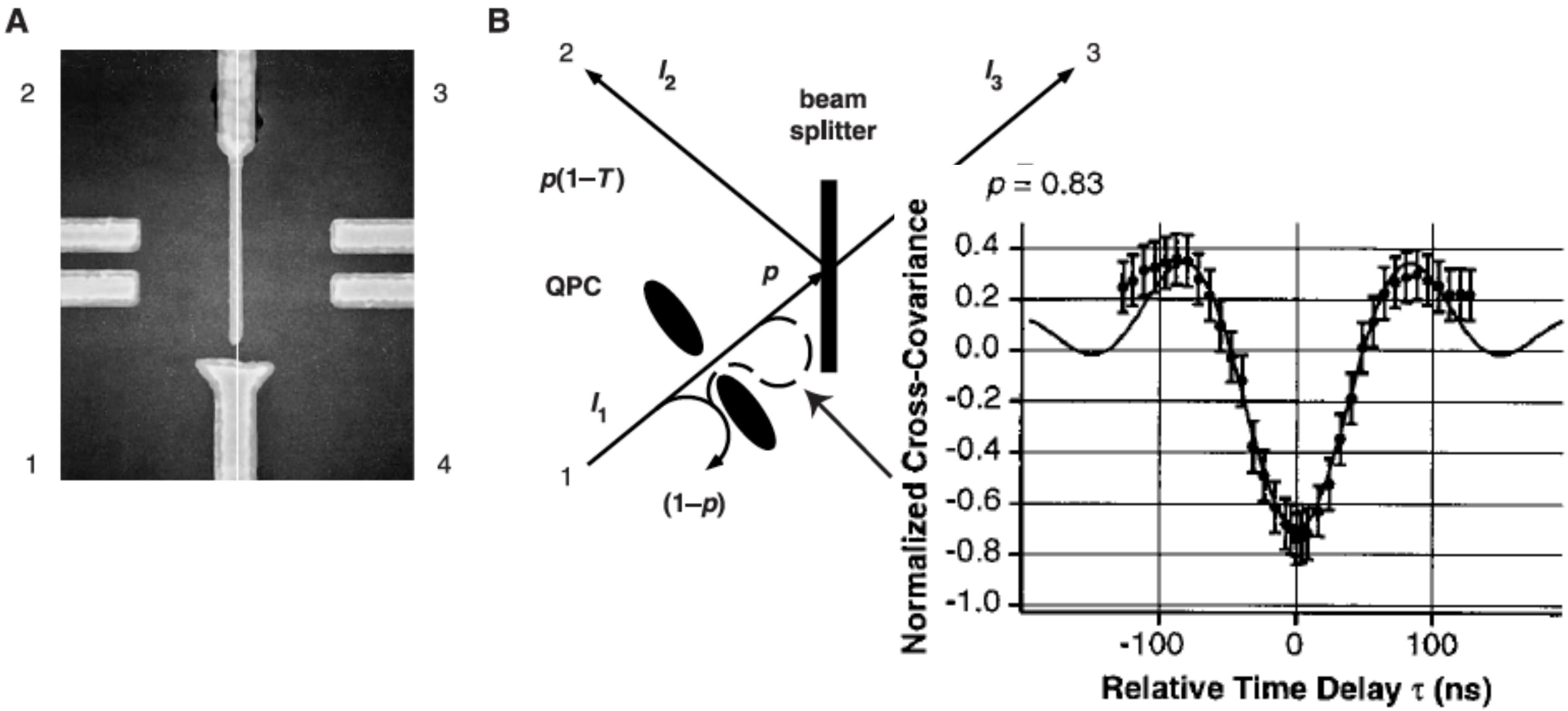
Statistics	Boson	Classical	Fermion
$S_{cross} = \langle \Delta I_c \Delta I_d \rangle$	Positive (for n_a>>1)	0	Negative

For spin polarized electrons:

$$S_{cross} \propto \langle (n_c - \frac{1}{2})(n_d - \frac{1}{2}) \rangle = \langle n_c n_d \rangle - \frac{1}{2^2} = -\frac{1}{4}$$

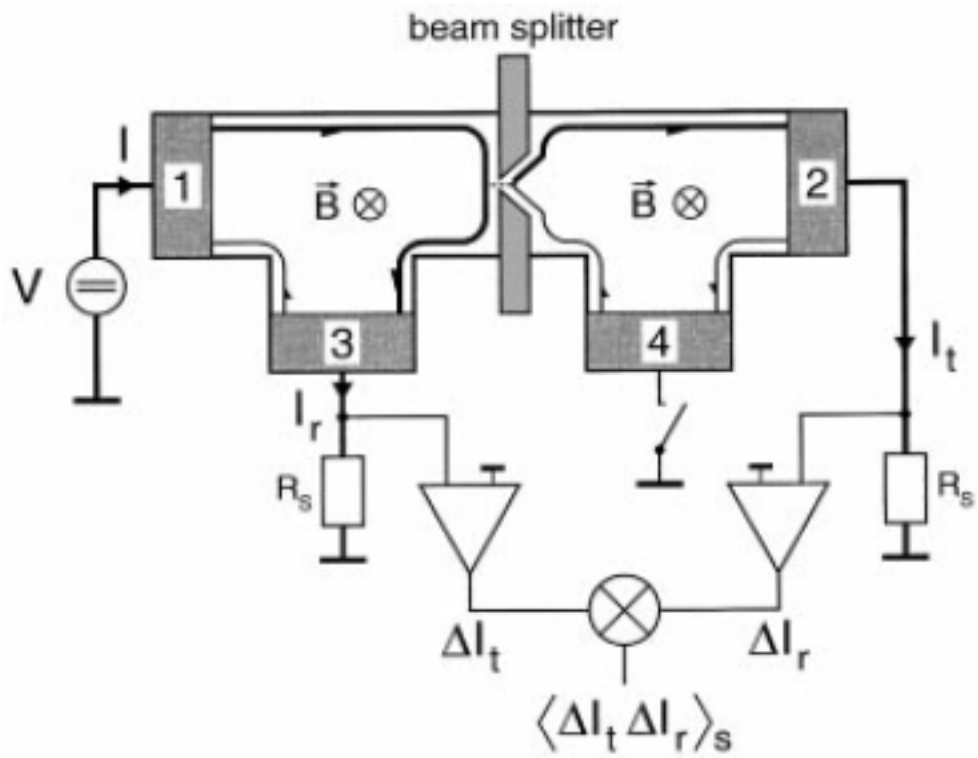
Cf. $S_c \propto \langle (n_c - \frac{1}{2})^2 \rangle = \langle n_c^2 \rangle - \frac{1}{2^2} = \frac{1}{4}$

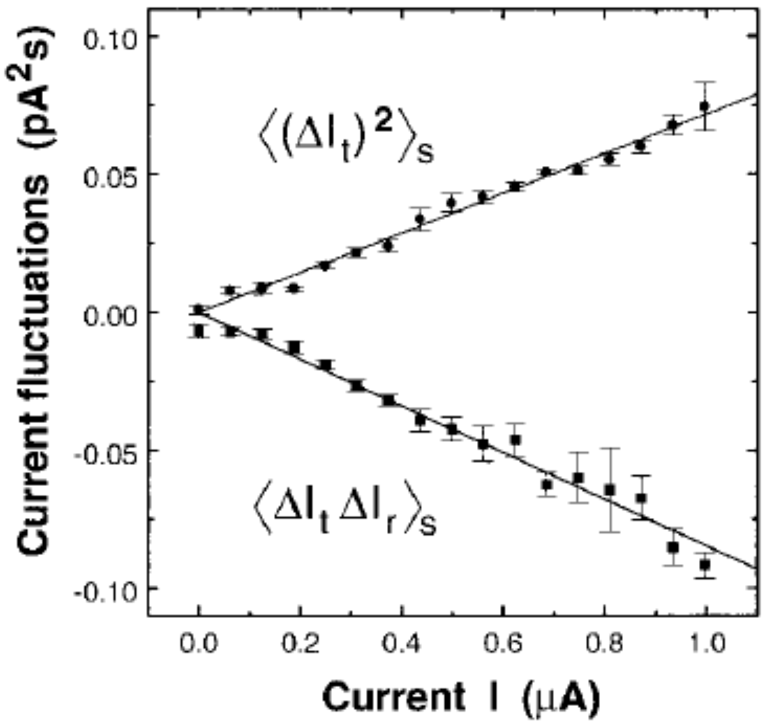
Hanbury Brown and Twiss



W. D. Oliver, J. Kim, R. C. Liu, Y. Yamamoto, Science 284, 296 (1999).

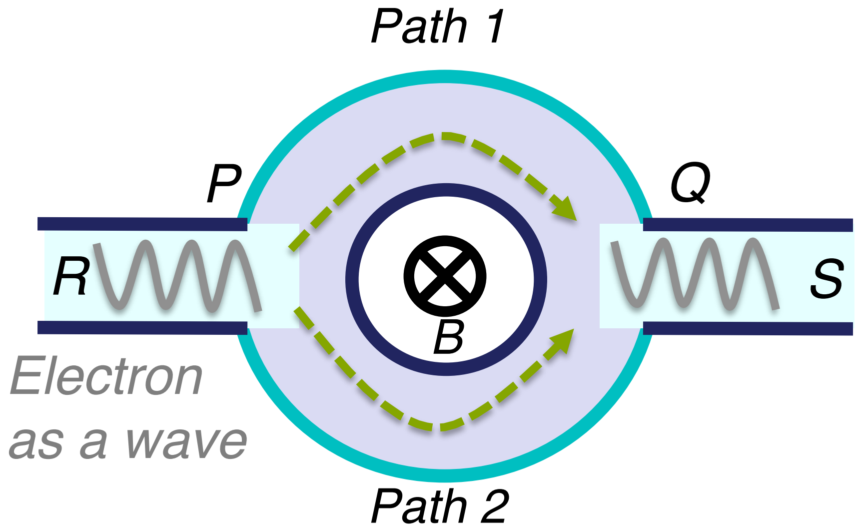
HBT experiment with edge states





M. Henny, et al. Science 284, 296 (1999).

Quantum coherence: AB interference



Two-terminal Aharonov-Bohm ring

Onsager's law

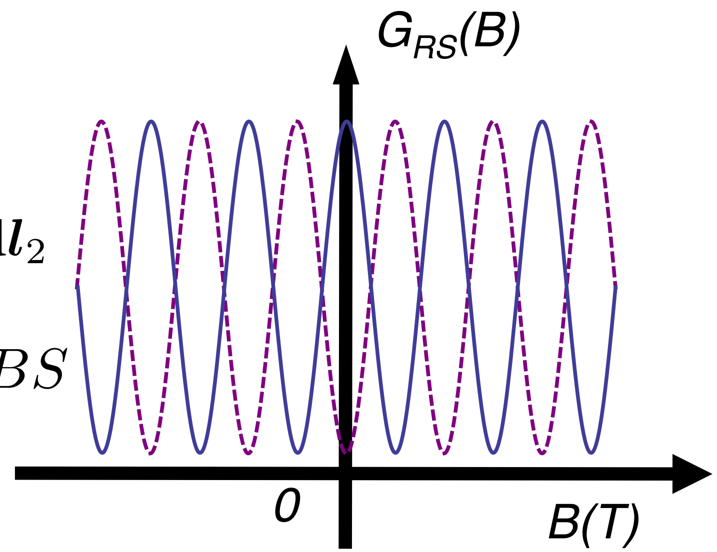
(G_{RS} : linear conductance from P to Q)

$G_{RS}(B) = G_{SR}(B)$: Current conservation

$G_{RS}(B) = G_{SR}(-B)$: Time reversal symmetry

→ *$G_{RS}(B) = G_{RS}(-B)$*

$$\varphi_1 - \varphi_2 = \int_P^Q \left(\boldsymbol{k} - \frac{e}{\hbar}\boldsymbol{A}\right)\cdot \mathrm{d}\boldsymbol{l}_1 - \int_P^Q \left(\boldsymbol{k} - \frac{e}{\hbar}\boldsymbol{A}\right)\cdot \mathrm{d}\boldsymbol{l}_2$$
$$= \oint \boldsymbol{k}\cdot \mathrm{d}\boldsymbol{l} - \frac{e}{\hbar}\oint \boldsymbol{A}\cdot \mathrm{d}\boldsymbol{l} = \oint \boldsymbol{k}\cdot \mathrm{d}\boldsymbol{l} - \frac{e}{\hbar}BS$$



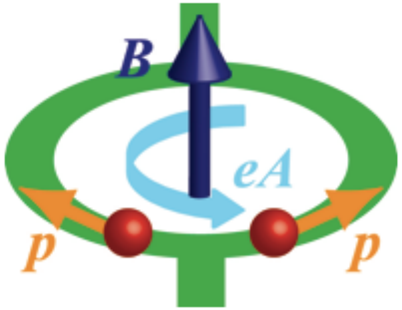
T. Hatano, T. Kubo, Y. Tokura, S. Amaha, S. Teraoka, and S. Tarucha, Phys. Rev. Lett. 106, 076801 (2011).

Geometric phases

Aharonov-Bohm (AB) phase

$$P = -i\hbar\nabla + eA$$ ← Vector potential

$$\phi_{AB} = \frac{1}{\hbar}\oint eA\cdot dl = 2\pi\frac{\Phi}{\Phi_0}\ ,\ \Phi_0 = \frac{h}{e}$$



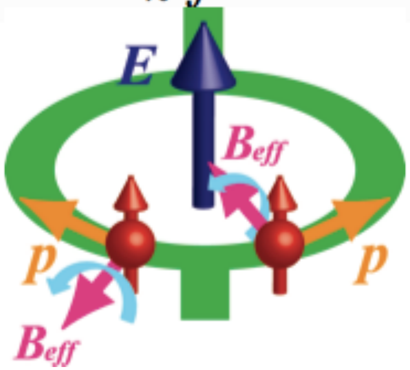
Y. Aharonov, 2010

Aharonov-Casher(AC) phase

Effective spin vector potential →

$$P = -i\hbar\nabla + eA_{SO}\ ,\ A_{SO} = \frac{1}{2}\mu\sigma\times E$$

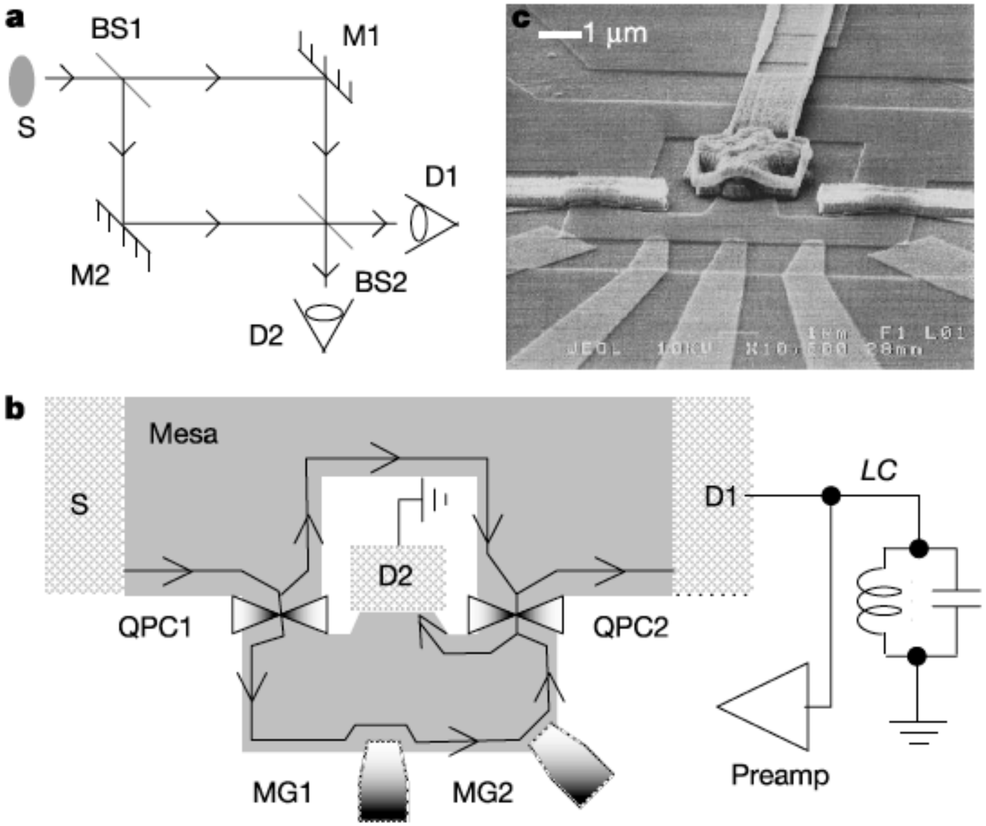
$$\phi_{AC} = \frac{1}{\hbar}\oint eA_{SO}\cdot dl = \frac{2\pi r m^{*}\alpha_{SO}}{\hbar^2}$$



A. Casher, 2010

AB interferometer with edge states

Y. Ji, et al., Nature 422, 415 (2003).



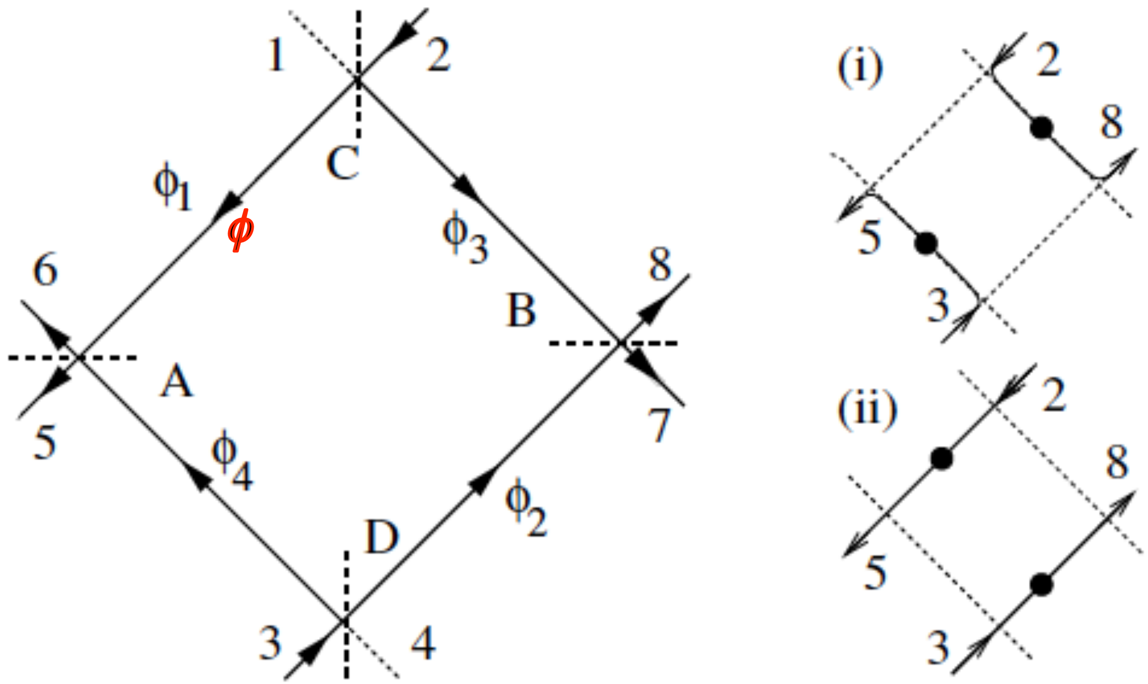
Two half mirrors are made of T=1/2 QPCs. Air-bridge technology is essential.

Phase coherence length is estimated from the visibility of the AB oscillations

L_ϕ~24 µm @ 20 mK

P. Roulleau, et al., Phys. Rev. Lett. 100, 126802 (2008).

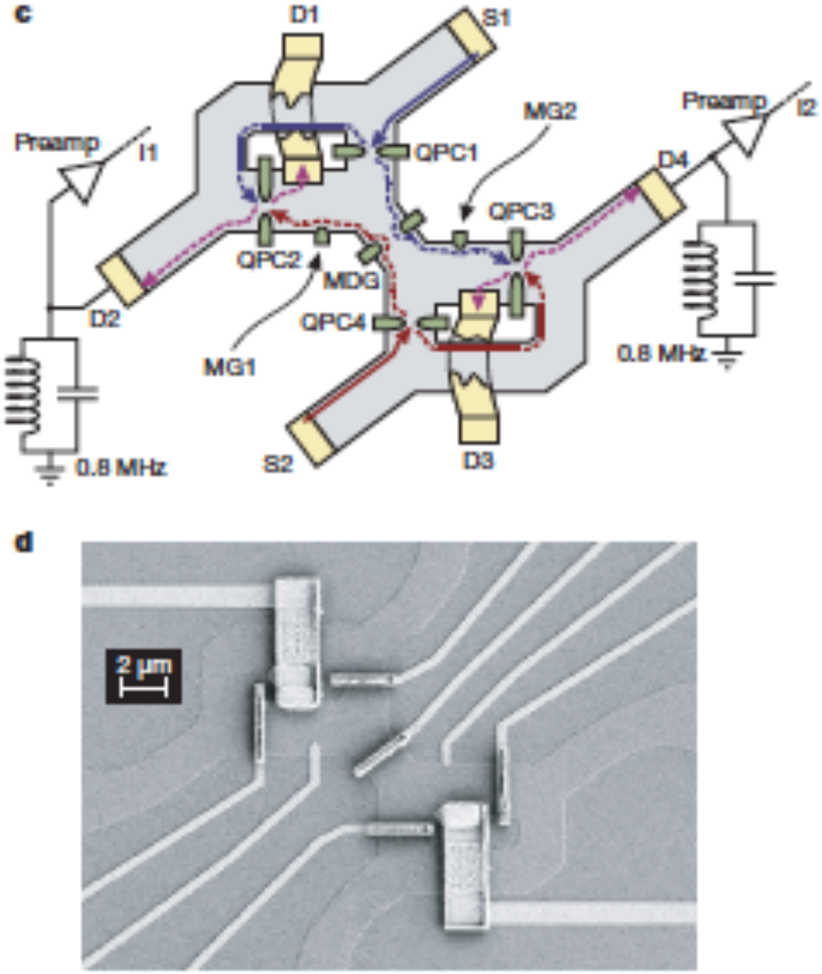
Two-electron interference



Single electron current is independent of the flux ϕ, but current correlations are dependent on ϕ.

P. Samuelsson, E. V. Sukhorukov, and M. Buttiker, Phys. Rev. Lett. 92, 026805 (2004).

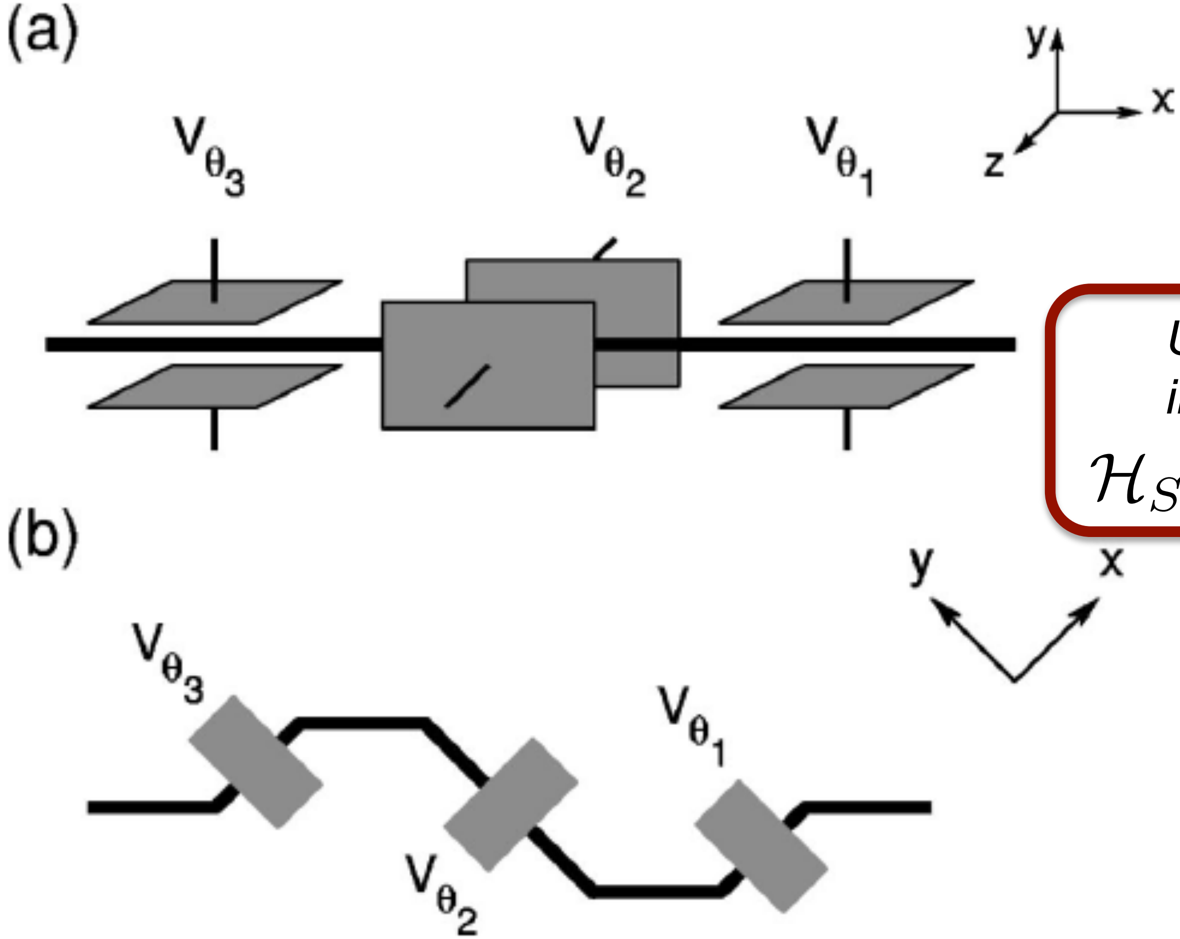
HBT experiments II



Experimental confirmation of two-electron interference.

I. Neder, et al., Nature 448, 333 (2007).

Alternative SU(2) control of spin qubit

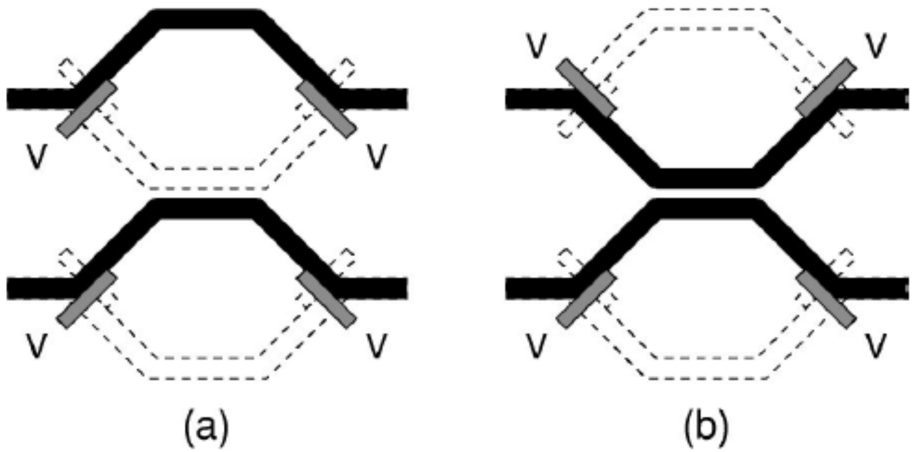


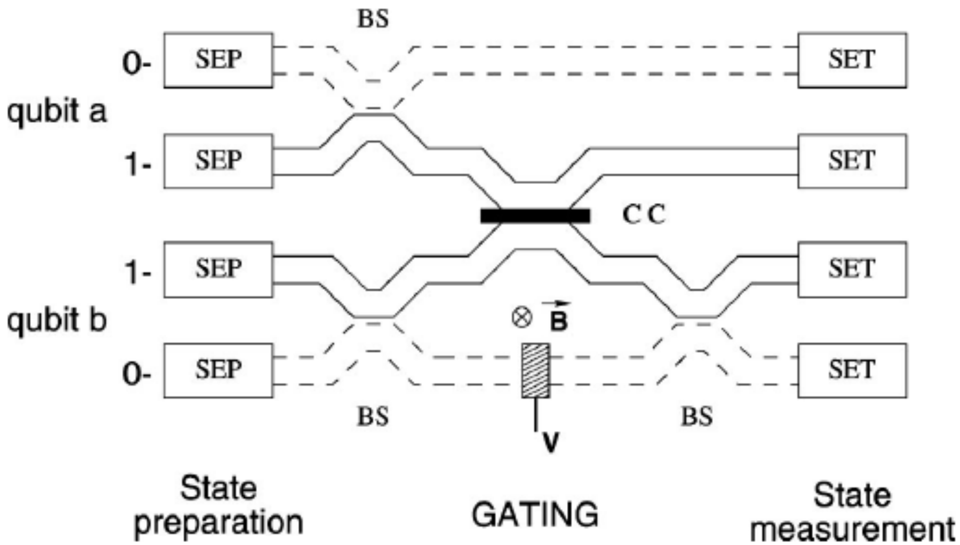
Using Rashba spin-orbit interaction

$$\mathcal{H}_{SOI} \quad = \quad \lambda\vec{p}\times\vec{E}\cdot\sigma$$

A. E. Popescu and R. Ionicioiu, Phys. Rev. B 69, 245422 (2004).

Two qubit interaction and C-NOT



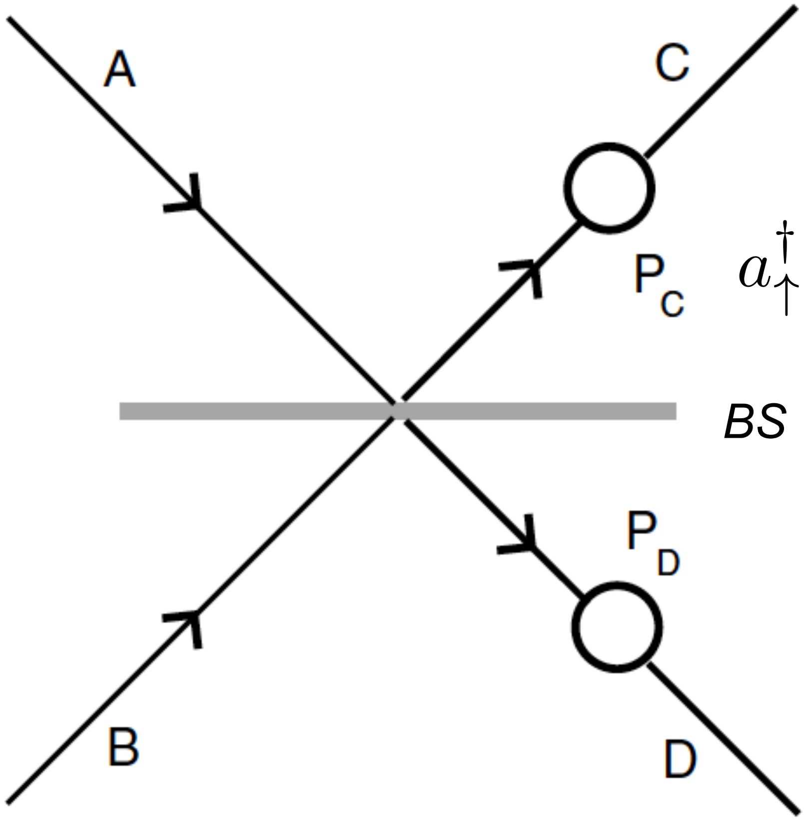


Using exchange interaction

$$\mathcal{H}_{ex} = J\vec{S}_1 \cdot \vec{S}_2$$

R. Ionicioiu, P. Zanardi, and F. Rossi, Phys. Rev. A 63 050101(R) (2001).

Entanglement gen. with post selection



Beam splitter

$$a_{\uparrow}^{\dagger}b_{\downarrow}^{\dagger}|0\rangle \rightarrow \frac{1}{2}(c_{\uparrow}^{\dagger}c_{\downarrow}^{\dagger} - d_{\uparrow}^{\dagger}d_{\downarrow}^{\dagger} - c_{\uparrow}^{\dagger}d_{\downarrow}^{\dagger} - c_{\downarrow}^{\dagger}d_{\uparrow}^{\dagger})|0\rangle$$

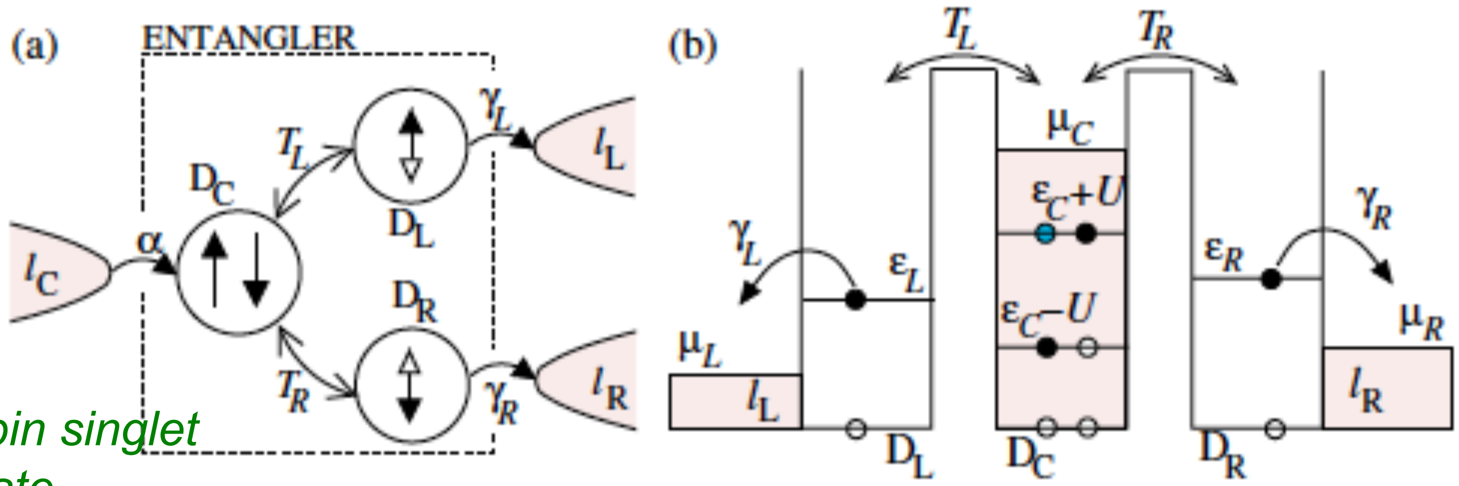
$$\rightarrow -\frac{1}{\sqrt{2}}|T_0\rangle$$

Post selection (only singlet electrons in each path)

Spin triplet state

S. Bose and D. Home, Phys. Rev. Lett. 88, 050401 (2002).

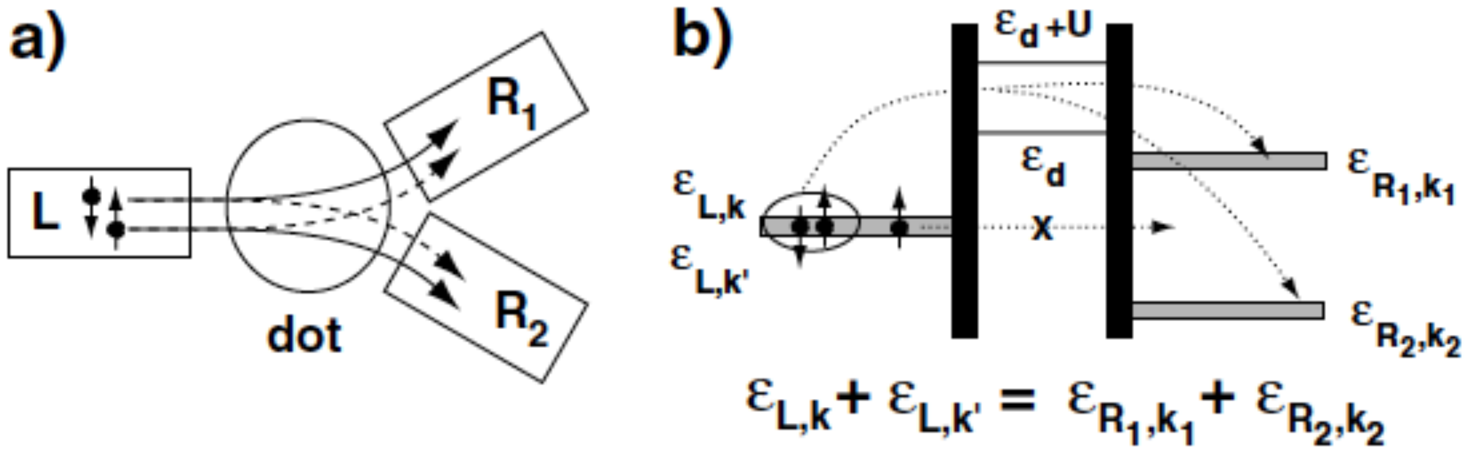
Entangle source of triple quantum dots



Spin singlet state

D. S. Saraga and D. Loss, Phys. Rev. Lett. 90, 166803 (2003).

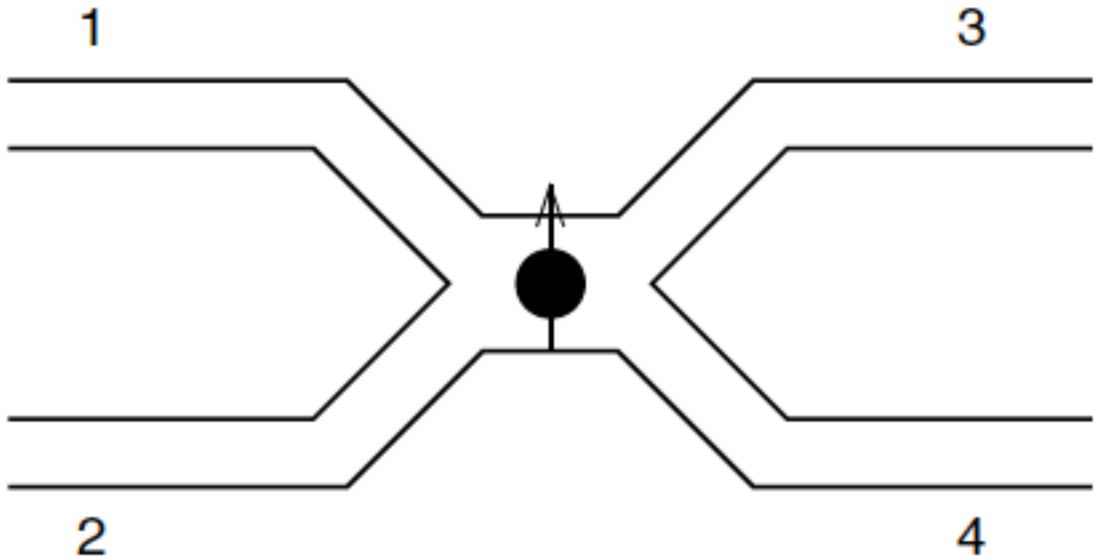
Entangler with QD and narrow-width chs.



The channels' band width should be narrow enough.

W. D. Oliver, F. Yamaguchi, and Y. Yamamoto, Phys. Rev. Lett. 88, 037901 (2002).

Robust entangler with localized spin



s-d T matrix
in Born approx.

$$\mathcal{T} = J\sum_{l=1,2}\sum_{k,k'}\{S^+a^\dagger_{lk\downarrow}a_{lk'\uparrow} + S^-a^\dagger_{lk\uparrow}a_{lk'\downarrow} + S^z[a^\dagger_{lk\uparrow}a_{lk'\uparrow} - a^\dagger_{lk\downarrow}a_{lk'\downarrow}]\}$$

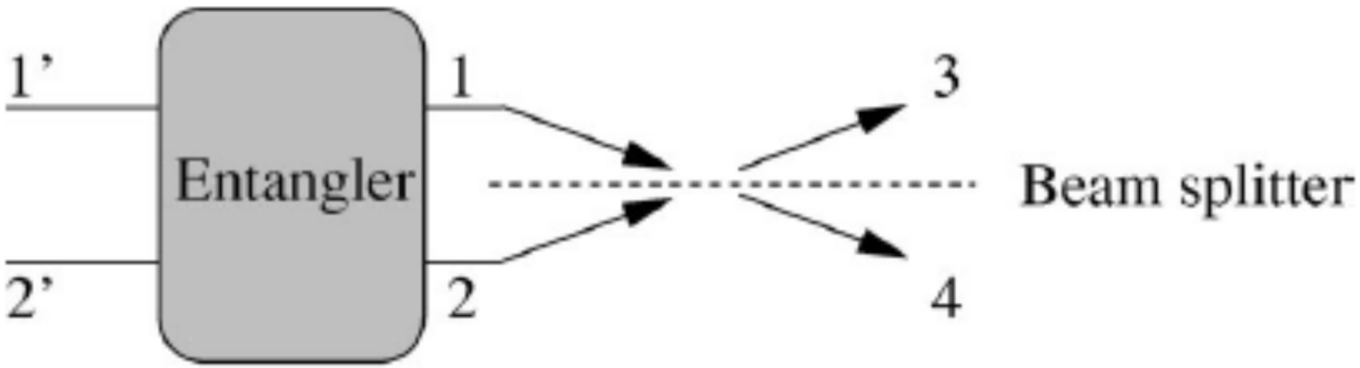
$$a^\dagger_{1k_F\uparrow}a^\dagger_{2k_F\uparrow}|0\rangle \otimes |\downarrow\rangle_S$$

$$\rightarrow -2\sqrt{2}i\pi J\rho|T_0\rangle \otimes |\uparrow\rangle_S$$

ρ: density of states

A. T. Costa, Jr. and S. Bose, Phys. Rev. Lett. 87, 277901 (2001).

Verification of entanglement

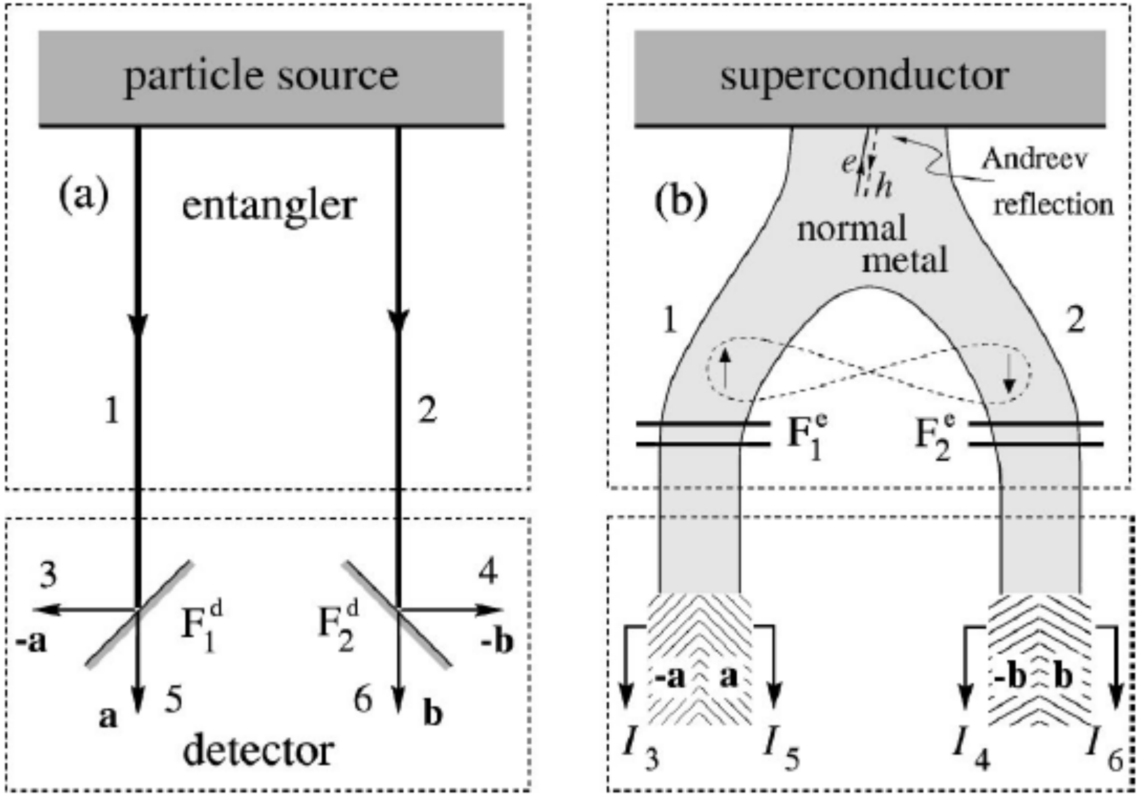


$$\frac{1}{\sqrt{2}}(a_\uparrow^\dagger b_\downarrow^\dagger + a_\downarrow^\dagger b_\uparrow^\dagger)|0\rangle \rightarrow -\frac{1}{\sqrt{2}}(c_\uparrow^\dagger d_\downarrow^\dagger + c_\downarrow^\dagger d_\uparrow^\dagger)|0\rangle$$

$$S_{cross} \quad = \quad \langle \Delta I_3 \Delta I_4 \rangle > 0$$

G. Burkard, D. Loss, and E. V. Sukhorukov,
Phys. Rev. B 61, R16303 (2000).

Bell inequality analysis



Bell's inequality: $E(\boldsymbol{a},\boldsymbol{b}) + E(\boldsymbol{a}',\boldsymbol{b}) + E(\boldsymbol{a},\boldsymbol{b}') - E(\boldsymbol{a}',\boldsymbol{b}') < 2$

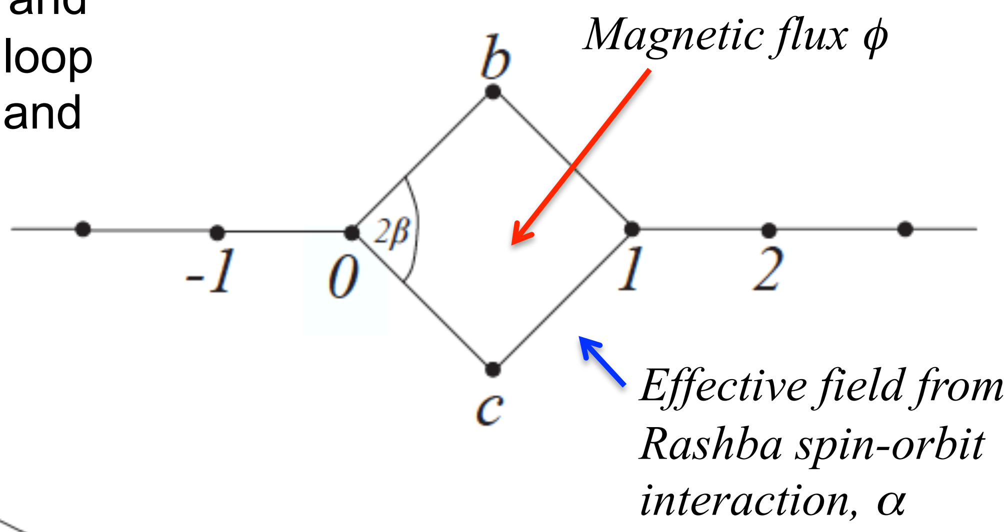
$$E(\boldsymbol{a},\boldsymbol{b}) = \frac{S_{56} + S_{34} - S_{36} - S_{45}}{S_{56} + S_{34} + S_{36} + S_{45}}$$

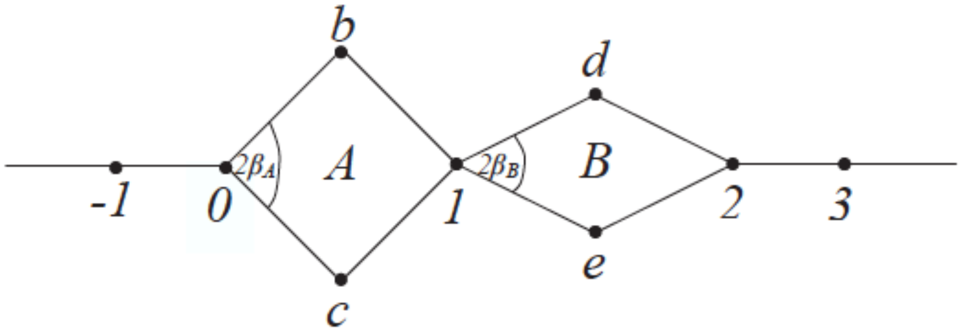
Need spin analyzer/filter.

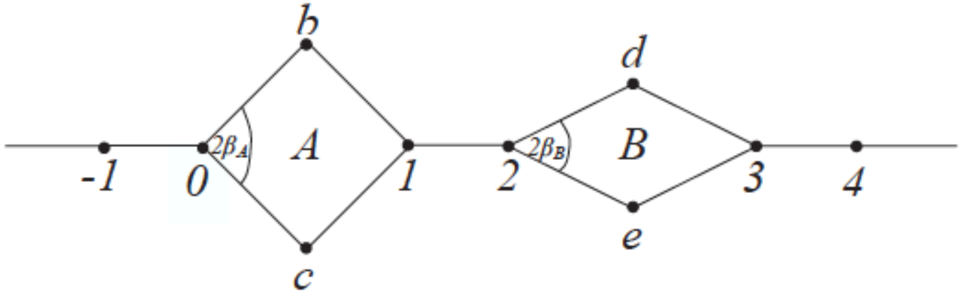
S. Kawabata, J. Phys. Soc. Jpn 70, 1210 (2001). N. M. Chtchelkatchev, et al., Phys. Rev. B 66, 161320(R) (2002).

Perfect spin filter

Controlled spin-orbit interaction and magnetic flux in a diamond-like loop
- works as an emitter, rotator, and detector of flying spin qubits



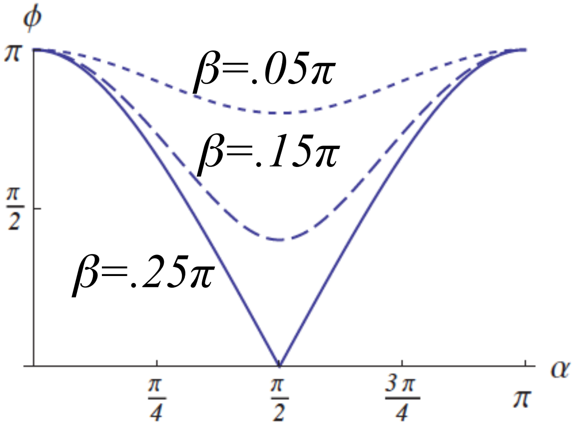




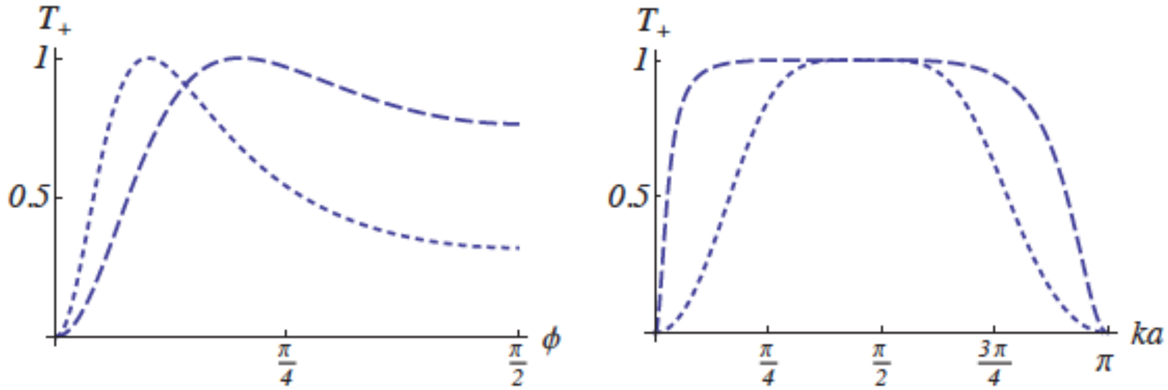
Coupled diamonds offer more flexible, and ideal realization of Datta-Das spin transistor

A. Aharony, Y. Tokura, Guy Z. Cohen, O. Entin-Wohlman, and S. Katsumoto, Phys. Rev. B 84, 035323 (2011).

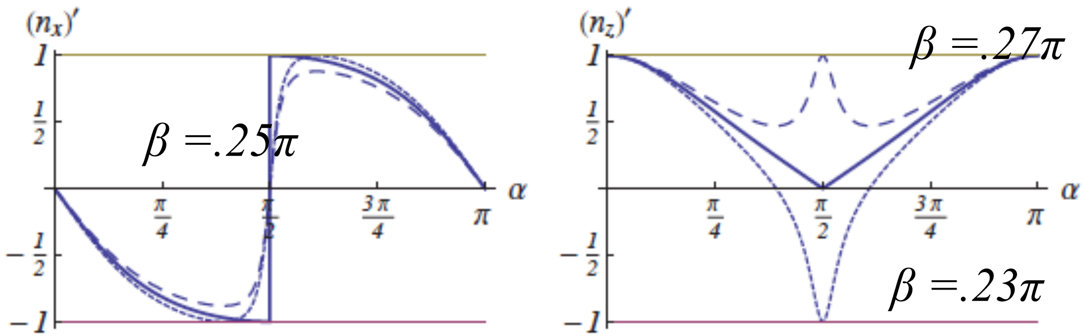
Model calculations



Condition of full fibetween ltering the AB flux ϕ and the Rashba SOI strength α

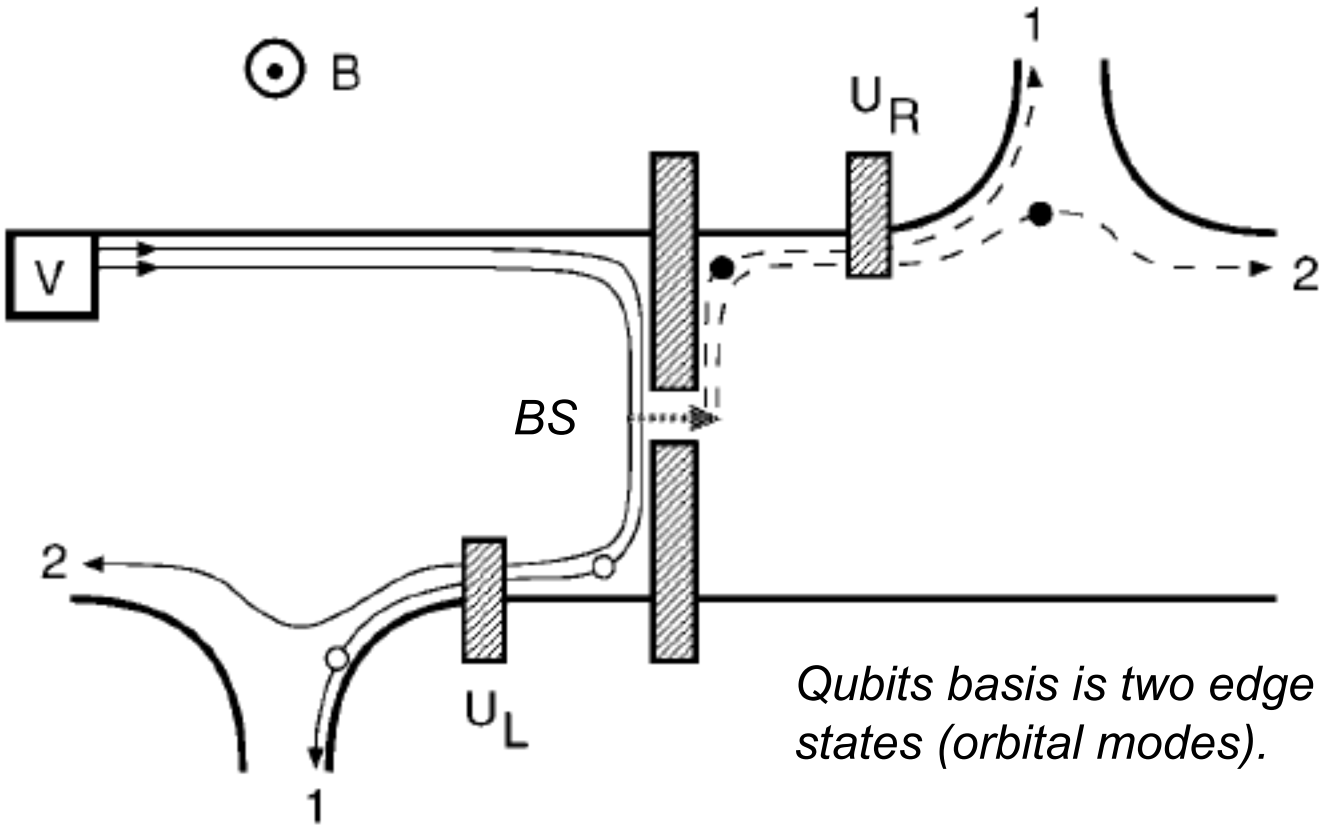


Transmission of the polarized electrons, T+. LHS: in the band center (ε = 0) versus the AB flux ϕ. RHS: versus ka.



Outgoing spin components as a function of the Rashba SOI strength α. The lower panel shows the actual spin directions in the xz-plane for β =π/4, as a increases from zero to π (left to right).

Electron-hole entanglement



Qubits basis is two edge states (orbital modes).

U_R and U_L are used for the analysis of Bell-inequality

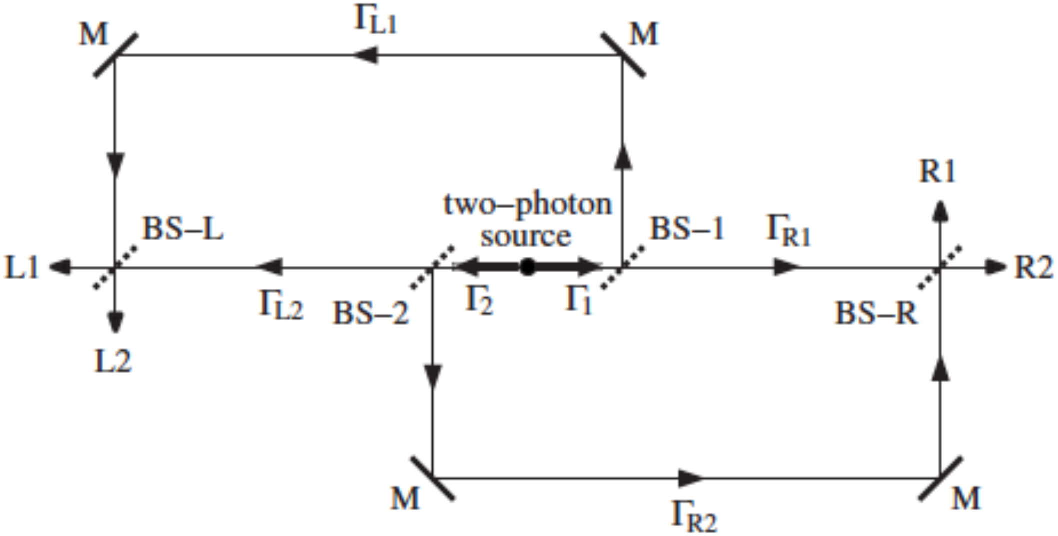
$$\varepsilon = E(U_L, U_R) + E(U'_L, U_R) + E(U_L, U'_R) - E(U'_L, U'_R),$$

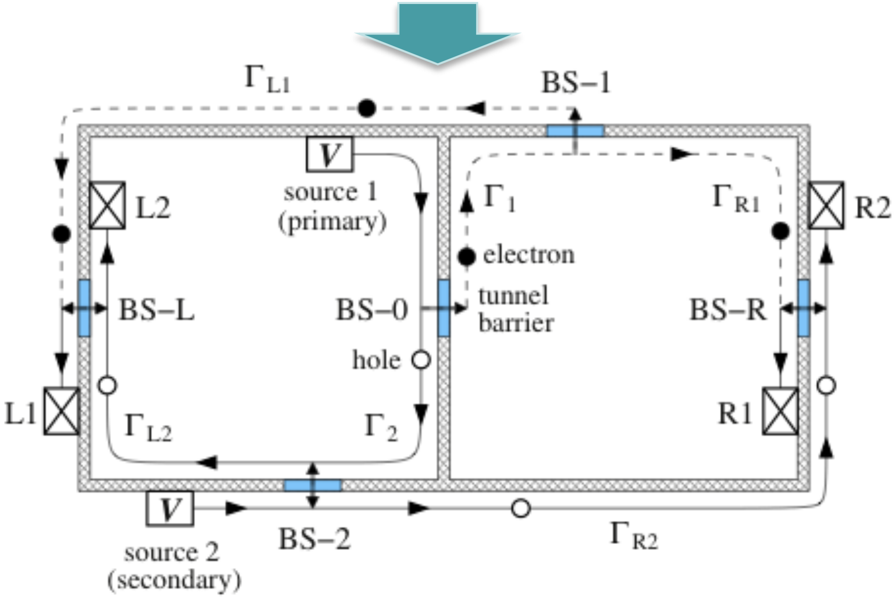
$$\varepsilon_{max} = 2\sqrt{1 + C^2}$$

C: concurrence

C. W. J. Beenakker, C. Emary, M. Kindermann, and J. L.van Velsen, Phys. Rev. Lett. 91, 147901 (2003).

Electron-hole interferometer

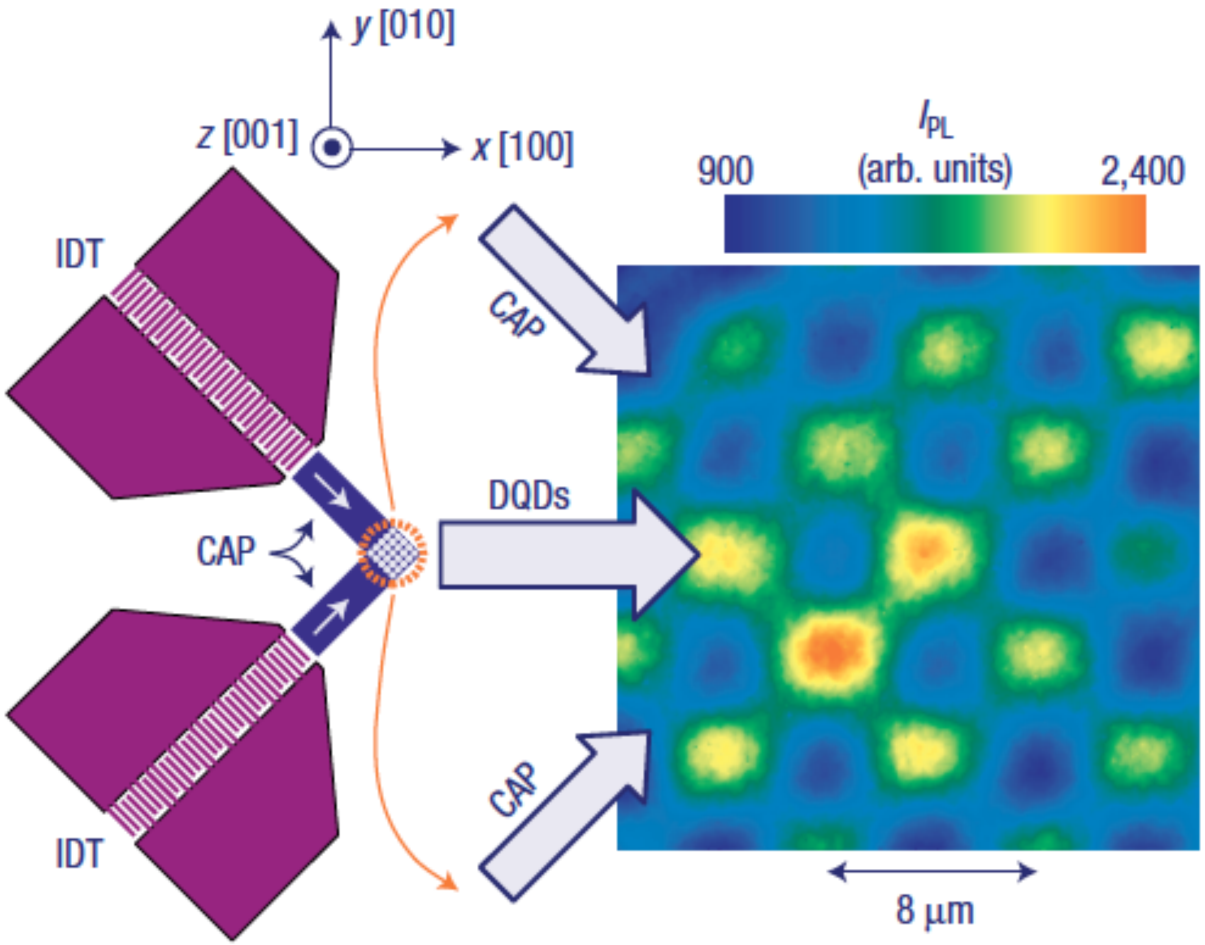




Proposed device using single edge state

D. Frustaglia and A. Cabello, Phys. Rev. B 80, 201312R (2009).

Encapsulated flying qubits



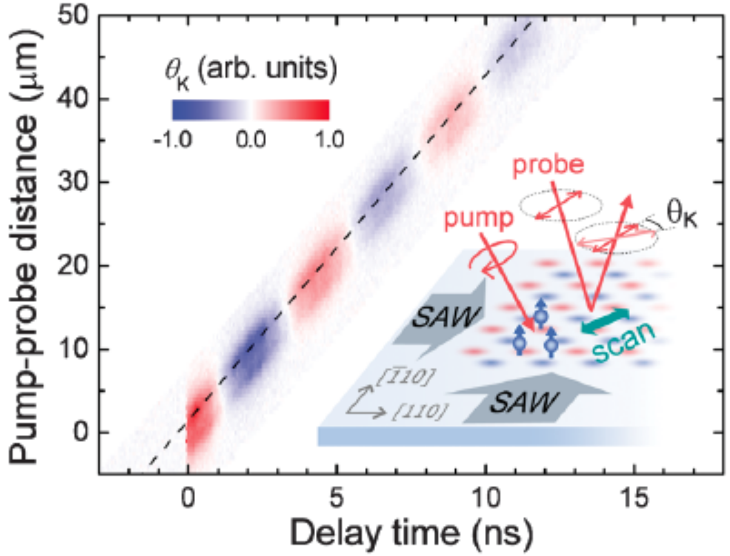
IDT: interdigitated transduser
CAP: coherent acoustic phonon

Stroboscopic photoluminescence image

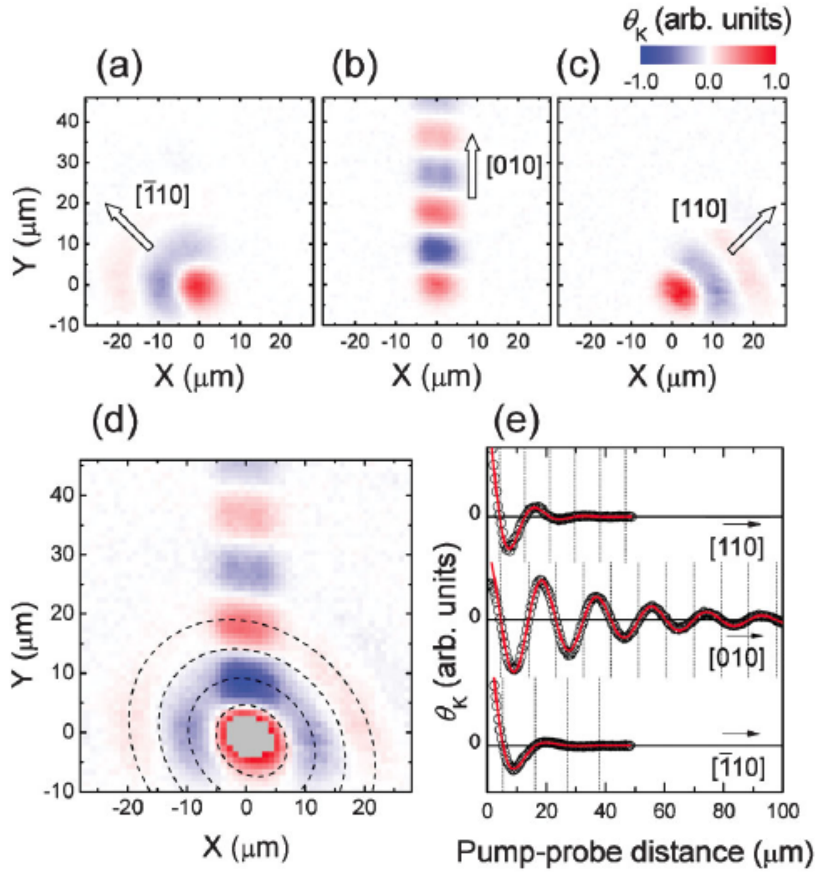
Piezo-electric material, like GaAs, forms moving (dynamic) quantum dots (DQDs) by the surface acoustic waves (SAWs).

J. A. H. Stotz, R. Hey, P. V. Santos and K. H. Ploog, Nature Materials 41, 585 (2005).

Spin rotates



Spatiotemporal evolution of the magneto-optic Kerr Rotation signal

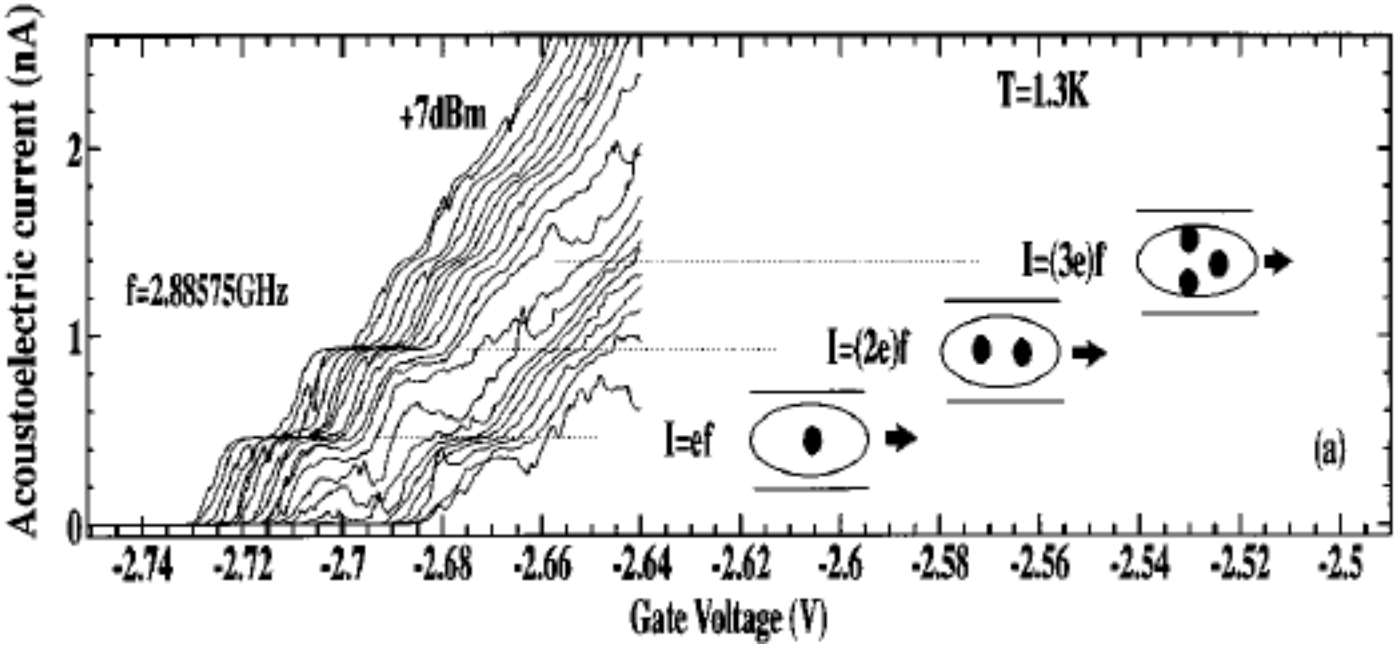


The spin rotation is induced from the internal magnetic field originating from the spin-orbit interactions.

Spin coherence length > 100 μm!

H. Sanada, et al., Phys. Rev. Lett. 106, 216602 (2011).

Quantized current by SAW

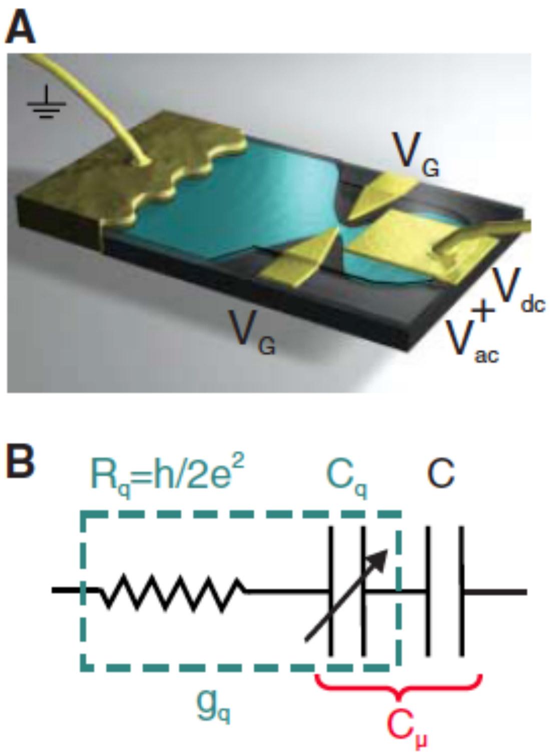


SAW can accommodate a few electrons per period.

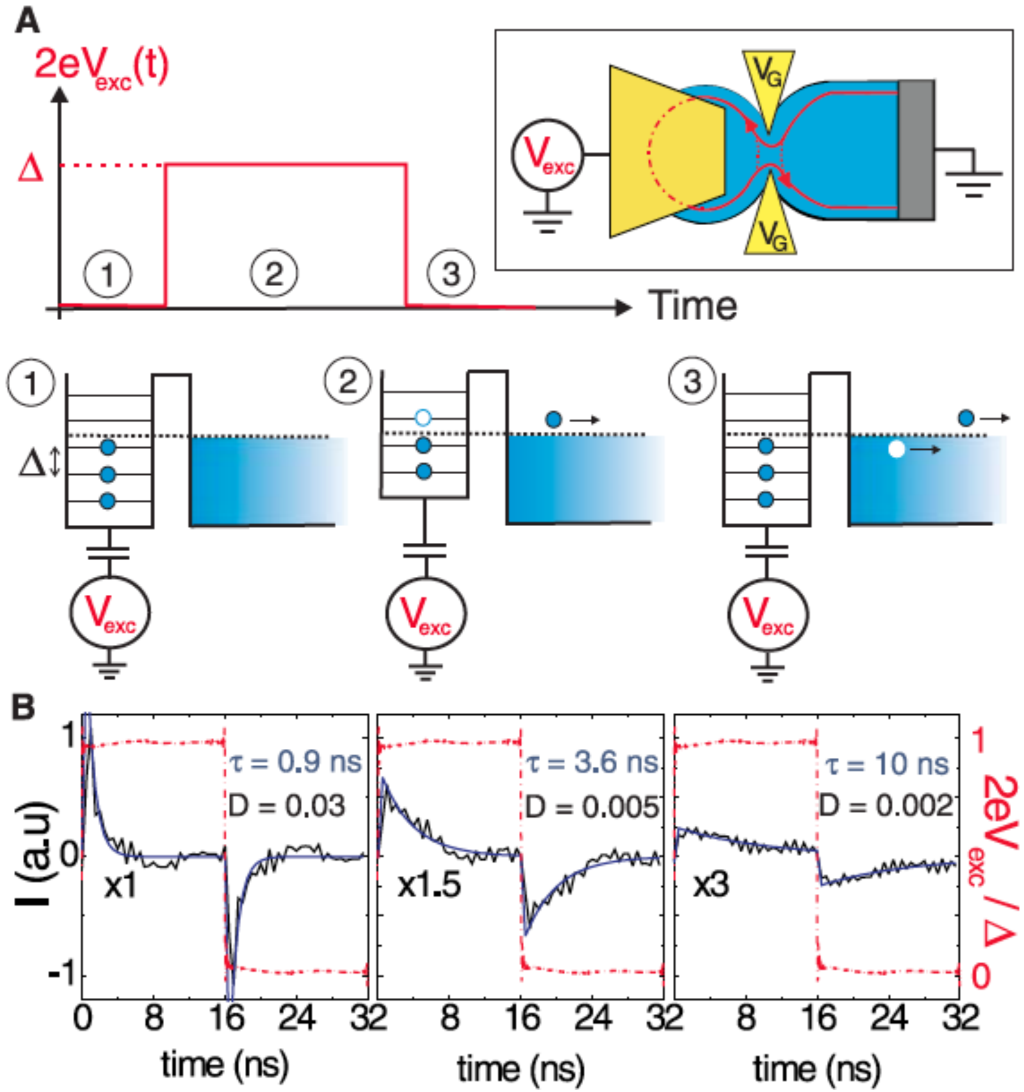
$$I = nef$$

V. I. Talyanskii, et al., Phys. Rev. B 56, 15180 (1997).

Single electron source

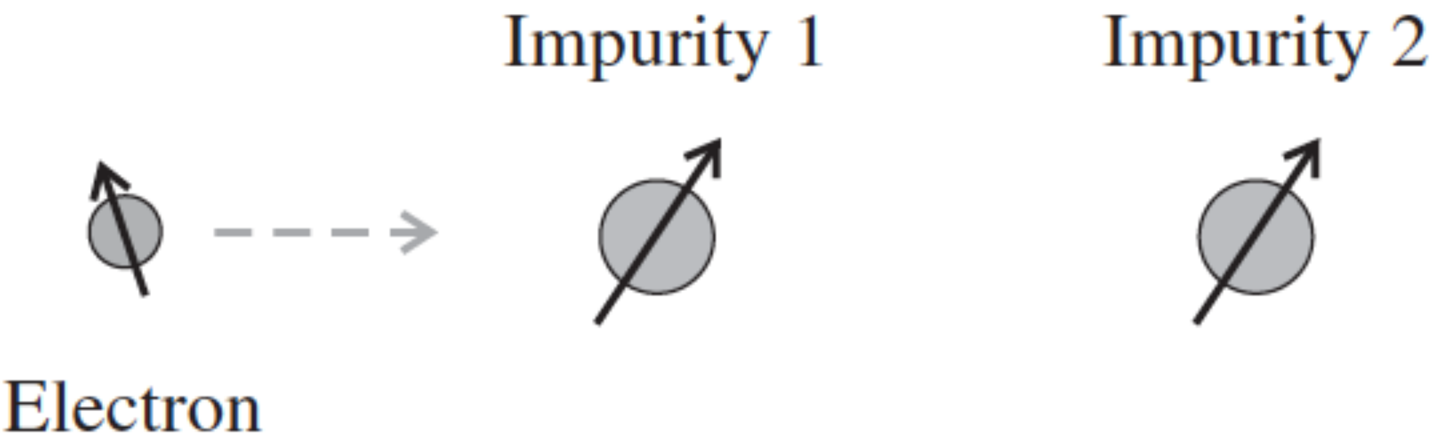


Pulse signal to the gate electrodes, release single electron/hole to the reservoir



J. Gabelli, et al., Science 313, 499 (2006).
G. Feve, et al., ibid 316, 1169 (2007).

Flying qubit as an entangler



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T. Kasuya, Prog. Theor. Phys. 16, 45 (1956).
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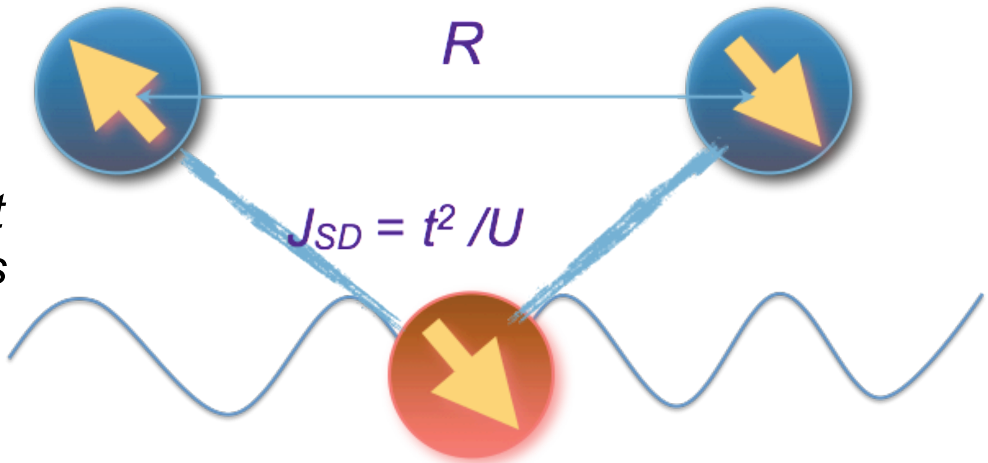
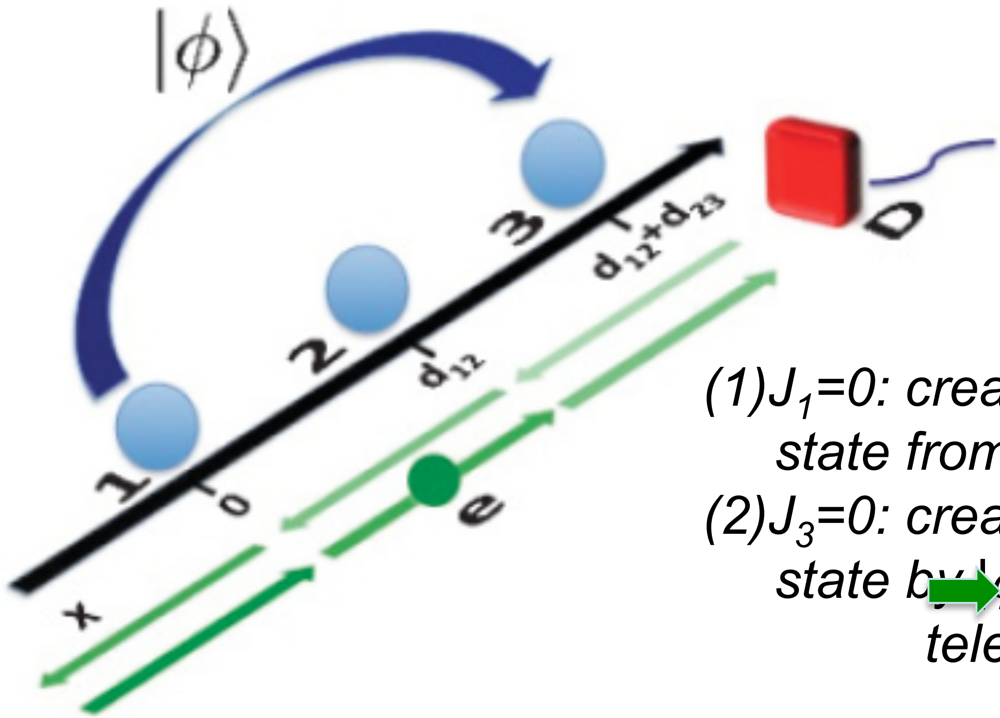
RKKY interaction is an example of entanglement by flying qubits (electrons in the reservoirs).



Y. Avishai and Y. Tokura, Phys. Rev. Lett. 87, 9703 (2001).
A. T. Costa, Jr., S. Bose, and Y. Omar, Phys. Rev. Lett. 96, 230501 (2006).

Quantum teleportation with flying qubits



(1)J_1=0: create maximally entangled state from $|u>_2$ and $|d>_3$.

(2)J_3=0: create maximally entangled state by $|\phi>_1$ and $|\psi>_2$

teleportation $|\phi>_1$ -> $|\phi>_3$

$$\mathcal{H} = \{J_1\vec{S}_1 + J_2\vec{S}_2 + J_3\vec{S}_3\} \cdot \vec{\sigma}$$

Trick: for (1) and $J_2=J_3$, no dynamics by $H=J(S_2+S_3)\sigma$ for spin singlet!

Usage of SAW would be promising.

F. Ciccarello, S. Bose, and M. Zarcone, Phys. Rev. A 81, 042318 (2010).

Conclusions

- *I reviewed recent progress on the research of realizing flying qubits in semiconductor systems.*
- *There are many proposals to generate entangled flying qubits, but not yet experimentally confirmed.*
- *Singlet electron sources and spin filters are proposed and start being demonstrated.*
- *Surface acoustic wave is a promising technology since it generates encapsulated flying qubits with amazingly long spin coherence length.*
- *Using flying qubits and an entangler of localized qubits is another interesting direction of the research.*

Thank you.

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