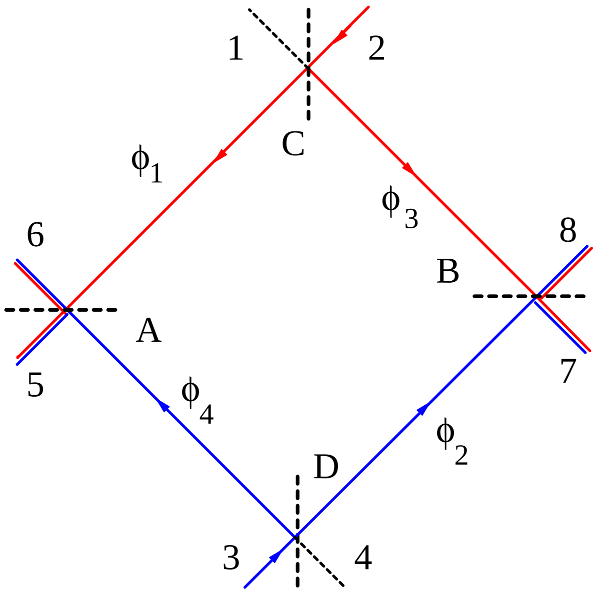
Lecture 3

Shot noise correlations: The two-particle Aharonv-Bohm effect



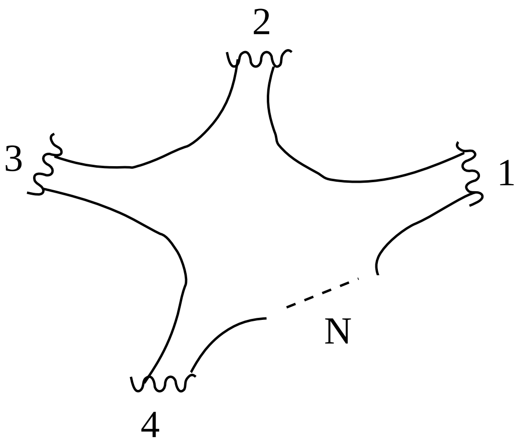
Markus Buttiker

University of Geneva

IV-th Windsor Summer School on Condensed Matter Theory,
organized by B. Altshuler, P. Littlewood and J. von Delft.
Cumberland Lodge, Windsor Royal Park, Windsor, UK, 06 -19 August, 2007.

Shot Noise: Multi-terminal

Mesoscopic conductor with N contacts



$$S=\begin{pmatrix} s_{11} & s_{12} & s_{13} & \cdots & s_{1N} \\ s_{21} & s_{22} & s_{23} & \cdots & \\ s_{31} & s_{32} & s_{33} & & \\ \vdots & \vdots & & \ddots & \\ s_{N1} & & & & s_{NN} \end{pmatrix}$$

At kT = 0,

$$G_{\alpha\beta} = -\frac{e^2}{h}\mathrm{Tr}\left[s^{\dagger}_{\alpha\beta}s_{\beta\alpha}\right]$$

$$S_{\alpha\beta} = 2\int dt \langle \Delta\hat{I}_{\alpha}(t)\Delta\hat{I}_{\beta}(0)\rangle$$

At kT = 0, M contacts with $f_{\gamma} = f$, N-M contacts at $f_{\delta} = f_0$

$$S_{\alpha\beta} = -2\frac{e^2}{h}\int dE\,\mathrm{Tr}\left[B^{\dagger}_{\alpha\beta}B_{\beta\alpha}\right], \qquad B_{\alpha\beta} = \sum_{\gamma=1}^{M} s_{\alpha\gamma}s^{\dagger}_{\beta\gamma}(f_{\gamma}-f_0)$$

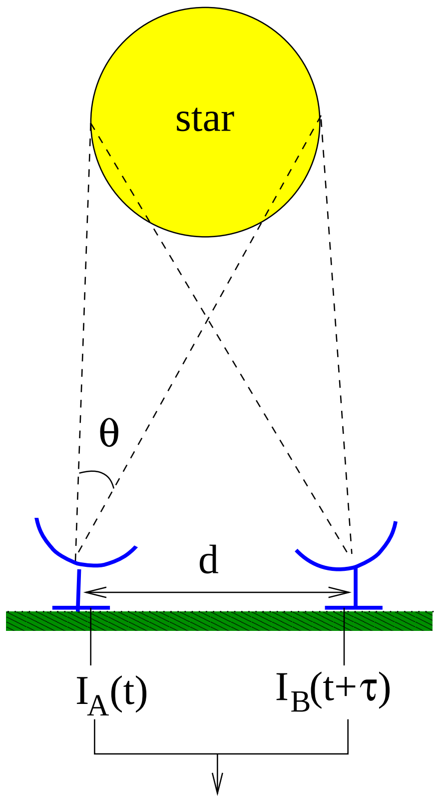
M=1, partition noise

M > 1, relative phase of scattering matrix elements becomes important

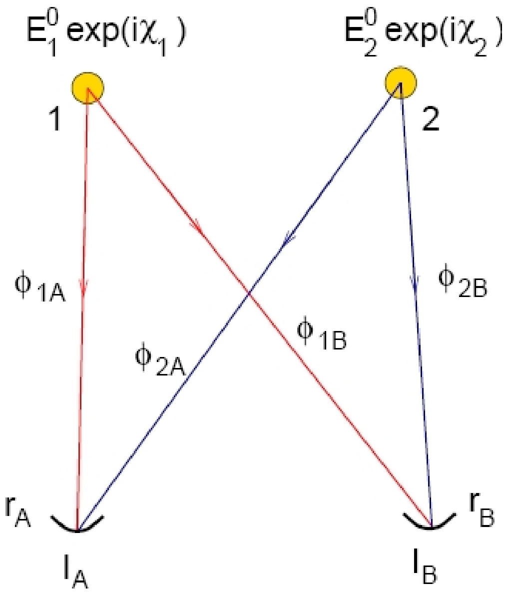
Exchange interference effects: Buttiker, PRL 68, 843 (1992)

Intensity-Interferometers

Hanbury Brown and Twiss,
Nature 177, 27 (1956)



Mandel,
Phys. Rev. A 28, 929 (1983)



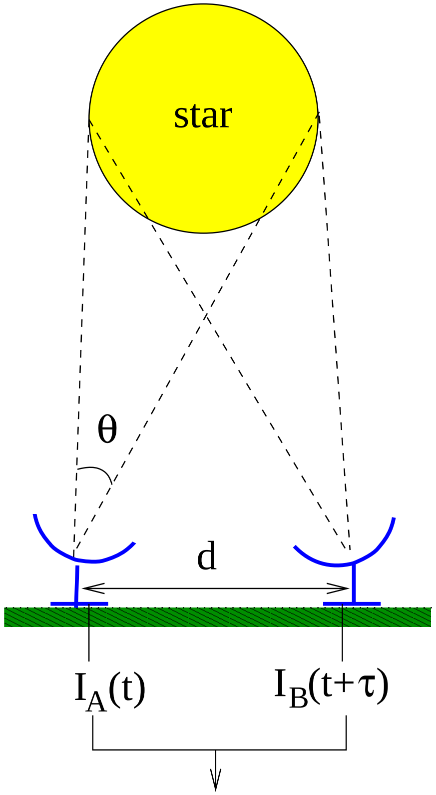
Interference of independent photons:

R. Kaltenbach et al. (Zeilinger), PRL 96, 240502 (2006) (synchronization)

M. Halder, et al. (Gisin), unpublished. (down conversion)

HBT-Intensity Interferometer

Hanbury Brown and Twiss, Nature 177, 27 (1956)



Interference not of amplitudes but of intensities

Optics: classical interpretation possible

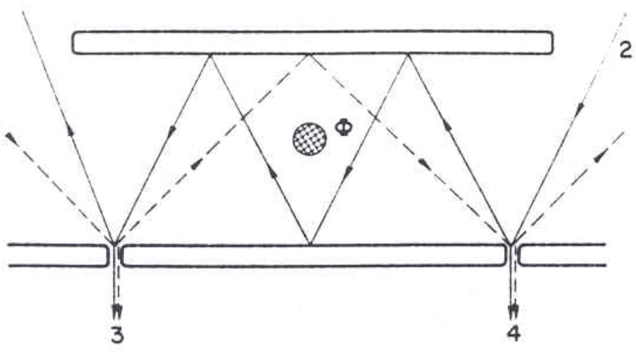
Quantum mechanical explanation:
Purcell, Nature 178, 1449 (1956)

Indistinguishable particles:

Statistics, exchange amplitudes

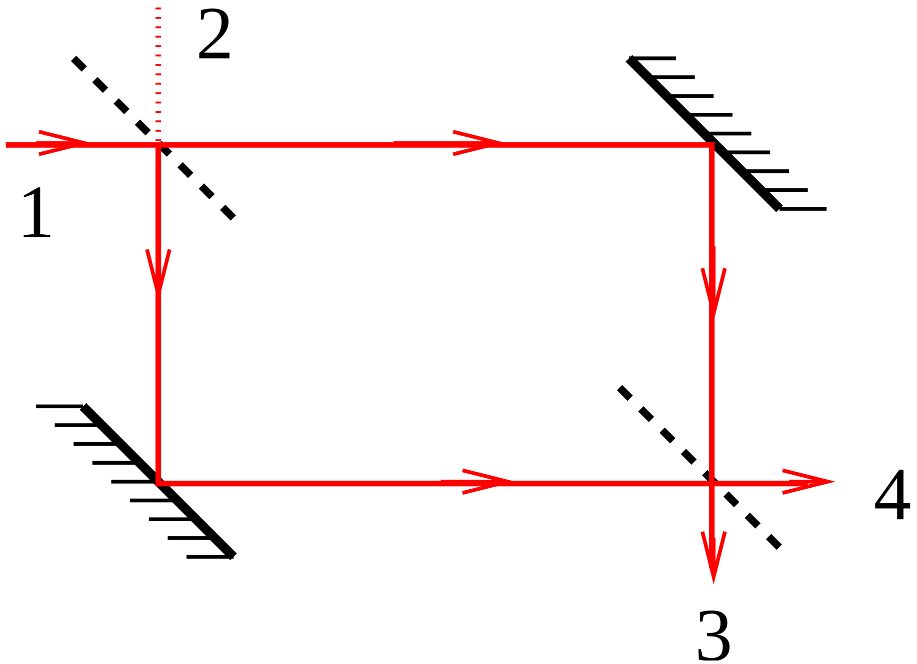
$$\int d\tau \langle \Delta I_A(t) \Delta I_B(t+\tau) \rangle = f\left(\frac{d\theta}{\lambda}\right)$$

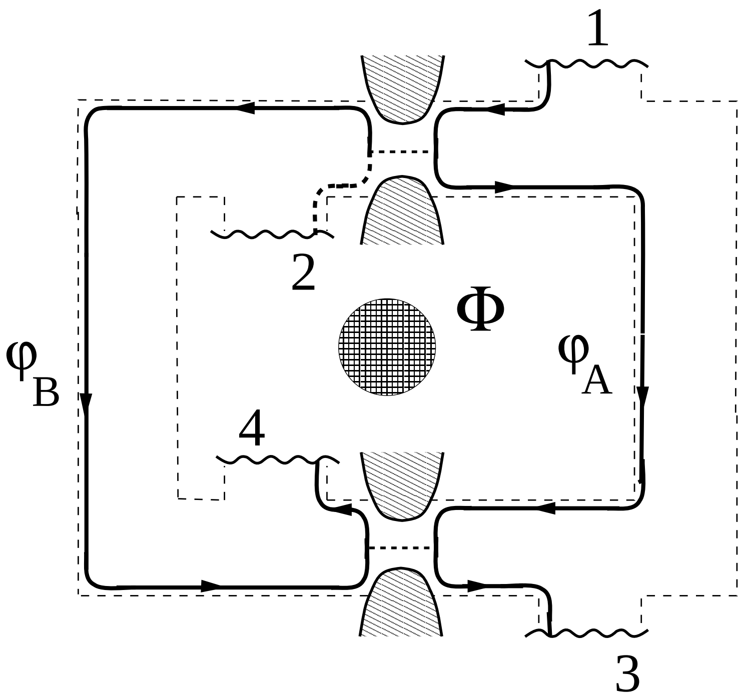
M. Büttiker / The quantum phase of flux correlations in waveguides



"The Quantum Phase of Flux Correlations in Wave Gudies", Buttiker, Physica B175, 199 (1991); PRL 68, 843, (1992).

Optical and Electrical Mach-Zehnder-Interferometer





One particle Aharonov-Bohm effect

Ji et al (Heiblum), Nature 422, 415 (2003)

$$\chi_1 - \chi_2 = 2\pi\Phi/\Phi_0$$

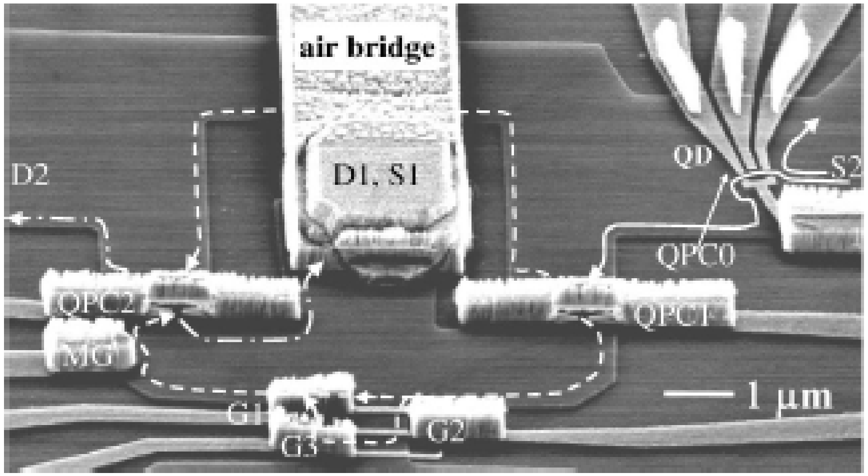
$$s_{31} = \frac{1}{2}\left[e^{i(\phi_A - \chi_1)} + e^{i(\phi_B - \chi_2)}\right]$$

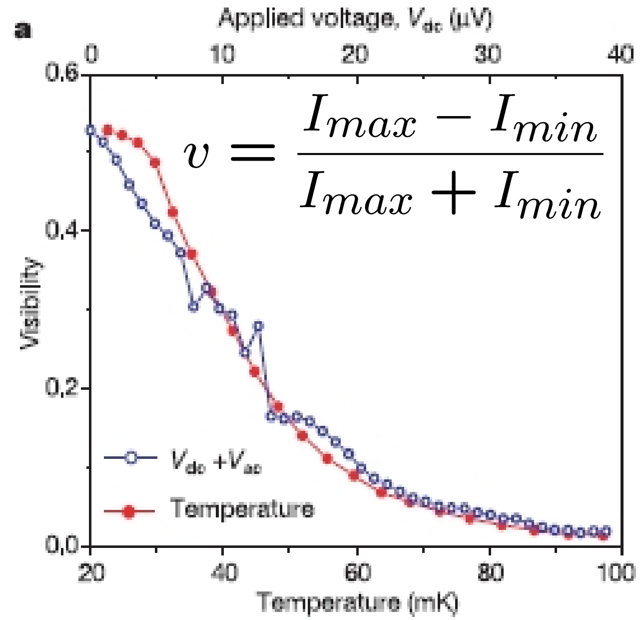
$$G_{31} = \frac{e^2}{2h}\left[1 + \cos(\phi_A - \phi_B - 2\pi\Phi/\Phi_0)\right]$$

$$S_{34} = -2\,\frac{e^2}{8h}\,|eV|\,\left[1 + \cos(2(\phi_A - \phi_B - 2\pi\Phi/\Phi_0))\right]$$

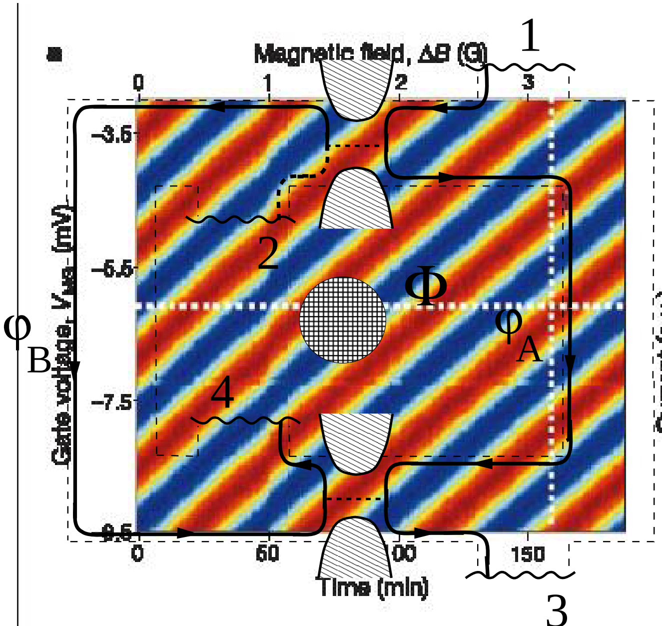
Electrical Mach-Zehnder-Interferometer

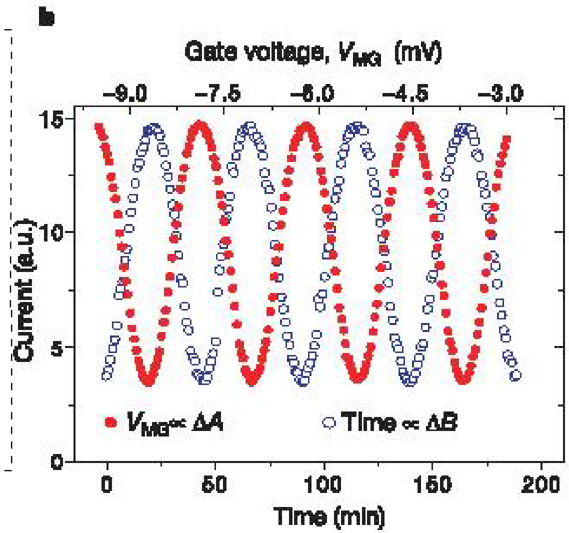
Ji et al (Heiblum), Nature 422, 415 (2003)

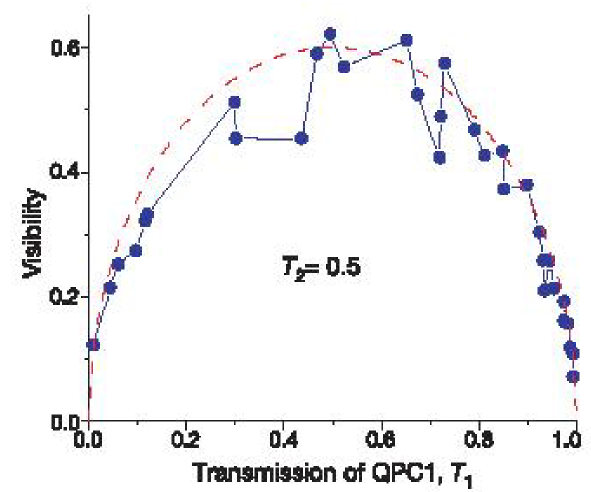




$$v = \frac{I_{max} - I_{min}}{I_{max} + I_{min}}$$

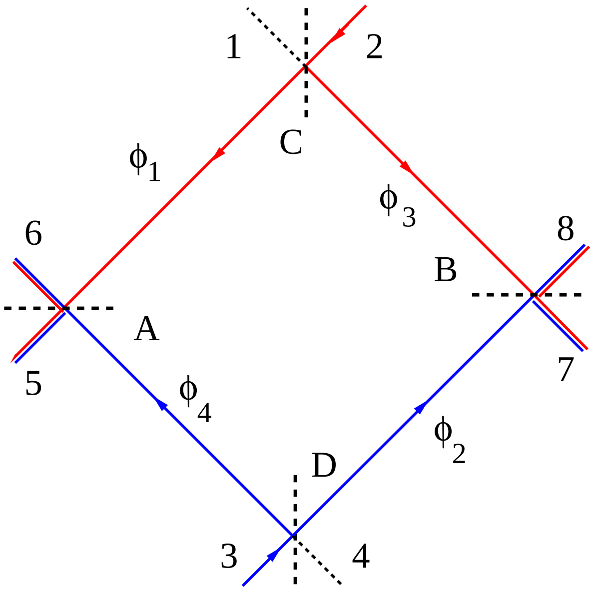




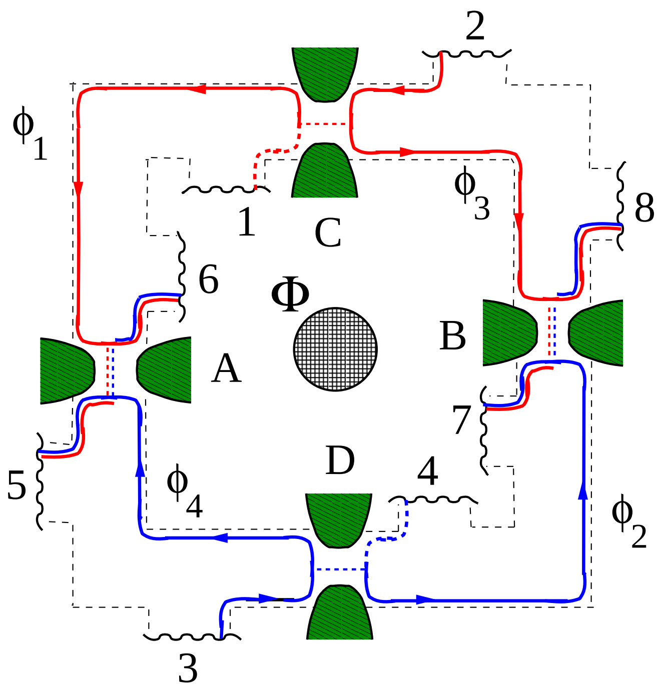


Two-particle interferometer

Samuelsson, Sukhorukov, Buttiker, PRL 92, 026805 (2004)



Yurke and Stoler, PRA 46, 2229 (1992)

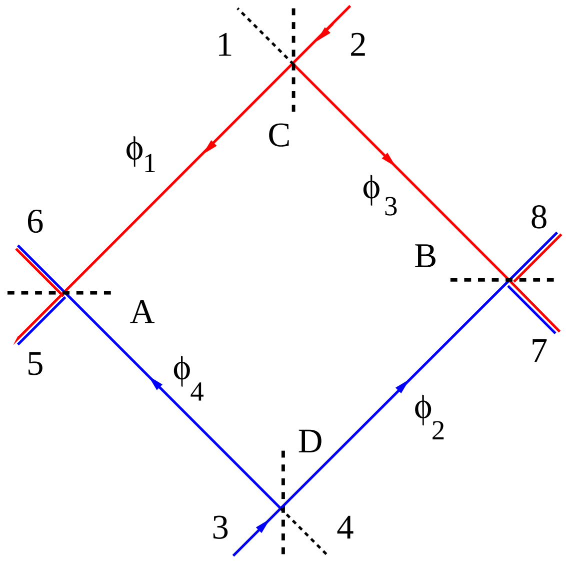


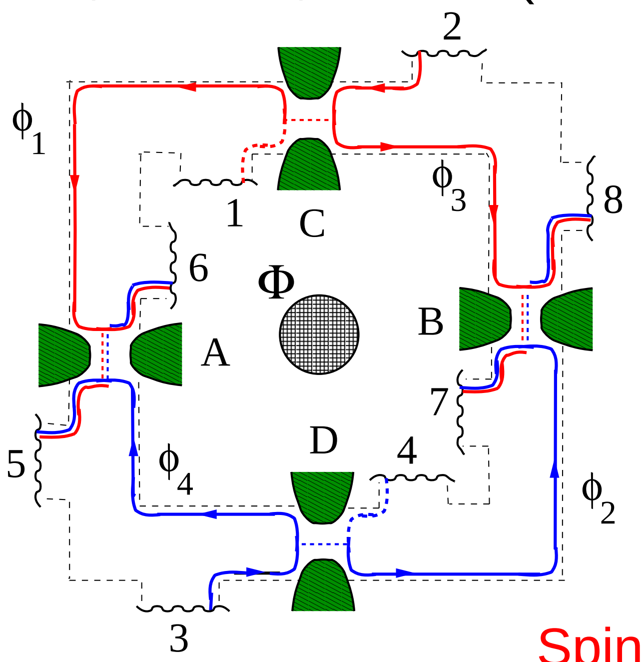
$$s_{52} = T_A^{1/2} e^{i(\phi_1 + \chi_1)} T_C^{1/2} \Rightarrow \qquad G_{52} = -\frac{e^2}{h} T_A T_C$$

All elements of the conductance matrix are independent of AB-flux

Two-particle Aharonov-Bohm Effect

Samuelsson, Sukhorukov, Buttiker, PRL 92, 026805 (2004)





Spin polarized

$$S_{\alpha\beta} = 2\int dt \langle \Delta I_\alpha(0)\Delta I_\beta(t)\rangle$$

$$S_{58} = -2\frac{e^2}{h}\int dE |s_{52}^* s_{82} + s_{53}^* s_{83}|^2 (f - f_0)^2$$

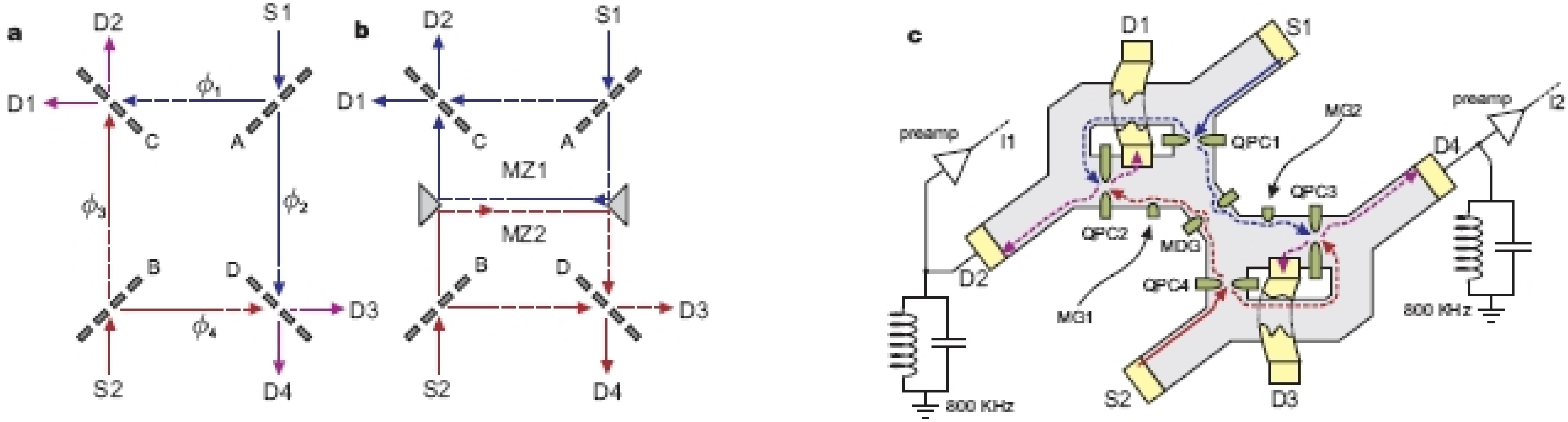
For $T_A = T_B = T_C = T_D = 1/2\,;$

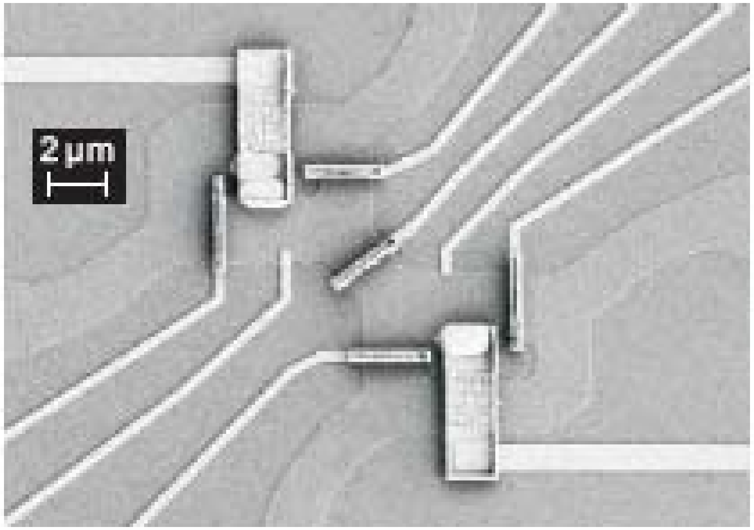
$$S_{58} = -\frac{e^2}{4h}|eV|\left[1 + \cos\left(\phi_1 + \phi_2 - \phi_3 - \phi_4 + 2\pi\frac{\Phi}{\Phi_0}\right)\right]$$

[N >2 ; Sim and Sukhorukov (2006)]

Two-particle Aharonov-Bohm effect: Experiment I

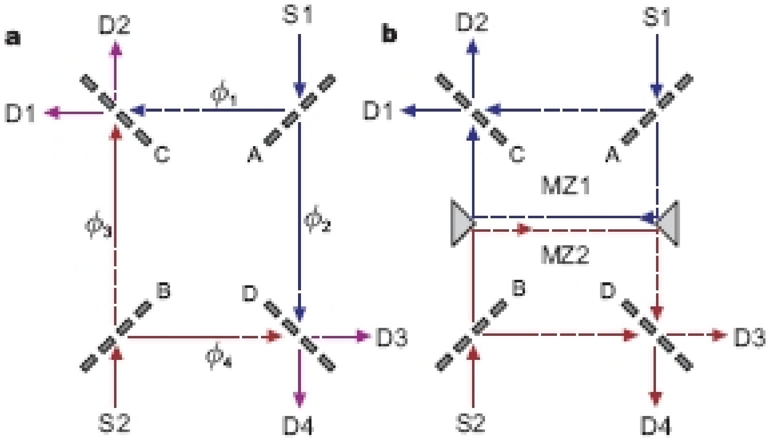
I. Neder, N. Ofek, Y. Chung, M. Heiblum, D. Mahalu and V. Umansky, Nature 448, 333 (2007).

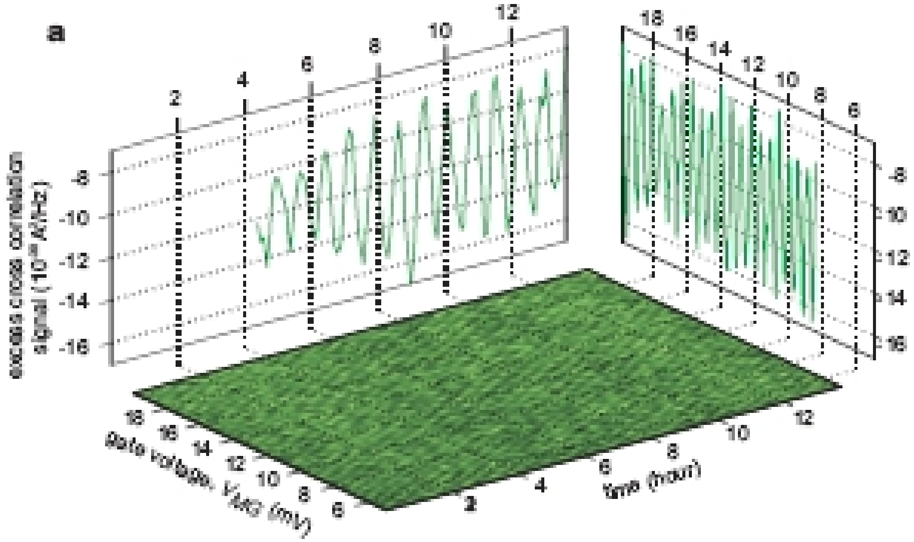




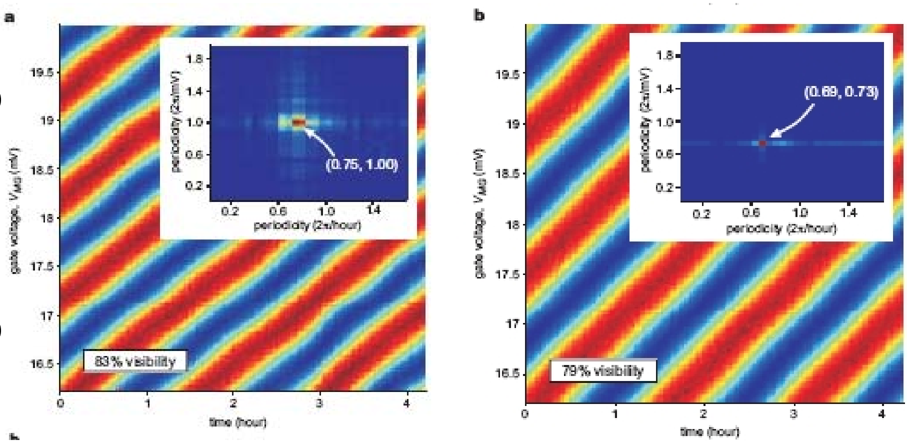
Two-particle Aharonov-Bohm effect: Experiment II

I. Neder, N. Ofek, Y. Chung, M. Heiblum, D. Mahalu and V. Umansky, Nature 448, 333 (2007).

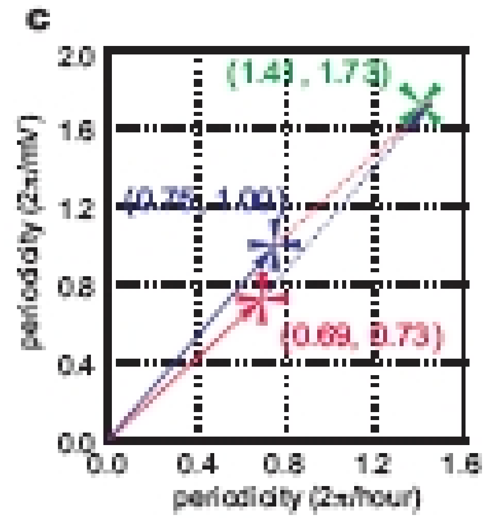




gate voltage



flux Φ

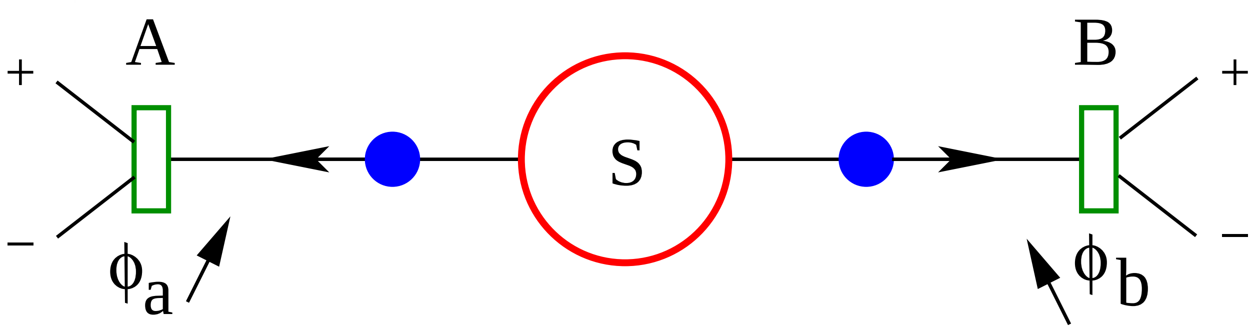


Spin entanglement

PHYSICAL REVIEW VOLUME 108, NUMBER 4 NOVEMBER 15, 1957

Discussion of Experimental Proof for the Paradox of Einstein, Rosen, and Podolsky

D. Bohm and Y. Aharonov
Technion, Haifa, Israel
(Received May 10, 1957)



"..a kind of correlation … quite different from previously known correlations.."

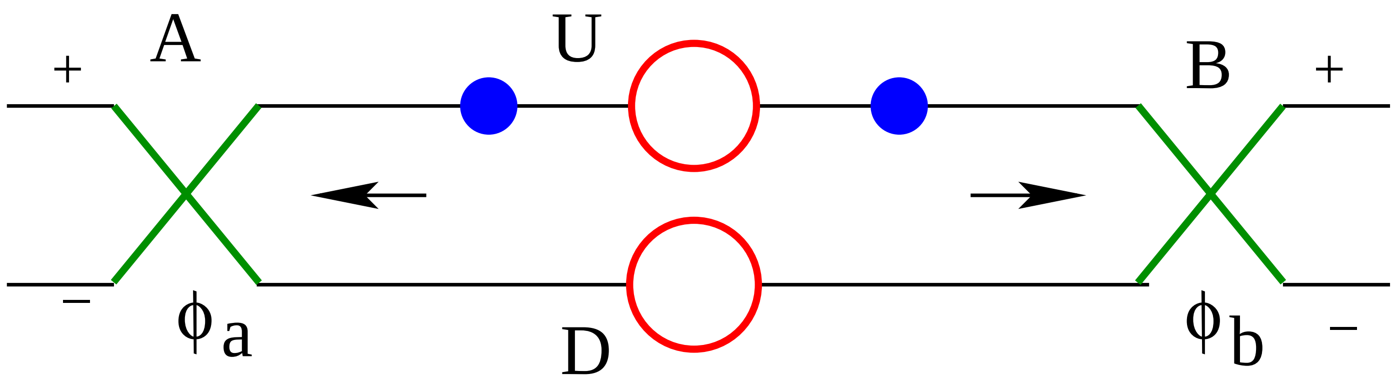
$$\Psi = \frac{1}{\sqrt{2}}\left[\Psi_{\uparrow}(A)\Psi_{\downarrow}(B) - \Psi_{\downarrow}(A)\Psi_{\uparrow}(B)\right]$$

Quantum communication

Quantum computation ?

Here: **Orbital entanglement**

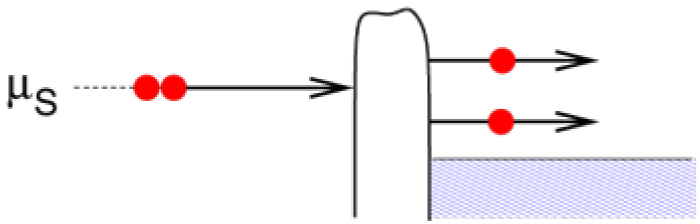
Orbital entanglement



$$\Psi = \frac{1}{\sqrt{2}}[\Psi_U(A)\Psi_U(B) + \Psi_D(A)\Psi_D(B)]$$

NS-structures

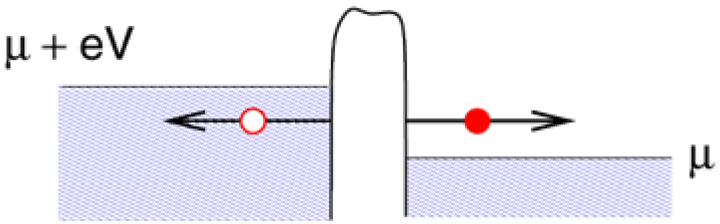
Pair-tunneling picture



Samuelsson, Sukhorukov, Büttiker, PRL 91, 157002 (2003)

Normal conductors

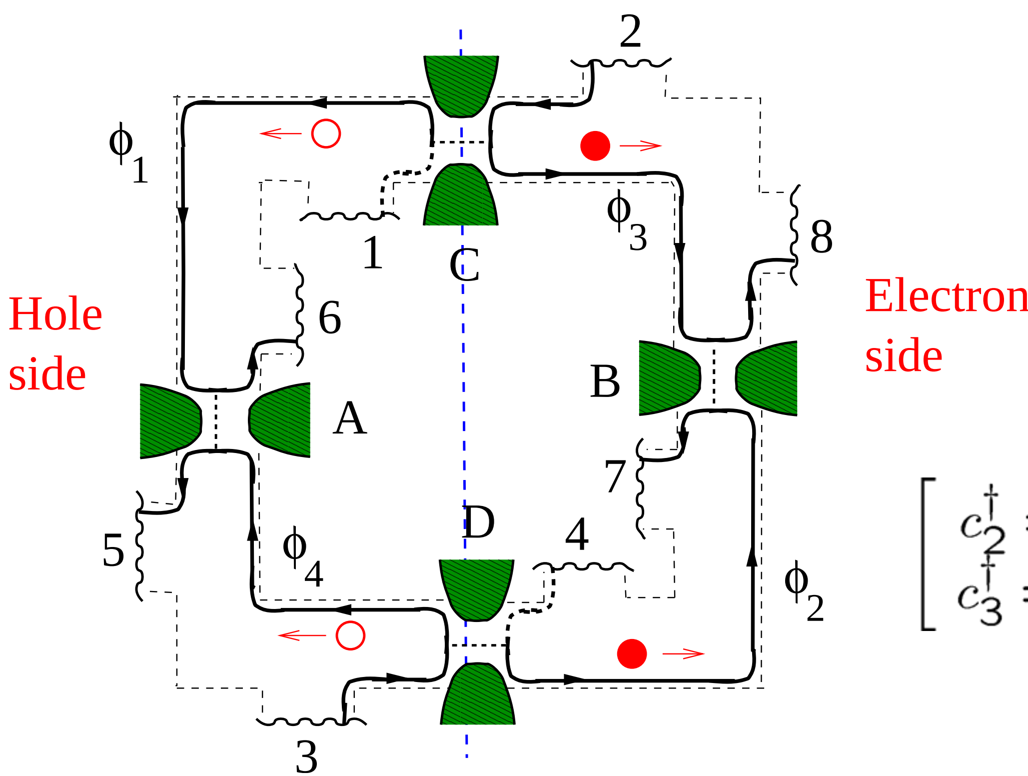
Electron-hole picture



Beenakker, Emary, Kindermann, van Velsen, PRL 91, 147901 (2003)

Two-particle entanglement

Samuelsson, Sukhorukov, Buttiker, PRL 92, 026805 (2004)



$$\begin{bmatrix} c_2^\dagger = t_C c_{2A}^\dagger + r_C c_{2B}^\dagger \\ c_3^\dagger = r_D c_{3A}^\dagger + t_D c_{3B}^\dagger \end{bmatrix}$$

$R_C = T_D = R \ll 1 \; ; \tau_C = \hbar/eV \; ; \tau \sim \hbar/eVR$, tunneling limit

$$|\Psi_{in}\rangle = \prod_{0<E<eV} c_2^\dagger(E) c_3^\dagger(E)|0\rangle$$ incident state

$$|\Psi\rangle = |\bar{0}\rangle + \sqrt{R}\int_0^{eV} dE \left[c_{3B}^\dagger c_{3A} + c_{2B}^\dagger c_{2A}\right]|\bar{0}\rangle + O(R)$$ orbitally entangled e-h-state

Entanglement test: Bell Inequality

Comparison of classical local theory with quantum mechanical prediction. Here: entanglement test

Bell Inequality: Clauser *et al*, PRL **23**, 880 (1969)

$$S_B = |E(\phi_A,\phi_B) - E(\phi'_A,\phi_B) + E(\phi_A,\phi'_B) + E(\phi'_A,\phi'_B)| \leq 2$$

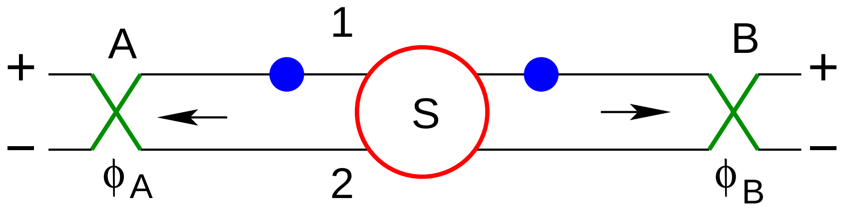
$$E(\phi_A,\phi_B) = P_{++} + P_{--} - P_{+-} - P_{-+}$$

$$P_{\alpha\beta} \propto \langle b^\dagger_\beta(t) b^\dagger_\alpha(t+\tau) b_\alpha(t+\tau) b_\beta(t)\rangle \quad (\tau\Delta\omega \ll 1)$$

16 measurements

- **Orbital**

$$s_{A/B} = \begin{pmatrix} \cos\phi_{A/B} & -\sin\phi_{A/B} \\ \sin\phi_{A/B} & \cos\phi_{A/B} \end{pmatrix}$$



violation of BI implies entanglement
but
not all entgangled states violate BI
not invarinant under local rotations

Samuelsson et al. PRL 91, 157002 (2003)
Chtchelkatchev et al, PRB 66, 161320 (2002);
Faoro, Taddei, Fazio, PRB 69, 125326 (2004)

Electron-electron entanglement through postselection

Symmetric interferometer $T, R \approx 1/2$

Electron-hole picture not appropriate

Incident electron state is a product state: no intrinsic entanglement

Two-particle effects nevertheless persists

A Bell Inequality can be violated

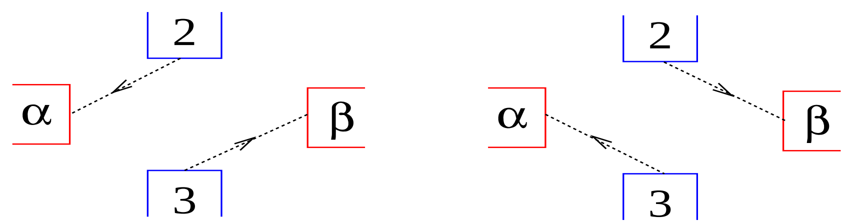
Explanation: Entanglement through ``postselection" (measurement)

Joint detection probability

$$P_{\alpha\beta} \propto \langle b^\dagger_\beta(t) b^\dagger_\alpha(t) b_\alpha(t) b_\beta(t)\rangle = (h^2/e^2)[(1/2\tau_c) S_{\alpha\beta} + I_\alpha I_\beta]$$

$$= |s_{\alpha 3} s_{\beta 2} - s_{\alpha 2} s_{\beta 3}|^2 \qquad \tau_c = \hbar/eV$$

$$\langle I_\alpha \rangle = \frac{e^2}{h} V(|s_{\alpha 2}|^2 + |s_{\alpha 3}|^2)\,,$$

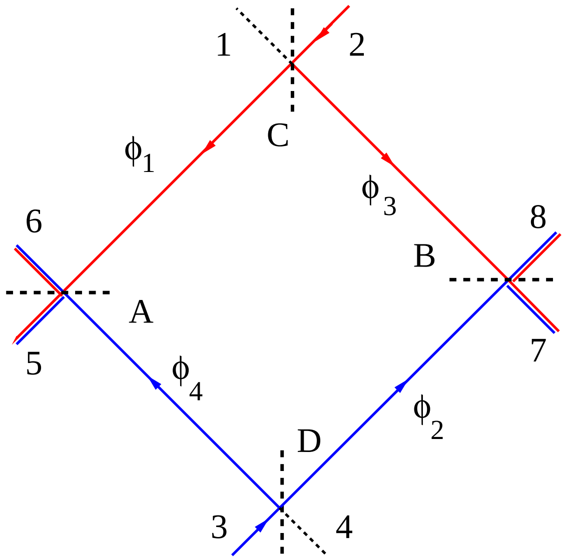


Bell parameter (Bell Inequality):

$$S_B^{max} = 2\sqrt{1+\cos^2\phi_0},\ \ \phi_0 = \phi_1 + \phi_2 - \phi_3 - \phi_4 + 2\pi\Phi/\Phi_0$$

Short time statistics: Pauli principle leads to injection of at most one electron in a short time interval: only two-particle transmission probability enters

Black body radiation sources



Sources: black body

Energy window: narrow band filters $\Delta\omega = 2\pi/\tau_C$

$$P_{\alpha\beta} \propto \langle b^\dagger_\beta(t) b^\dagger_\alpha(t) b_\alpha(t) b_\beta(t)\rangle \propto [(1/2\tau_c)S_{\alpha\beta}+I_\alpha I_\beta] \ ,$$

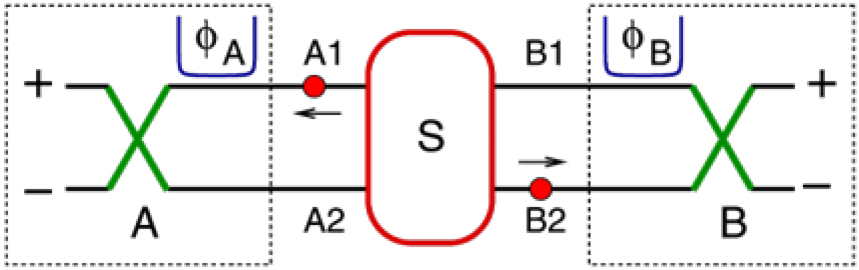
$$S_B^{max} = (2/3)\sqrt{1+\cos^2\phi_0} \ ,$$

No violation: In contrast to electron injection through a single quantum channel where in each time-slot only one particle is injected, in the bosonic case, many particles can be injected.

Quantum Tomography with current and shot noise measurements

A complete reconstruction of one and two particle density matrices with current and shot-noise mesurements

Samuelsson, Büttiker, Phys. Rev. B 73, 041305 (2006)



Matrix elements $n, m, k, l \in \{1, 2\}$

$$\rho_A = \sum_{n,m=1}^{2} \rho_{nm} b^\dagger_{An} |0\rangle\langle 0| b_{Am} \qquad \rho_{nm} = \langle b^\dagger_{Am} b_{An} \rangle$$

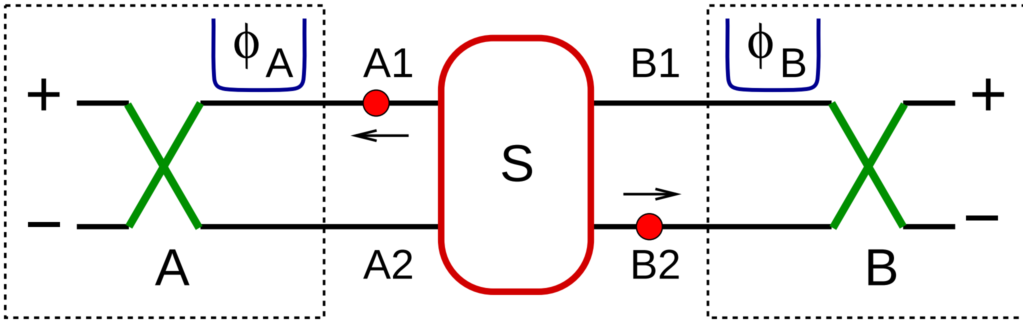
$$\rho_{AB} = \sum_{n,m,k,l=1}^{2} \rho^{kl}_{nm} b^\dagger_{An} b^\dagger_{Bk} |0\rangle\langle 0| b_{Bl} b_{Am} \qquad \rho^{kl}_{nm} = \langle b^\dagger_{Am} b^\dagger_{Bl} b_{Bk} b_{An} \rangle$$

Entanglement determined by ρ_{AB}

$$E = E(\rho_{AB})$$

Quantum state tomography with quantum shot noise

P. Samuelsson and M. Buttiker, Phys. Rev. B 73, 041305 (2006)



$$\{|1\rangle_A, |2\rangle_A\}$$

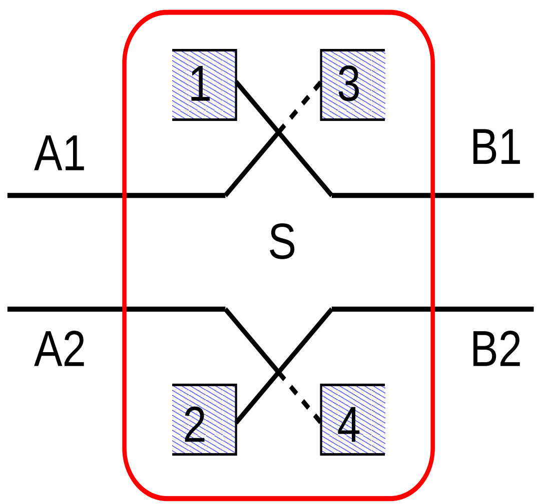
$$\rho_A = \frac{1}{2}\sum_{i=0}^{3} c_i\sigma_i = \frac{1}{2}\begin{pmatrix} c_0 + c_3 & c_1 - ic_2 \\ c_1 + ic_2 & c_0 - c_3 \end{pmatrix}$$

Reconstruction of one-particle d.m.

$$I_A^+/(e^2V/h) = \langle n_A^+\rangle = \mathrm{tr}\,(\rho_A \mathcal{A})$$

$$\mathcal{A} = \begin{pmatrix} R_A & \sqrt{T_AR_A}e^{-i(\phi_A+\varphi_A)} \\ \sqrt{T_AR_A}e^{i(\phi_A+\varphi_A)} & T_A \end{pmatrix}$$

Setting	Parameters
I	T_A=0, ϕ_A arb.
II	T_A=1, ϕ_A arb.
III	T_A=1/2, ϕ_A=0
IV	T_A=1/2, ϕ_A=$\pi/2$



$$j_A(0) = \mathcal{A}(I) + \mathcal{A}(II) = 1$$

$$j_A(1) = \mathcal{A}(III) - [\mathcal{A}(I) + \mathcal{A}(II)] = \sigma_x,$$

$$j_A(2) = 2\mathcal{A}(IV) - [\mathcal{A}(I) + \mathcal{A}(II)] = \sigma_y,$$

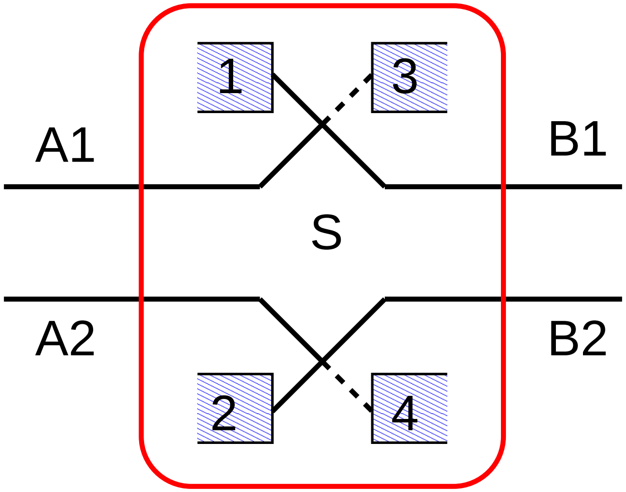
$$j_A(3) = \mathcal{A}(I) - \mathcal{A}(II) = \sigma_z$$

$$s_A = \begin{pmatrix} \sqrt{R_A}e^{i\varphi_{A2}} & \sqrt{T_A}e^{i(\varphi_{A3}-\phi_A)} \\ \sqrt{T_A}e^{i(\varphi_{A1}+\varphi_{A2})} & -\sqrt{R_A}e^{i(\varphi_{A1}+\varphi_{A3}-\phi_A)} \end{pmatrix}.$$

Quantum State Tomography with shot noise

P. Samuelsson and M. Buttiker, Phys. Rev. B 73, 041305 (2006)

Setting	Parameters
I	T_A=0, ϕ_A arb.
II	T_A=1, ϕ_A arb.
III	T_A=1/2, ϕ_A=0
IV	T_A=1/2, ϕ_A=$\pi/2$



$$Q = \begin{pmatrix} 1 & 1 & 0 & 0 \\ -1 & -1 & 2 & 0 \\ -1 & -1 & 0 & 2 \\ 1 & -1 & 0 & 0 \end{pmatrix}$$

reduced density matrix

single particle

$\{|1\rangle_A, |2\rangle_A\}$

$$\rho_A = \frac{1}{2}\sum_{j=0}^{3} c_i\sigma_i = \frac{1}{2}\begin{pmatrix} c_0 + c_3 & c_1 - ic_2 \\ c_1 + ic_2 & c_0 - c_3 \end{pmatrix}$$

$$\bar{c}_j = \sum_{k=0}^{3} Q_{jk}\langle n_A^{+}(k)\rangle$$

two particle

$\{|1\rangle_A|1\rangle_B, |1\rangle_A|2\rangle_B, |2\rangle_A|1\rangle_B, |2\rangle_A|2\rangle_B\}$

$$\rho_{AB} = \frac{1}{4}\sum_{i,j=0}^{3} c_{ij}\sigma_i \otimes \sigma_j$$

$$\bar{c}_{ji} = \sum_{k,l=0}^{3} Q_{jk}Q_{il}\langle n_A^{+}(k) n_B^{+}(l)\rangle$$

8 current measurements

16 current correlation measurements

(same as for BI but in contrast to BI, completely determines entanglement)

Summary

Interference of independently emitted electrons

Two-particle Aharonov-Bohm effect

Orbital entanglement

Bell test of orbital entanglement

Orbital quantum state tomography $E = E(\rho_{AB})$

Pumping of entanglement

Quantum electronics: from Schottky to Bell

Markus Büttiker
University of Geneva

Coherence and Quantum Optics 9
Rochester, NY, June 13, 2007

Quantum optics/electronics

Experiments and theory of quantum coherent electron transport resemble more and more quantum optics

Important difference: Electrons are Fermions and carry charge

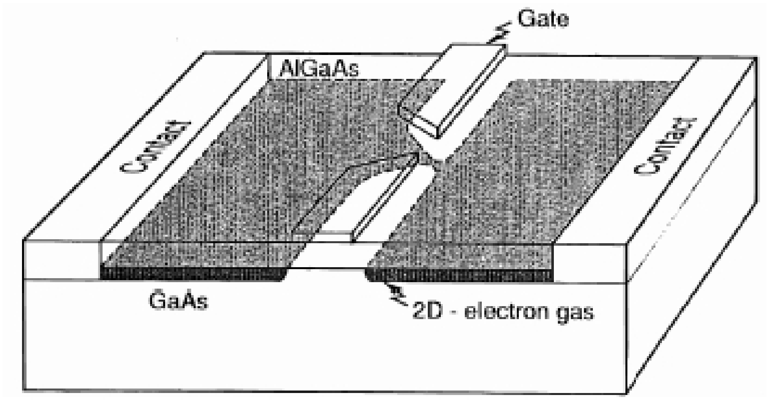
Counting statistics

Quantum measurements

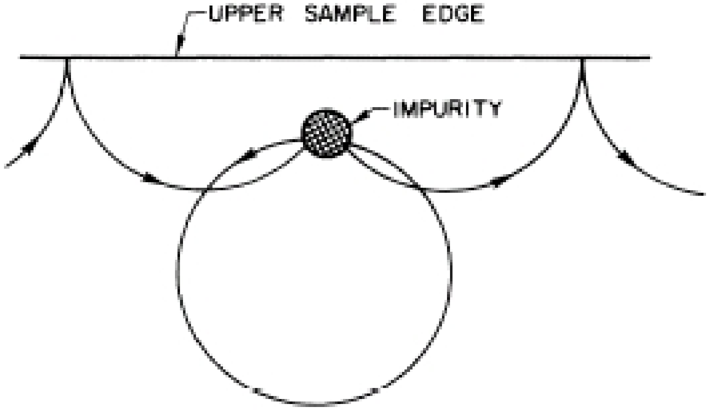
Generation of entangled states

Quantum Point Contact + Edge States = Beam Splitter

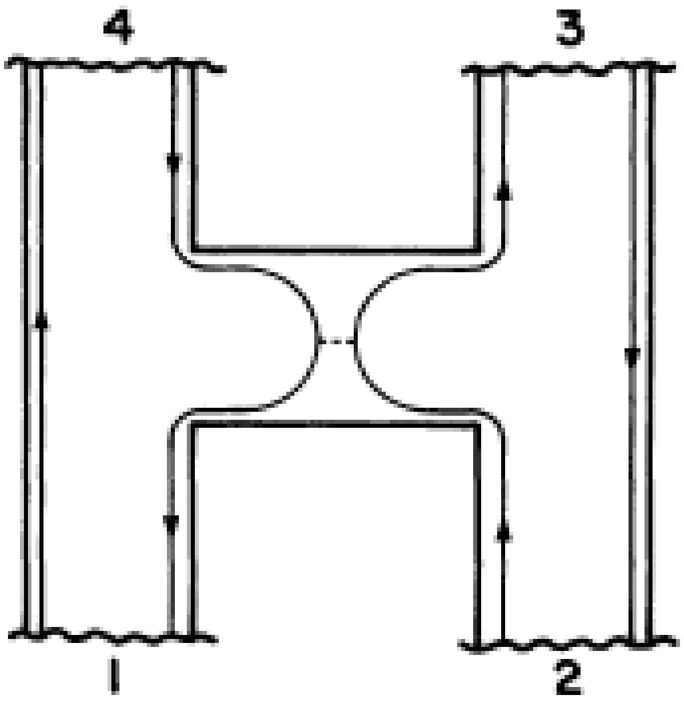
Quantum Point Contact



Edge state



Solid State – Beam Splitter



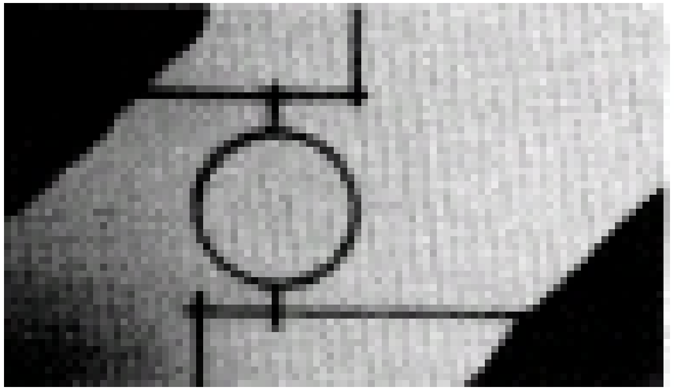
Transmission probability is a function of gate voltage

Opening the tool box..

Making quantum mechanics visible in man made structures

Looking at individual quantum systems

Webb et al. (1985)



diffusive

$$\lambda_F < l_e < L < l_\phi < l_{in}$$

ballistic

$$\lambda_F < L < l_e < l_\phi < l_{in}$$

Persistent currents

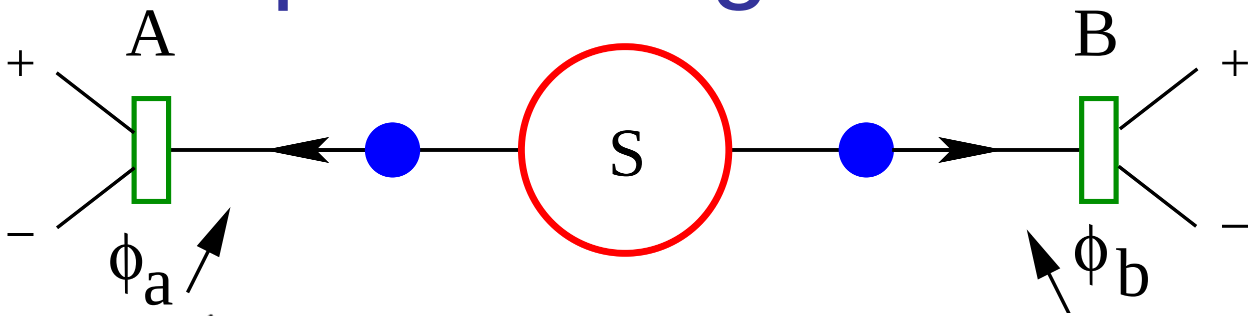
Aharonov-Bohm effect

Universal conductance fluctuations

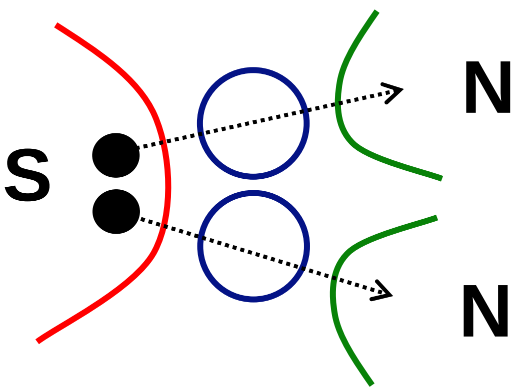
Conductance quantization

….

Spin entanglement



$$\Psi = \frac{1}{\sqrt{2}}\left[\Psi_{\uparrow}(A)\Psi_{\downarrow}(B) - \Psi_{\downarrow}(A)\Psi_{\uparrow}(B)\right]$$



Dot & superconductor entanglers

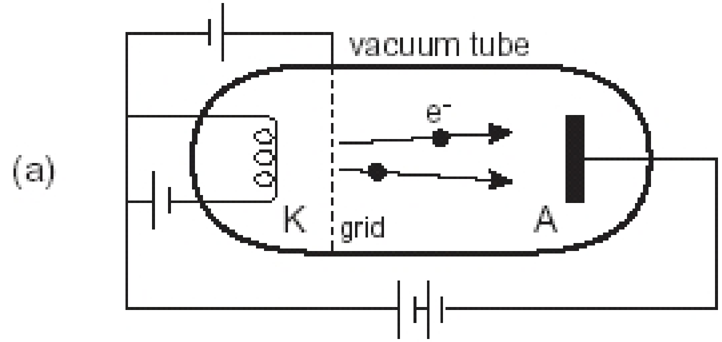
Recher *et al*. PRB **63** 165314 (2001)
Lesovik *et al.* EPJB **24**, 287 (2001)
Taddei and Fazio, PRB **65**, 075317 (2002)
Oliver *et al* PRL **88** 037901 (2002)
Bena *et al* PRL **89** 037901 (2002)
Saraga and Loss, PRL **90** 166803 (2003).......

+ Long spin coherence length
- Difficult to manipulate/detect

Quantum versus classical shot noise

Classical shot noise:

W. Schottky, Ann. Phys. (Leipzig) 57, 541 (1918)



$$\langle(\Delta I)^2\rangle_\nu = 2e\langle I\rangle$$

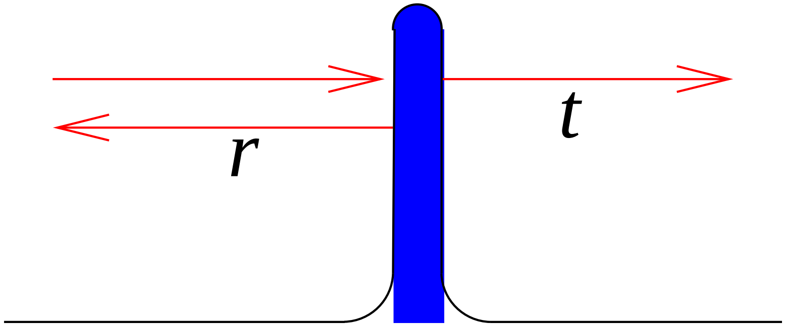
Quantum shot noise:

Khlus (1987), Lesovik (1989), Yurke and Kochanski (1989), Buttiker (1990), Beenakker and van Houten (1991)

$$|\Psi >_{inc} = e^{ikx}$$

$$|\Psi >_{ref} = re^{-ikx}$$

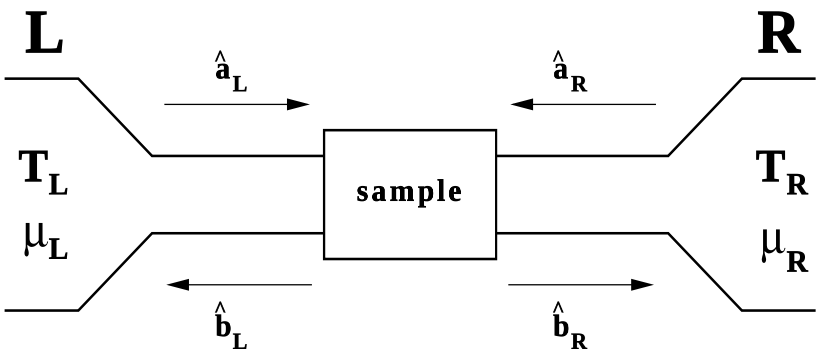
$$|\Psi >_{tra} = t\, e^{ikx}$$



$\Rightarrow$

$$\langle(\Delta n_T)^2\rangle = T(1-T) \quad \Rightarrow \quad \langle(\Delta I)^2\rangle_\nu = 2e\langle I\rangle(1-T)$$

Shot Noise: Two-terminal



Quantum partition noise: kT = 0, V>0,

$$S = 2\frac{e^2}{h}|eV|\, Tr[tt^\dagger rr^\dagger] = 2\frac{e^2}{h}|eV| \sum_n T_n(1-T_n)$$

If all $T_n \ll 1 \quad \Longrightarrow$ Buttiker (1990)

$$S = 2e(\frac{e^2}{h}\sum_n T_n)|V| = 2e\,|I|$$

Schottky (Poisson)

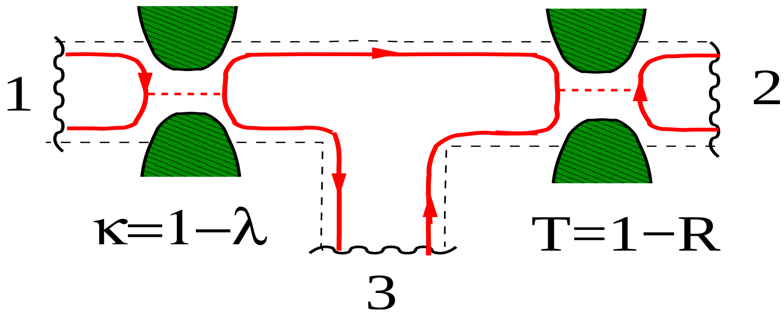
Fano factor

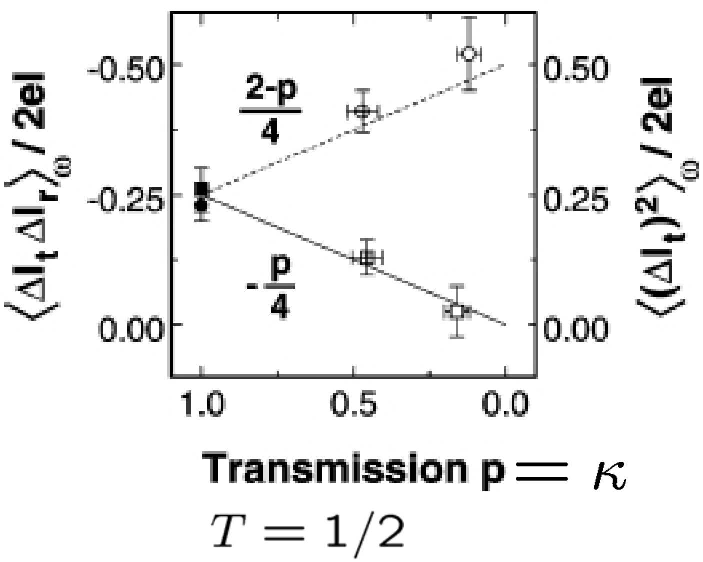
$$F = \frac{S}{S_P} = \frac{\sum_n T_n(1-T_n)}{\sum_n T_n}$$

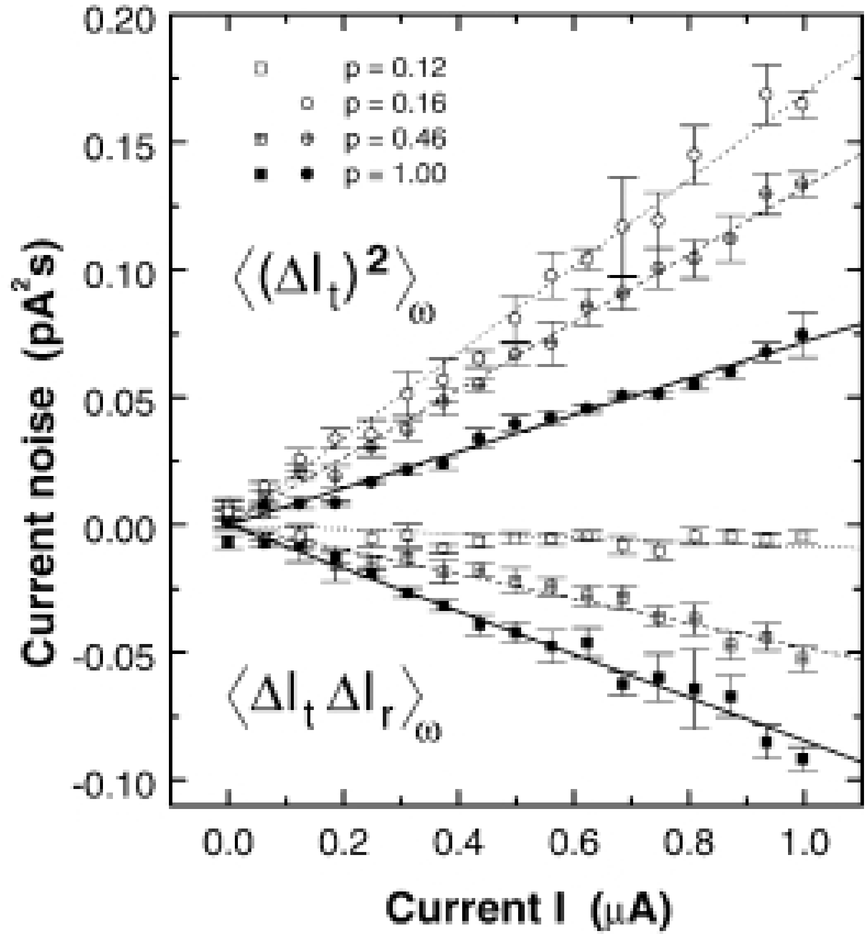
Experiments:
Reznikov (Heiblum) et al. PRL **75**, 3340 (1995)
Kumar, (Glattli) et al. PRL **76**, 2778 (1996)

Partition noise of fermions

Oberholzer, Henny, Strunk et al, Physica E6, 314 (2000)







See also: **Henny**, et al., *Science* 284, 296 (1999); Oliver et al. Science 284, 299 (1999)

Why interference from independent sources?

Probably the most interesting effect of an independent particle description of transport

Exchange can be made visible

Vital * for implementation of quantum networks and quantum computing schemes:

quantum repeaters

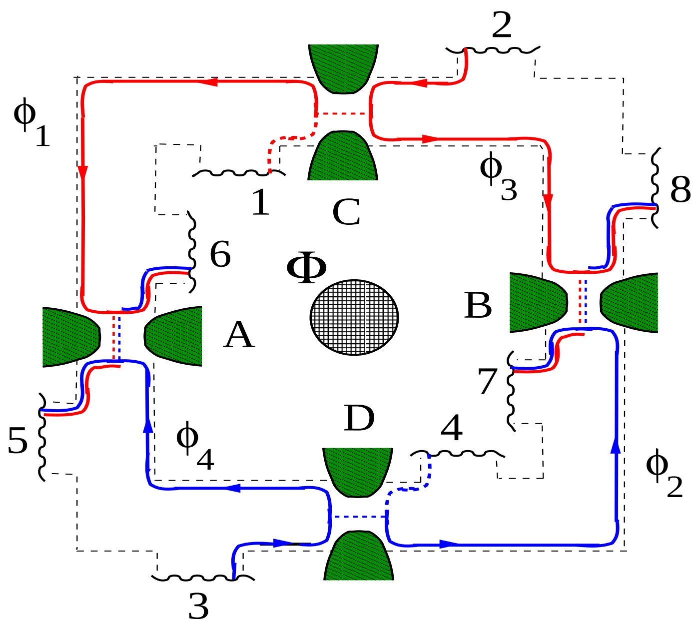
Knill-Laflamme-Milburn (linear) quantum computing schemes

In opitcs interference of independent sources is only possible with active synchronization of the sources.

*Kaltenbaek (Zeilinger) et al. PRL 96, 240502 (2006)

Visibility and violation of Bell Inequality

(Dephasing)



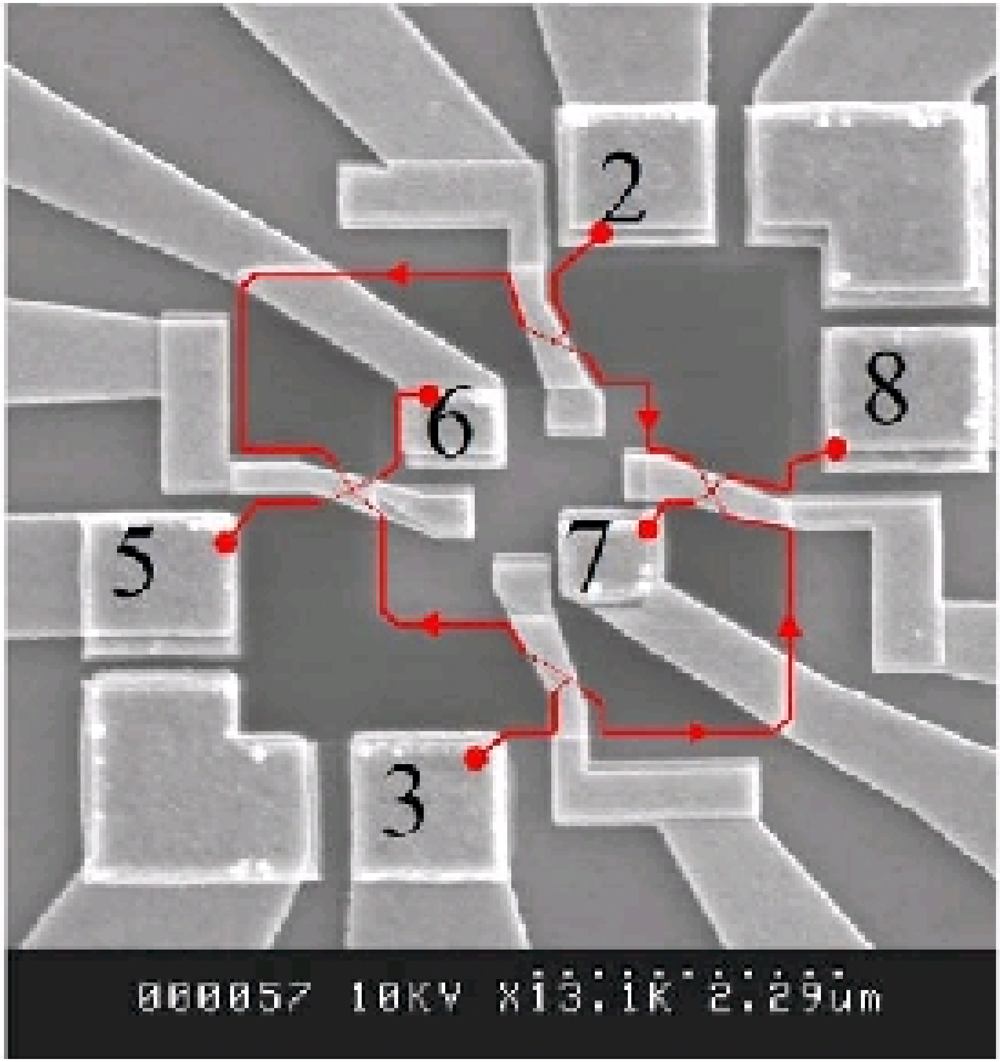
Spatially seprated sources: qubit protectet against relaxation:

$$|\rho\rangle = |UU\rangle\langle UU| + |DD\rangle\langle DD| + \gamma(|UU\rangle\langle DD| + |DD\rangle\langle UU|)/2$$

$$S_{58} = -\frac{e^2}{4h}|eV|\left[1+\gamma^2\cos(\phi_0)\right]$$

$$S_B^{max} = 2\sqrt{1+\gamma^2\cos^2\phi_0}, \quad \phi_0 = \phi_1+\phi_2-\phi_3-\phi_4+2\pi\Phi/\Phi_0$$

Two-particle Intensity Interferometers



Glattli et al.

Schoenenberger

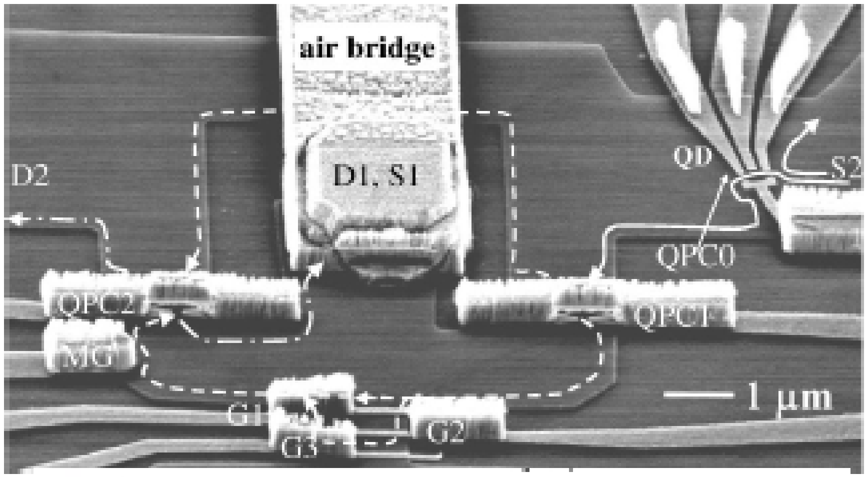
Heiblum et al.

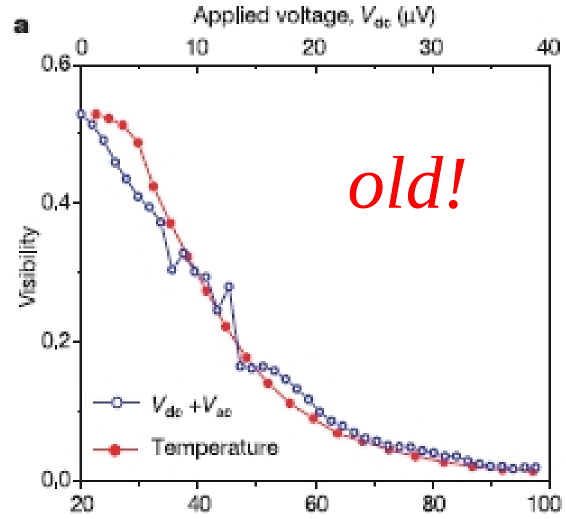
2004

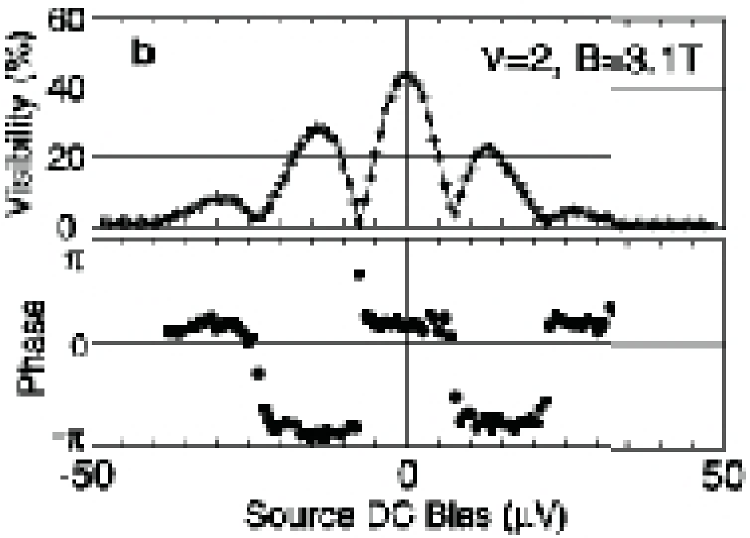
but no success!

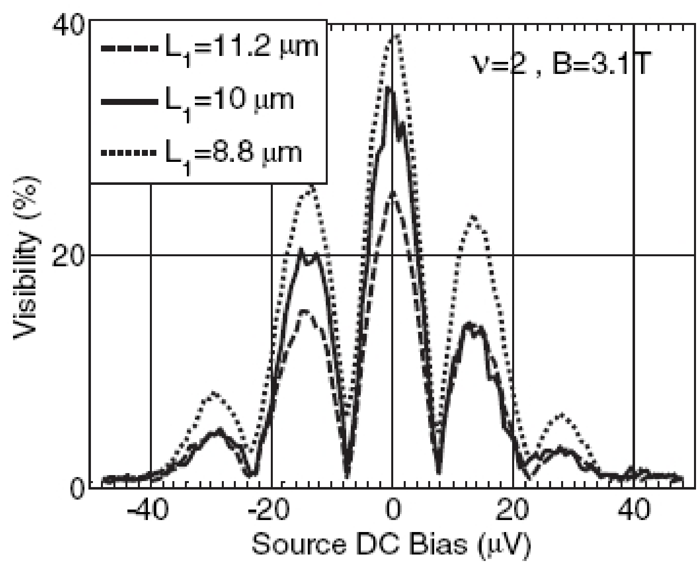
Electrical Mach-Zehnder Interferometer II

Neder, Heiblum, Levinson, Mahalu, Umansky, PRL 96, 016804 (2006)



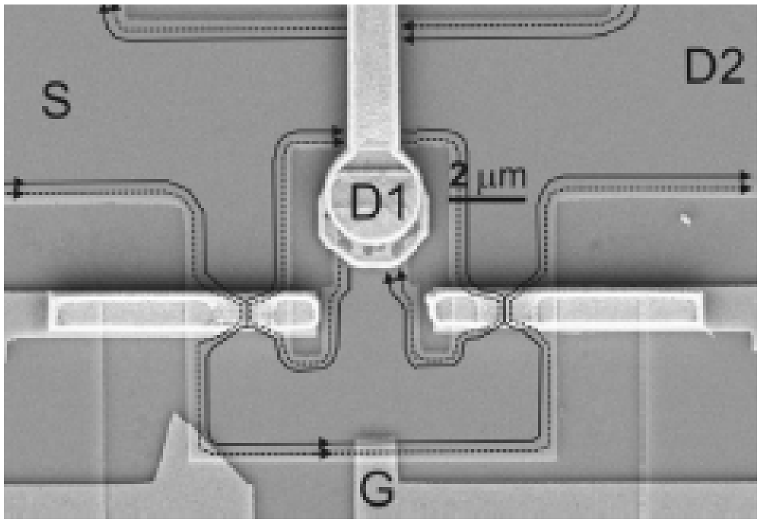


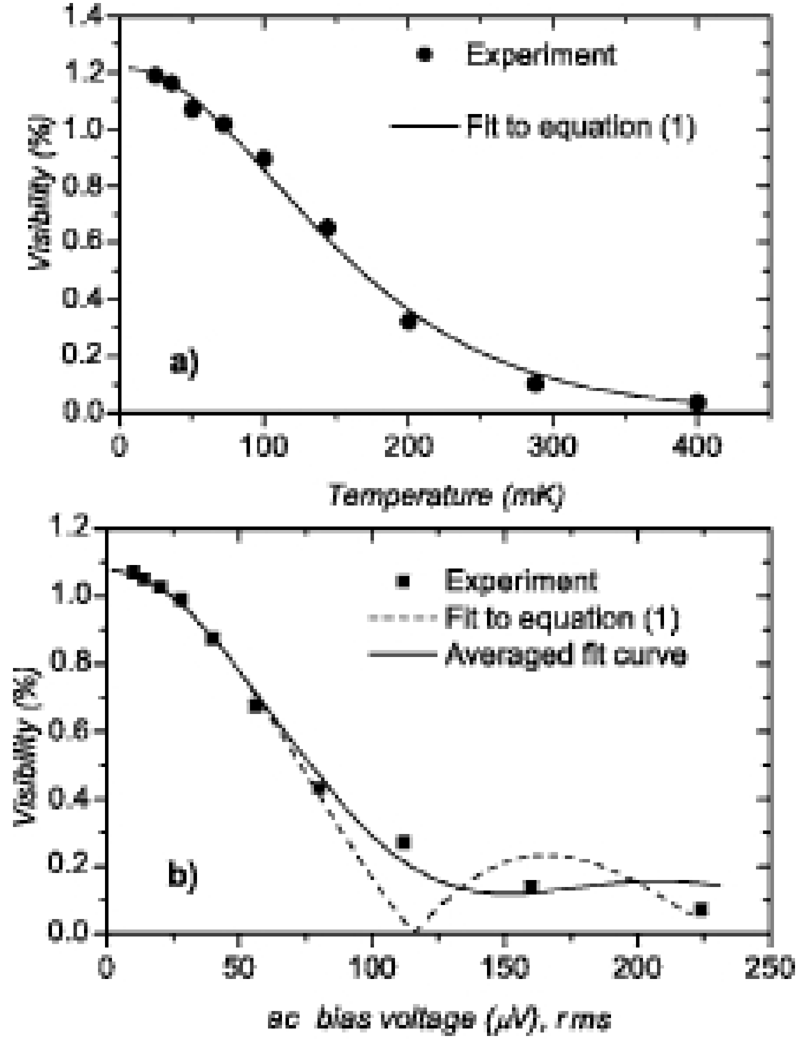




Electrical Mach-Zehnder Interferometer III

Litvin, Tranitz, Wegscheider and Strunk, PRB 75, 033315 (2007)





$$E_b \approx \hbar v_D/\Delta L \,, T_A = T_B = 1/2$$

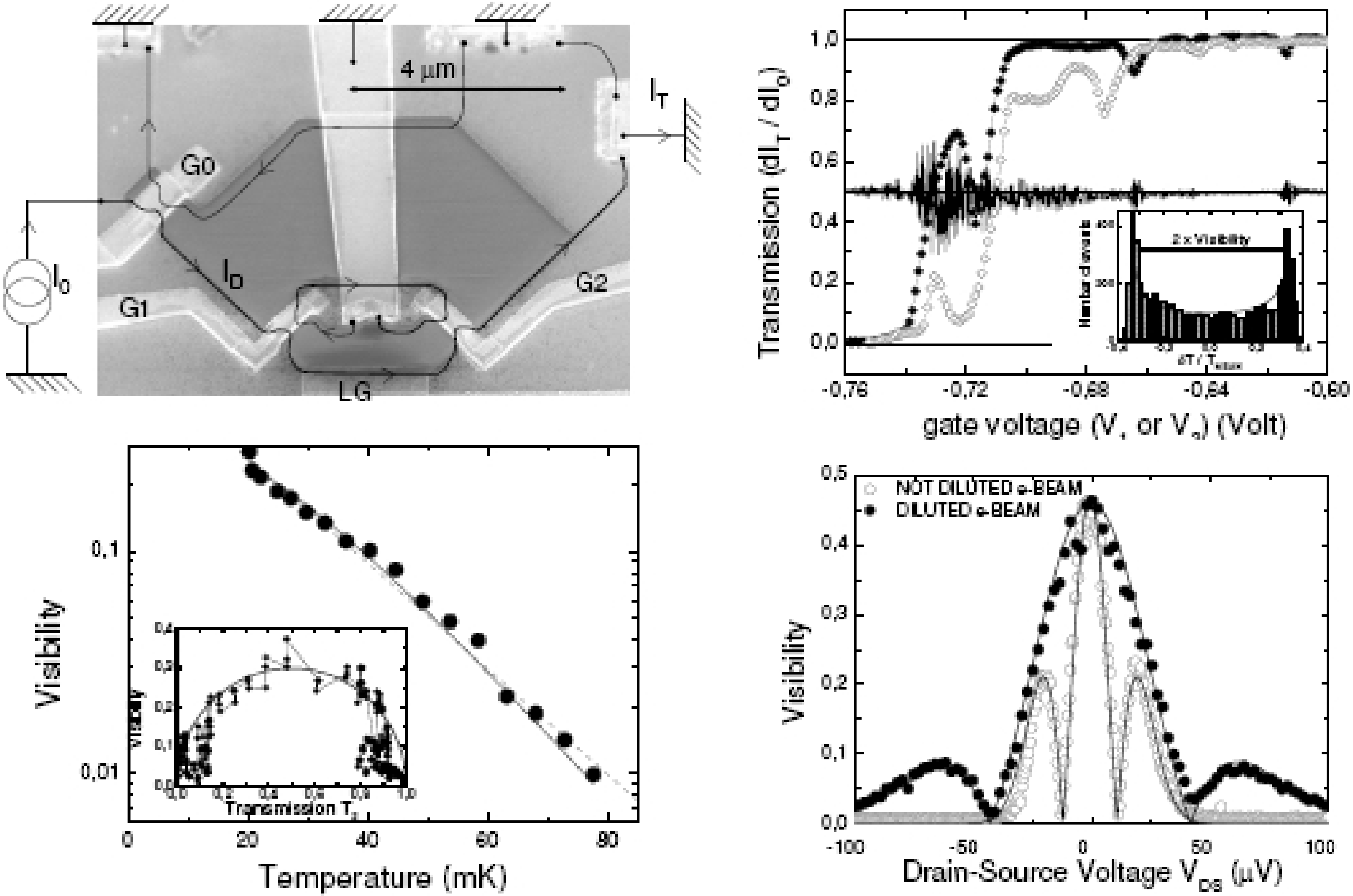
$$v = \frac{2\pi k_B T}{eV} \frac{|sin(\frac{eV}{2E_b})|}{sinh(\frac{\pi k_B T}{E_b})}$$

Chung, Samuelsson, and Buttiker, PRB 72, 125320 (2005)

Electrical Mach-Zehnder Interferometer IV

Roulleau, Portier, Glattli, Roche, Faini, Gennser, and D. Mailly, cond-mat/0704.0746

phase fluctuations!



Failure to see two-particle AB-effect: Is there something wrong with theory?

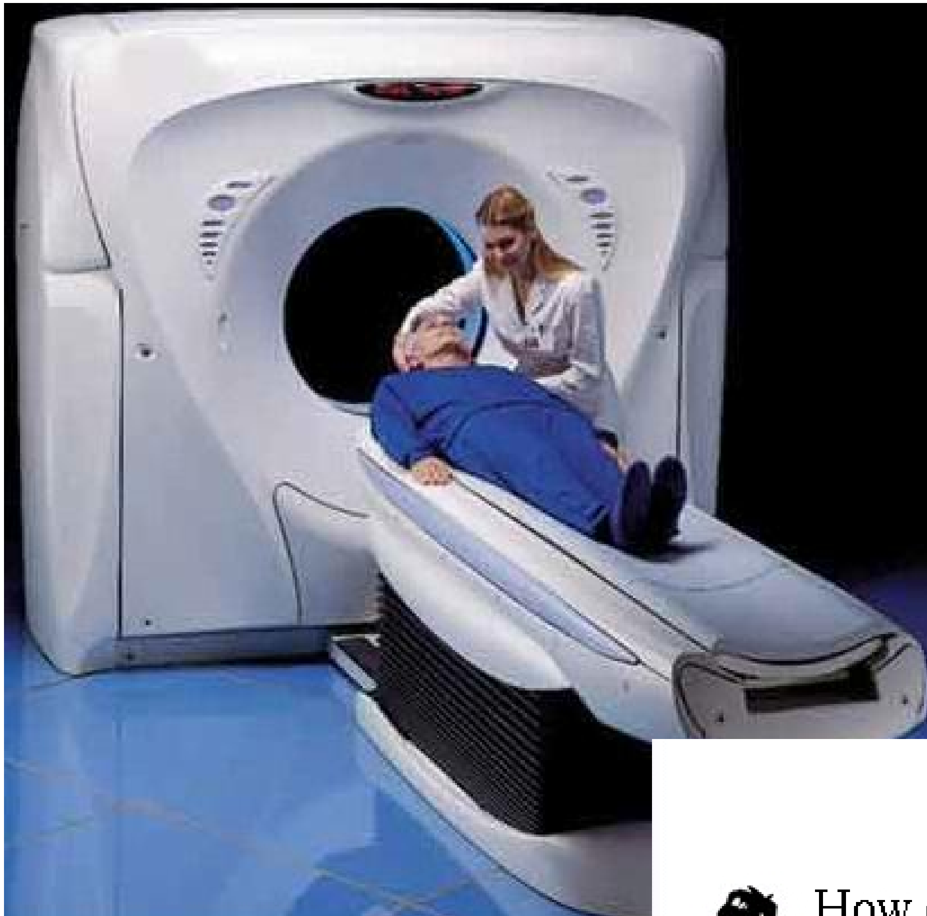
Theory missing Luttinger like physics

Resonant dephasing of the electronic Mach-Zehnder interferometer
E.V. Sukhorukov, V. V. Cheianov, cond-mat/0609288

Electrons in different reservoirs already entangled

Suppression of Visibility in a Two-Electron Mach-Zehnder Interferometer
Ya. M. Blanter, Yuval Gefen, cond-mat/0703186

Tomography: Medical

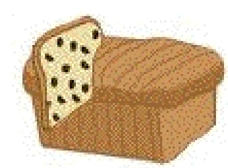


Cormack and Hounsfield

J. Radon, 1917

Projecting Shadows

How can you get a picture of a slice of something without cutting it apart?



Pauli's question

M. G. Raymer, Contemporary Physics, 38, 343 (1997)

Pauli's question (1933) :

Can the wave function $\Psi(x)$ be determined uniquely from the distribution of position and momentum?

No: such data is not tomographically complete.

Pauli question generalized:

Can one infer the whole complex function $\Psi(x)$ from some series of measurements on a large collection of identically prepared particles?

Yes.

J. Bertrand and P. Bertrand, Found. Phys., 17, 397 (1997)

Continuous variable tomography

Wigner function

$$W(x,p_x) = \frac{1}{2\pi\hbar}\int \Psi(x+x'/2)\Psi^*(x-x'/2)exp(-ix'p_x/\hbar)dx'$$

measure

$$|\Psi_\zeta(\zeta)|^2 = \int\int W(x,p_x)\,\delta(\zeta-x-(p_x/m)t)\,dx\,dp_x$$

with Radon transformation obtain Wigner function

from Wigner obtain via inverse Fourier transform $\Psi(x+x'/2)\Psi^*(x-x'/2)$

taking $x = x'/2$ gives $\Psi(2x)\Psi^*(0)$

Quantum State Tomography: Experiments

Angular momentum state of an electron in hydrogene atom

J.R. Ashburn et al, Phys. Rev. A 41, 2407 (1990).

Quantum state of squeezed light

D.T. Smithey et al, Phys. Rev. Lett. 70, 1244 (1993).

Vibrational state o a molecule

T.J. Dunn, et al, Phys. Rev. Lett. 74, 884 (1995).

Trapped ions

D. Liebfried et al, Phys. Rev. Lett. 77, 4281 (1996).

Atomic wave packets

Ch. Kurtsiefer, T. Pfau, and Mlynek, Nature 386, 150 (1997).

Polarization entangled photons

P.G. Kwiat, et al, Nature 409, 1014 (2001);

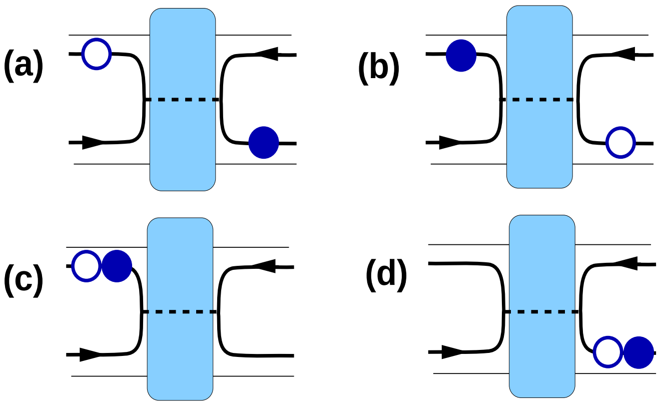
T. Yamamoto et al ibid 421, 343 (2003).

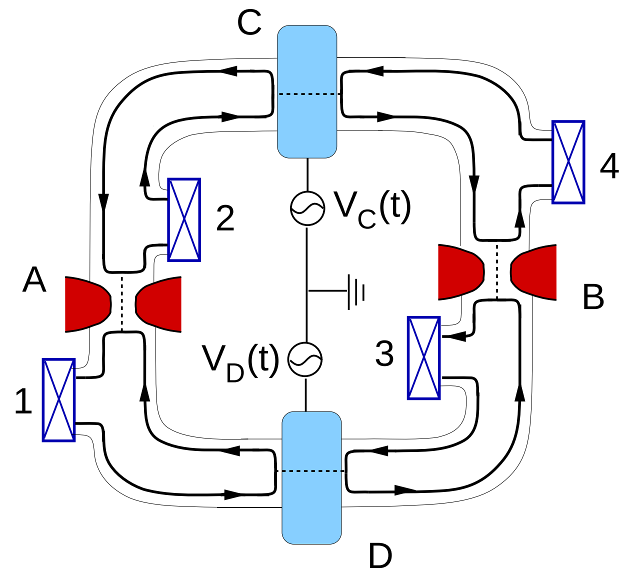
Entanglement of two superconducting qubits

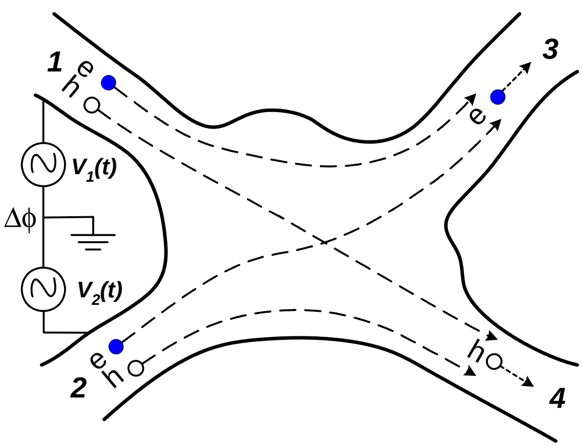
Matthias Steffen et al, *Science* 313, 1423 (2006)

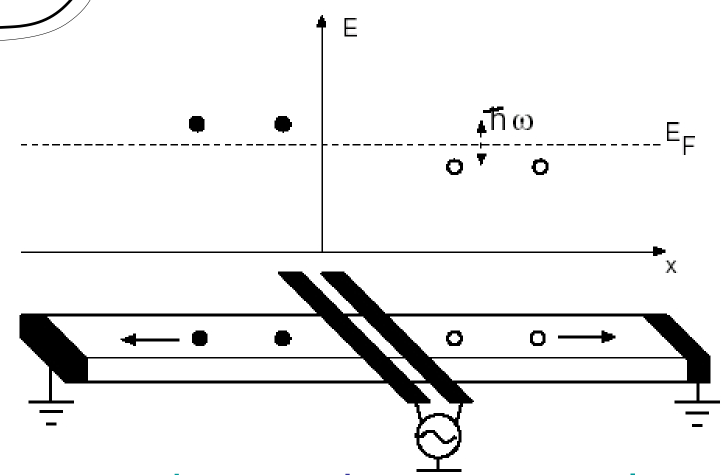
Dynamic electron-hole generation

Samuelsson and Buttiker, Phys. Rev. B 72, 155326 (2005)









Rychkov, Polianski, Buttiker,

Phys. Rev. B 72, 155326 (2005)

C. W. J. Beenakker, M. Titov, and B. Trauzettel,

Phys. Rev. Lett. 94, 186804 (2005)

Multi-particle correlations of an oscillating scatterer,

M. Moskalets, M. Buttiker,

PRB 73, 125315 (2006).

Summary

Shot noise correlations probe two-particle physics

Two-particle Aharonov-Bohm interferometer

Orbital entanglement

Bell test of orbital entanglement

Orbital quantum state tomography

Shot noise measurements determine the reduced two-particle density matrix up to local rotations

Tomography delivers not only a criteria for entanglement but allows to experimentally quantify entanglement

$$E = E(\rho_{AB})$$