Controlled Dephasing of Mesoscopic Systems

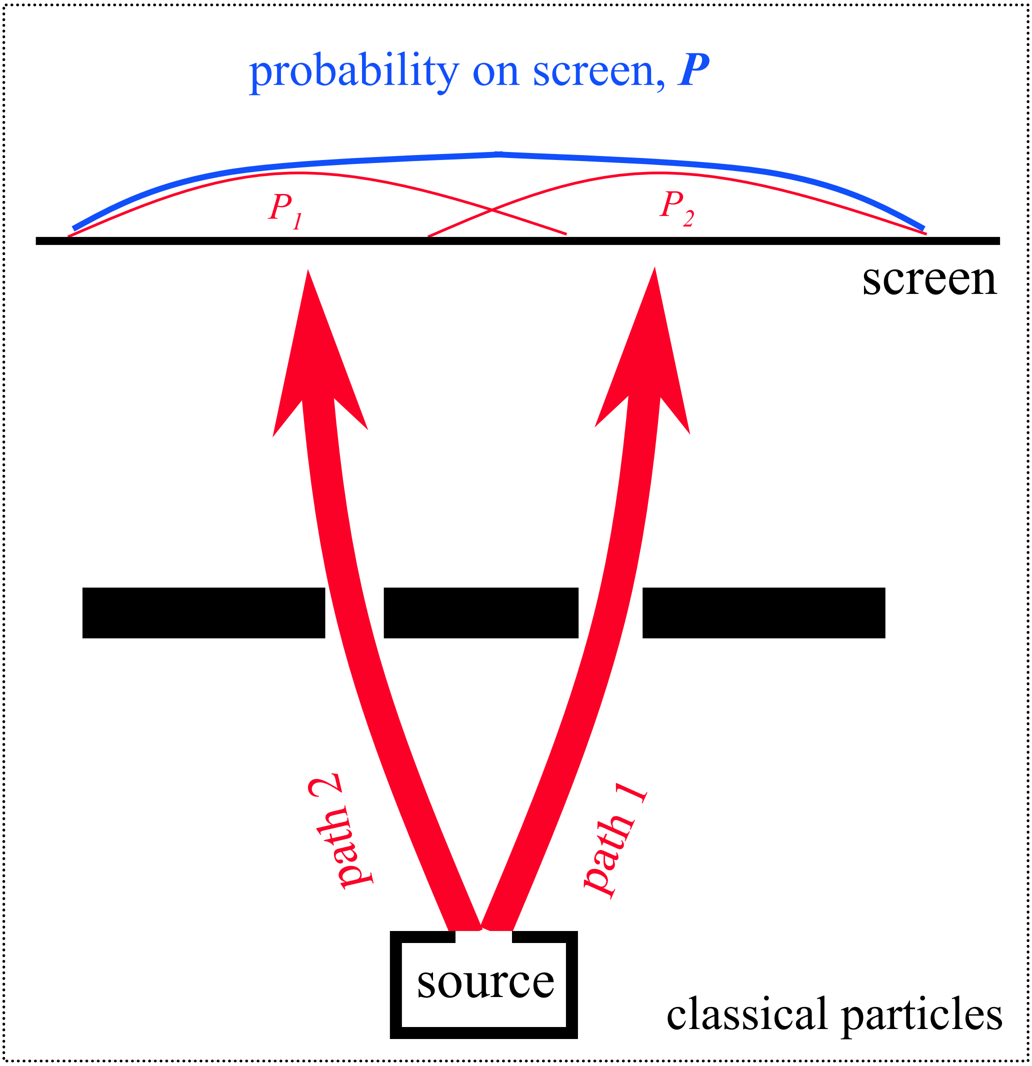
- *which path* experiments -

Braun Center for Sub Micron Research
Weizmann Institute of Science, Israel

M. Heiblum

- build interferometer – basic blocks
- employ two types of *which path* detectors

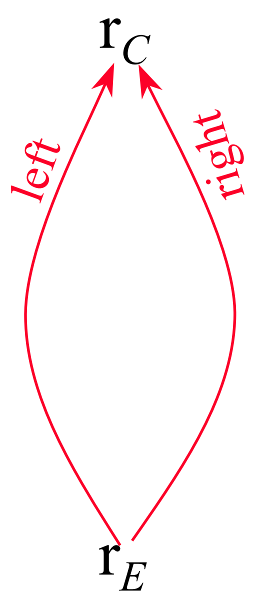
classical particles



$$P = P_1 + P_2$$

quantum particles

A. Stern *et al*., PRA **41**, 3436 ('90)



no coupling to environment

$$|\psi\rangle = |\varphi_l\rangle + e^{i\Delta\theta}|\varphi_r\rangle$$

wave function of interferometer

probability density to find electron at collector

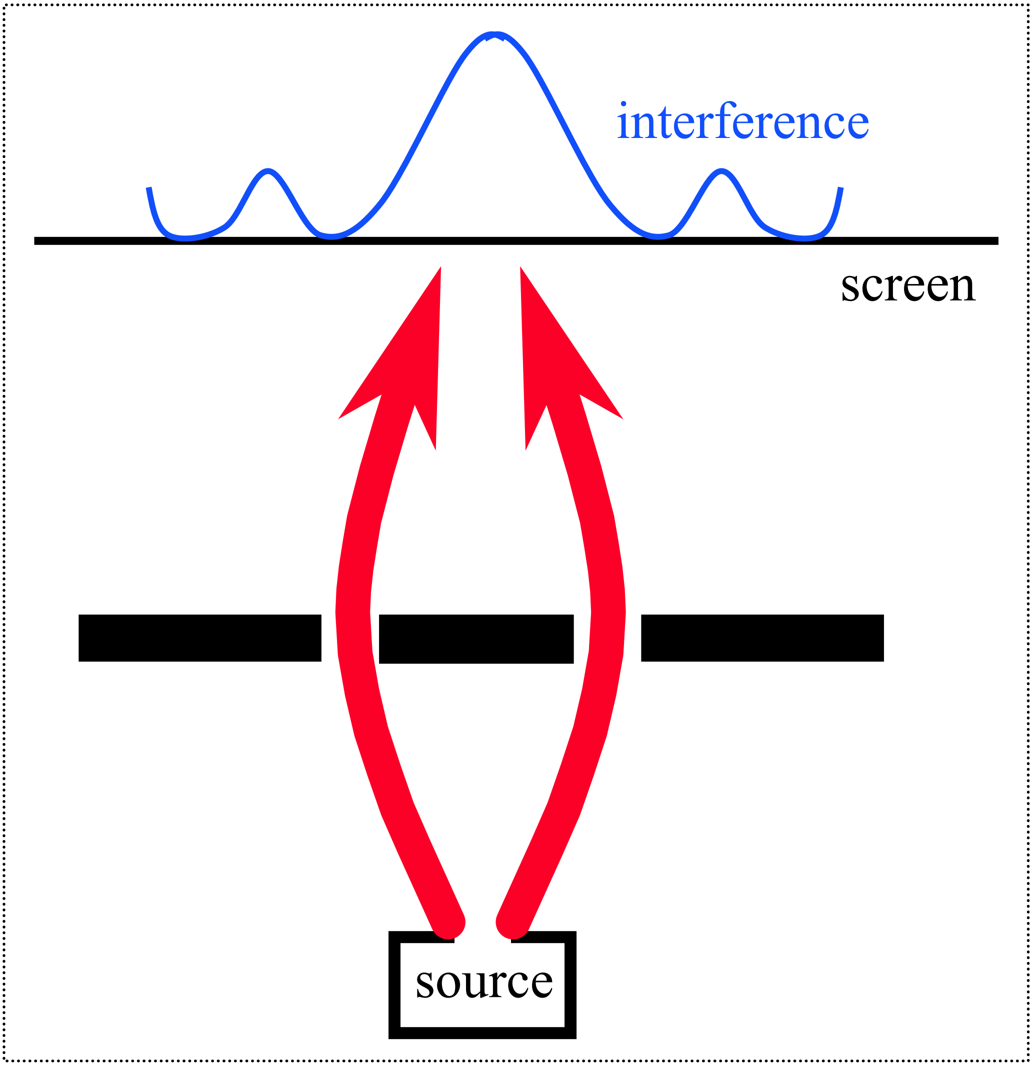
$$P(r_C) = \left|\langle\psi|r_C\rangle\right|^2$$

T_{EC}

$$P(\mathrm{r}_C) = \left|\langle\varphi_l|\mathrm{r}_C\rangle\right|^2 + \left|\langle\varphi_r|\mathrm{r}_C\rangle\right|^2 + 2\,Re\left[e^{i\Delta\theta}\langle\varphi_l|\mathrm{r}_C\rangle\cdot\langle\mathrm{r}_C|\varphi_r\rangle\right]$$

interference term

resulting interference



dephasing - decoherence

loss of interference

two equivalent ways to understand dephasing

Stern, Aharonov, Imry, PRL (1989)

<u>phase randomization</u>

- electron-phonon
- electron-electron
- spin flip
- potential fluctuations

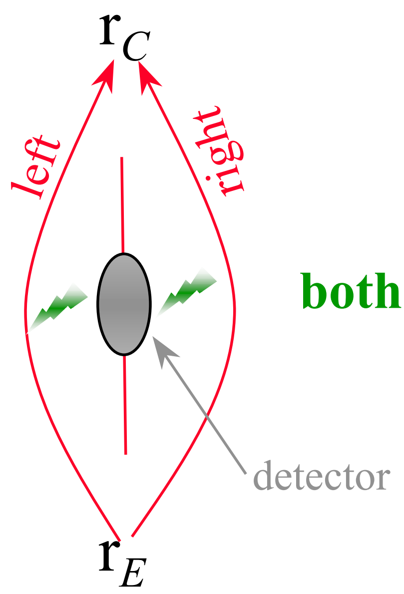
<u>path determination</u>

- a detector
  ‘even if possible
  only in principle’

employ *which path* detectors – serving as controlled environment

to control dephasing

symmetric coupling of *two path* interferometer with environment



both paths couple equally to environment

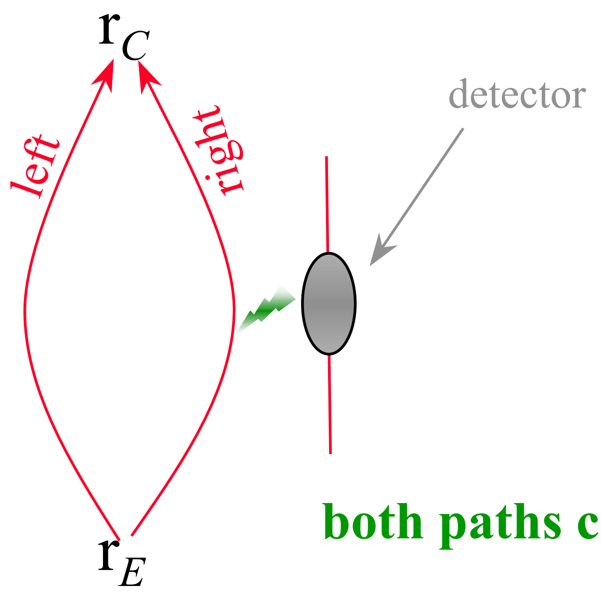
normalized wave function of detector $\langle\chi|\chi\rangle = 1$

$$|\psi\rangle = \left[|\varphi_l\rangle + e^{i\Delta\theta}|\varphi_r\rangle\right] \otimes |\chi\rangle$$

wave function of coupled system

- the wave function of the whole system is factorable
- detector cannot determine electron’s path
- interference exists !

non-symmetric coupling of *two path* interferometer with environment



both paths couple differently to environment

$$|\psi\rangle = |\varphi_l\rangle \otimes |\chi_l\rangle + e^{i\Delta\theta}|\varphi_r\rangle \otimes |\chi_r\rangle$$

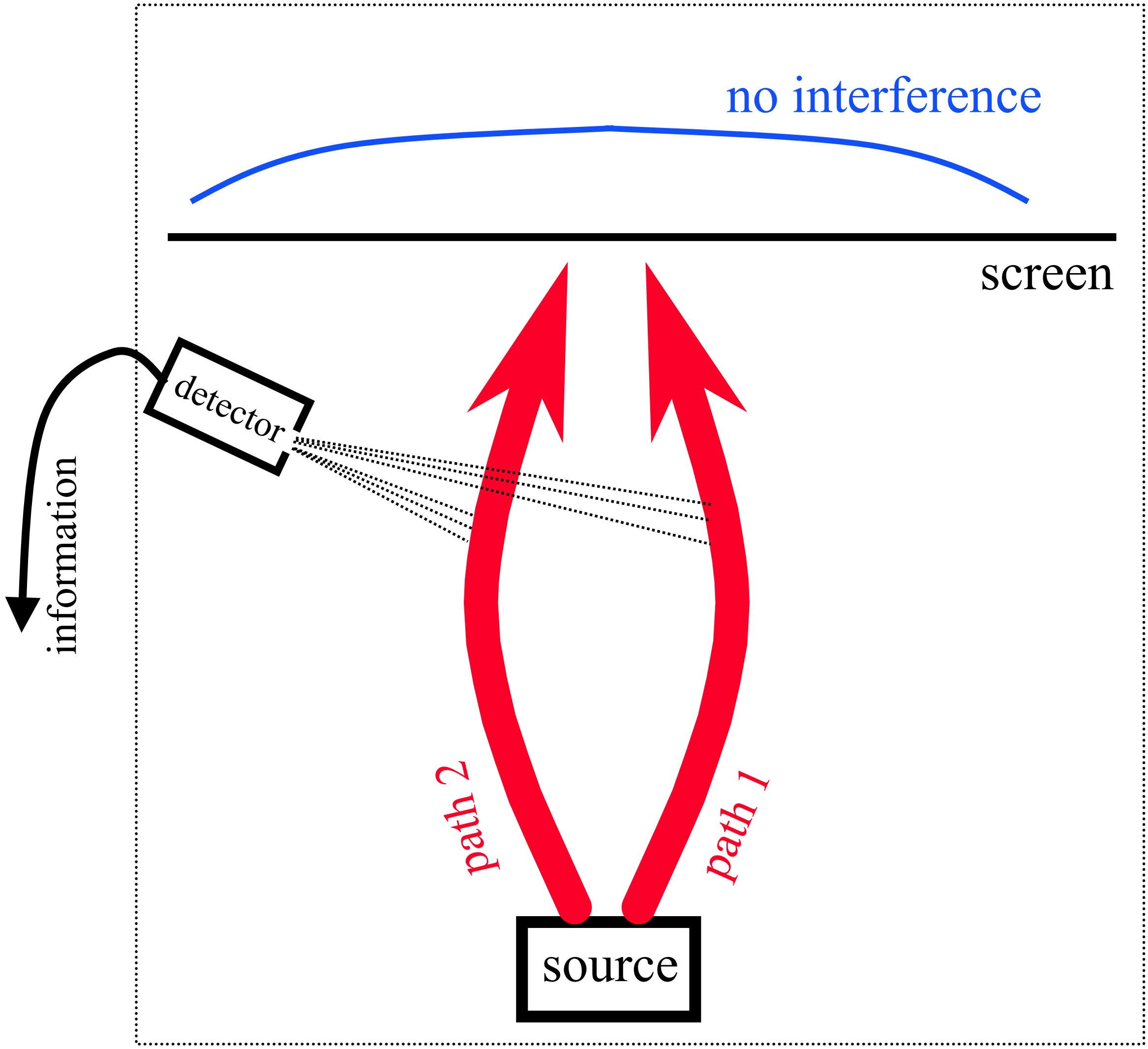
wave function of coupled system
entangled – non factorable

probability density to find electron at collector

$$P(\mathrm{r}_C) = \sum_i \left| \langle\psi|\mathrm{r}_C\rangle \otimes |\chi_i\rangle_d \right|^2$$; *i* - two detector states

$$P(\mathrm{r}_C) = \left| \langle\varphi_l|\mathrm{r}_C\rangle \right|^2 + \left| \langle\varphi_r|\mathrm{r}_C\rangle \right|^2 + 2\,Re\left[e^{i\Delta\theta} \langle\varphi_l|\mathrm{r}_c\rangle \cdot \langle\mathrm{r}_c|\varphi_r\rangle \cdot \boxed{\langle\chi_r|\chi_l\rangle}\right]$$

dephasing = paths determination

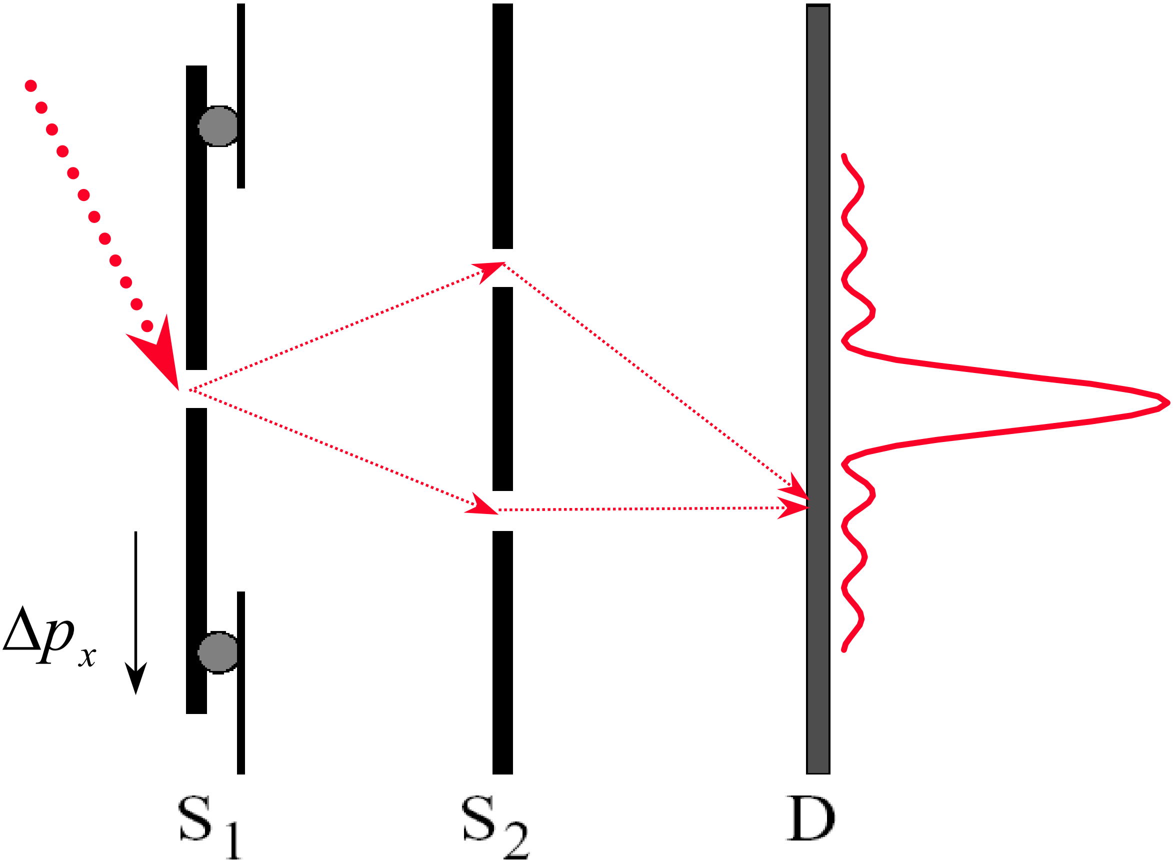


- when paths are fully distinguishable…*or:*
- when detector interacts and dephases paths

interference vanishes

which slit detection

Einstein - Bohr GedankenExperiment

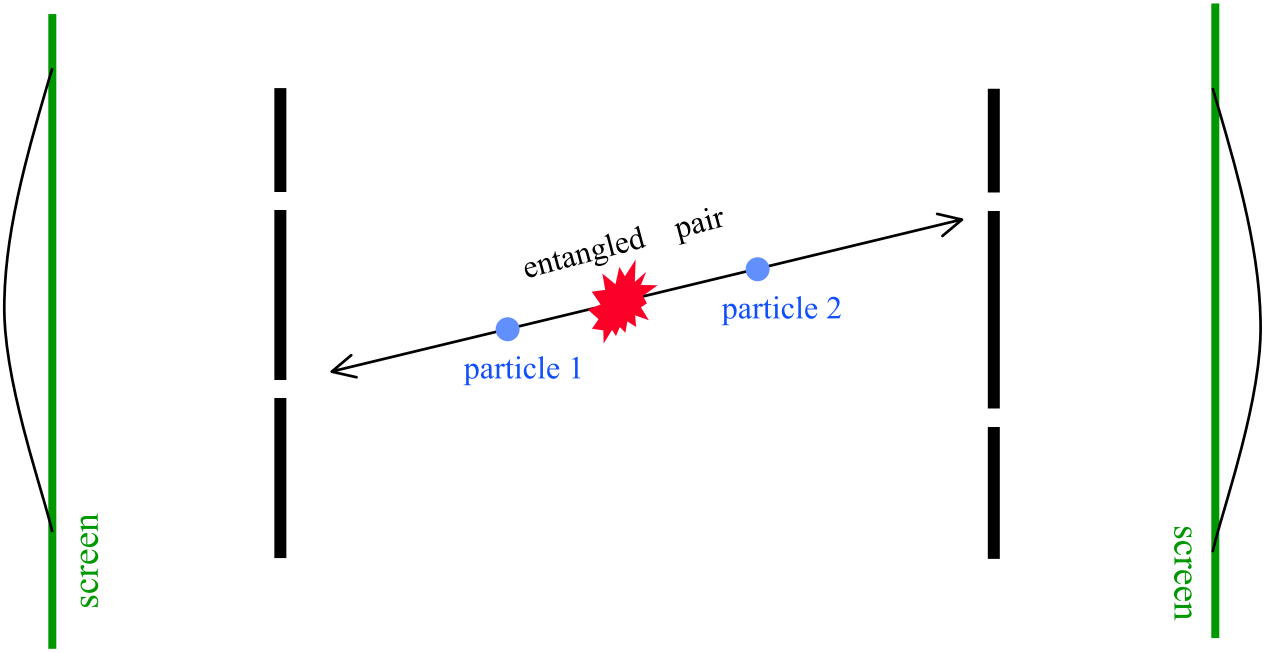


Schematic setup for Einstein's "recoiling-slit" thought-experiment. The single slit S_1 is movable with respect to the double slit S_2 and the detector D, so that the momentum transfer from the particle to S_1 can be measured, in order to determine which slit in S_2 the particle traversed on its way to the detector D.

$$\Delta p_x \approx h / \Delta x$$

path detection via EPR paradox

- entanglement of electrons -



two particles are entangled in momentum:

- knowing momentum of particle 1 determines that of particle 2 ;
- Particle 1 or particle 2 won’t interfere individually on each screen ;
- coincidence interference of both particles on both screens exists.

each particle serves as **the detector** of the other particle

visibility due to *which path* measurement

visibility of the interference pattern ………….. $\nu = \nu_0 \nu_d$

$$\nu_0 = \frac{2\left|\,\langle\varphi_l|\mathrm{r}_c\rangle \bullet \langle\mathrm{r}_c|\varphi_r\rangle\,\right|}{\left|\,\langle\varphi_l|\mathrm{r}_c\rangle\,\right|^2 + \left|\,\langle\varphi_r|\mathrm{r}_c\rangle\,\right|^2} < \mathbf{1}$$

a priori which path informatio

$$\nu_d = \left|\,\langle\chi_r|\chi_l\rangle\,\right| < \mathbf{1}$$

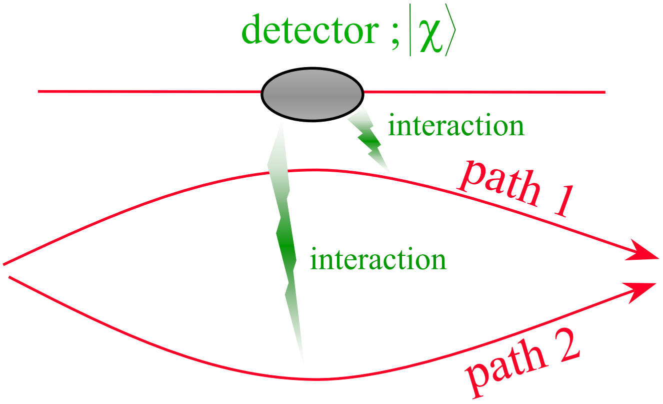
which path information

$$\nu_d(t) \equiv e^{-t/\tau_\varphi}$$

……… τ_φ -- *dephasing time*

entanglement -- leads to dephasing !

remember: two views of dephasing



electron in path 1 -- detector in state $|\chi_1\rangle$

electron in path 2 -- detector in state $|\chi_2\rangle$

$\langle\chi_1|\chi_2\rangle < 1$ → path discrimination

↓

DEPHASING

potential fluctuations in the detector scramble the phase in paths

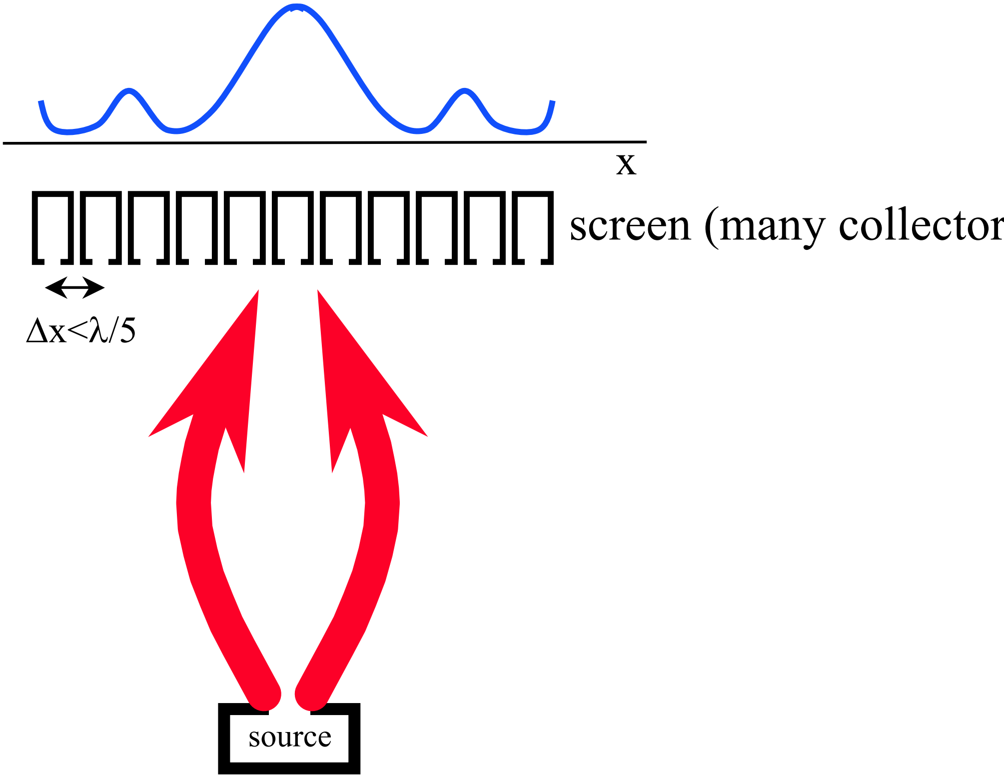
↓

DEPHASING

$$P(\mathrm{r}_C) = \left|\,\langle\varphi_l|\mathrm{r}_C\rangle\,\right|^2 + \left|\,\langle\varphi_r|\mathrm{r}_C\rangle\,\right|^2 + 2\,Re\left[e^{i\Delta\theta}\langle\varphi_l|\mathrm{r}_C\rangle\cdot\langle\mathrm{r}_C|\varphi_r\rangle\right]$$

observing interference

photons



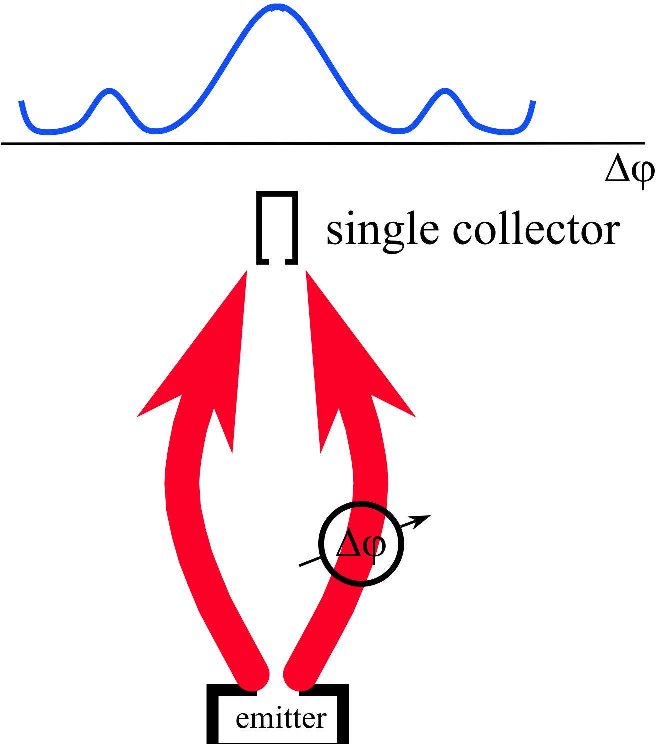
x

screen (many collector

Δx<λ/5

source

electrons



Δφ

single collector

Δφ

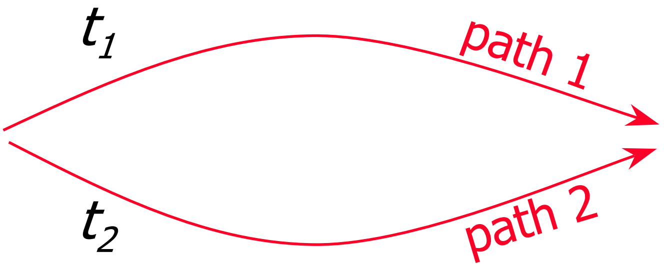
emitter

but, we measure conductance

Landauer conductance $G = \left| \sum t_i e^{i\varphi_i} \right|^2$

transmission amplitude $\dfrac{\langle \psi_i | r_C \rangle}{\langle \psi_i | r_E \rangle} = t_i e^{i\varphi_i}$

transmission coefficient $T_i = \left| t_i e^{i\varphi_i} \right|^2$



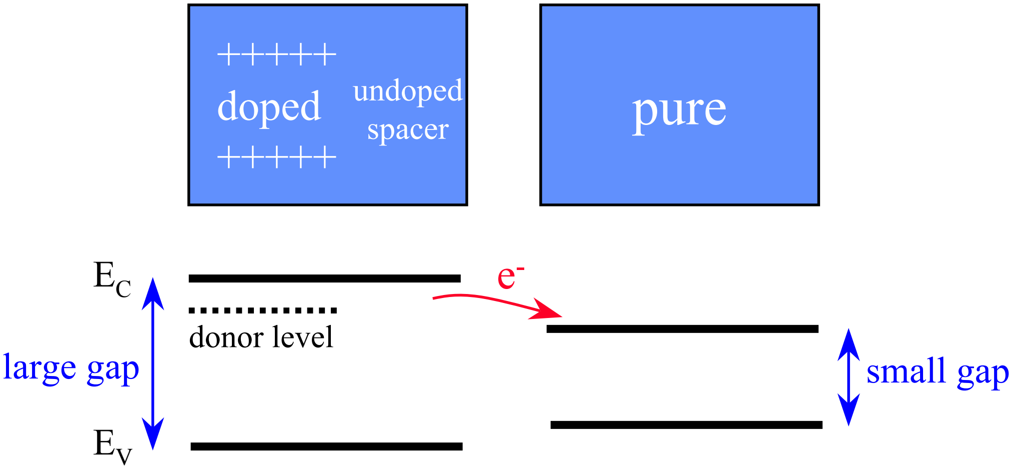
$$G = \frac{e^2}{h} \{ T_1 + T_2 + 2t_1 t_2 \cos[\varphi(t_1) - \varphi(t_2)] \}$$

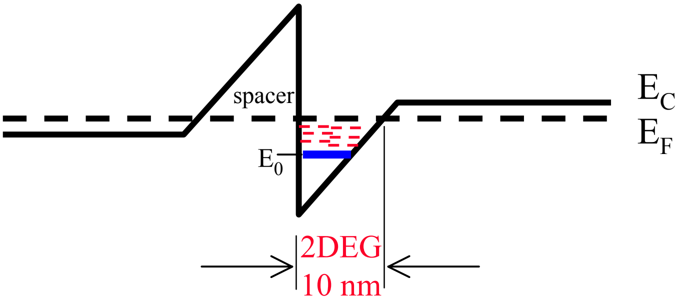
experimental playground

Two **D**imensional **E**lectron **G**as **(2DEG)**

⇓

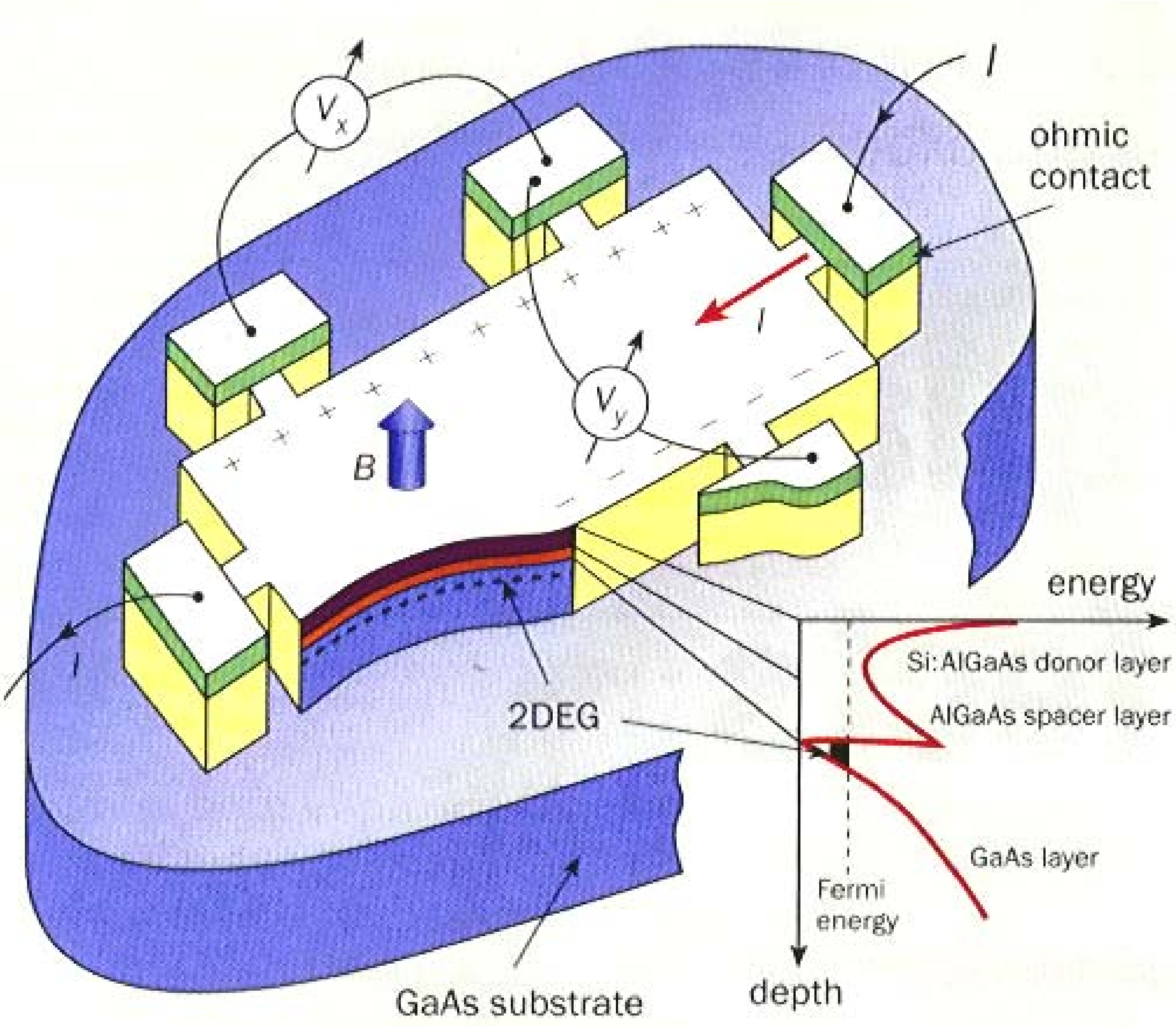
minimum scattering and long dephasing length





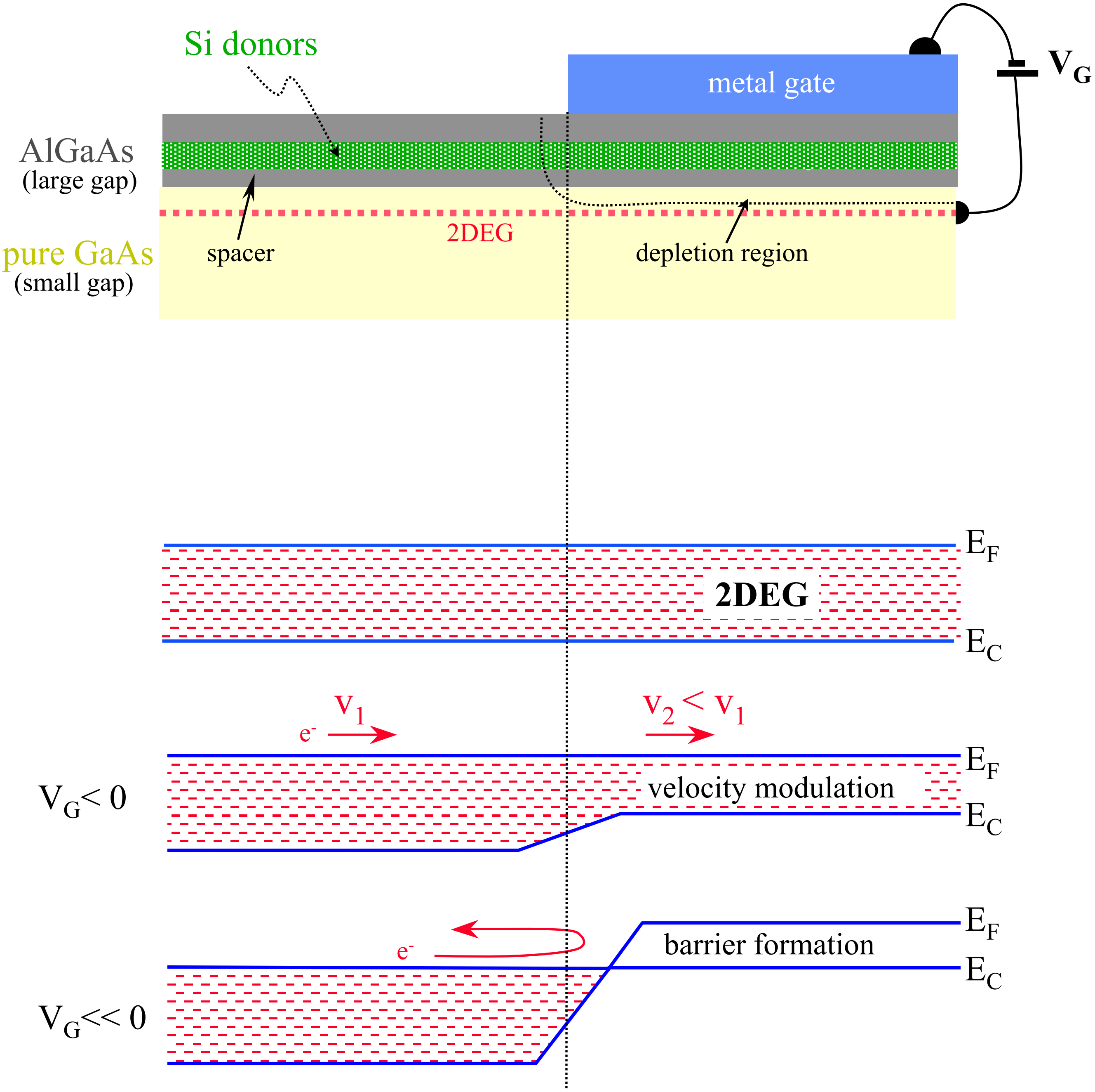
Temp. < 1 K
mfp ≈ 1- 150 µm
$n_s \approx 10^{11}\text{-}10^{12}$ cm^{-2}
$E_F \approx 10 - 20$ meV

making 2DEG

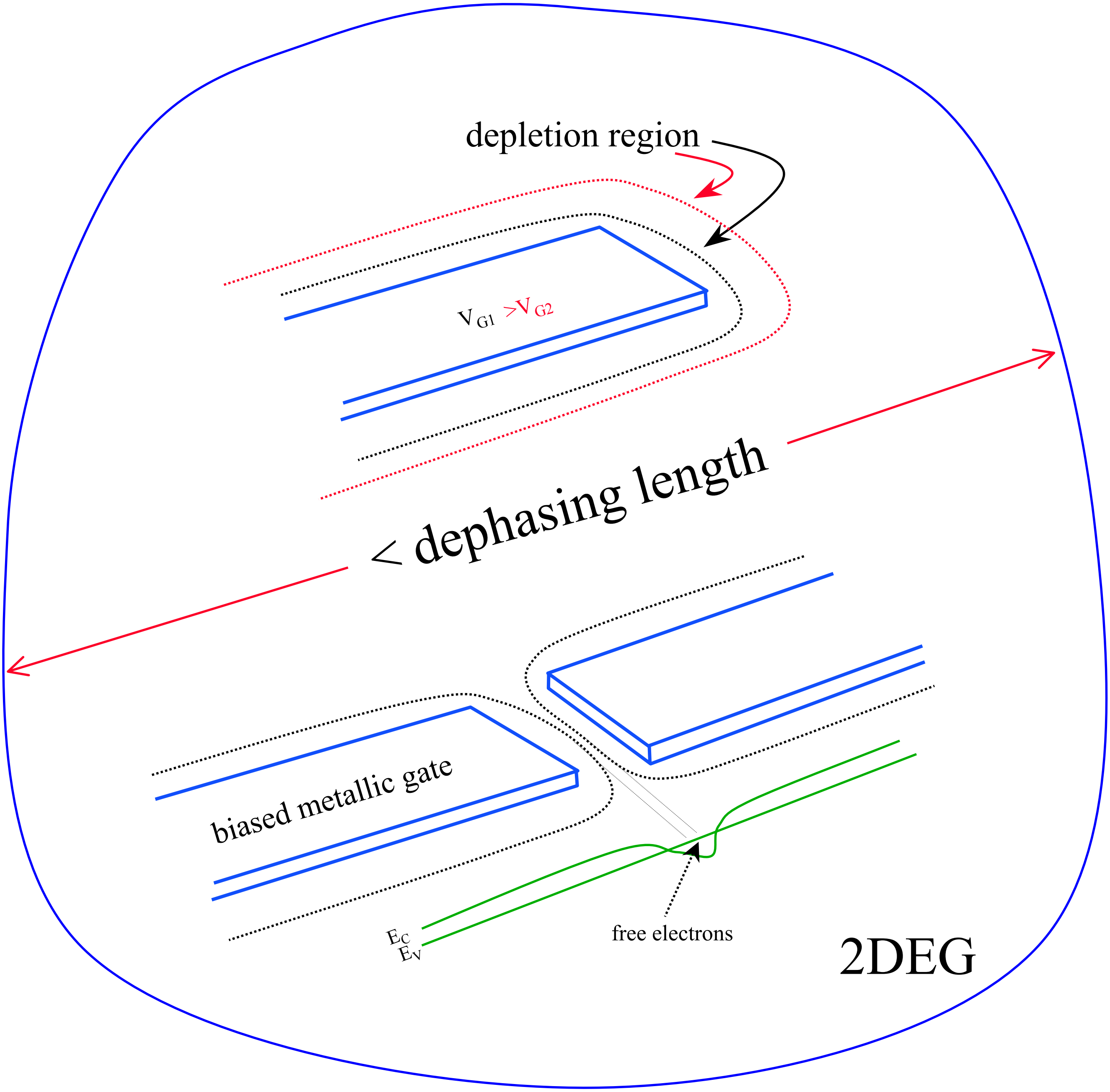


V_x
I
ohmic contact
I
B
V_y
I
energy
Si:AlGaAs donor layer
AlGaAs spacer layer
2DEG
GaAs layer
Fermi energy
GaAs substrate
depth

gates on 2DEG

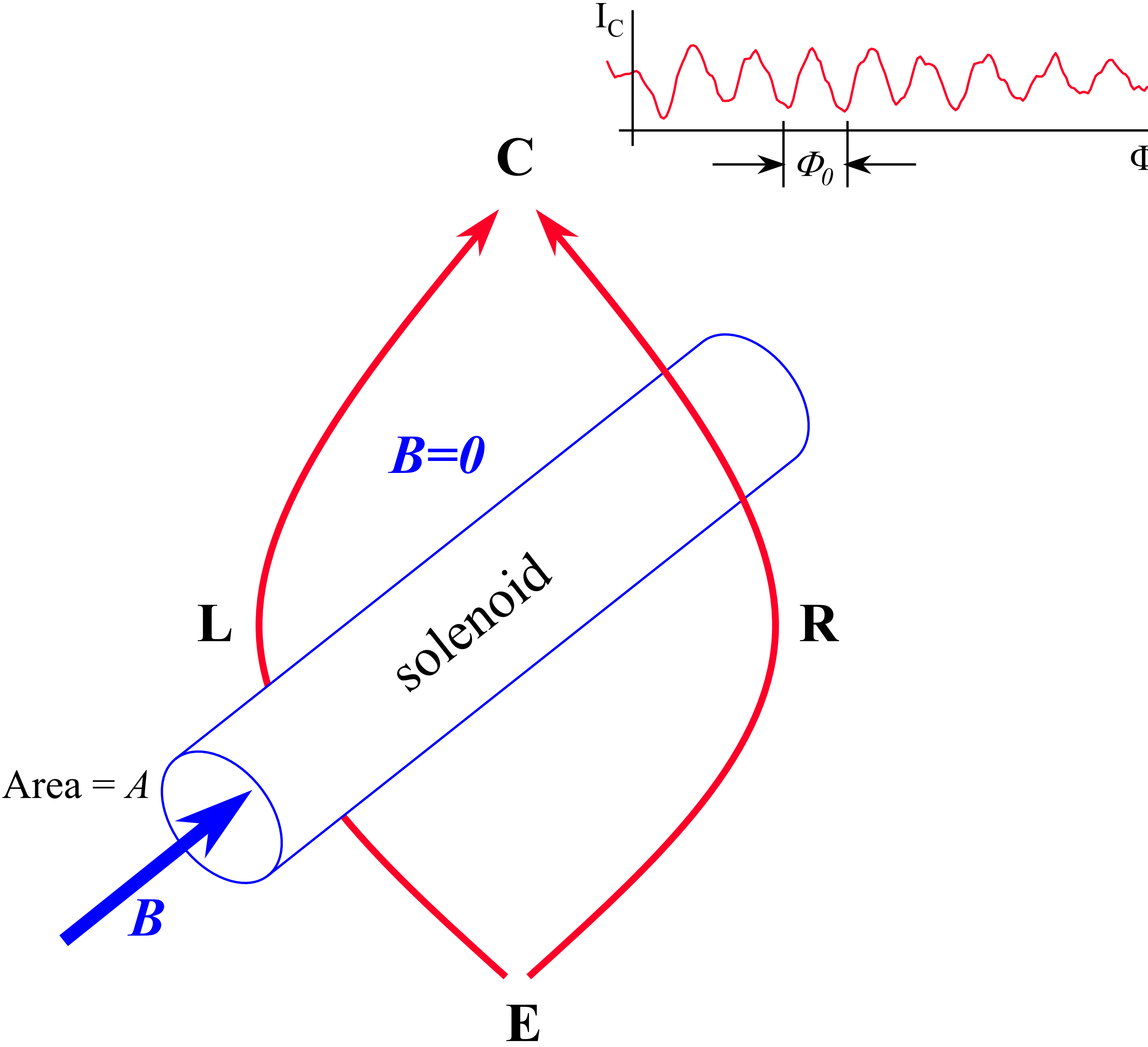


patterning 2DEG



build interferometer and detector on 2DEG …

$\Delta\varphi$ … Aharonov-Bohm phase

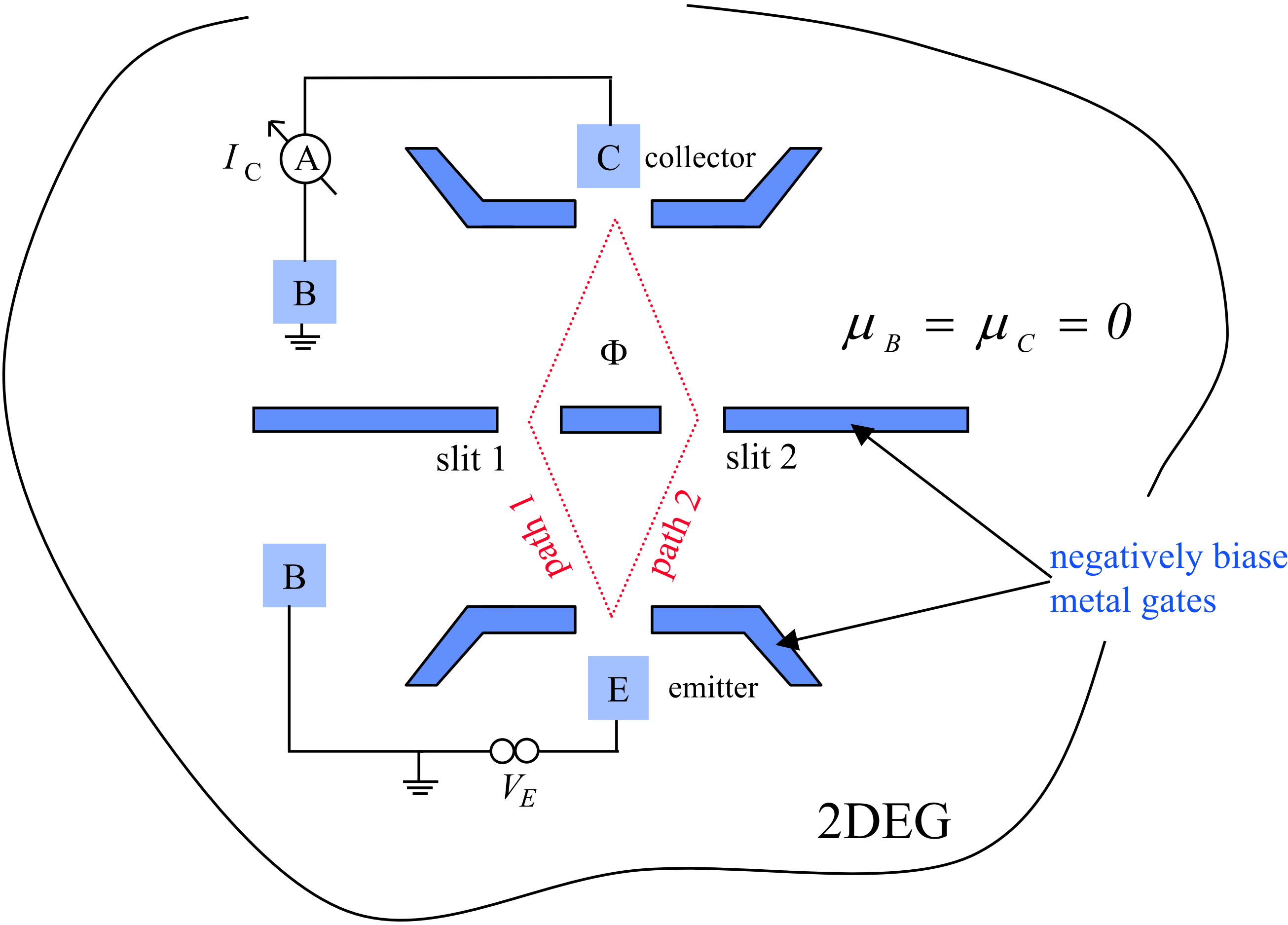


$$\Delta\varphi = \Delta(\varphi_R - \varphi_L) = \varphi_{A-B} = 2\pi \frac{\overset{\Phi}{B \cdot A}}{\Phi_0}$$

$\Phi_0 = h/e$

flux quantum

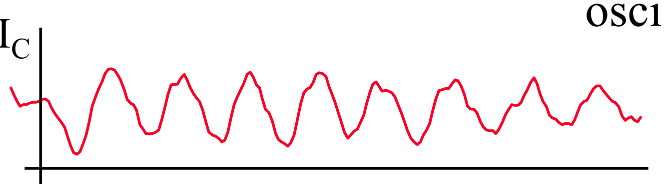
two path interferometer - realization in 2DEG



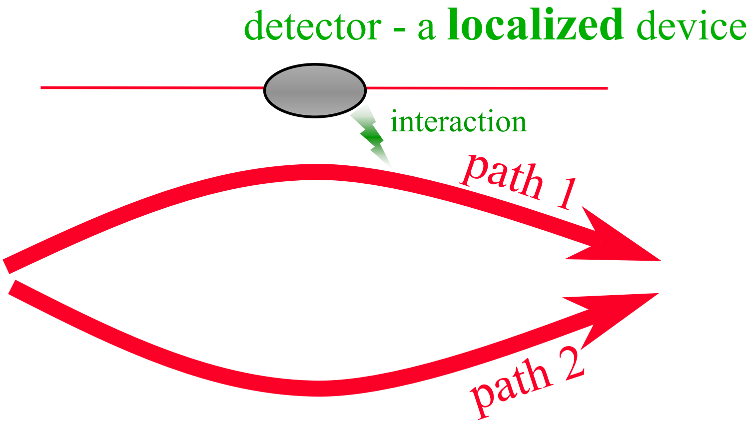
$$T_{EC} = \left|t_{EC}\right|^2 = \left|t_{slit\,1} + e^{i\Delta\varphi} \cdot t_{slit\,2}\right|^2$$

AB phase

$$T_{EC} = \left|t_{slit\,1}\right|^2 + \left|t_{slit\,2}\right|^2 + \underbrace{2\left|t_{slit\,2}\right| \cdot \left|t_{slit\,1}\right| cos(\Delta\varphi + \varphi_{slit\,2} - \varphi_{slit\,1})}_{\text{oscillatory behavior with phase!}}$$



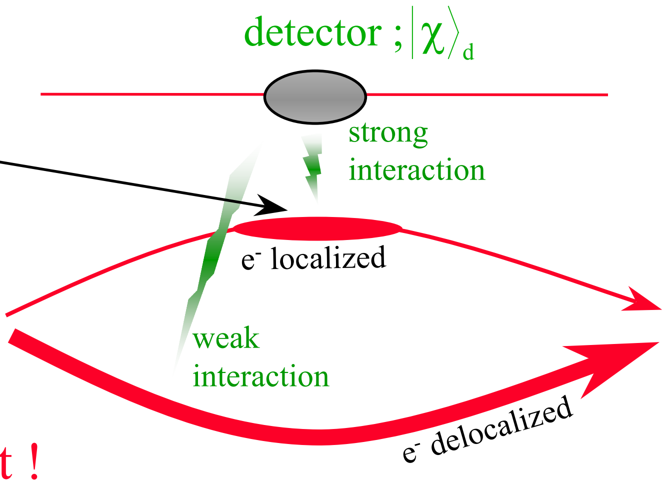
adding a detector



electrons are ***delocalized*** !

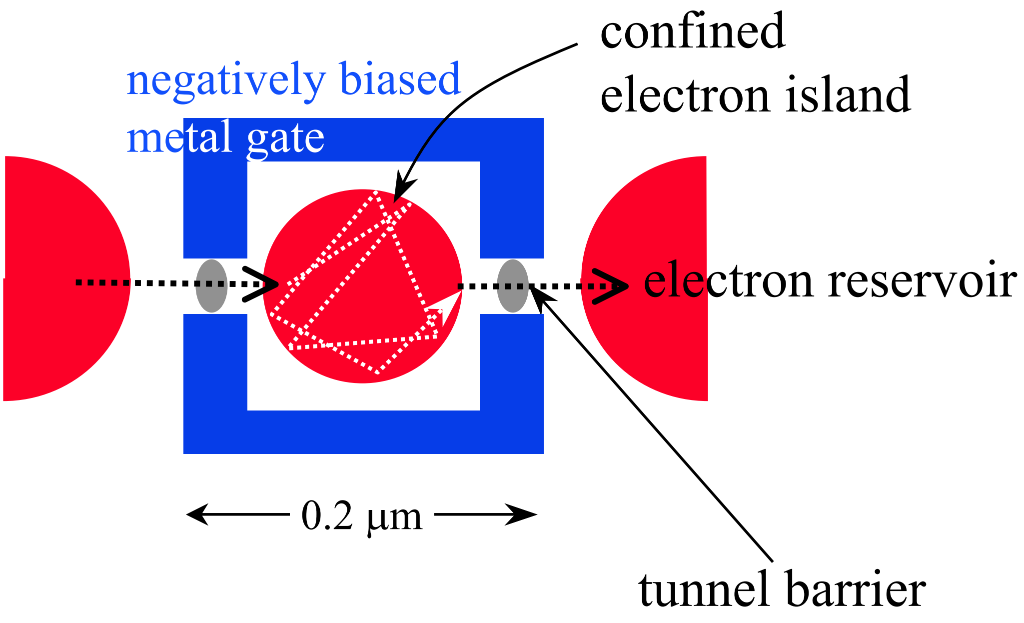
weak ‘*detector* - *electron in path*’ interaction

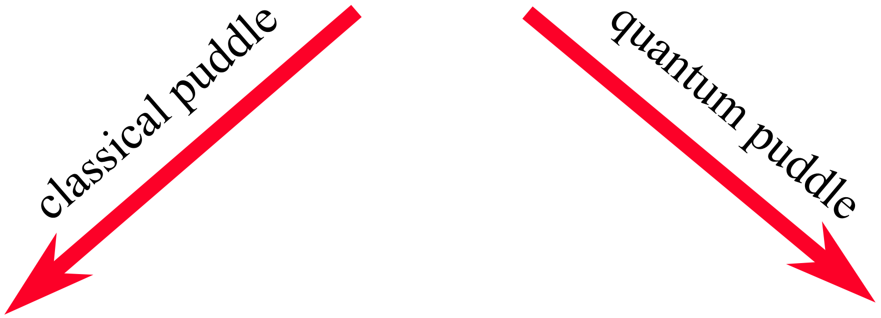
localize electron in path 1



localization must be coherent !

localizing electrons by a confined puddle



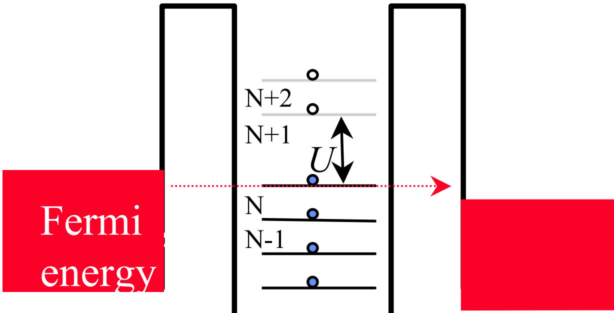


small capacitance

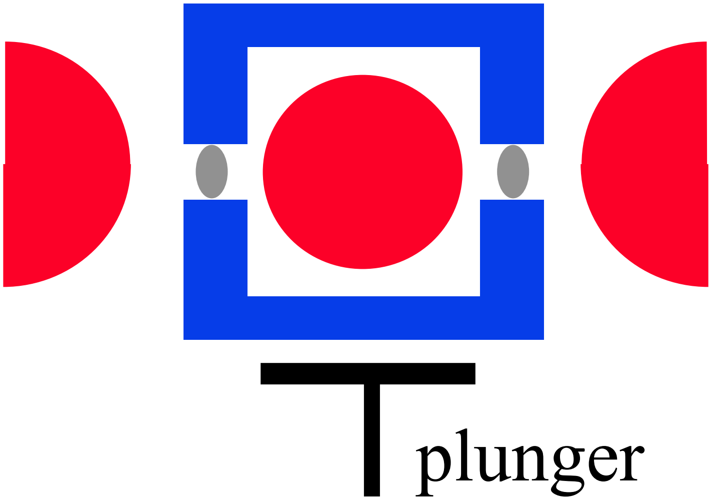
energy quantization

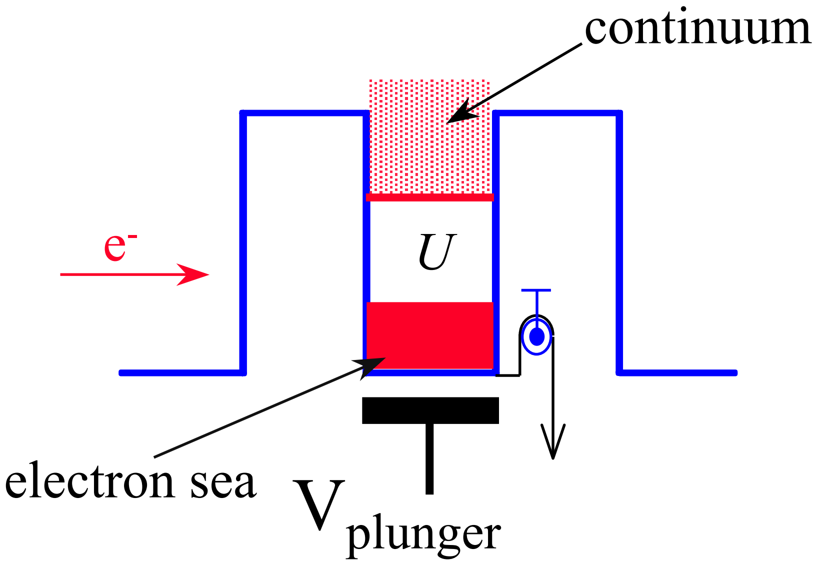
adding electron requires

charging energy $U = e^2/2C$

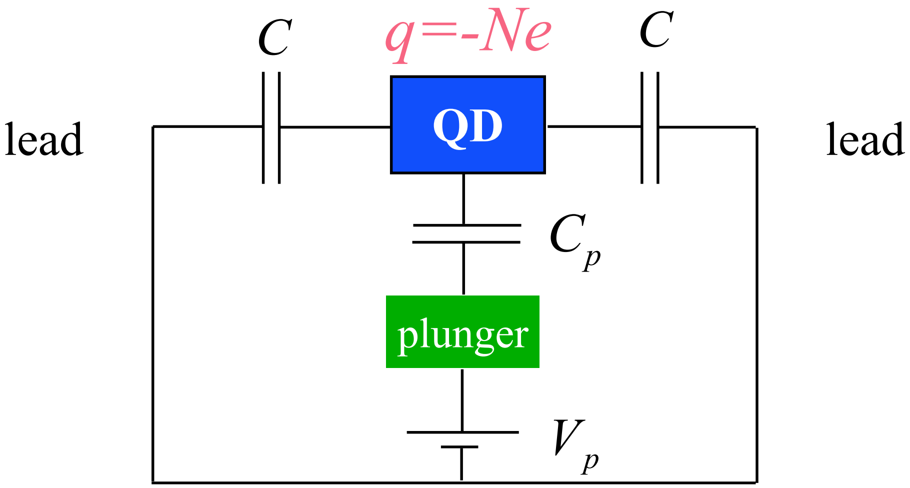


classical puddle



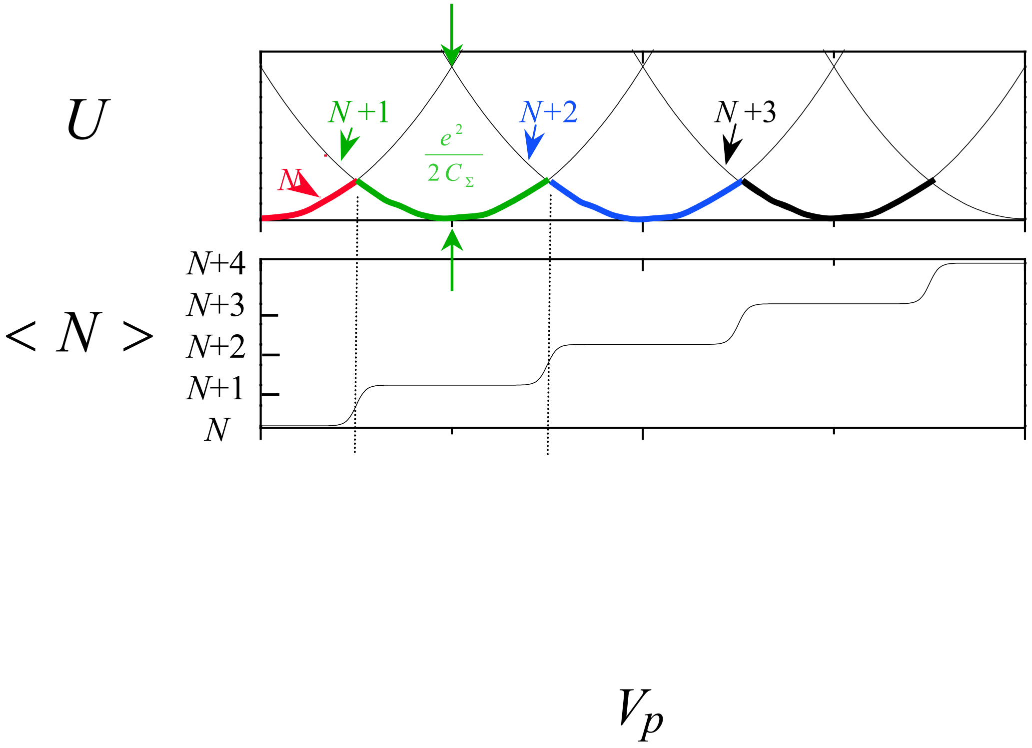


modeling classical puddle



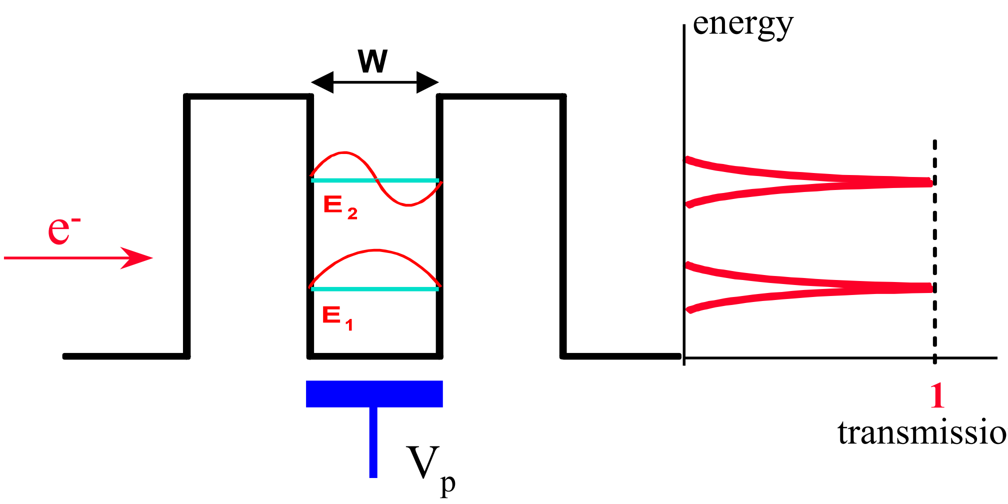
electrostatic energy ……… $$U = \frac{(C_pV_p + q)^2}{2C_\Sigma}$$

$$C_\Sigma = 2C + C_p$$

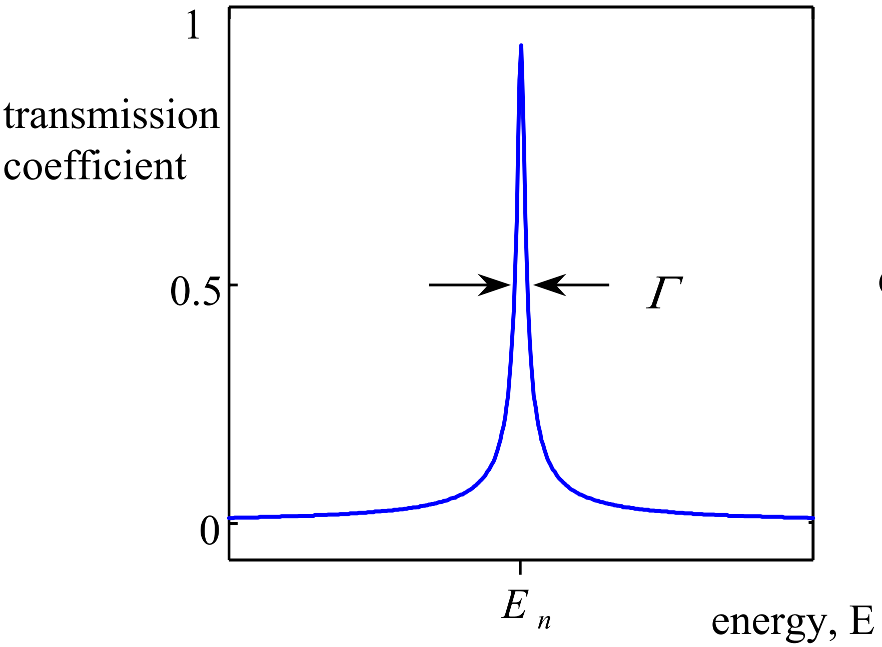


modeling quantum puddle

- quantum dot (QD) -



resonant tunnelling

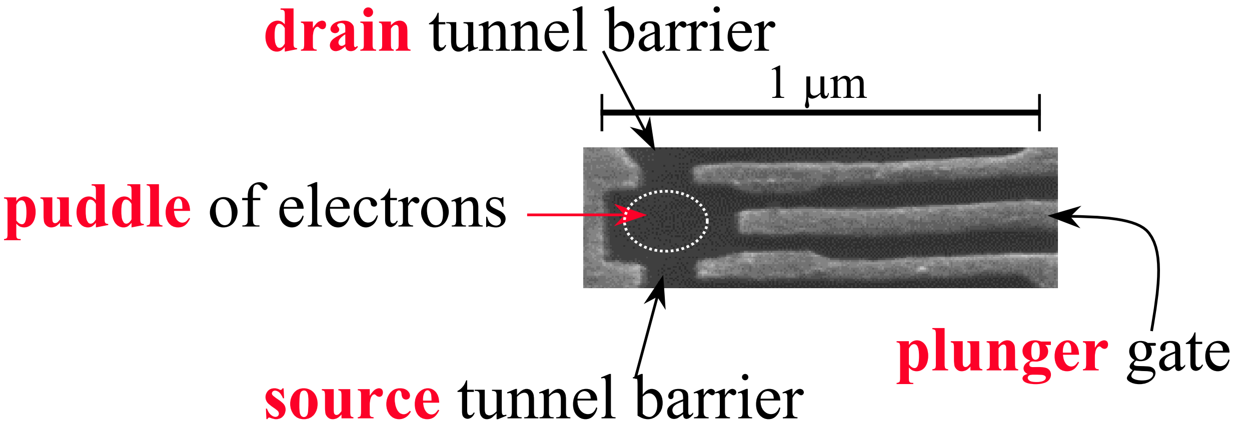


dwell time ~ h/Γ

$$\left|t_{QD}\right|^2 = \left|C_n\right|^2 \frac{(\Gamma/2)^2}{(E-E_n)^2+(\Gamma/2)^2}$$

transmission coefficient

realization of a quantum dot



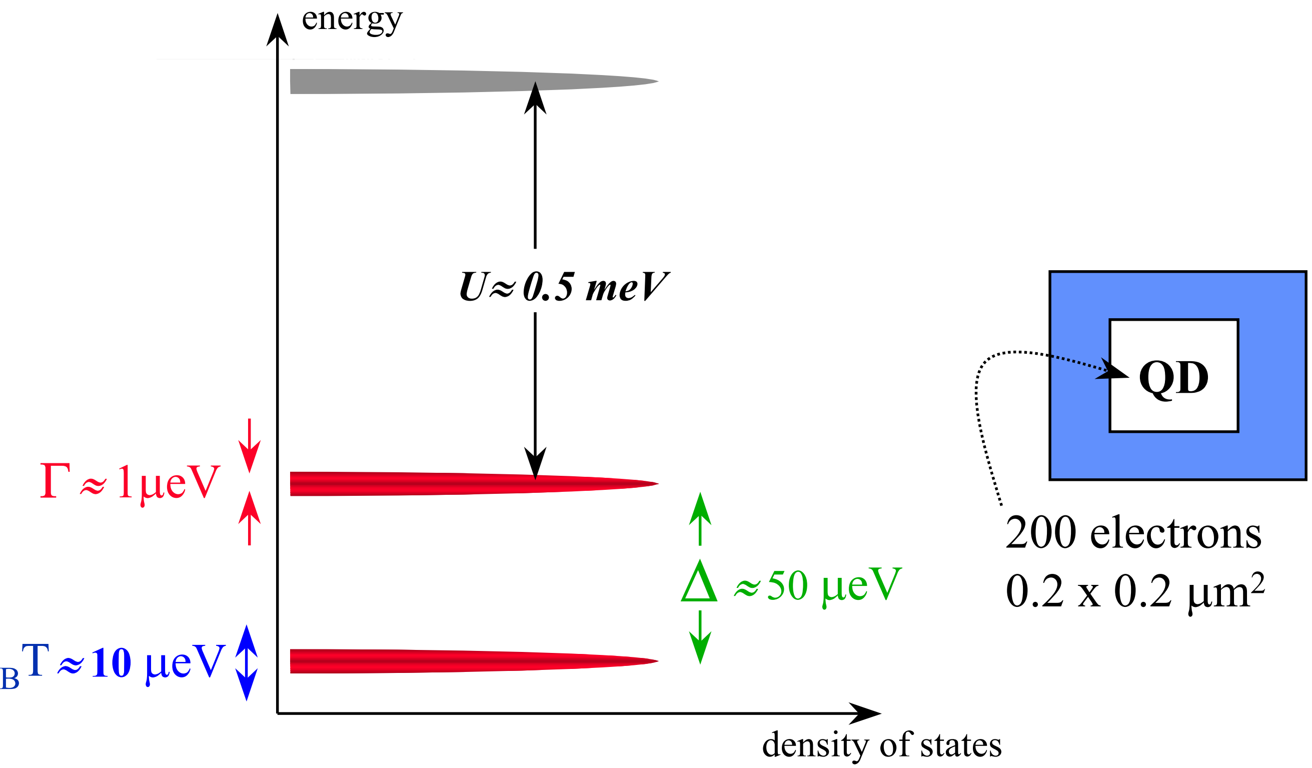
drain tunnel barrier

1 μm

puddle of electrons

plunger gate

source tunnel barrier



energy

$U \approx 0.5$ meV

$\Gamma \approx 1 \mu\text{eV}$

$\Delta \approx 50\ \mu\text{eV}$

$_{B}T \approx \mathbf{10}\ \mu\text{eV}$

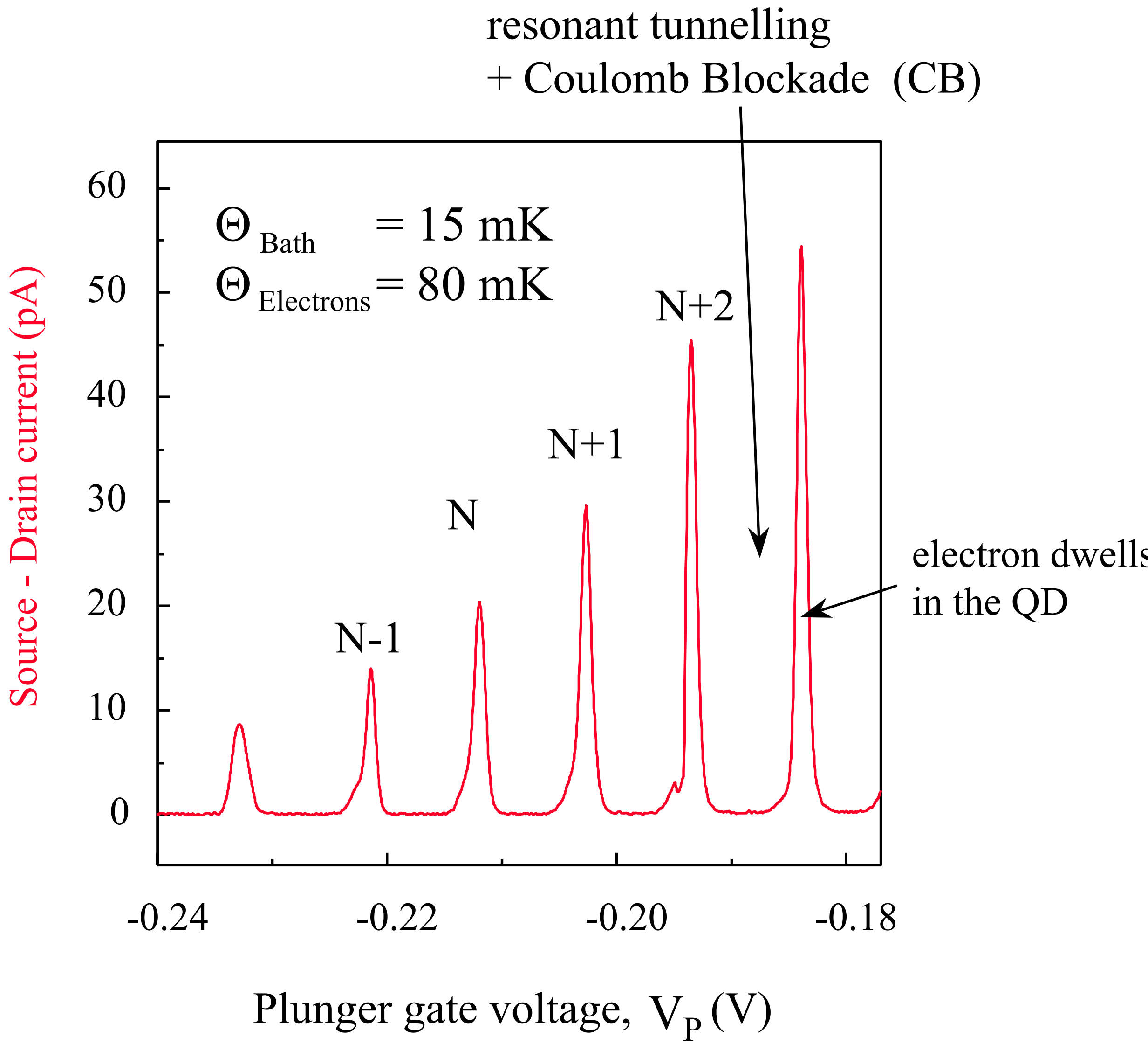
density of states

QD

200 electrons
0.2 x 0.2 μm^2

dwell time $\leq$ *10 nS*

typical characteristics of a QD



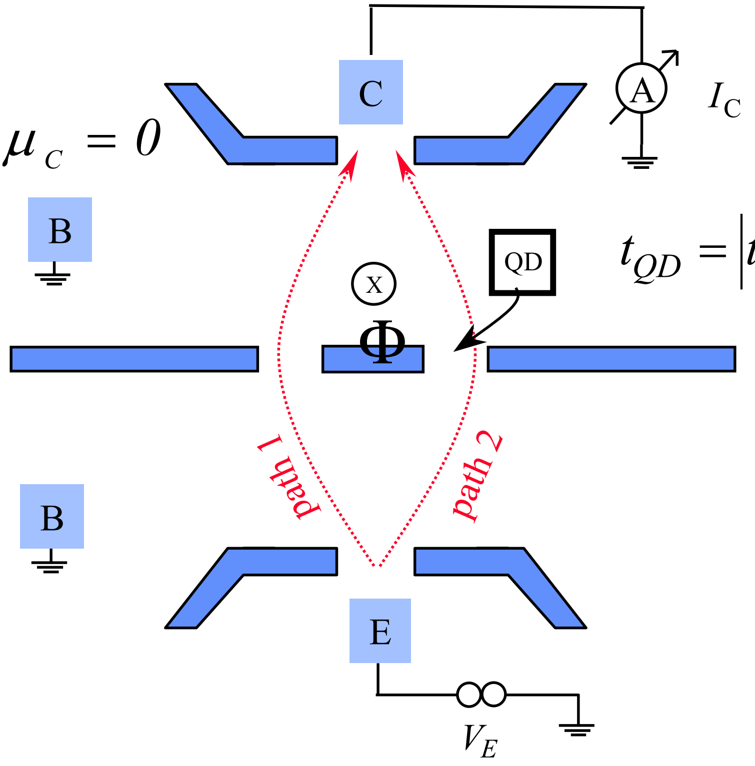
resonant tunnelling
+ Coulomb Blockade (CB)

electron dwells
in the QD

does QD maintain coherence ?

testing coherence of QD

$$\mu_B = \mu_C = 0$$

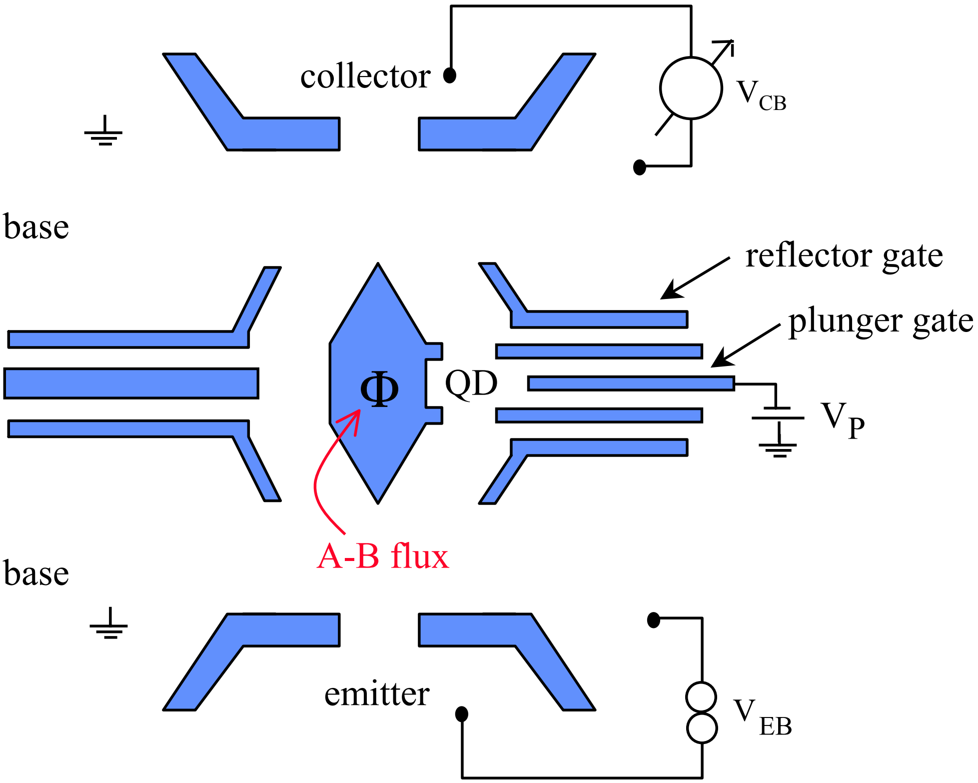


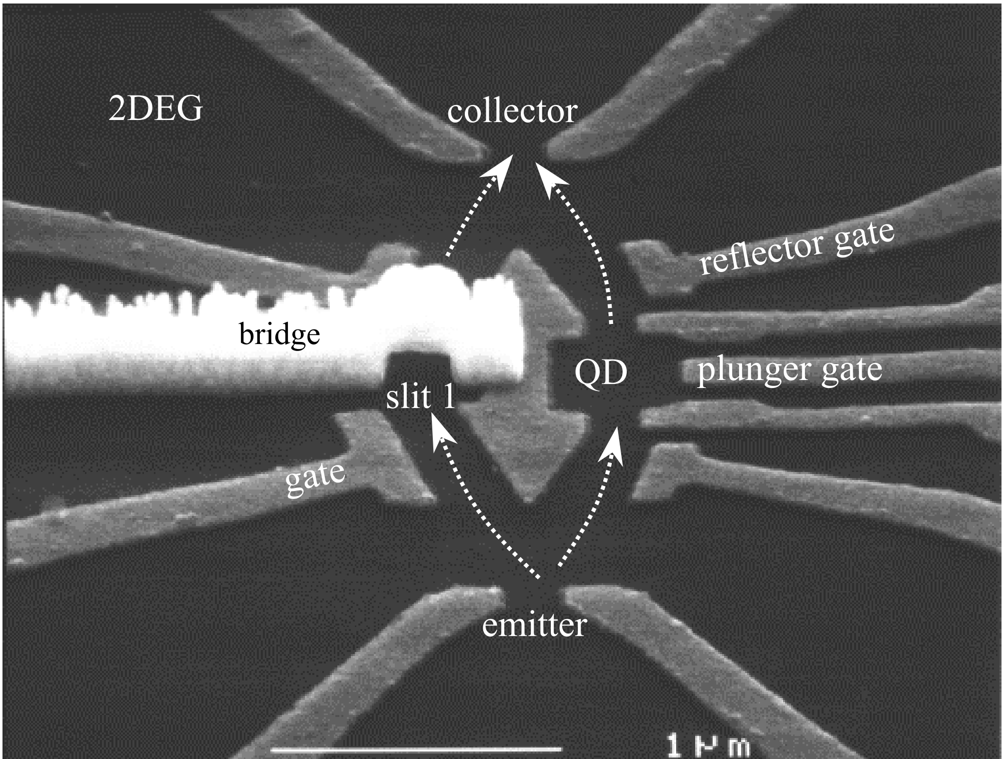
$$t_{QD} = \left|t_{QD}\right| e^{i\varphi_{QD}}$$

$$ {}_{\mathrm{EC}} = \left|t_{\mathrm{slit1}}\right|^2 + \left|t_{\mathrm{QD}}\right|^2 + 2\left|t_{\mathrm{slit1}}\right| \cdot \left|t_{\mathrm{QD}}\right| \cos(\varphi_{\mathrm{slit1}} - \varphi_{\mathrm{QD}} - \varphi_{\mathrm{AB}} $$

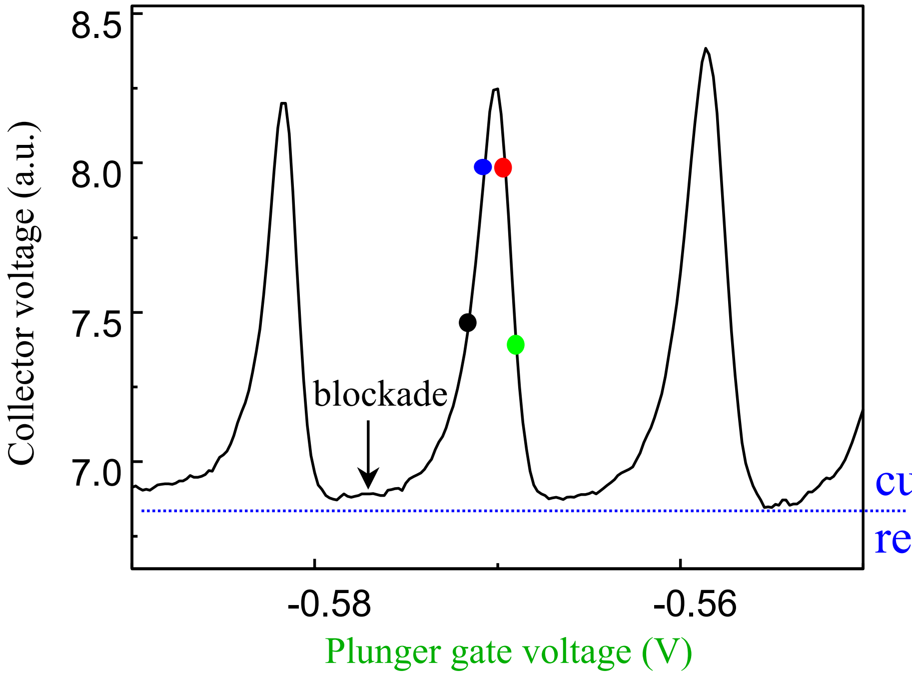
oscillatory behavior with phase → proves coherence !

experimental realization

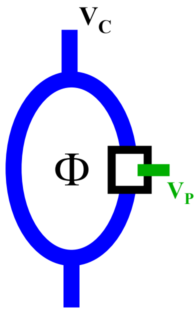


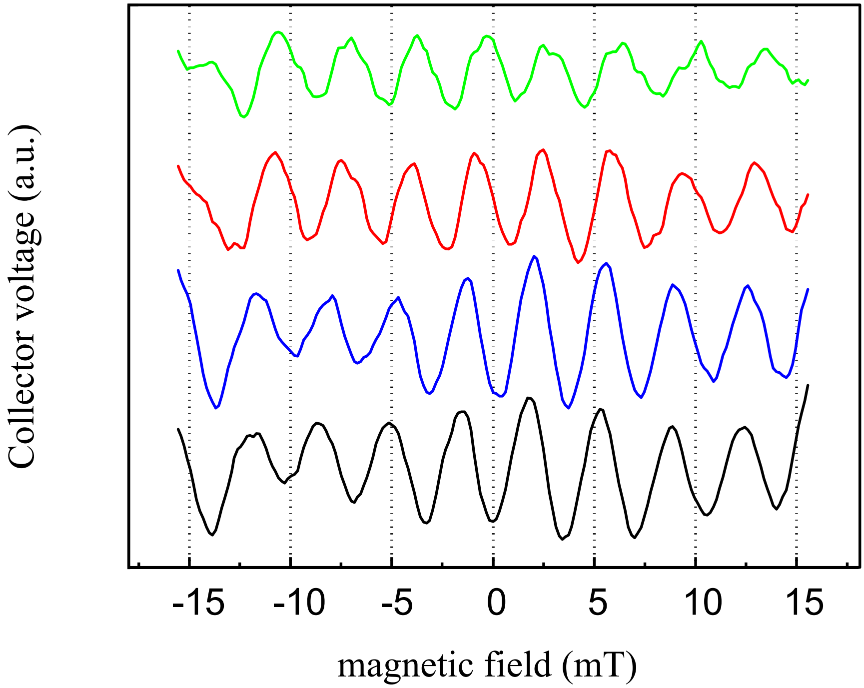


is the QD coherent ?



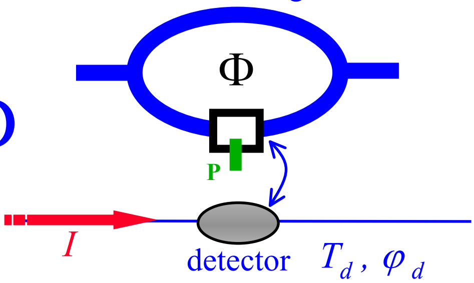
current of reference arm



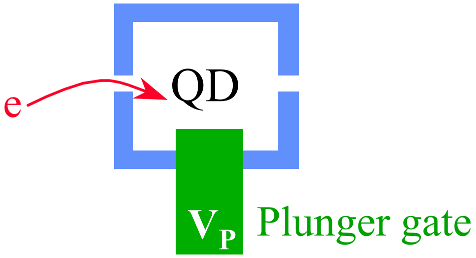


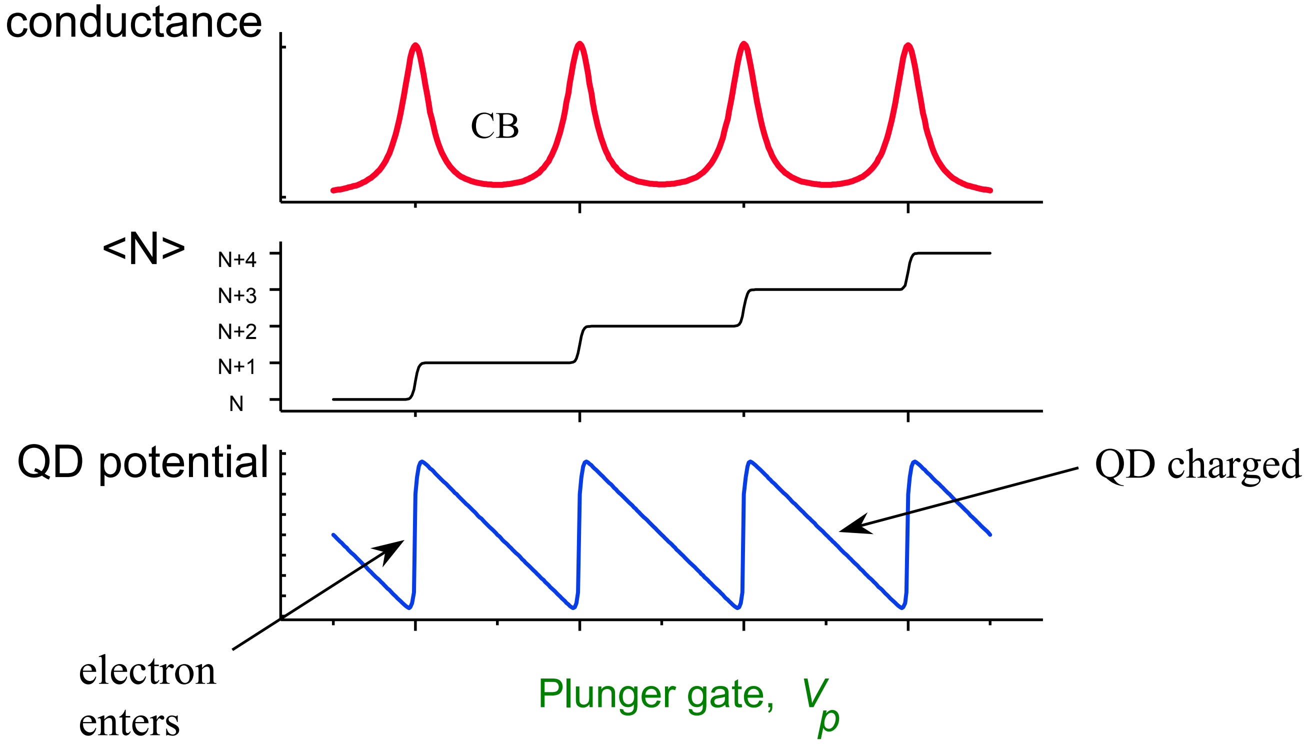
★ existence of oscillations → proof of **QD coherence** !

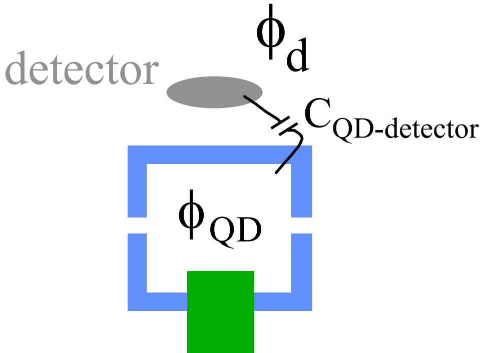
detection of electron in a QD



charging a QD with electrons







$$\phi_d = \phi_{QD}\frac{C_{QD-detector}}{C_\Sigma}$$

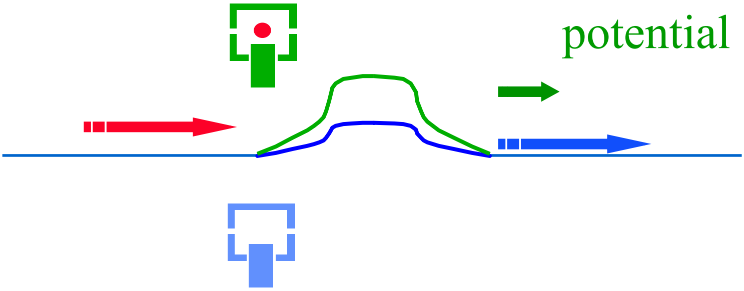
two possible detection schemes

- sensitive to potential -

- *conductance change of detector*

$t_d(\varphi_d) \to t_d(\varphi_d) + \Delta t_d$

$\Delta\varphi_d = 0$



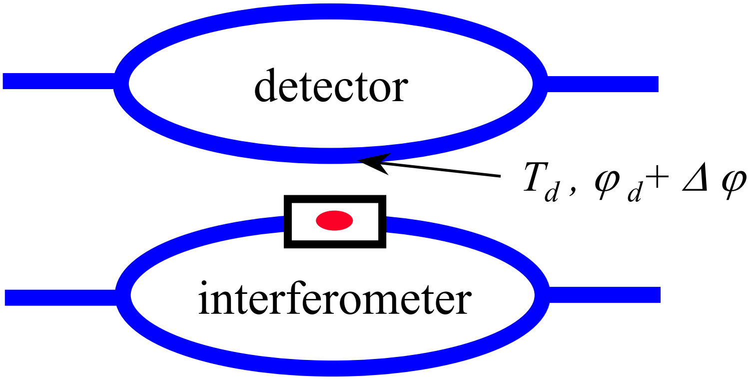
potential dependent curren

- *phase change in detector*

$\varphi_d \to \varphi_d + \Delta\varphi$

$\Delta t_d = 0$

potential dependent phas



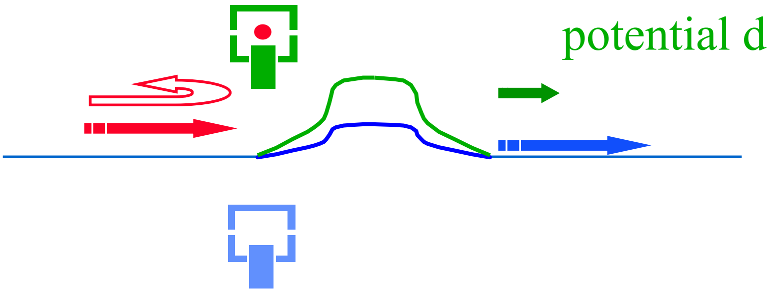
constructing a detector

- selective of the two paths
- high sensitivity to a single electron
- minimal internal noise
- tunable properties

via conductance change

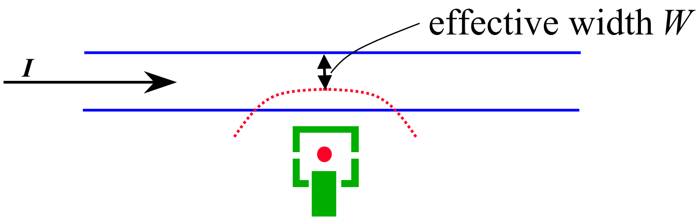
$T_d \rightarrow T_d+\Delta T_d$

$\Delta\varphi_d=0$



potential dependent current

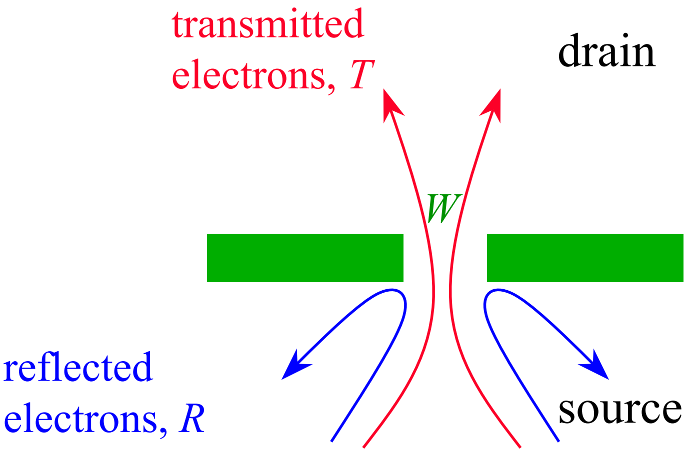
affecting resistance of a quantum wire...

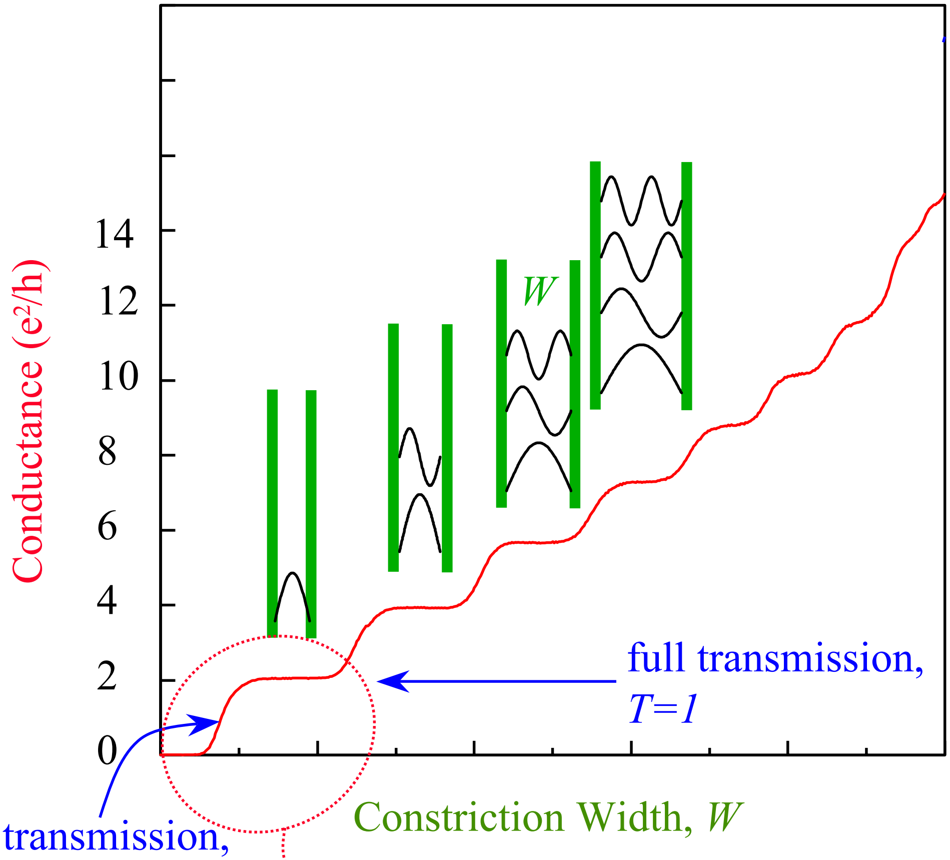


without electron in QD…………….	W	T_d	R
with electron in QD ………………..	$W - \Delta W$	$T_d - \Delta T_d$	$R+\Delta R$

resistance change → change in power dissipation → measurement

a short wire – a constriction
a dissipating detector





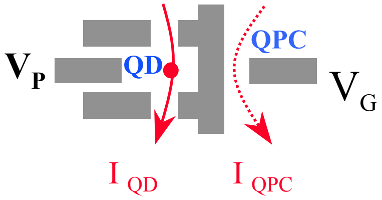
full transmission, $T=1$

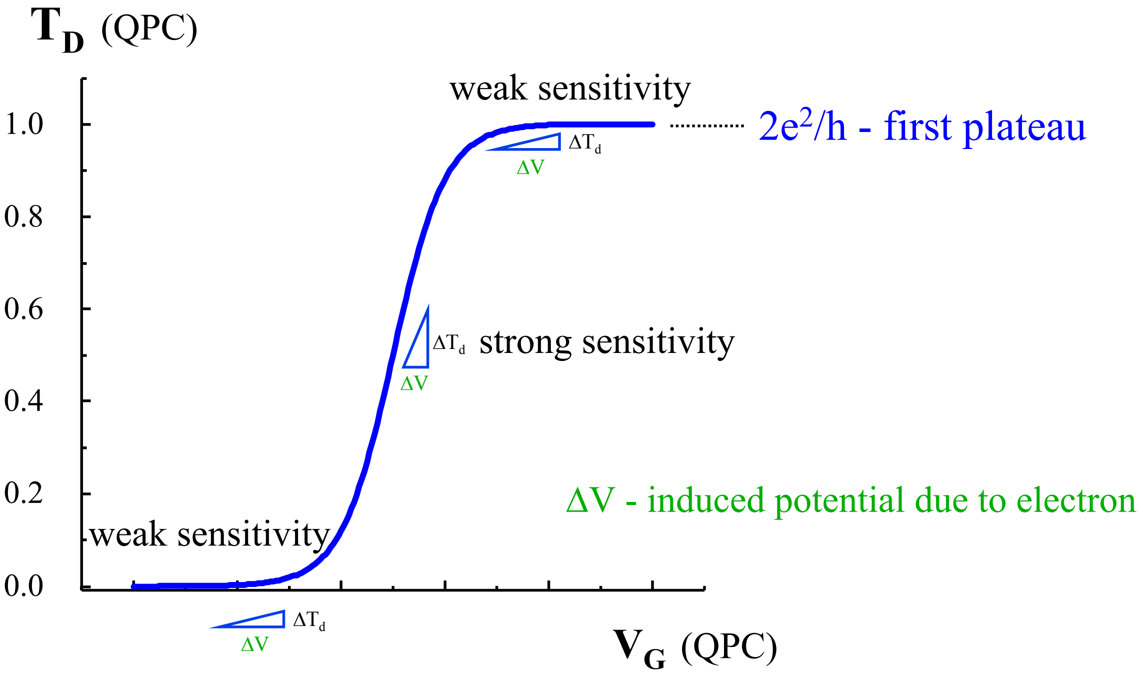
partial transmission, $T<1$

partly transmitted channel: $g = T\frac{2e^2}{h}$

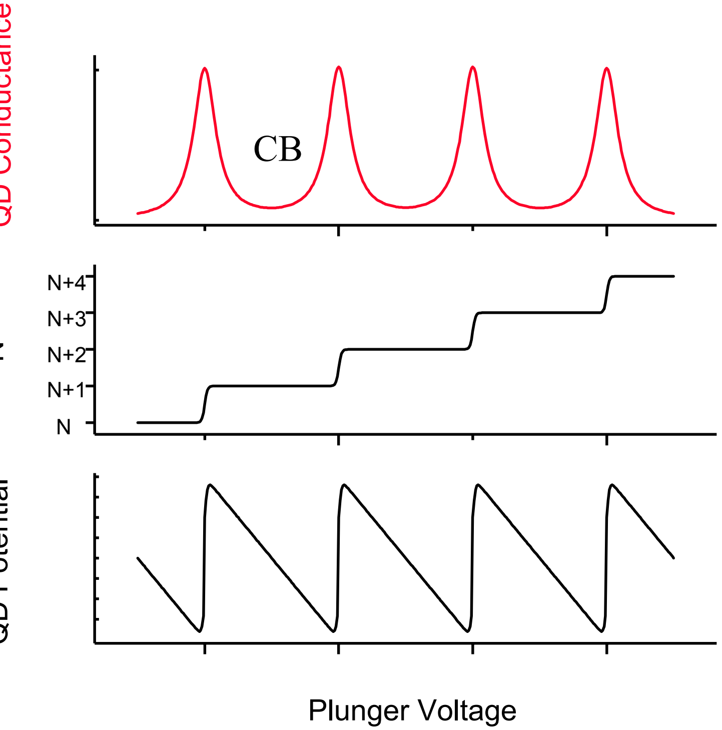
QD + constriction

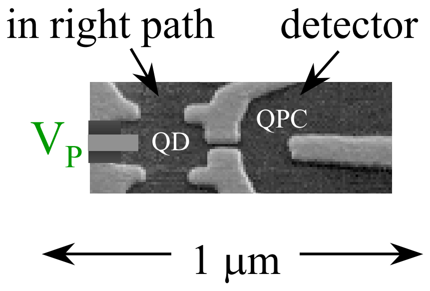
Quantum Point Contact (QPC)

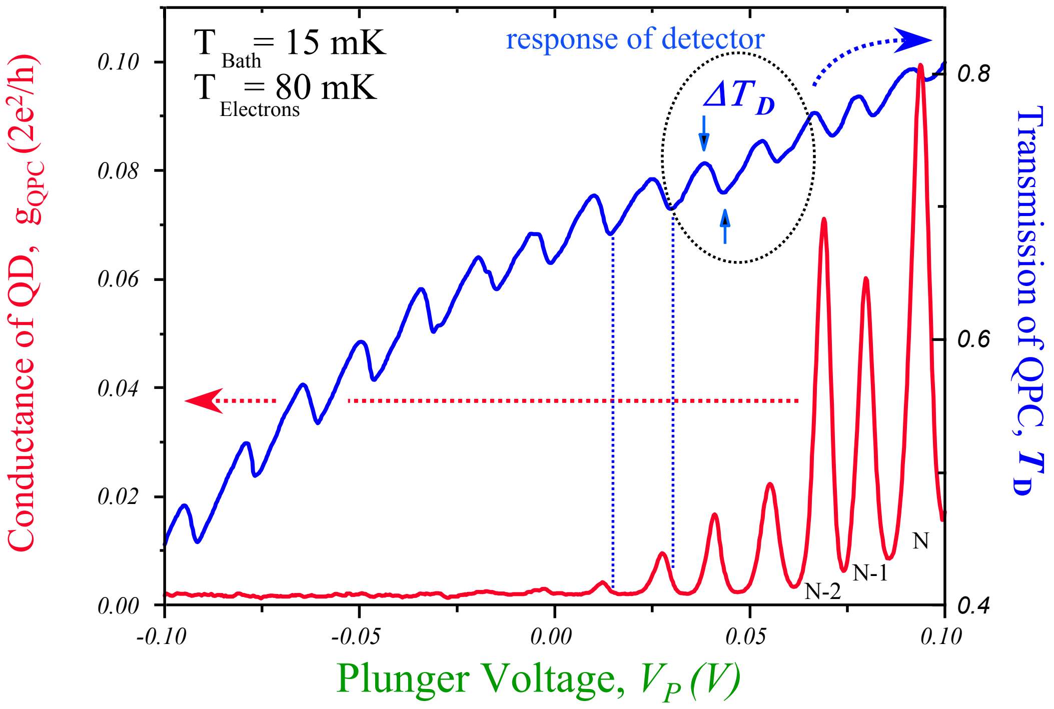




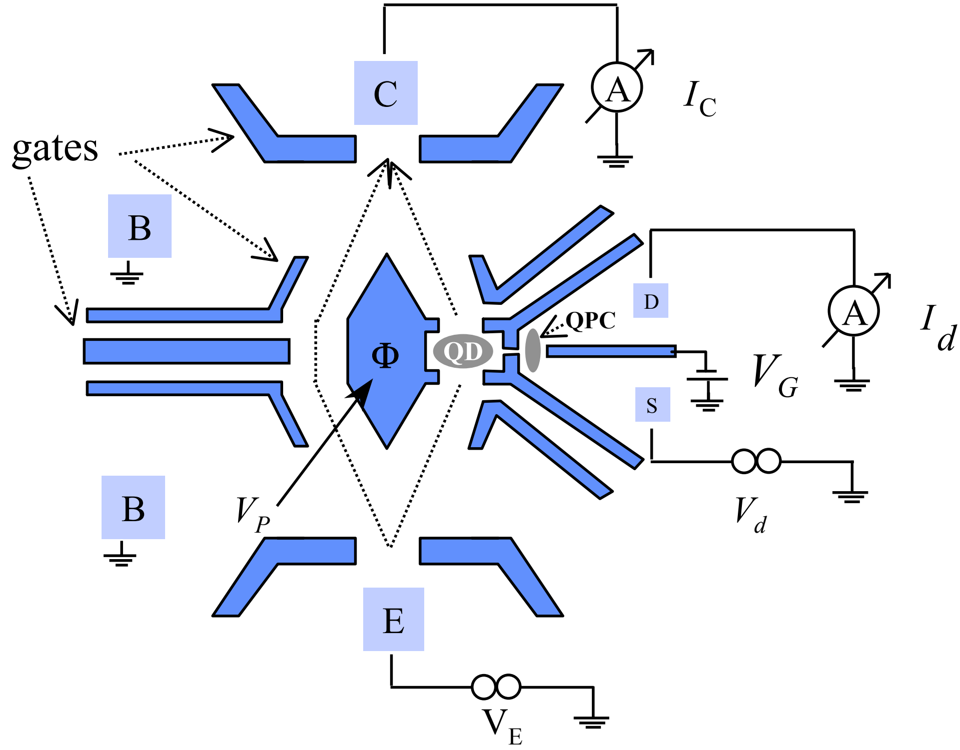
QD - QPC interaction

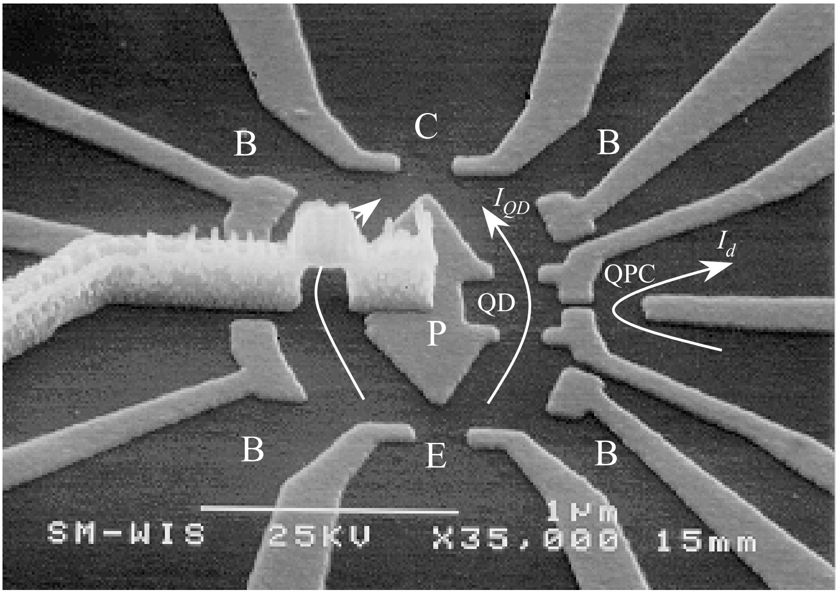






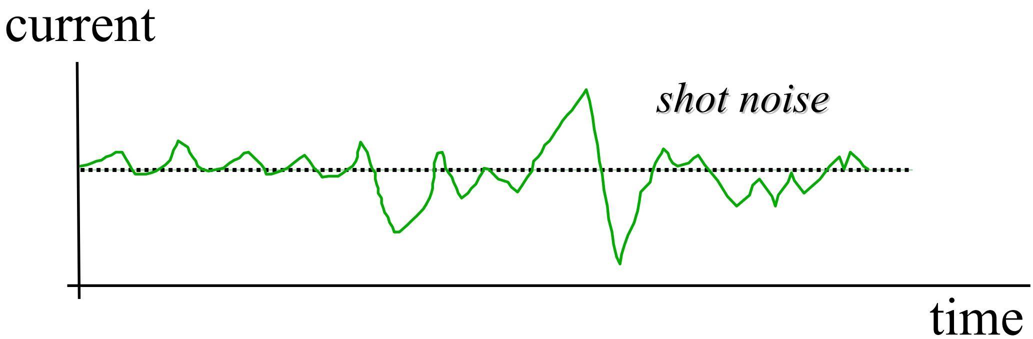
experimental realization

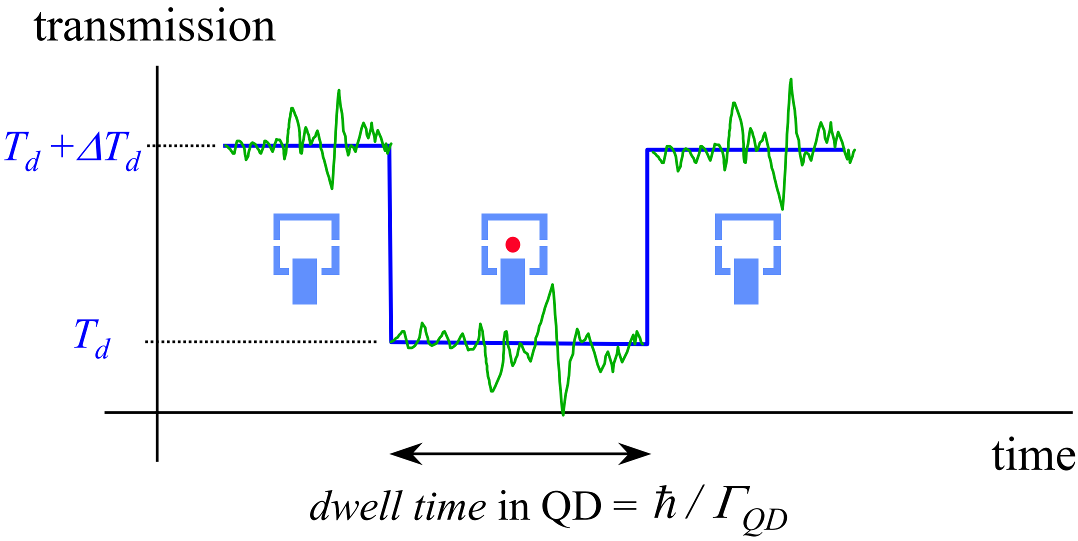




but, the QPC has unavoidable noise

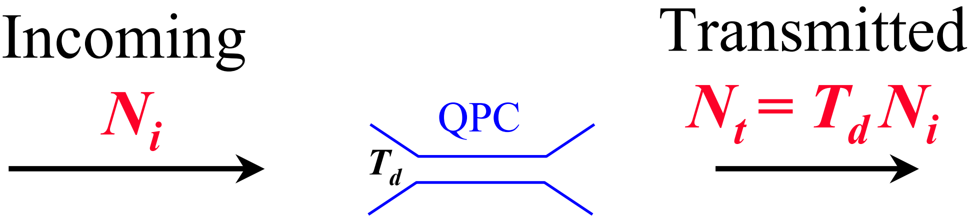
charge is discreet ➡ ***shot noise***





competition between ΔT_d and ***shot noise***

shot noise = partition noise



Incoming

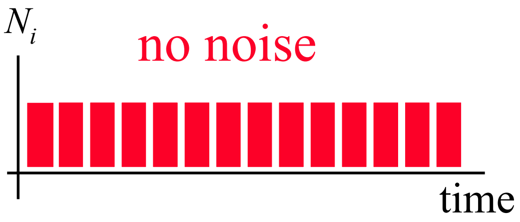
N_i

QPC

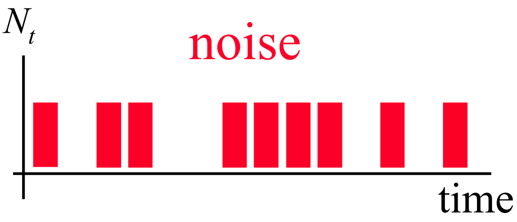
T_d

Transmitted

$N_t = T_d N_i$

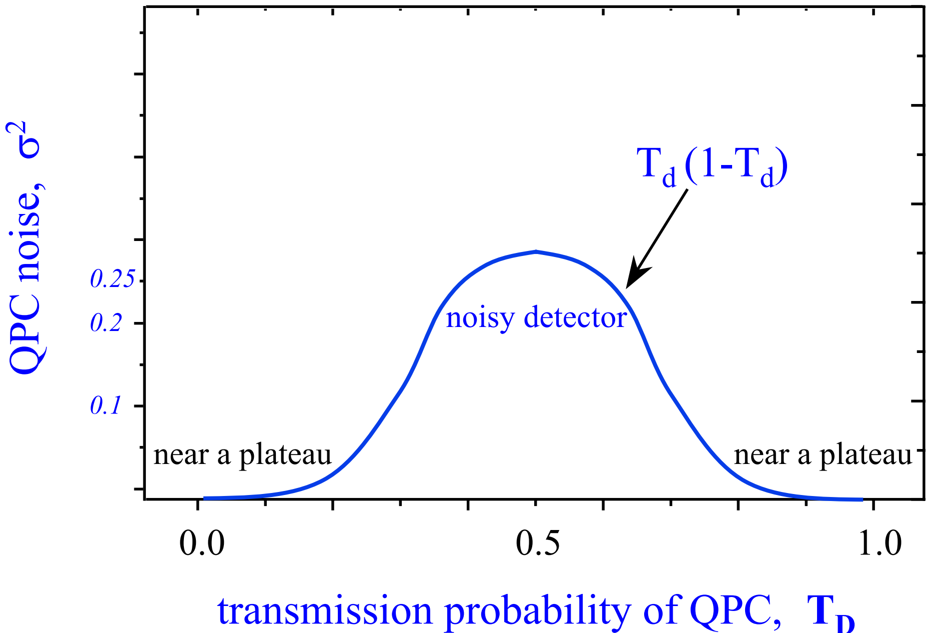


full Fermi reservoir
(ordered electrons at T=0 K)

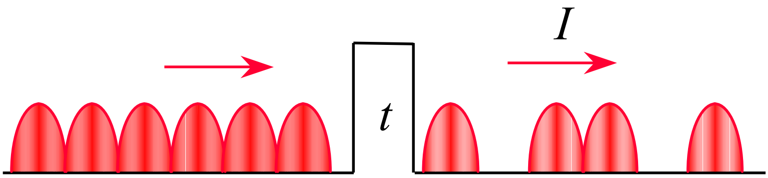


partition noise
(random electrons)

$$\sigma(N_t) = \sqrt{N_i\ \ T_d(1 - T_d)}$$



expected *shot noise* in QPC

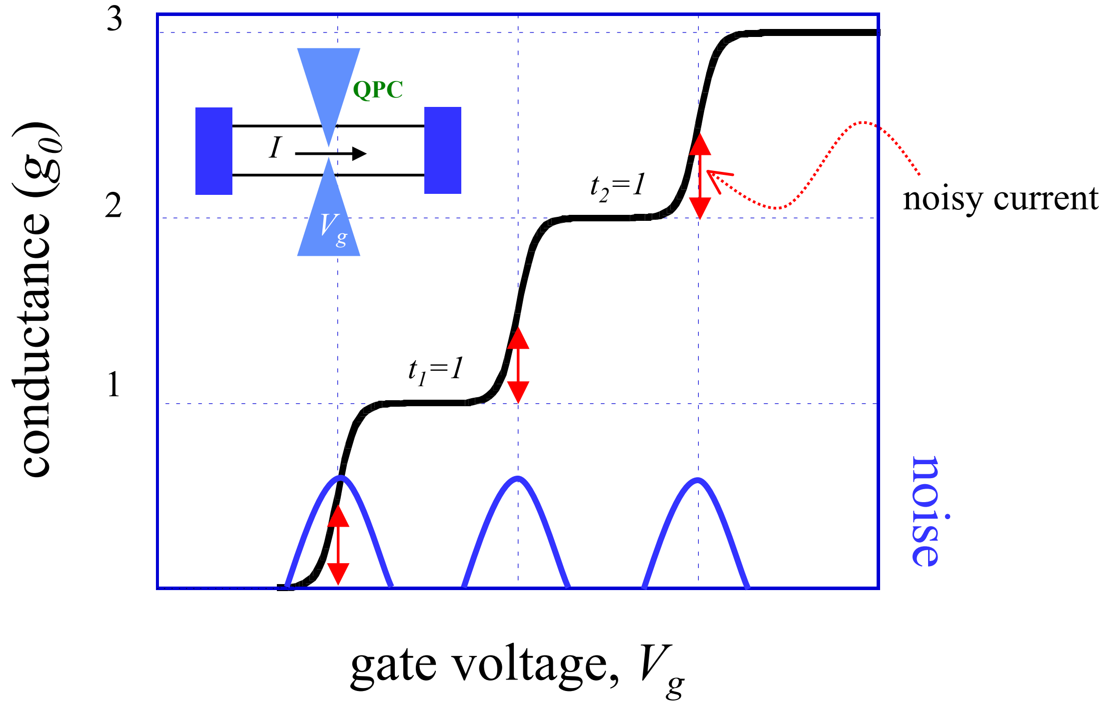


binomial distribution

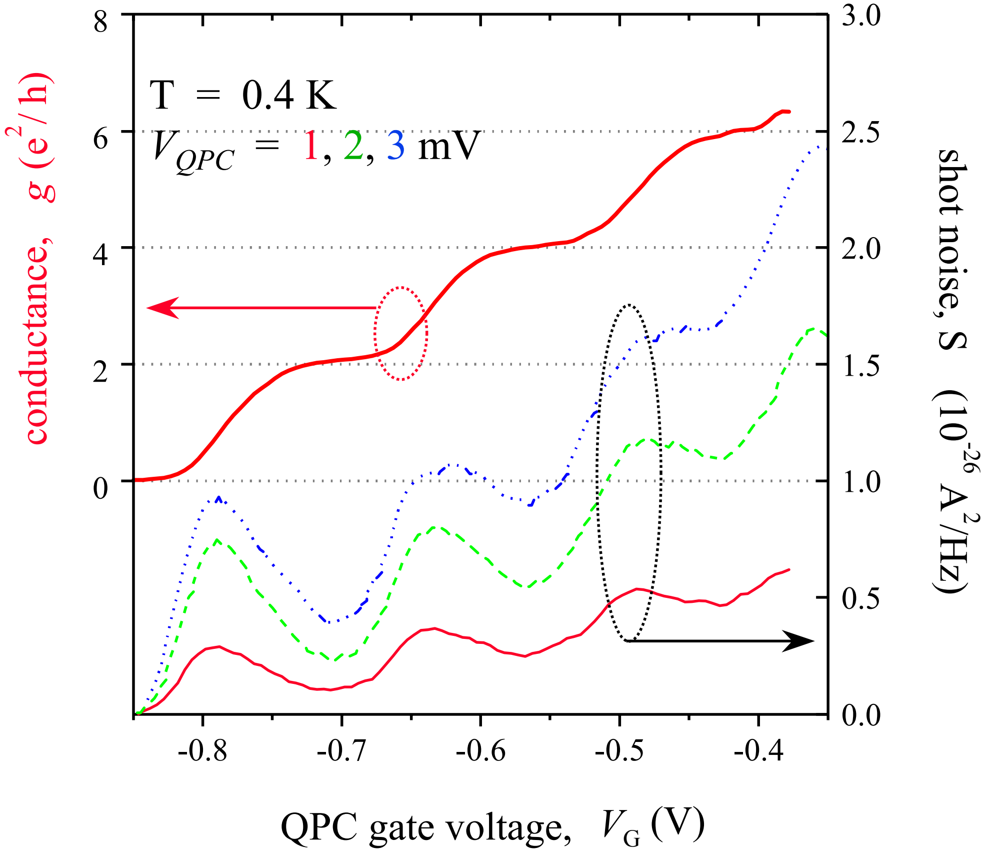
$$S_i(\nu) \equiv \frac{<(\Delta i)^2>_{\Delta\nu}}{\Delta\nu} = 2 < \frac{(\Delta Q)^2}{\tau} > = 2eI(1-T)$$

Khlus, 1987
Lesovik, 1989

(A^2/Hz)



actual *shot noise* in QPC



Reznikov *et al.*, PRL **75**, 3340 ('95)

simple dephasing arguments

- DC current in the QPC

$$< I_{QPC} >= V_{QPC}\frac{2e^2}{h}< T_D >$$

conductance

- when an electron *dwells* in the QD:

$$< \Delta I_{QPC} >= V_{QPC}\frac{2e^2}{h}< \Delta T_D >$$

- during *dwell* time, τ_d , Δn_{QPC} electrons pass the QPC

$$\Delta n_{QPC} = \frac{\Delta Q}{e} = \frac{1}{e}\tau_d \cdot V_{QPC}\frac{2e^2}{h}< \Delta T_D >$$

- for *which path* information, Δn_{QPC} must be **larger** than the *Quantum Shot Noise Number* fluctuations

$$S(0) = 2\frac{< (\Delta Q)^2 >}{\tau_d} = \underbrace{2e}_{2e} \cdot \underbrace{V_{QPC}\frac{2e^2}{h}< T_D >}_{I_{QPC}} \cdot \underbrace{(1 - < T_D >)}_{(1\text{-}<T_D>)}$$

$$\underbrace{2e \otimes I_{QPC}}_{\text{classical shot noise}} \otimes \underbrace{(1\text{-}<T_D>)}_{\text{suppression}}$$

- number fluctuations:

$$\Delta N = \frac{\Delta Q}{e} = \sqrt{\tau_d \frac{S(0)}{2e^2}}$$

$$\Delta N = \sqrt{\frac{1}{e}\tau_d V_{QPC} \frac{2e^2}{h} < T_D > (1 - < T_D >)}$$

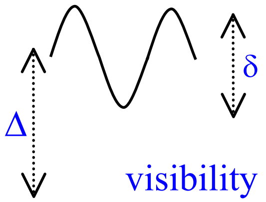
- For **Δn** (due to ΔT_D) > **ΔN** (noise) ……detector dephases

$$\underbrace{\frac{1}{\tau_d}}_{\text{measurement rate}} \approx \underbrace{\frac{2eV_{QPC}}{h} \frac{(< \Delta T_D >)^2}{< T_D > (1 - < T_D >)}}_{\text{define: dephasing rate}} \equiv \frac{\Gamma_{\text{dephasing}}}{\hbar}$$

$$\boxed{\frac{1}{\tau_\varphi} = \frac{2eV_d}{h} \frac{(\Delta T_d)^2}{8T_d(1 - T_d)}}$$

- The visibility of interference oscillation :

$$\nu = e^{-\frac{\tau_{\mathrm{d}}}{\tau_{\mathrm{dephasing}}}} \cong 1 - \frac{\Gamma_{\mathrm{dephasing}}}{\Gamma_{\mathrm{QD}}}$$



visibility = δ/ Δ

$$\nu = 1 - \frac{eV}{8\pi\Gamma_{QD}} \cdot \frac{(\Delta T_d)^2}{T_d(1-T_d)}$$

-- Y. Levinson, Europhys. Lett. **39**, 299 (1997)

-- S. Gurvich, Phys. Rev. B **56,** 15215 (1997)

-- I. L. Aleiner, N. S. Wingreen, and Y. Meir, Phys.Rev. Let. **79,** 3740 (1997)

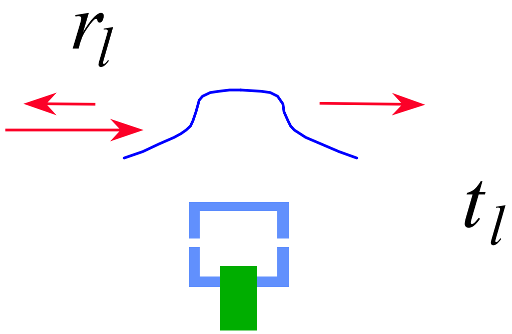
-- Y. Imry, Phys. Scripta **T76,** 171 (1998)

more rigorous dephasing estimate

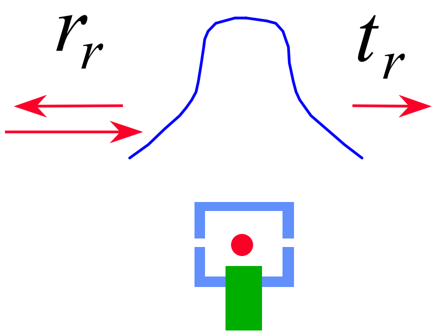
$$\nu_d = \left| {}_d\langle \chi_r | \chi_l \rangle_d \right|$$

$$|\chi_l\rangle_d = t_l |t\rangle_d + r_r |r\rangle_d$$

$$|\chi_r\rangle_d = t_r |t\rangle_d + r_r |r\rangle_d$$

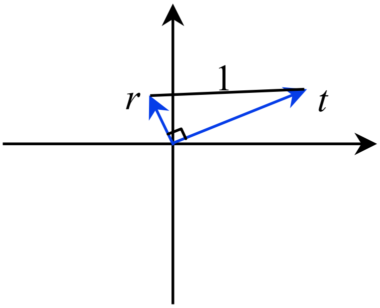


going through left path



going through path with QD

symmetric barrier



$t_l = cos\theta_l\, exp(i\varphi_l)$

$r_l = i\, sin\theta_l\, exp(i\varphi_l)$

$t_r = cos\theta_r\, exp(i\varphi_r)$

$r_r = i\, sin\theta_r\, exp(i\varphi_r)$

for a single electron probing the interferometer

$$v_d^1 = \left|t_r^* t_l + r_r^* r_l\right| = \left|\cos\theta_r \cos\theta_l + \sin\theta_r \sin\theta_l\right| = \left|\cos(\theta_r - \theta_l)\right|$$

$$\Delta\theta \equiv \theta_r - \theta_l << 1 \;;\; \theta_l \cong \theta_r = \theta$$

$$\cos^2\theta = T_d = \left|t_d\right|^2$$

$$\boxed{v_d^1 \approx 1 - (\Delta\theta)^2/2}$$

$$\Delta T_d = \cos^2\theta_l - \cos^2\theta_r = \left(\cos\theta_l + \cos\theta_r\right)\cdot\left(\cos\theta_l - \cos\theta_r\right)$$

$$\Delta T_d = 2\cos\frac{\theta_l + \theta_r}{2}\cos\frac{\Delta\theta}{2}\cdot(-2\sin\frac{\theta_l + \theta_r}{2}\sin\frac{\Delta\theta}{2})$$

$$\Delta T_d = 2 \quad \cos\theta \qquad 1 \qquad -2\sin\theta \qquad \frac{\Delta\theta}{2}$$

$$\Delta\theta = \Delta T_d /(-2\cos\theta\sin\theta)$$

$$\nu_d^1 = 1 - \frac{(\Delta T_d)^2}{8T_d(1-T_d)}$$

for *n* independent electrons probing the interferometer

$$\nu_d^n = (\nu_d^n)^n$$

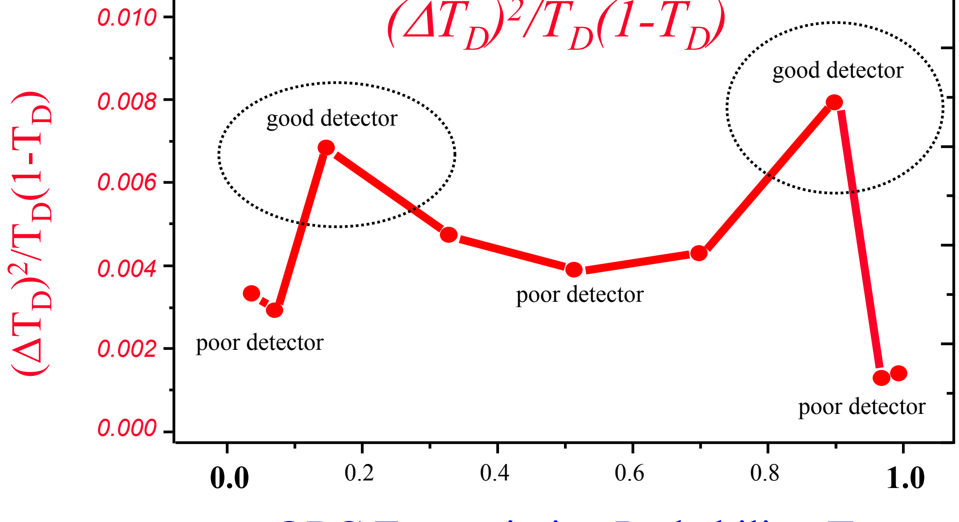
probing rate …. $n=2eV_d/h$ (n electrons time t)

$$\nu_d^n \equiv e^{-t(n)/\tau_\varphi} \cong 1 - t/\tau_\varphi \cong 1 - n\nu_d^1$$

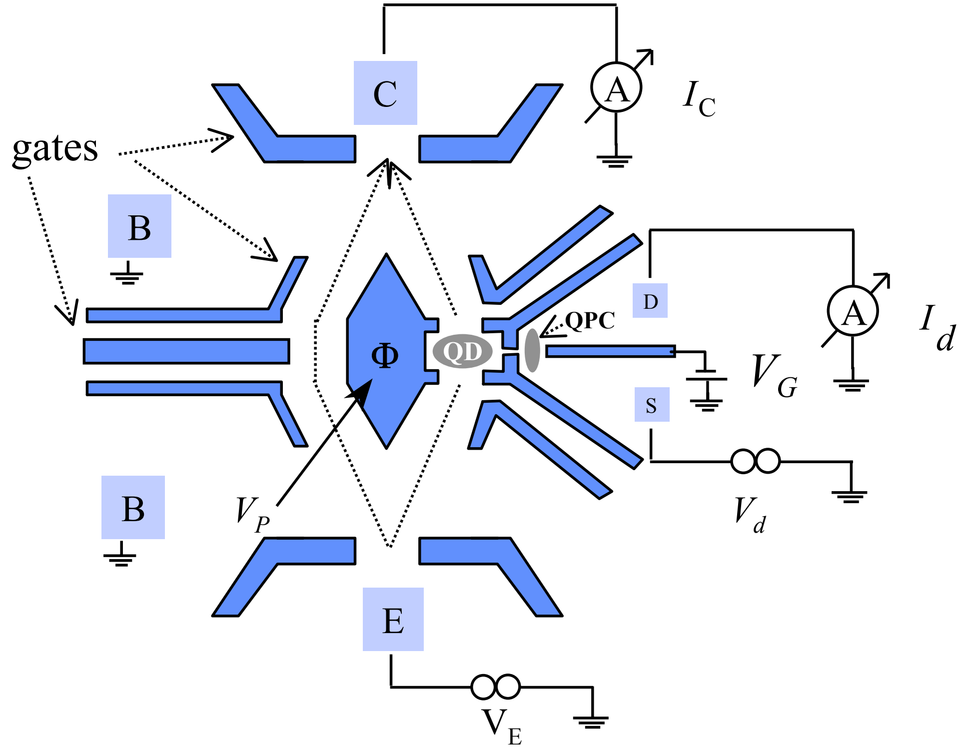
dephasing rate ……. $1/\tau_\varphi$

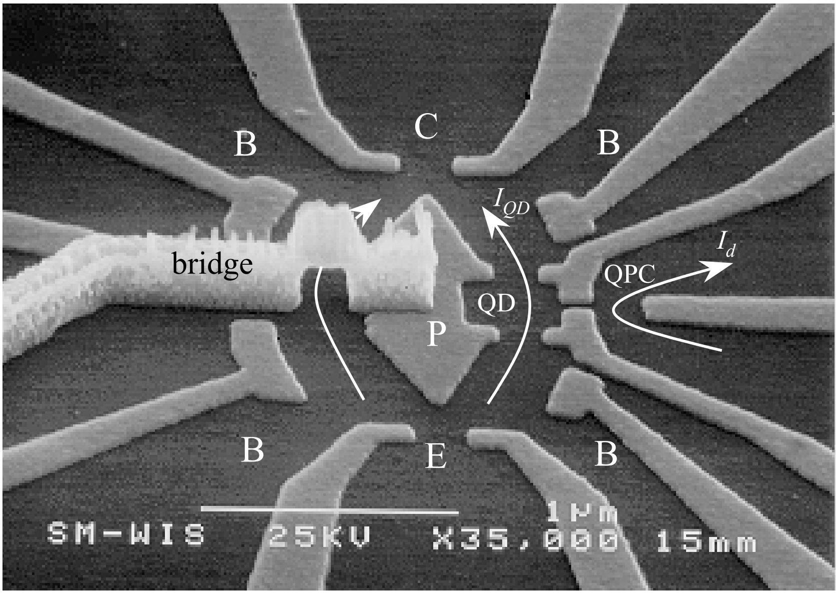
$$1/\tau_\varphi = 1 - \left|\nu_d^n\right| \cong \frac{2eV_d}{h}\frac{(\Delta T_d)^2}{8T_d(1-T_d)}$$

expected dephasing rate



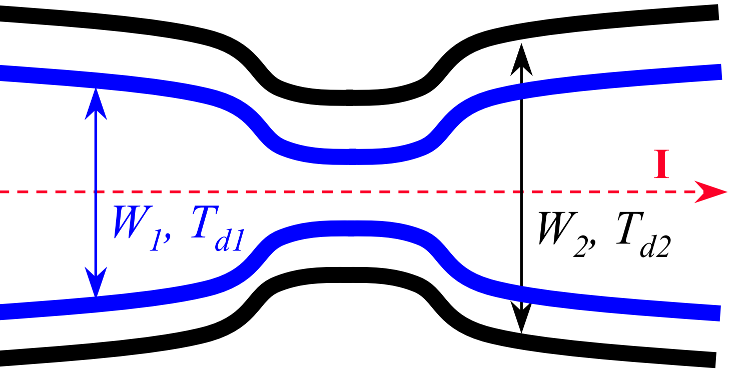
experimental realization

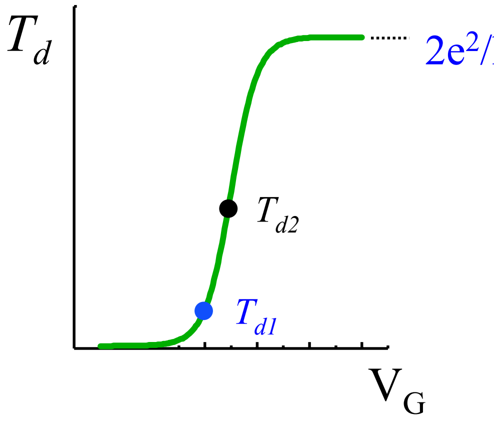


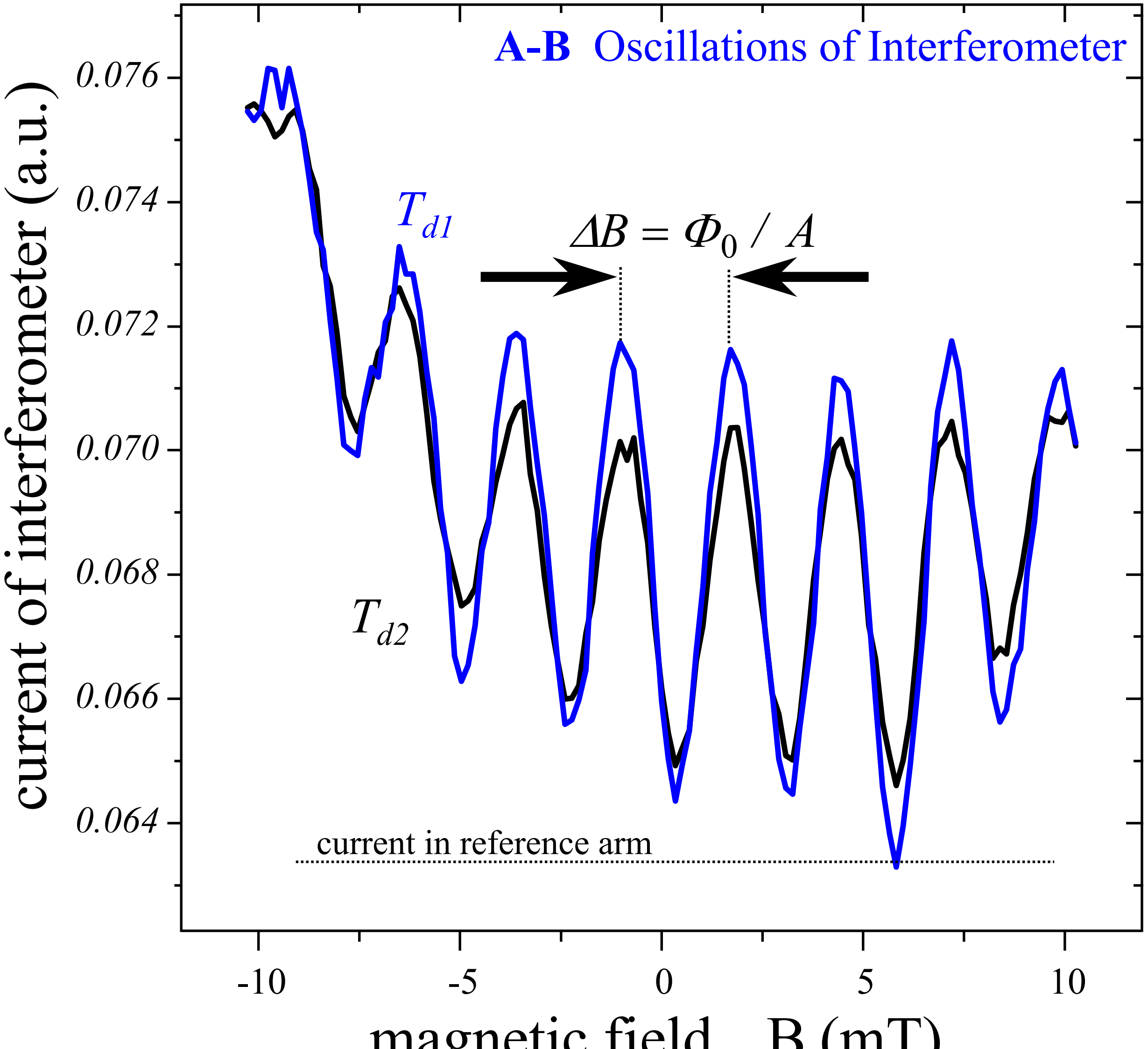


QD is tune
to a peak !

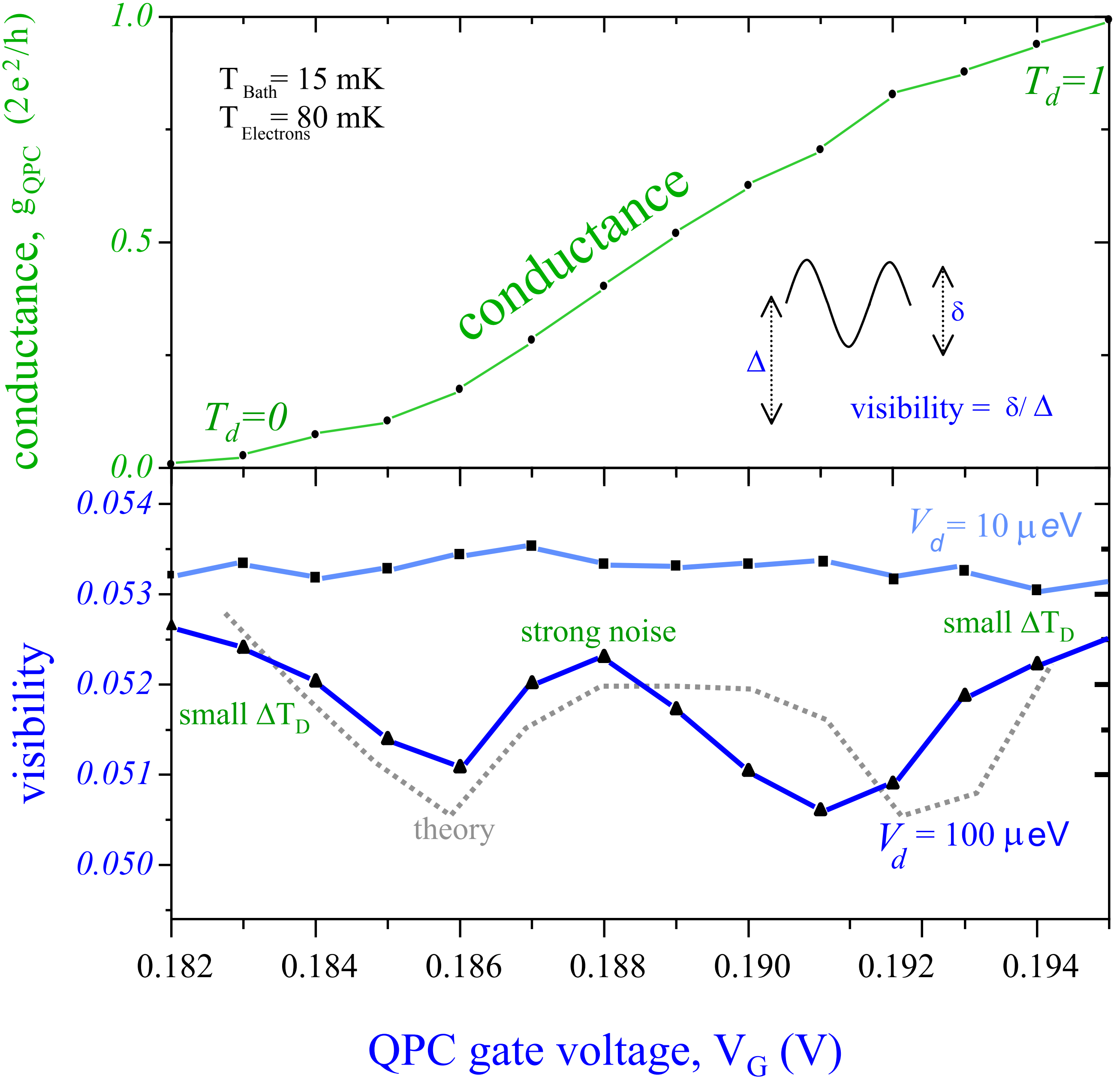
controlling dephasing







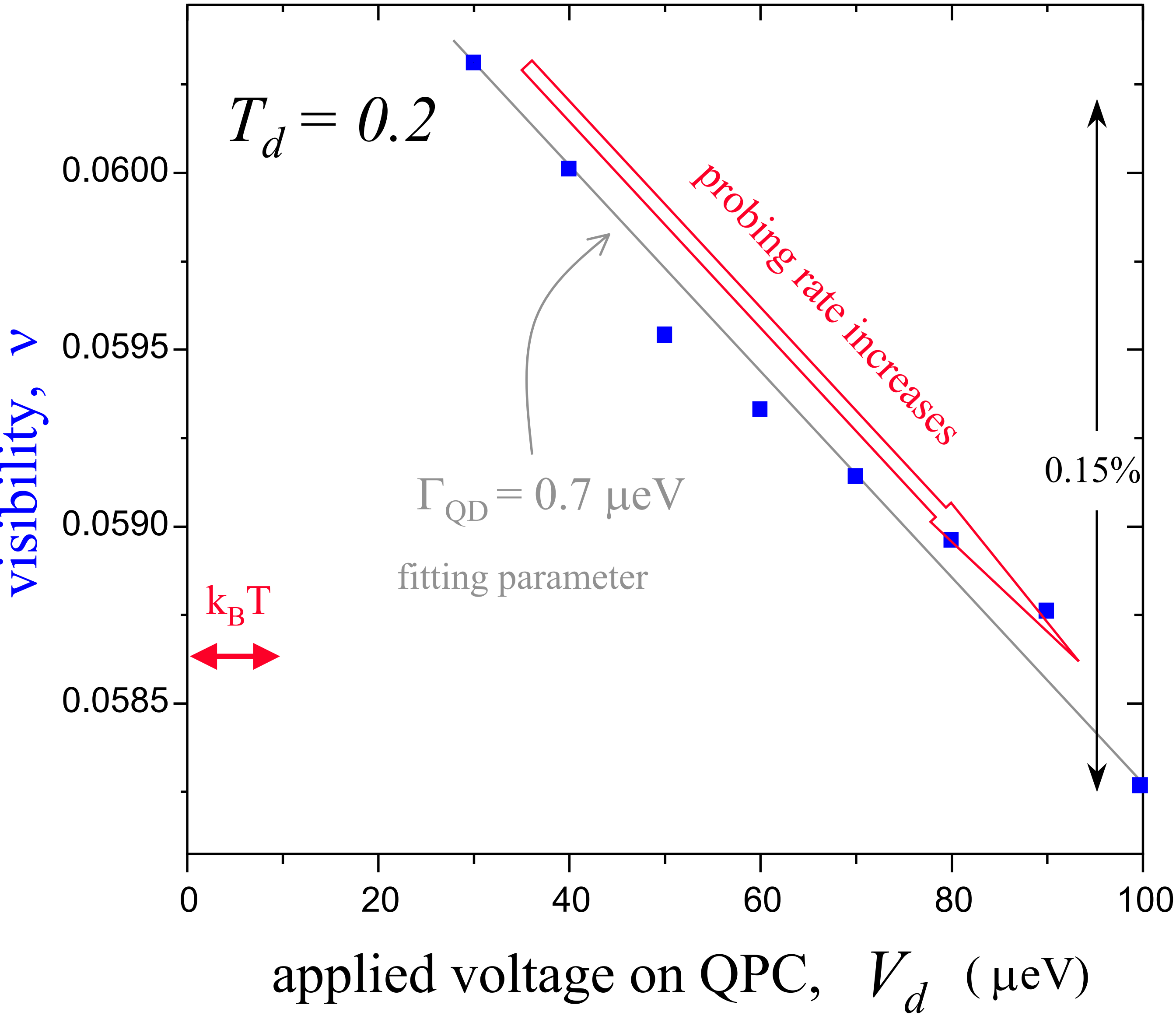
dephasing *vs* transmission



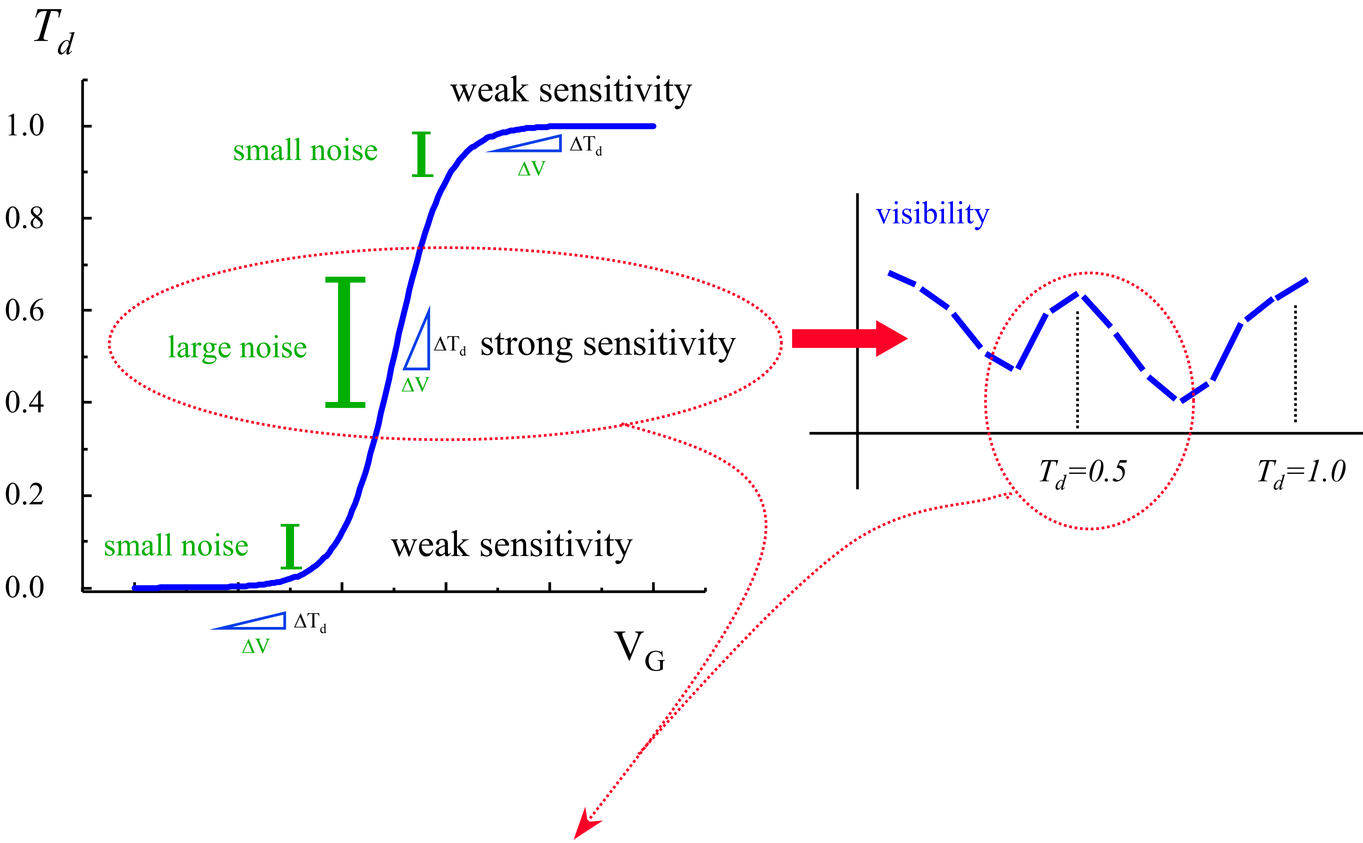
Γ_{QD}= 0.7 μeV

dephasing *vs* impinging rate

$$\nu = 1 - \alpha \cdot V_d$$



dephasing and intuition



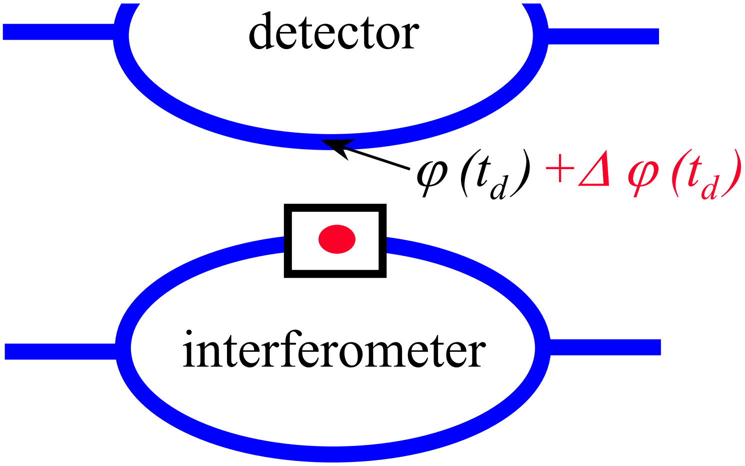
lephasing due to detection:

vhen noise is large → detection certainty is small → interference

~~lephasing due to scattering:~~

~~vhen noise is large → strong potential fluctuations → dephasing~~

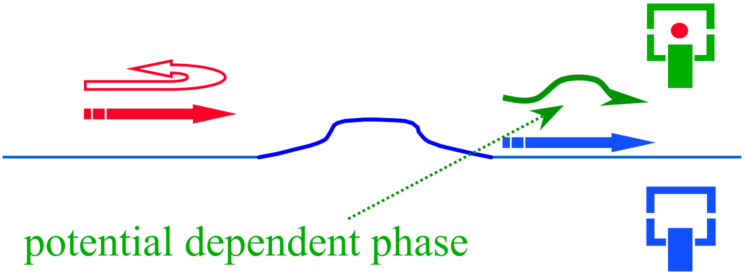
phase detector



detector circuit: $\varphi(t_d) + \Delta\varphi(t_d) \rightarrow R_d + \Delta R_d$

can it work if only phase is added *(without interference)* ?

$$\varphi(t_d) \rightarrow \varphi(t_d) + \Delta\varphi(t_d)$$



$\Delta T_d = 0$

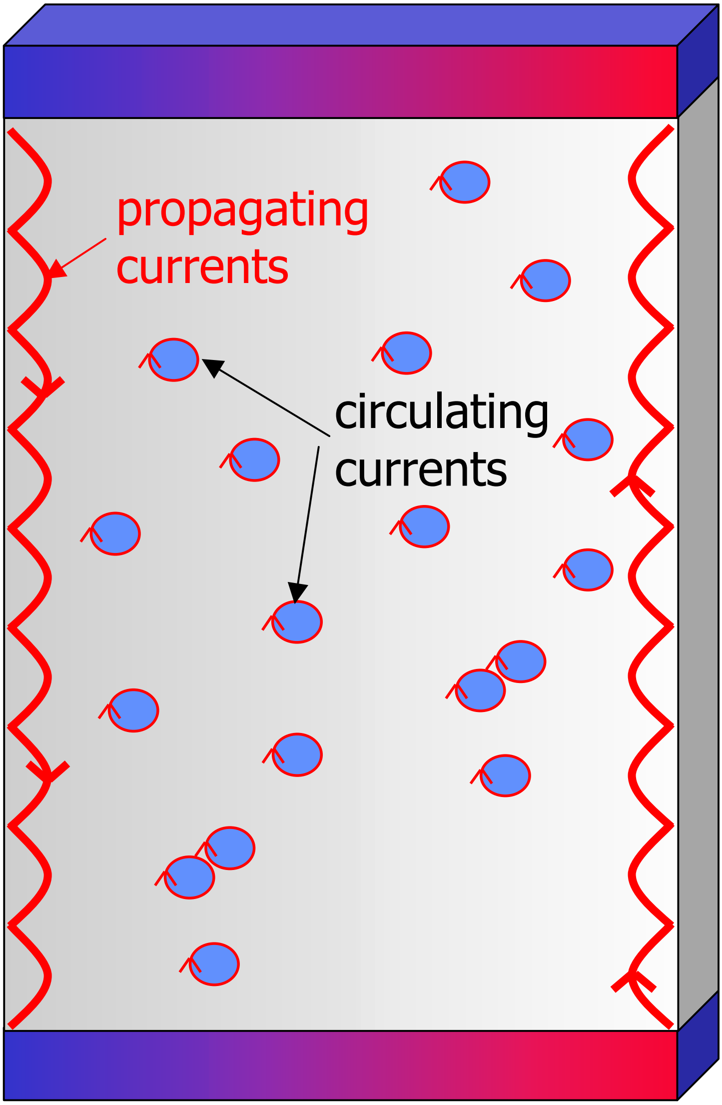
how to introduce ….. $\Delta\varphi\ (t_d\ ) \neq 0$

while keeping ….. $\Delta T_d = 0$

by preventing any backscattering !

applying magnetic field
leading to chirality…

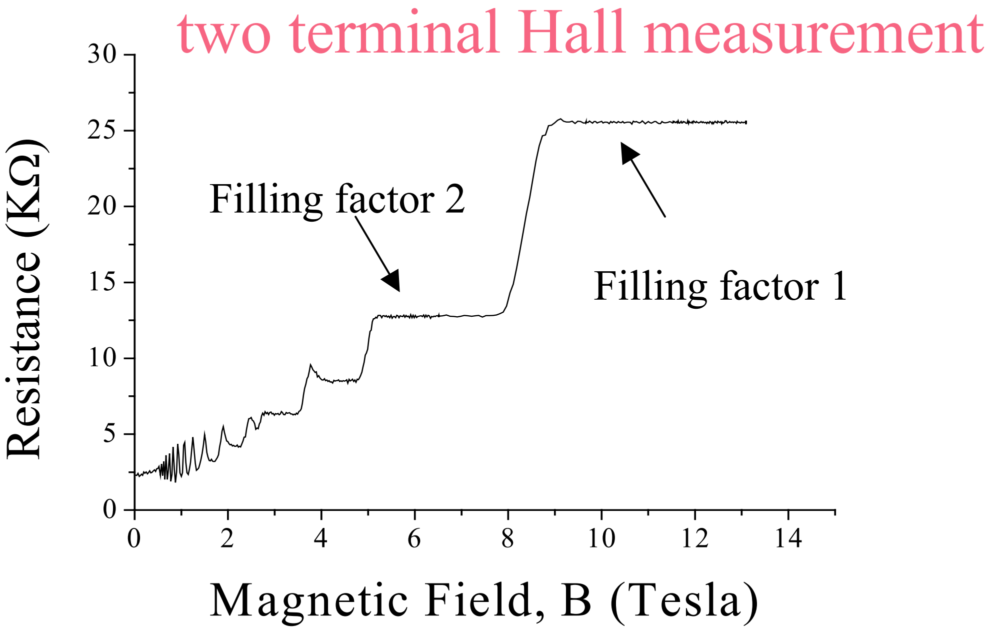
current flow under high magnetic field



classical : skipping orbits

quantum limit : edge states

chiral edge states



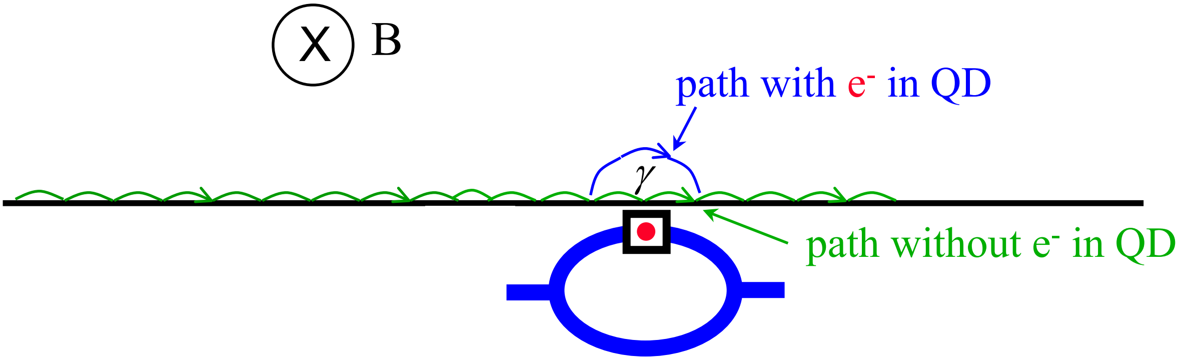
two terminal Hall measurement

Filling factor 2

Filling factor 1

conceptual realization with *edge states*

quantum Hall regime



will this system serve as *which path* experiment ?

- looking from the detector side:

  can detection be done *in principle* ?

- looking from the interfering electron side:

  what will dephase the electron?

- ➢ looking from the detector side:

  can detection be done *in principle* ?

measuring phase requires
comparison (interference) with a REFERENCE

NO REFERENCE SIGNAL!

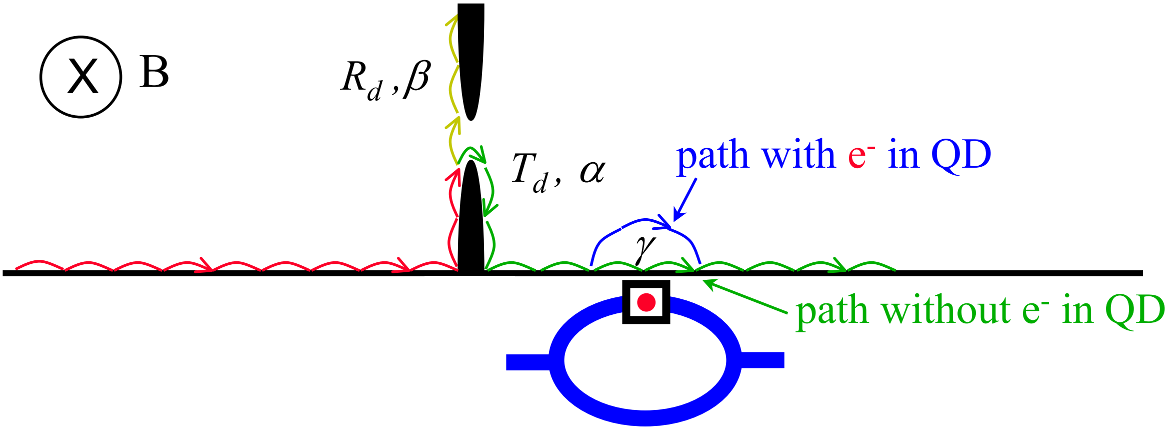
- ➢ looking from the interfering electron side:

  what will dephase the electron?

dephasing requires time dependent fluctuation
a noisy detector

NOISELESS DETECTOR !

a better *edge state* **phase detector**



$$\gamma = (\alpha_+ - \beta_+) - (\alpha_- - \beta_-)$$

$\gamma = \alpha_+ - \alpha_-$ …….. since β is constant

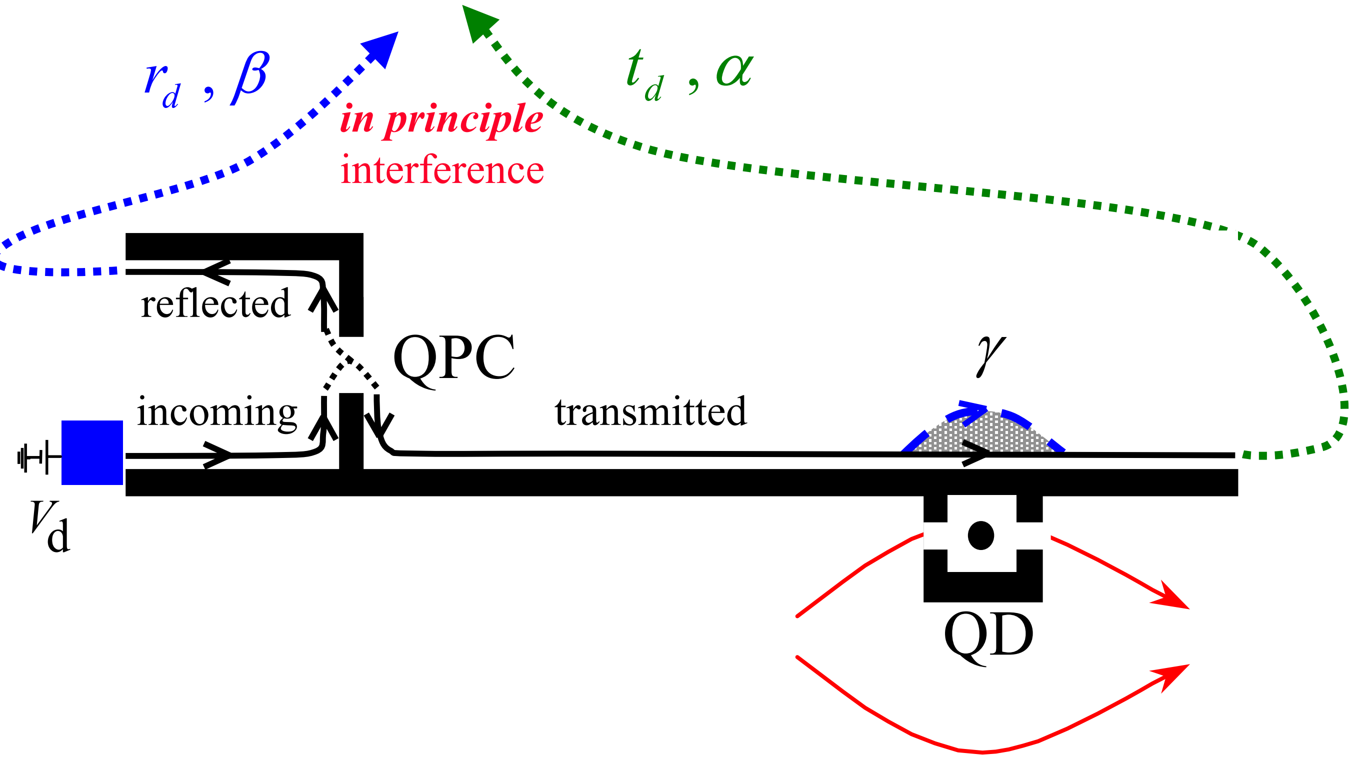
QPC splits the incoming edge:

-- provides a reference path

-- introduces noise to edge current

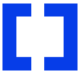
the *which path* information …

interference between transmitted and reflected edge states

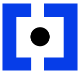


which path information $\nu_d = \left|\langle\chi_l|\chi_r\rangle\right|$

detector states



$|\chi_l\rangle = t|t\rangle_d + r|r\rangle_d$



$|\chi_r\rangle = e^{i\gamma}t|t\rangle_d + r|r\rangle_d$

for a single electron in the detector:

$$\left|\left\langle \chi_l \middle| \chi_r \right\rangle\right|^2 \equiv \left|\nu_d^1\right|^2 = \left|(e^{i\gamma} t^* \langle t| + r^* \langle r|) \cdot (t|t\rangle + r|r\rangle\right|^2 =$$

$$= \left|e^{i\gamma} t^2 + r^2\right|^2 = T^2 + R^2 + 2TR\cos\gamma =$$

$$= (T+R)^2 - 2TR\,(1+\cos\gamma)$$

$$\left|\nu_d^1\right|^2 = 1 - 4TR\sin^2\frac{\gamma}{2}$$

for n independent electrons probing the interferometer:

$$\left|\nu_d^n\right| = \left|\nu_d^1\right|^n = (1 - 4TR\sin^2\frac{\gamma}{2})^{n/2}$$

$$\left|\nu_d^n\right| \cong 1 - 2nTR\sin^2\frac{\gamma}{2}$$

probing rate …. $n=2eV_d/h$ (n electrons per unit time)

$$\nu_d^n(t) \equiv e^{-t/\tau_\varphi} \cong 1 - t/\tau_\varphi$$

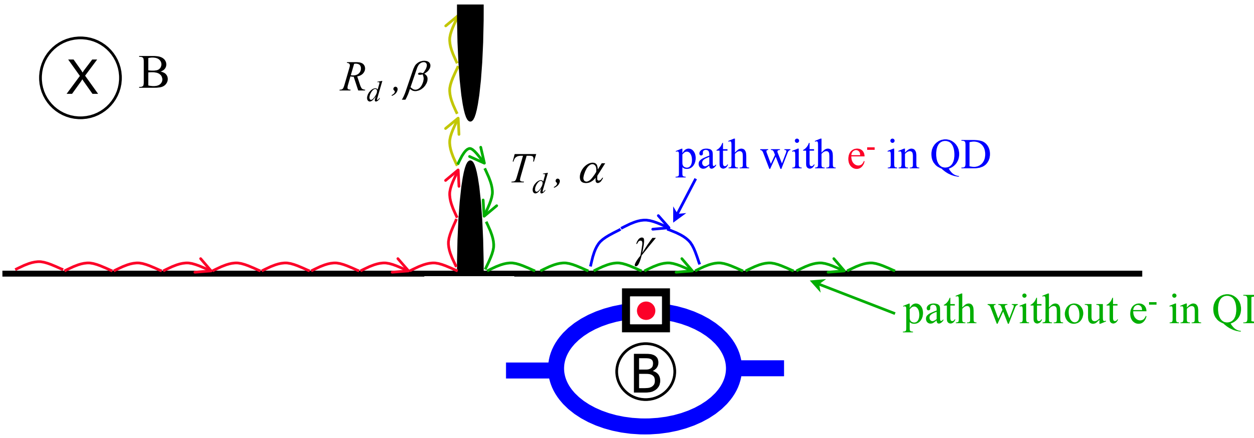
***dephasing rate* ……. $1/\tau_\varphi$**

$$1/\tau_\varphi = 1 - \left|\nu_d^n\right|$$

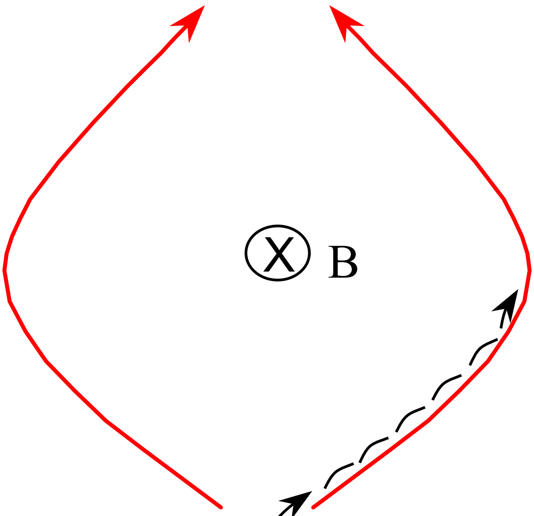
total dephasing rate

$$\frac{1}{\tau_\varphi} = \frac{eV_d}{h}\left[\frac{(\Delta T_d)^2}{8T_d(1-T_d)} + 4T_d(1-T_d)\sin^2\frac{\gamma}{2}\right]$$

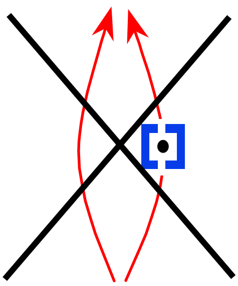
the interferometer…. in magnetic field ?



with magnetic field….



edge state transport



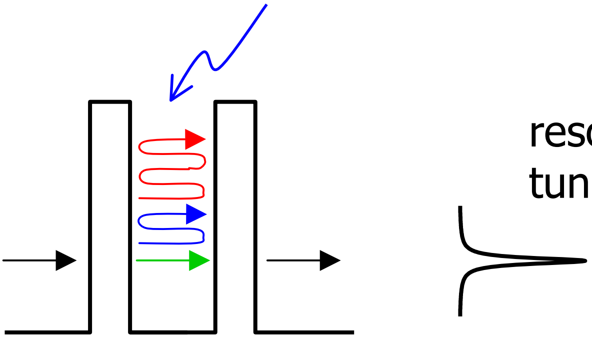
NO simple two path interference

a high field interferometer is needed….

e. g. Fabry-Perot interferometer

nterference of trajectories – NOT different paths

possible trajectories



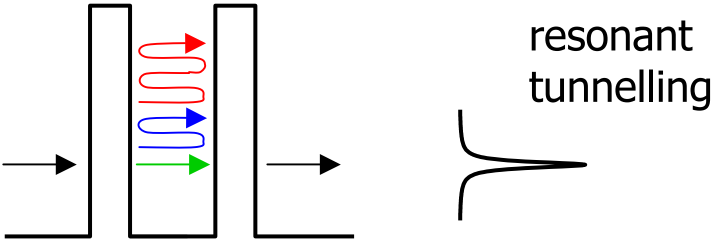
resonant tunnelling

Fabry-Perot interferometer
only slightly sensitive to magnetic field

F - P interferometer = quantum dot

what does the detector detect ?

I


resonant tunnelling

$$(E)=t_1e^{ikd}t_2+t_1e^{ikd}t_2(r_2e^{ikd}r_1t_2)+t_1e^{ikd}t_2r_2e^{ikd}r_1t_2(r_2e^{ikd}r_1t_2)+\ldots$$

short trajectories affect small number of detector’s electrons

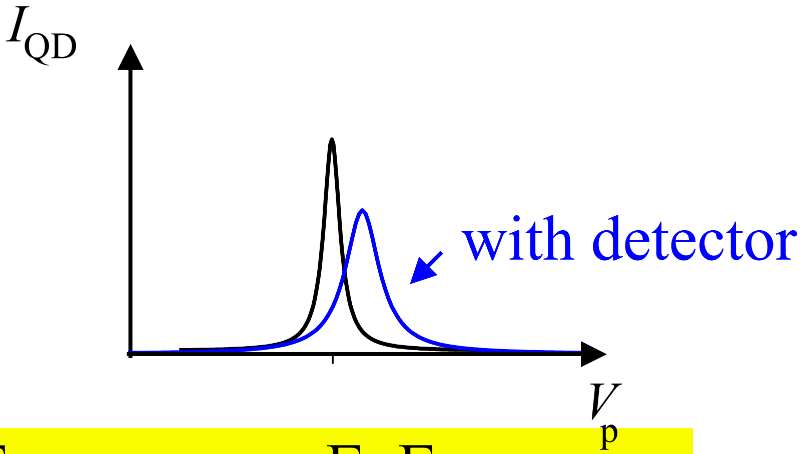
longer trajectories affect large number of detector’s electrons

∴ longer trajectories are better detected

$$\Gamma_e=\Gamma_1+\Gamma_2$$

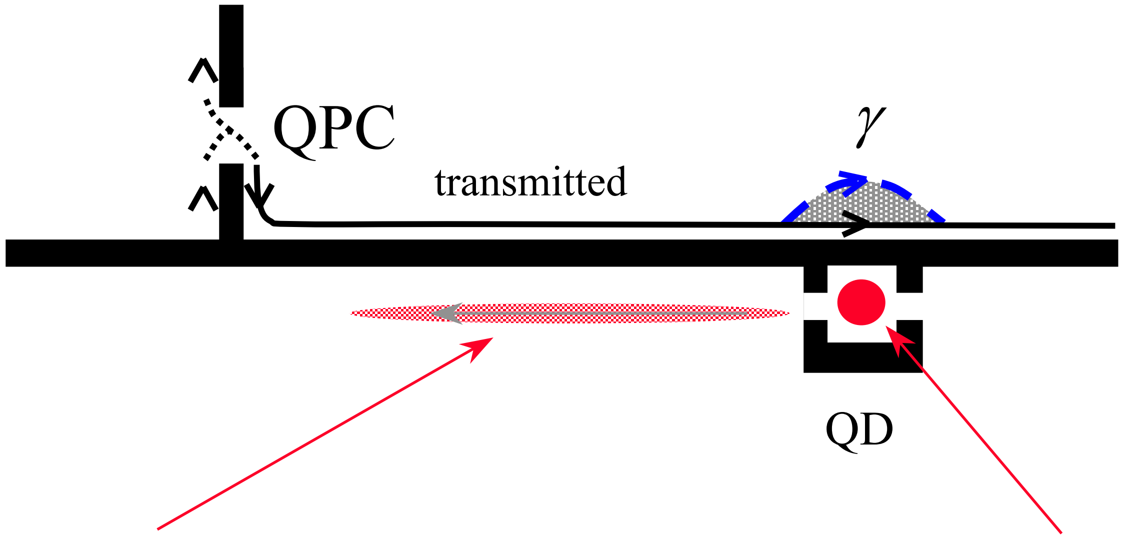
$$\boxed{\Gamma_i=\hbar/\tau_\varphi}$$

$$\Gamma_{tot}=\Gamma_e+\boxed{\Gamma_i}$$



$$T_{QD}=\frac{\Gamma_2\Gamma_1}{(\Gamma_2+\Gamma_1)^2}\frac{\Gamma_{tot}\Gamma_e}{(\varepsilon-\varepsilon_0+\Delta\varepsilon)^2+(\Gamma_{tot}/2)^2}$$

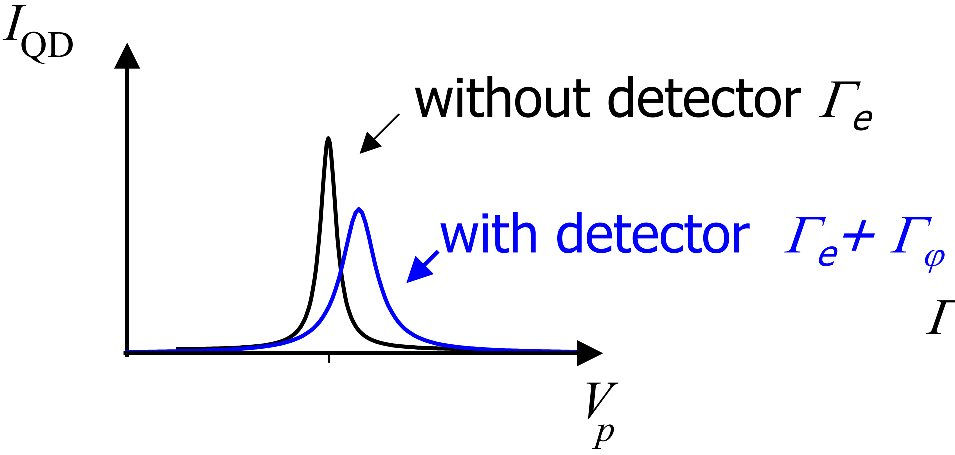
II



electron scatters back
short time near detector

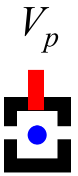
electron dwells in the Q
long time near detector

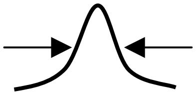
drawback of the single QD



$$\Gamma_\varphi = \hbar/\tau_\varphi$$

single
QD

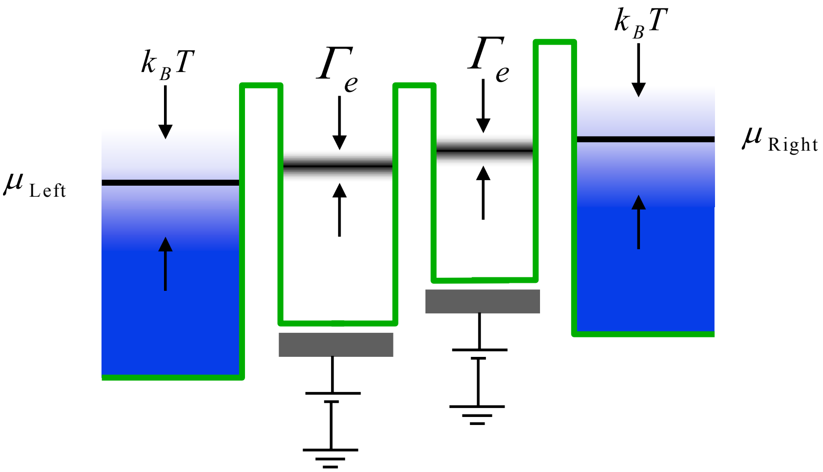




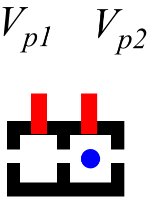
FWHM ~ $4k_BT$

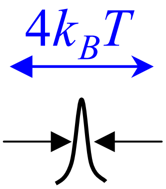
due to Fermi distribution in the leads

single QD → DQD



double
QD
DQD

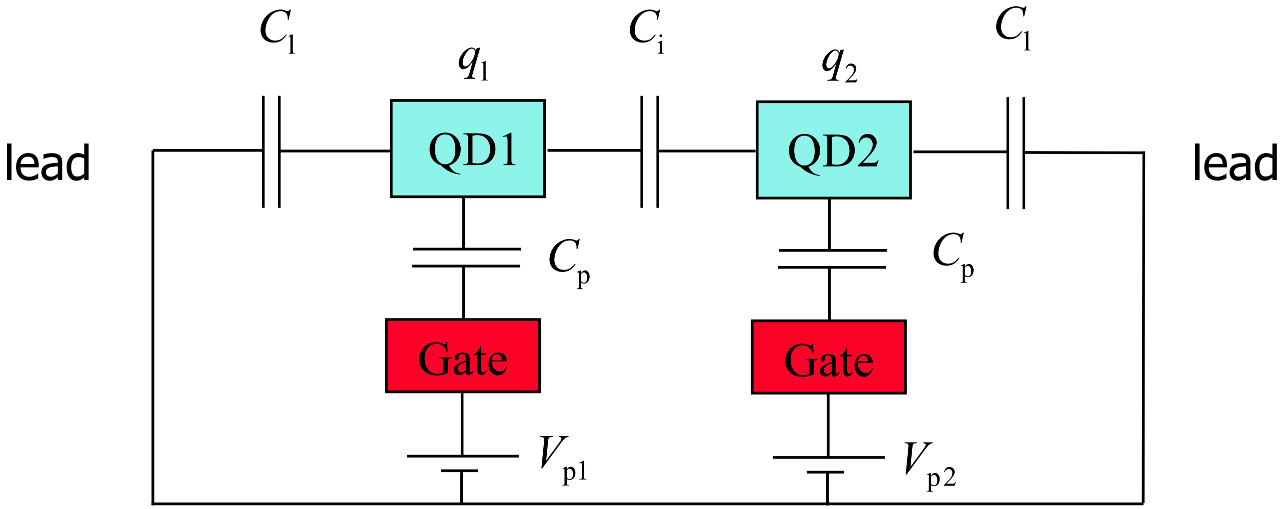




FWHM ~ $2\Gamma_e$

thermal broadening minimized

charging energy in DQD



electrostatic energy .... $U = U(q_1, q_2; V_{p1}, V_{p2})$

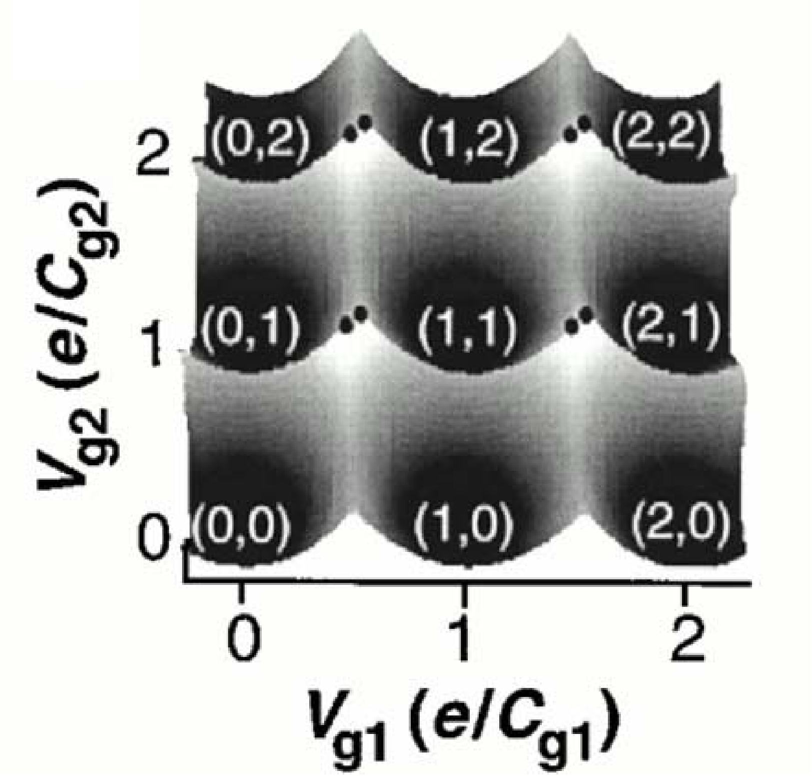
strong confinement of each QD .... $q_1 = -en_1$

$$q_2 = -en_2$$

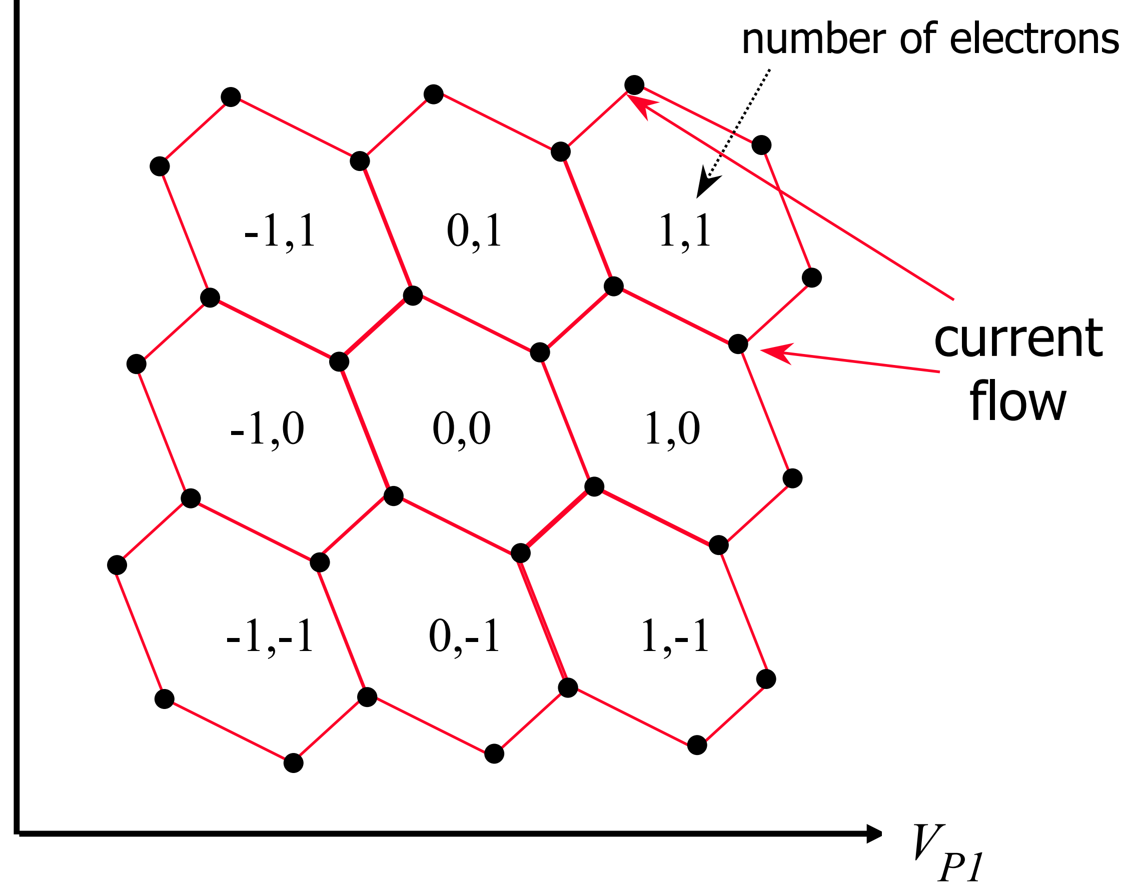
find n_1, n_2 that minimize U

adding electron to n_1+n_2 requires charging energy

Coulomb blockade in DQD



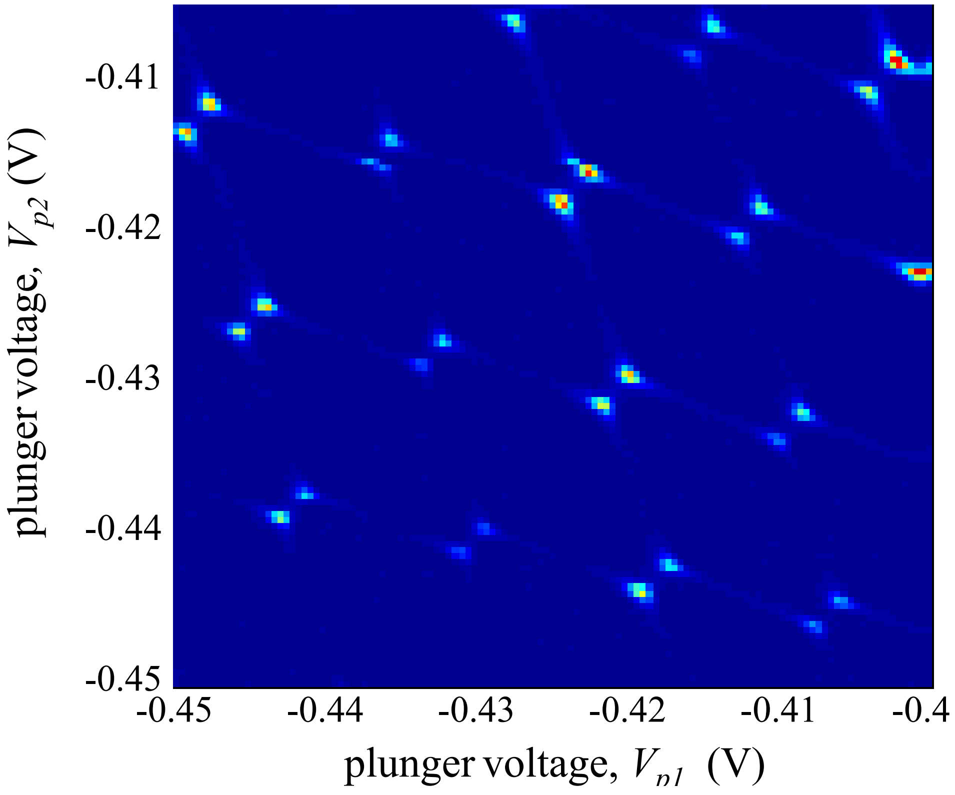
Livermore *et al.*, ‘

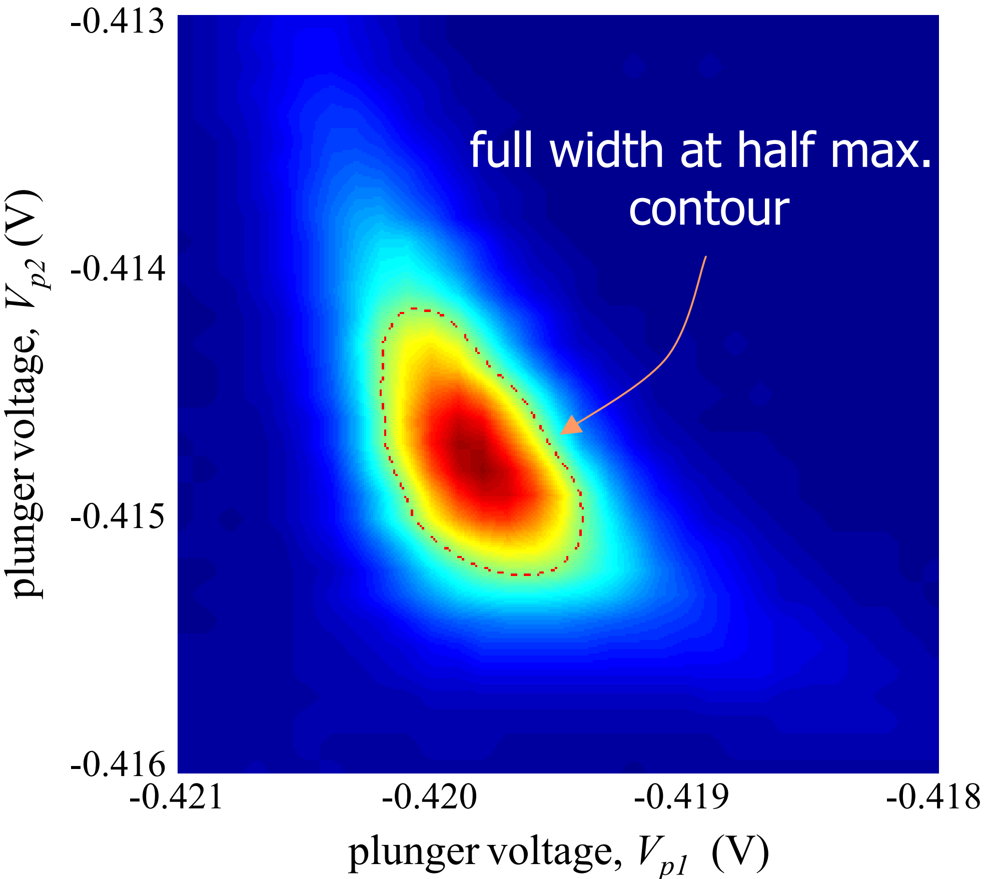


peak in conductance at triple degeneracy point

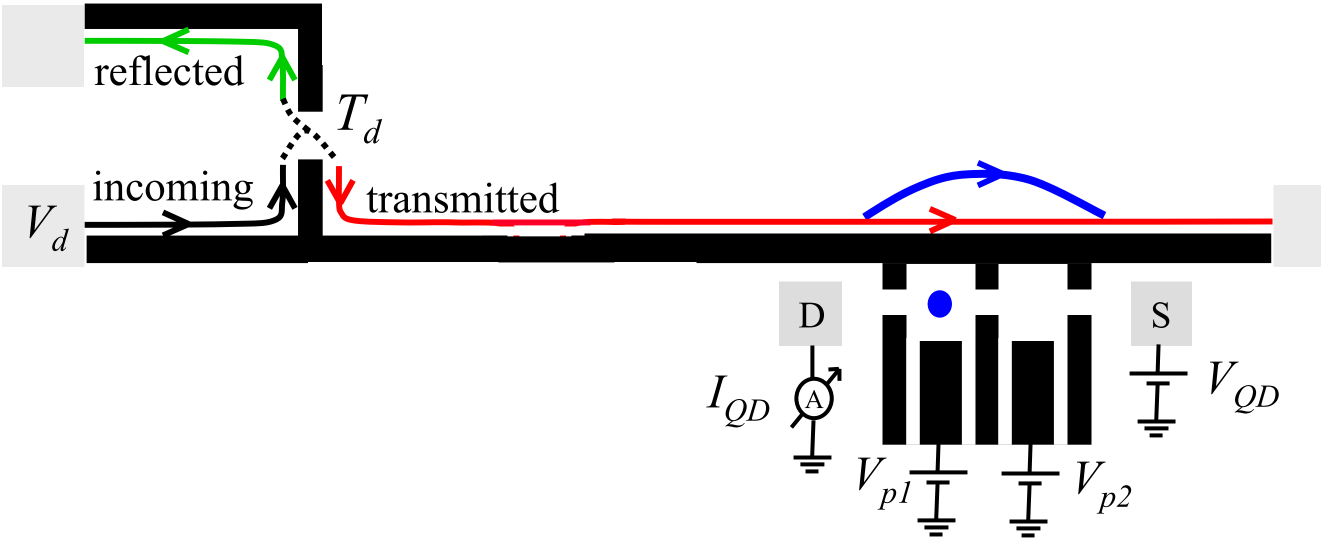
$$n, m \Longrightarrow n+1, m \Longrightarrow n, m+1 \Longrightarrow n, m$$

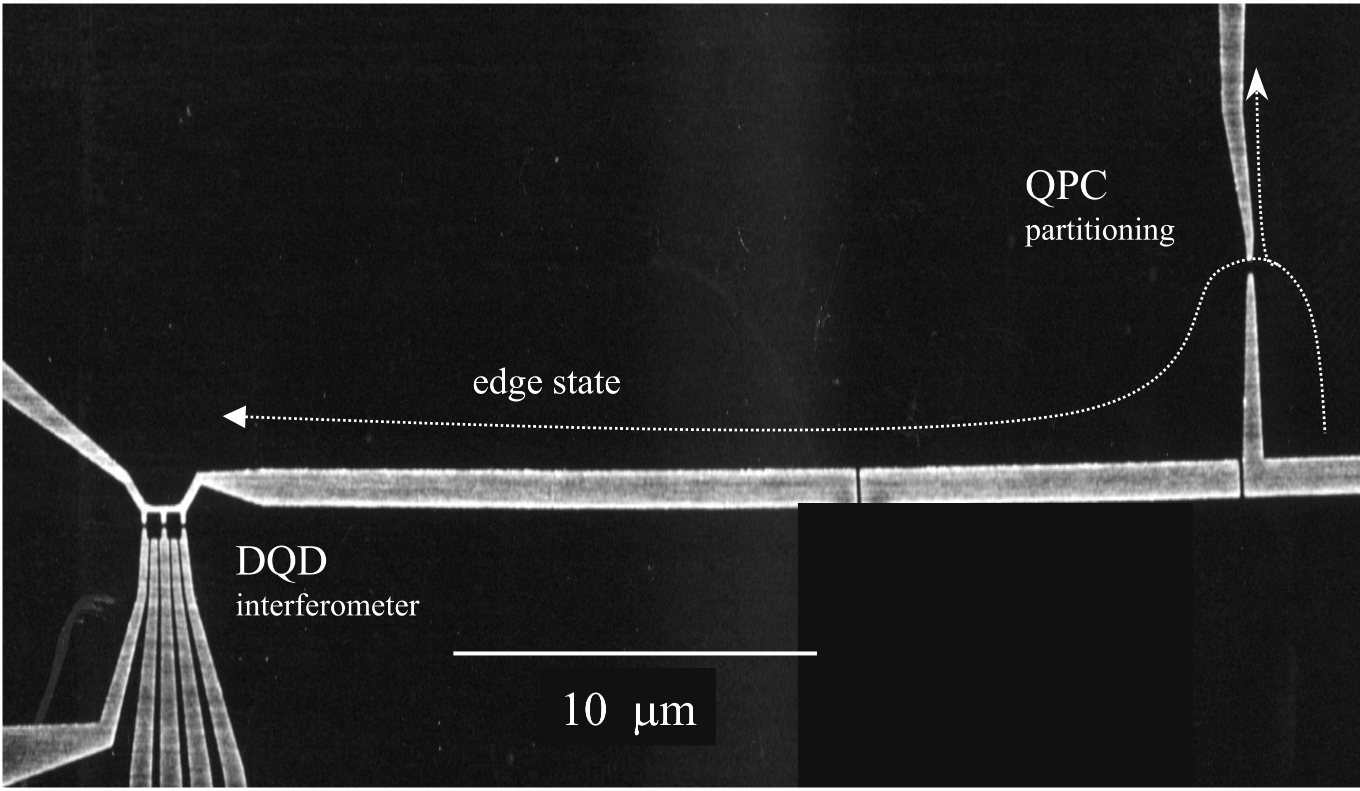
Coulomb blockade in DQD



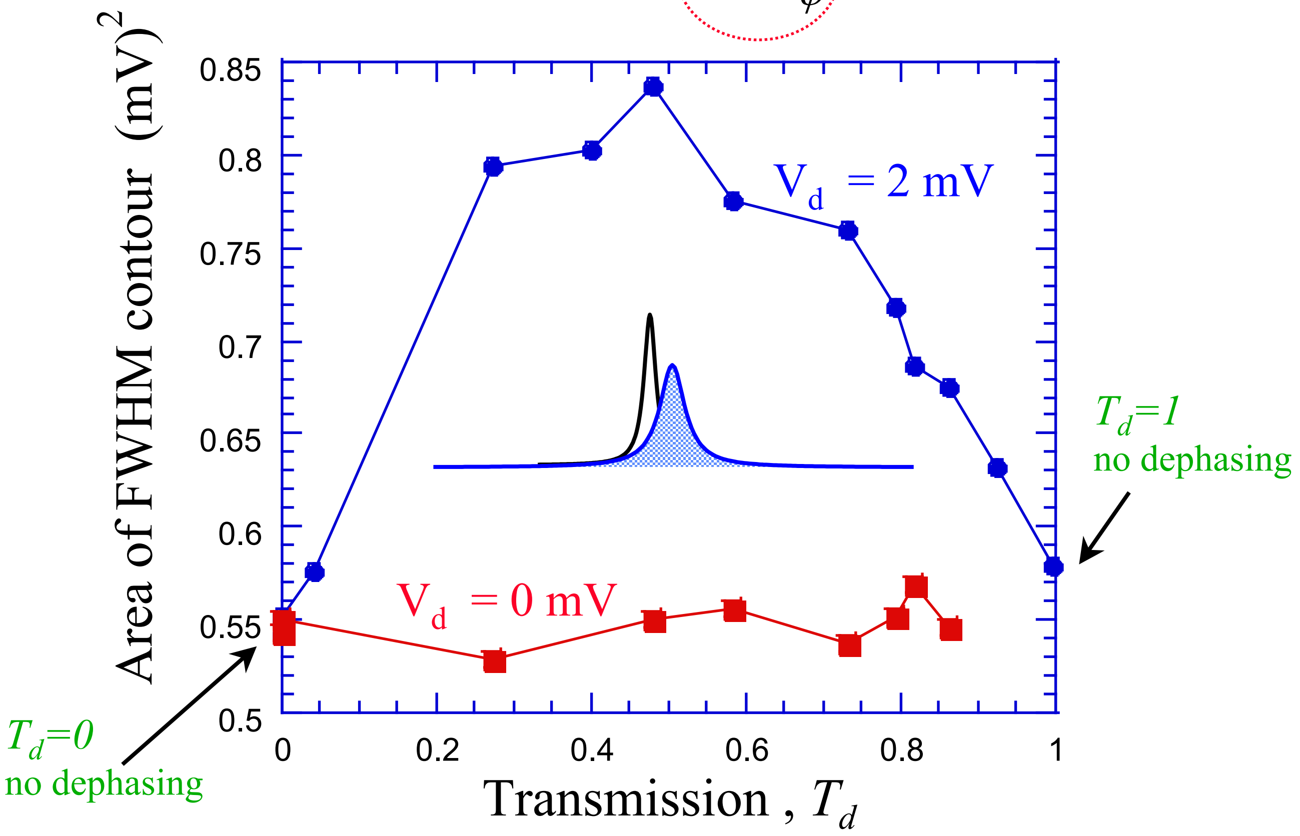

full width at half max. contour

experimental realization





$$\Gamma_e \to \Gamma_e + \boxed{\hbar / \tau_\varphi} \longrightarrow T_d(1-T_d)$$

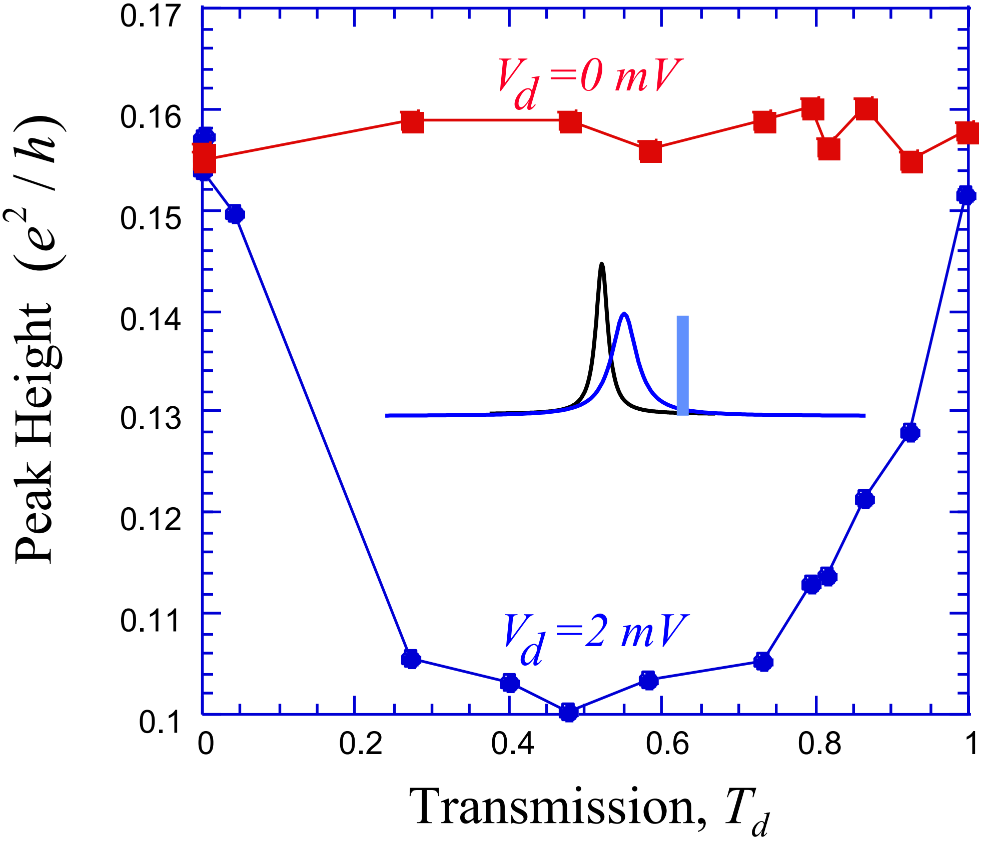


$T_d=1$
no dephasing

$T_d=0$
no dephasing

$T_d(1\text{-}T_d)$

$$peak \approx 1-\frac{\hbar/\tau_\varphi}{\Gamma_e}$$



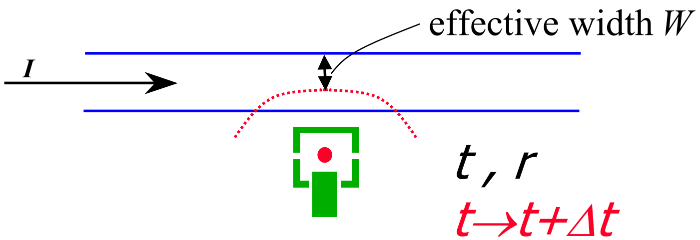
qualitatively, as predicted !

QUESTION #1:

why phase γ doesn't affect the dissipating detector ?

$$\frac{1}{\tau_\varphi} = \frac{eV_d}{h}\left[\frac{(\Delta T_d)^2}{8T_d(1-T_d)}\right]$$

dissipating detector:

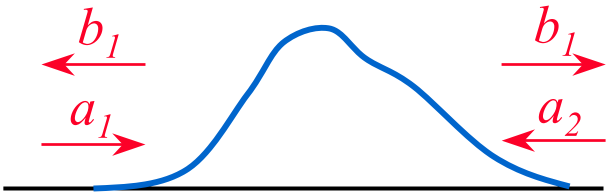


t , r

$t \rightarrow t+\Delta t$

scattering matrix $\overset{=}{S}$ obeying time reversal $S_{ij}=S_{ji}$:

$$\begin{pmatrix} b_1 \\ b_2 \end{pmatrix} = \begin{pmatrix} r & t \\ t & \tilde{r} \end{pmatrix}\begin{pmatrix} a_1 \\ a_2 \end{pmatrix}$$



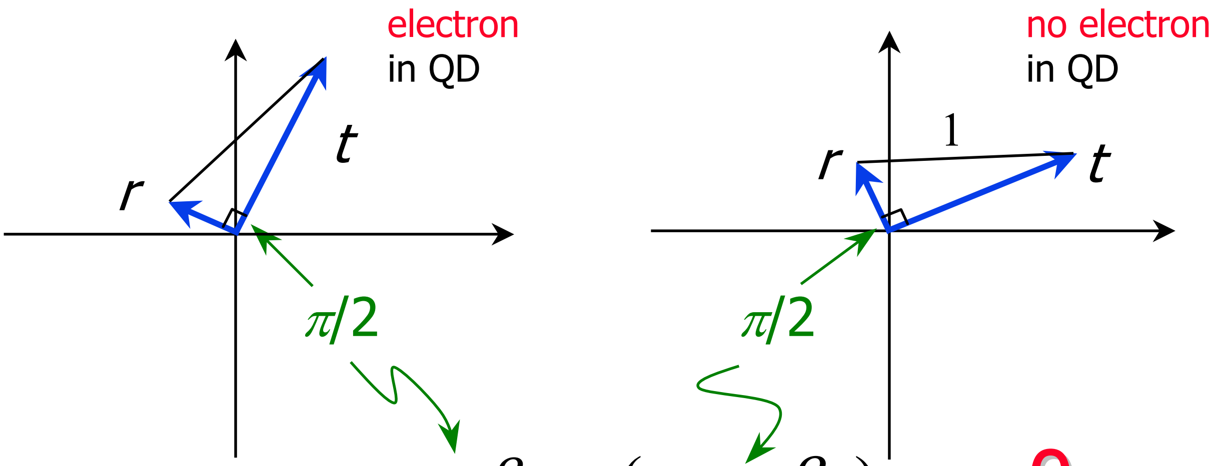
for a symmetric barrier … $r = \tilde{r}$

since $\overset{=}{S}$ is unitary $rt^{*}+tr^{*}=0$; $r = |r|e^{i\alpha}$ $t = |t|e^{i\beta}$

$$e^{i(\alpha-\beta)} = -e^{-i(\alpha-\beta)}$$

$$\alpha-\beta = -(\alpha-\beta)+\pi \quad ; \quad \boxed{\alpha-\beta = \pi/2}$$

our QPC barrier is ‘symmetric’



$$\gamma = \alpha_+ - \beta_+ - (\alpha_- - \beta_-) \rightarrow 0$$

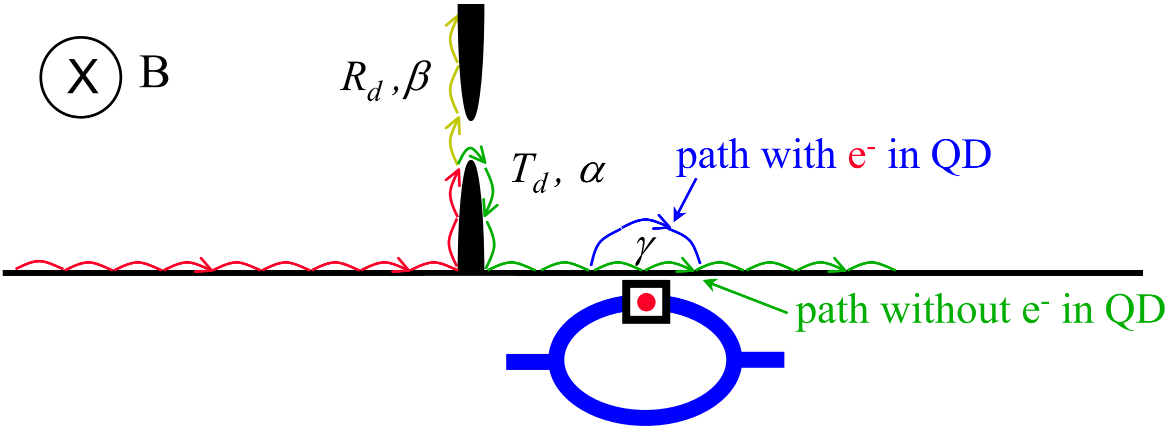
QUESTION #2:

why noise plays different roles in the two detectors ?

current fluctuations and potential (density) fluctuations

are not always the same !

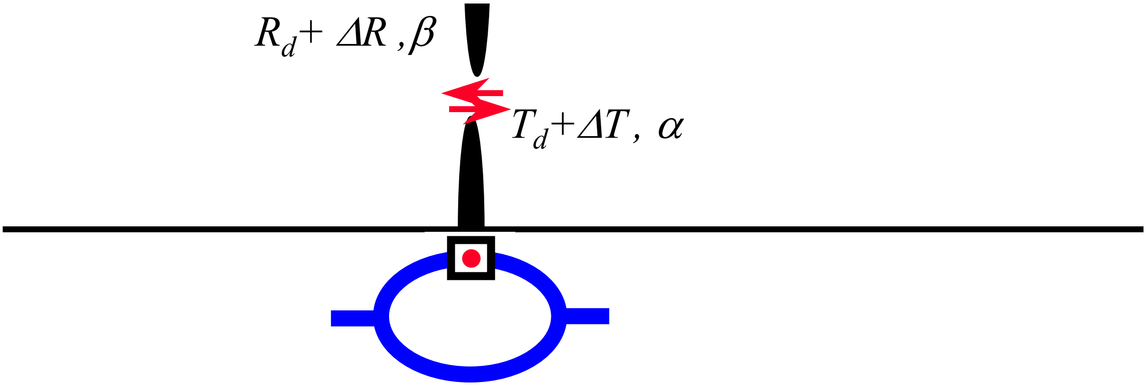
in edge state *phase* detector



$$j = e\rho\upsilon = e\psi^*\psi\upsilon$$

density and current fluctuations are similar

in dissipating detector



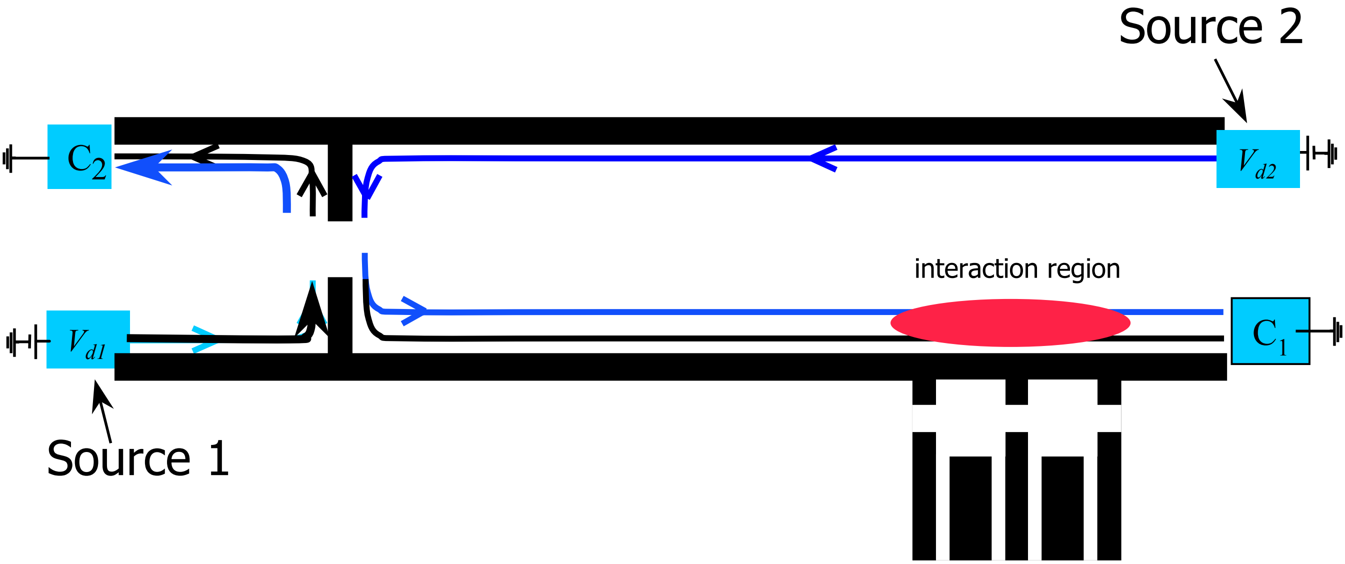
$$\psi = ae^{ikx} + be^{ikx}$$

$$\rho = e|\psi|^2 = |a|^2 + |b|^2 + \left(ab^* e^{2ikx} + c.c.\right)$$

$$j = -\frac{i\hbar}{2m}\left(\psi^*\psi + c.c\right) = |a|^2 - |b|^2$$

density and current fluctuation are different

more information ?



$$V_{d1} = V_{d2}$$

will more information enhance dephasing?

- the effect of the detector on interferometer …

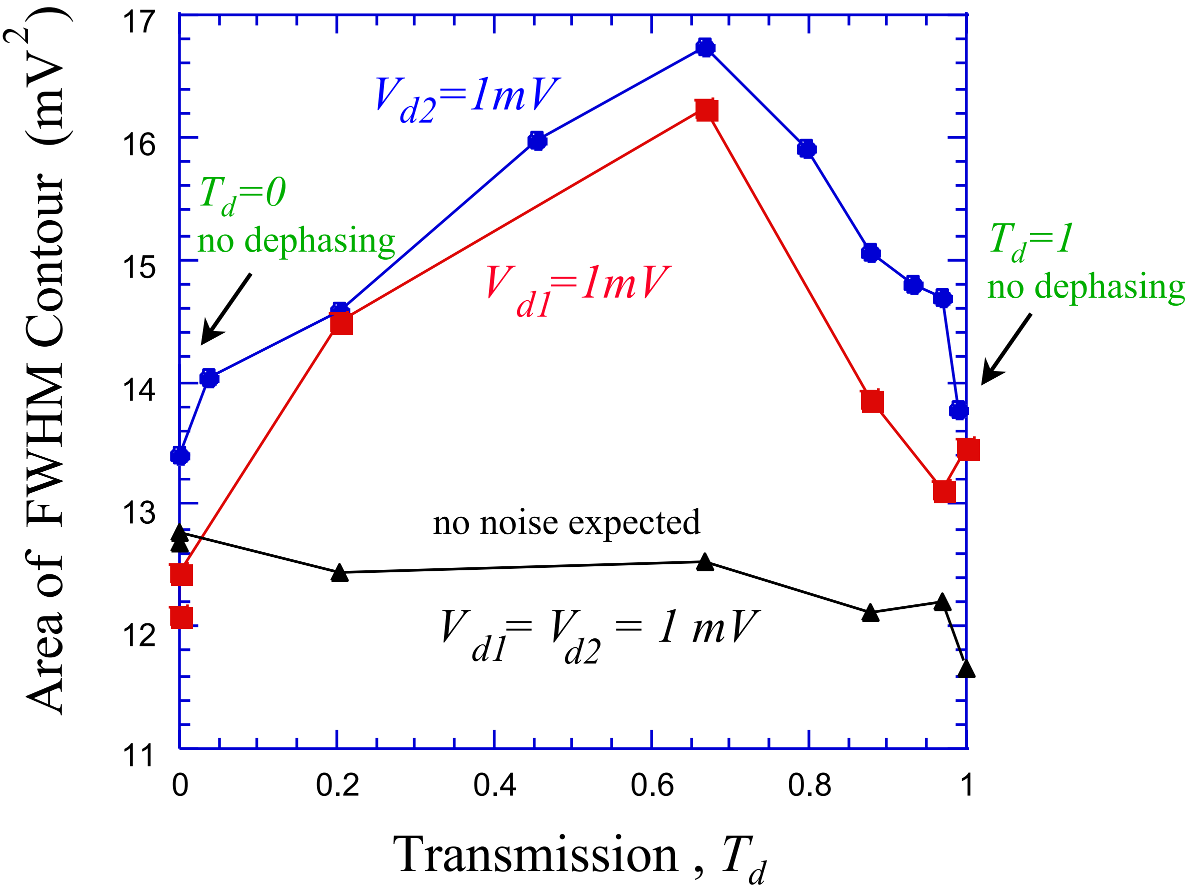
two full Fermi seas approach the QPC
partition is impossible

no noise in edge
no dephasing

- information provided by the detector …

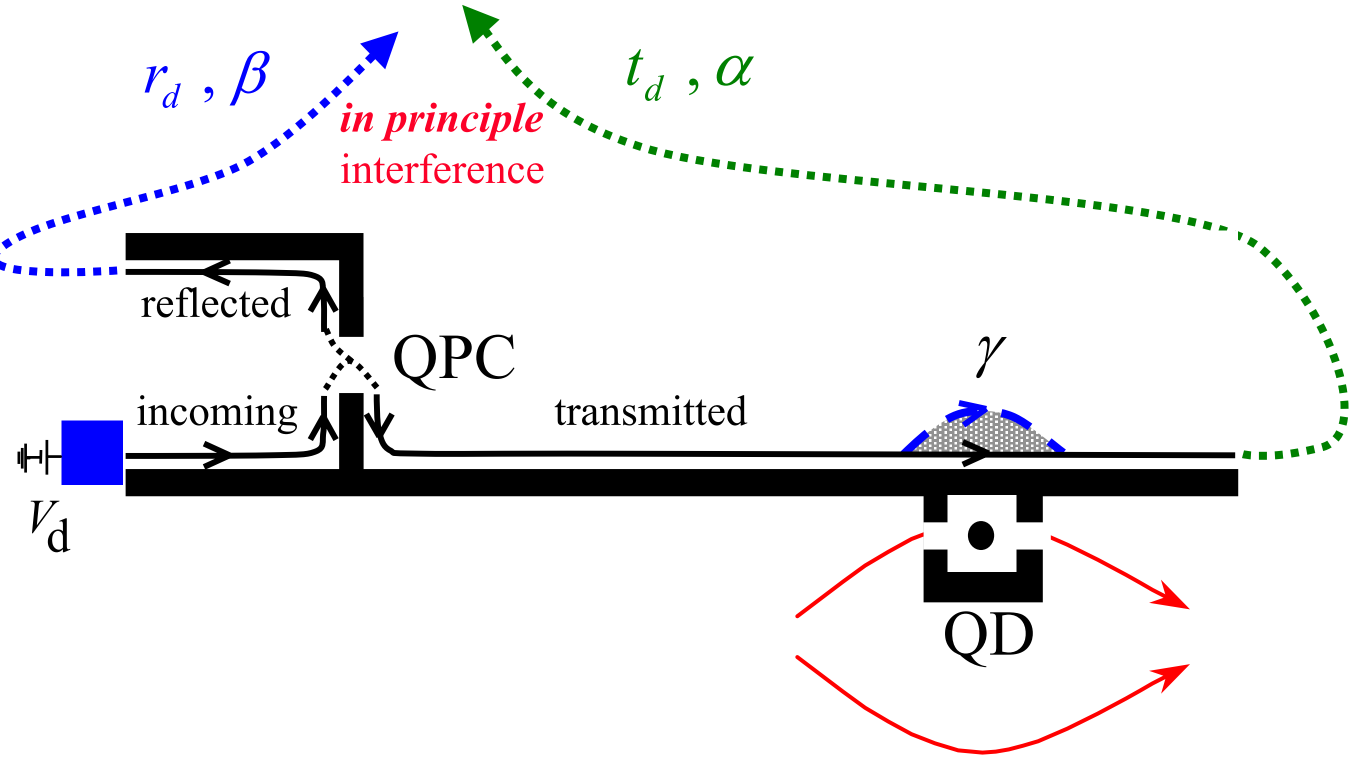
full Fermi sea in the two collectors C_1 and C_2
independent of the phase γ

no information provided by the detector


Area of FWHM Contour (mV^2)
17
16
15
14
13
12
11
V_{d2}=1mV
T_d=0
no dephasing
V_{d1}=1mV
T_d=1
no dephasing
no noise expected
V_{d1}= V_{d2} = 1 mV
0
0.2
0.4
0.6
0.8
1
Transmission , T_d

the *which path* information …

interference between transmitted and reflected edge states



which path information $\nu_d = \left|\langle \chi_l | \chi_r \rangle\right|$

detector states

[ ] $\left|\chi_l\right\rangle = t\left|t\right\rangle_d + r\left|r\right\rangle_d$

[•] $\left|\chi_r\right\rangle = e^{i\gamma} t\left|t\right\rangle_d + r\left|r\right\rangle_d$

for a single electron in the detector:

$$\left|\langle \chi_l | \chi_r \rangle\right|^2 \equiv \left|\nu_d^1\right|^2 = \left|(e^{i\gamma} t^* \langle t| + r^* \langle r|) \cdot (t|t\rangle + r|r\rangle)\right|^2 =$$

$$= \left|e^{i\gamma} t^2 + r^2\right|^2 = T^2 + R^2 + 2TR\cos\gamma =$$

$$= (T+R)^2 - 2TR\,(1+\cos\gamma)$$

$$\left|\nu_d^1\right|^2 = 1 - 4TR\sin^2\frac{\gamma}{2}$$

for *n* independent electrons probing the interferometer:

$$\left|\nu_d^n\right| = \left|\nu_d^1\right|^n = (1 - 4TR\sin^2\frac{\gamma}{2})^{n/2}$$

$$\left|\nu_d^n\right| \cong 1 - 2nTR\sin^2\frac{\gamma}{2}$$

probing rate …. $n=2eV_d/h$ (n electrons per unit time)

$$\nu_d^n(t) \equiv e^{-t/\tau_\varphi} \cong 1 - t/\tau_\varphi$$

dephasing rate ……. $1/\tau_\varphi$

$$1/\tau_\varphi = 1 - \left|\nu_d^n\right|$$

total dephasing rate

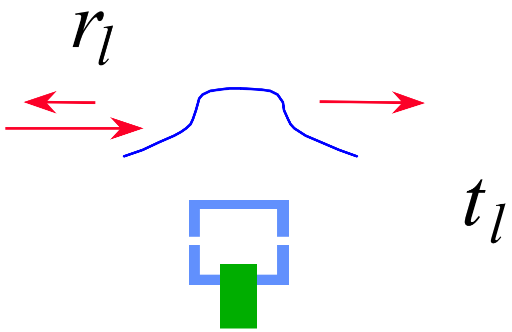
$$\frac{1}{\tau_\varphi} = \frac{eV_d}{h}\left[\frac{(\Delta T_d)^2}{8T_d(1-T_d)} + 4T_d(1-T_d)\sin^2\frac{\gamma}{2}\right]$$

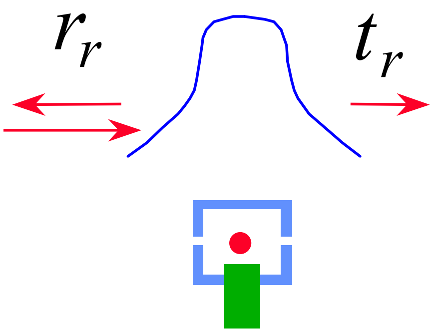
more rigorous dephasing estimate for the *dissipating* detector

$$\nu_d = \left|\, {}_d\langle \chi_r | \chi_l \rangle_d \right|$$

$$|\chi_l\rangle_d = t_l |t\rangle_d + r_r |r\rangle_d$$

$$|\chi_r\rangle_d = t_r |t\rangle_d + r_r |r\rangle_d$$

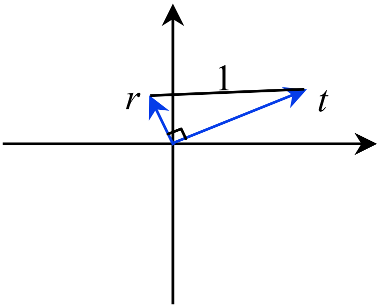




going through left path

going through path with QD

symmetric barrier



$$t_l = cos\theta_l\, exp(i\varphi_l)$$

$$r_l = i\, sin\theta_l\, exp(i\varphi_l)$$

$$t_r = cos\theta_r\, exp(i\varphi_r)$$

$$r_r = i\, sin\theta_r\, exp(i\varphi_r)$$

for a single electron probing the interferometer

$$\nu_d^1 = \left| t_r^* t_l + r_r^* r_l \right| = \left| \cos\theta_r \cos\theta_l + \sin\theta_r \sin\theta_l \right| = \left| \cos(\theta_r - \theta_l) \right|$$

$$\Delta\theta \equiv \theta_r - \theta_l << 1 \;\; ; \;\; \theta_l \cong \theta_r = \theta$$

$$\cos^2\theta = T_d = \left| t_d \right|^2$$

$$\boxed{\nu_d^1 \approx 1 - (\Delta\theta)^2 / 2}$$

$$\Delta T_d = \cos^2\theta_l - \cos^2\theta_r = \left(\cos\theta_l + \cos\theta_r\right) \cdot \left(\cos\theta_l - \cos\theta_r\right)$$

$$\Delta T_d = 2\cos\frac{\theta_l + \theta_r}{2} \cos\frac{\Delta\theta}{2} \cdot (-2\sin\frac{\theta_l + \theta_r}{2} \sin\frac{\Delta\theta}{2})$$

$$\Delta T_d = 2 \quad \cos\theta \qquad 1 \qquad -2\sin\theta \qquad \frac{\Delta\theta}{2}$$

$$\Delta\theta = \Delta T_d / (-2\cos\theta \sin\theta)$$

$$\nu_d^1 = 1 - \frac{(\Delta T_d)^2}{8T_d(1 - T_d)}$$

for *n* independent electrons probing the interferometer

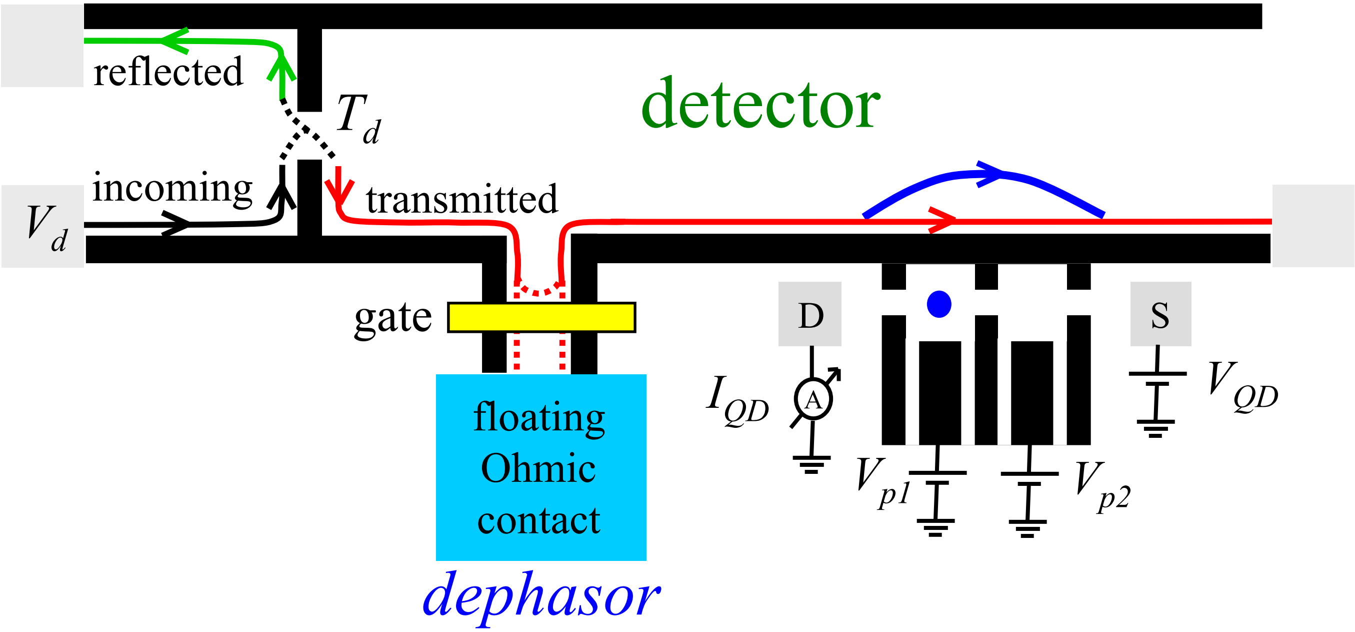
$$\nu_d^n = (\nu_d^n)^n$$

probing rate …. *n=2eV_d/h* (*n* electrons time *t*)

$$\nu_d^n \equiv e^{-t(n)/\tau_\varphi} \cong 1 - t/\tau_\varphi \cong 1 - n\nu_d^1$$

$$1/\tau_\varphi = 1 - \left|\nu_d^n\right| \cong \frac{2eV_d}{h}\frac{(\Delta T_d)^2}{8T_d(1 - T_d)}$$

adding a 'dephasor'



a dephasor in the detector prevents interference

rendering the *phase detector* ineffective !

on the other hand, current continuity preserves shot noise

can we describe the quantum states in the following way ?

detector states

without dephasor

$$|\chi_1\rangle = t|t\rangle_d + r|r\rangle_d$$

$$|\chi_2\rangle = e^{i\gamma} t|t\rangle_d + r|r\rangle_d$$

with dephasor

$$|\chi_1^d\rangle = t|t\rangle_d|d_t\rangle + r|r\rangle_d|d_r\rangle$$

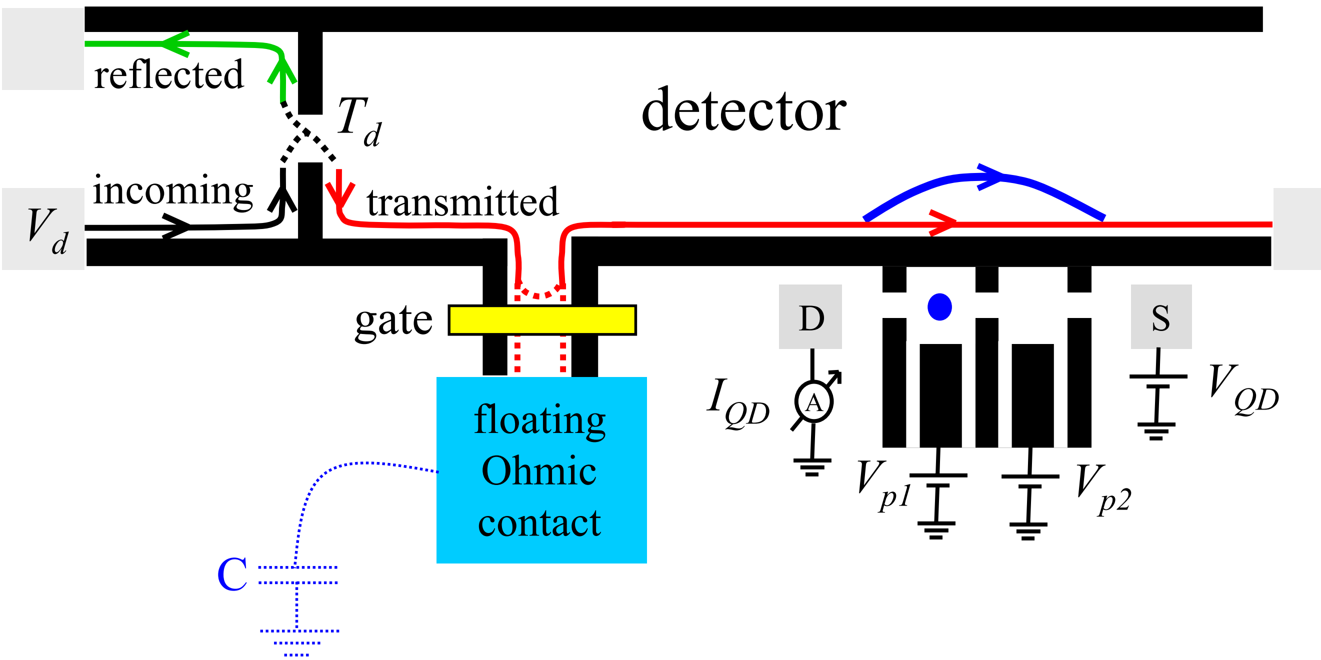
$$|\chi_2^d\rangle = e^{i\gamma} t|t\rangle_d|d_t\rangle + r|r\rangle_d|d_r\rangle$$

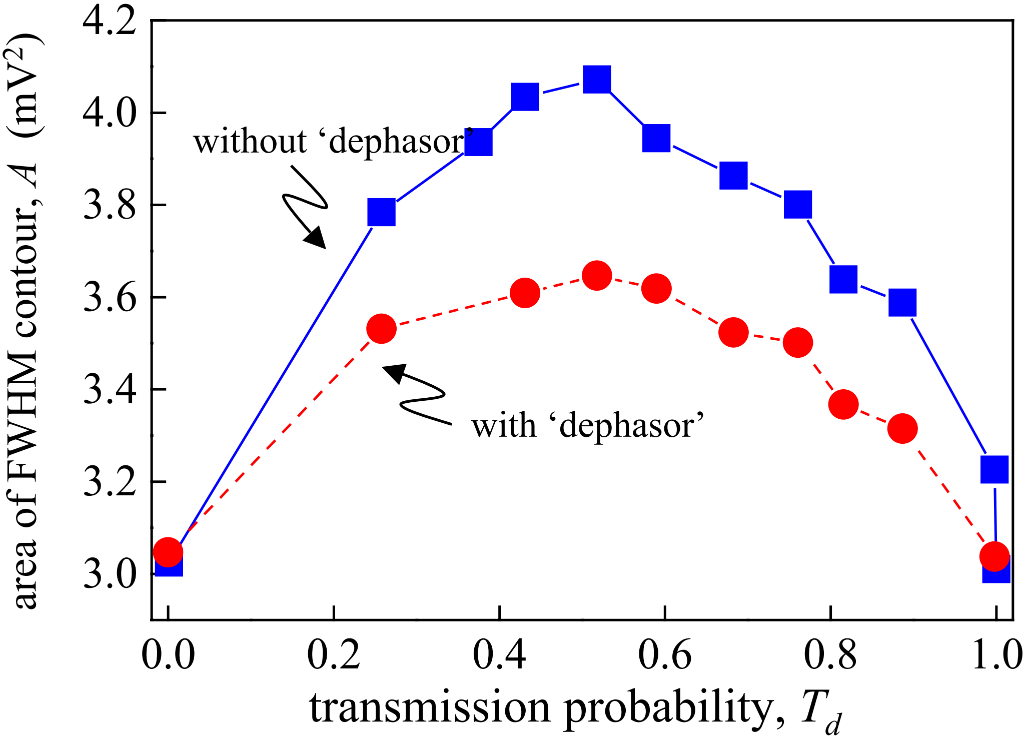
dephasor state

$$\left|\langle \chi_1^d | \chi_2^d \rangle\right| = \left|\langle \chi_1 | \chi_2 \rangle\right|$$

the detector still detects --- not a true dephasor !

a floating Ohmic contact = a dephasor ?





due to the finite *capacitance* of the *contact charge fluctuations* diminish

hence ...

- reservoir in thermal equilibrium cannot be described by orthogonal quantum states

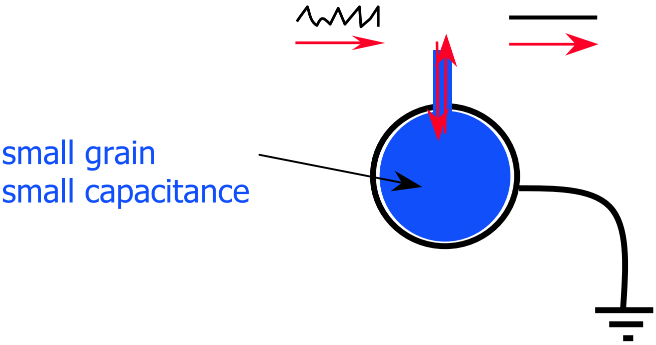
- how to build a true thermalizing reservoir ? how will it behave ?

  -- should quench shot noise in the edge current

  -- can do it *via* a large capacitance to ground

  -- does the reservoir have to be very large ?

  -- not necessarily…



-- a large capacitor induce *decoherence* via radiatio

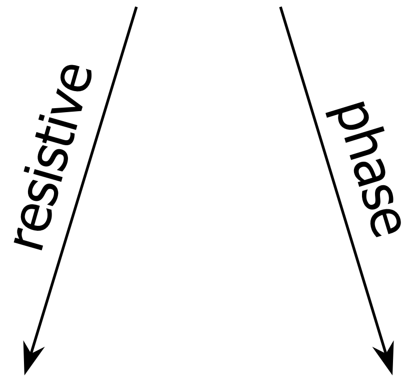
research done by:

E. Buks
D. Sprinzak

S. Gurvich
J. Imry
Y. Levinson

V. Umansky
H. Shtrikman
D. Mahalu

which path detectors



$$\frac{1}{\tau_\varphi}=\frac{eV_d}{h}\left[\frac{(\Delta T_d)^2}{8T_d(1-T_d)}+4T_d(1-T_d)\sin^2\frac{\gamma}{2}\right]$$

learn to use the dual picture to understand decoherence

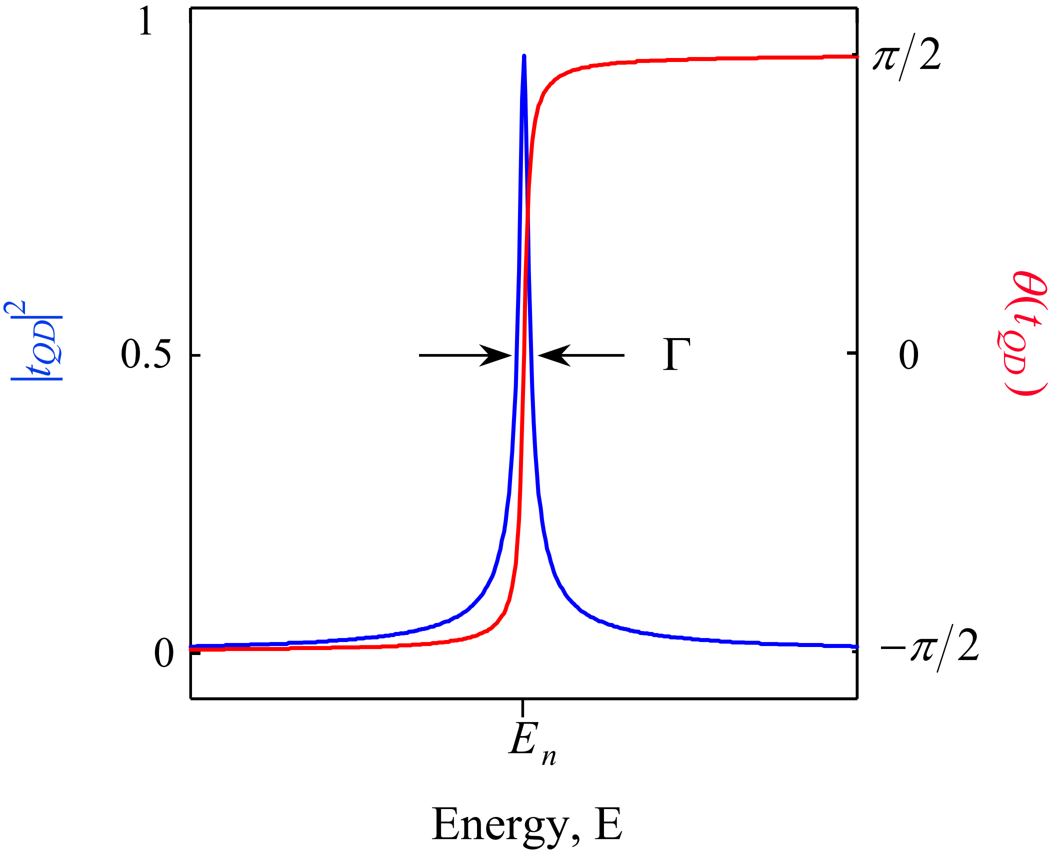
Phase Evolution in Coherent QD

Expected from Breit-Wigner formula :

$$t_{QD} = C_n \frac{i\Gamma/2}{(E-E_n)+i\Gamma/2}$$

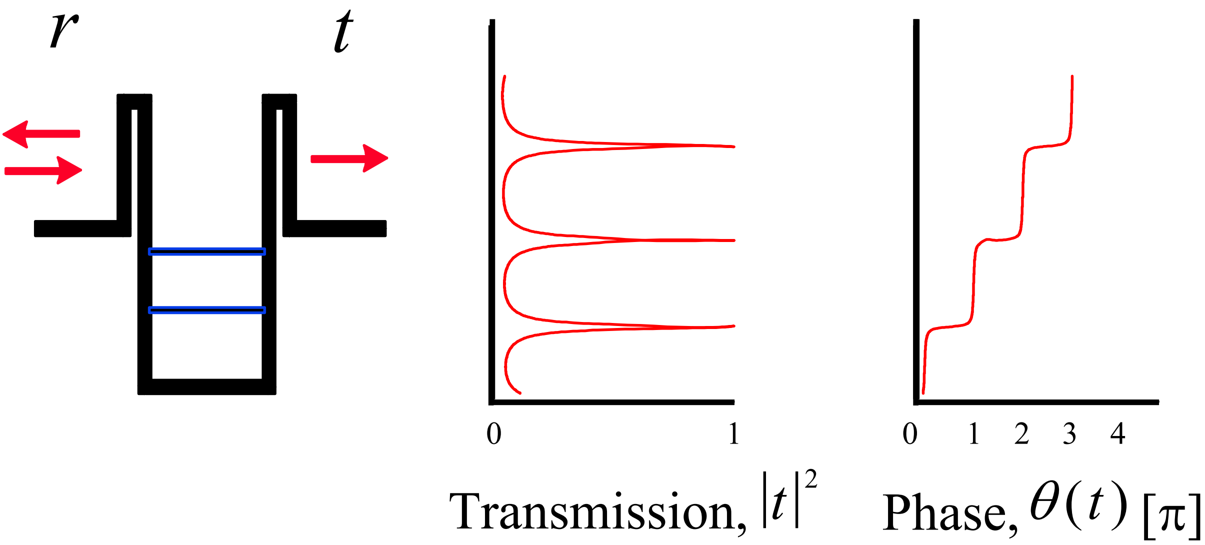
Transmission probability … $|t_{QD}|^2 = |C_n|^2 \frac{(\Gamma/2)^2}{(E-E_n)^2+(\Gamma/2}$

Phase …………….. $\theta(t_{QD}) = \theta(C_n) + \arctan\frac{2}{\Gamma}(E-E_n$



What are the allowed values of $\theta(C_n)$?

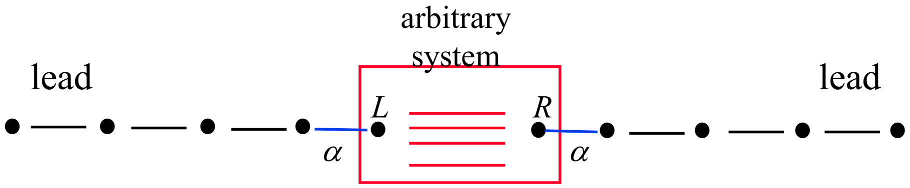
Example: 1D Rectangular Well (no e-e interaction)



- Each resonance leads to phase change of π.
- Consecutive resonances are out of phase.

$$\theta(C_{n+1}) - \theta(C_n) = \pi$$

General case, tight binding model



quasi bound states, ψ_n

small coupling $\alpha << 1$

$$\theta(C_n) = \theta[\psi_n^L(\psi_n^R)^*]$$

If time reversal symmetry holds than ψ_n can be chosen real

$$\theta(C_{n+1}) - \theta(C_n) \in \{0, \pi\}$$

Theory

Recent calculations are :

- I. L. Aleiner, N. S. Wingreen and Y. Meir, *Phys. Rev. Lett,* in press, cond - mat/9702001.
- Y. Levinson, *Europhys. Lett*. **39**, 299-304 (1997).
- E. Buks, R. Schuster, M. Heiblum, D. Mahalu and V.

Umansky, quant-ph/9709022.

$$\frac{1}{\tau_\varphi} = \frac{2eV_d}{h} \frac{(\Delta T_d)^2}{8T_d(1-T_d)}$$

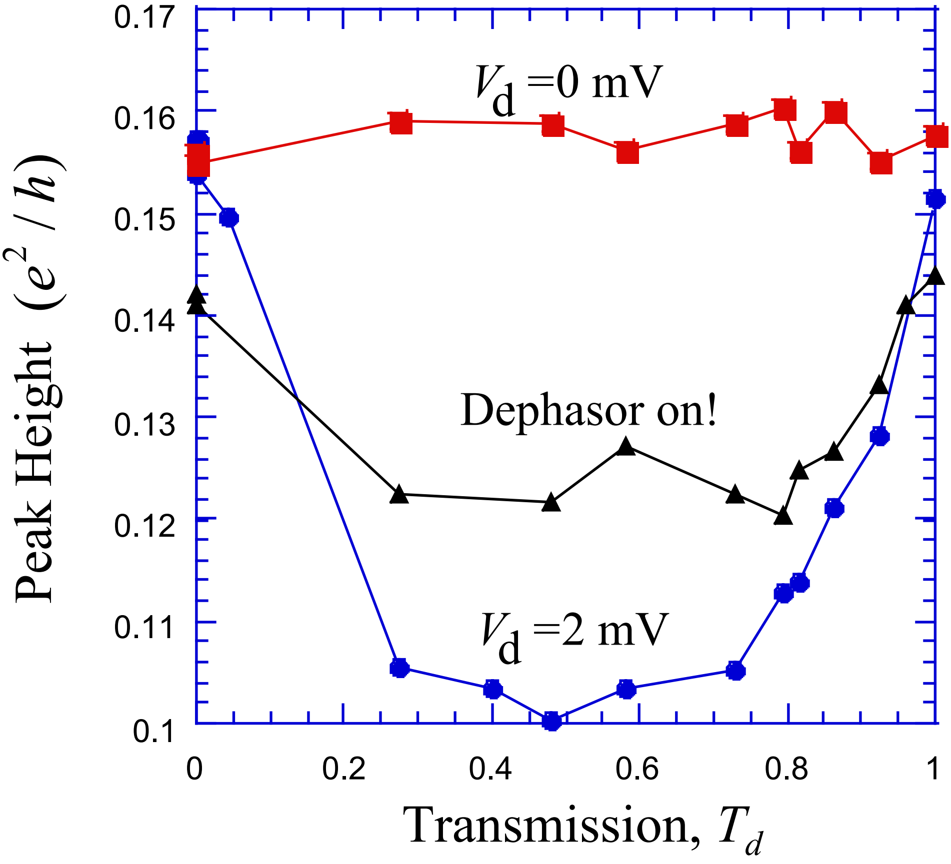
- S. A. Gurvitz, cond - mat/9706074.

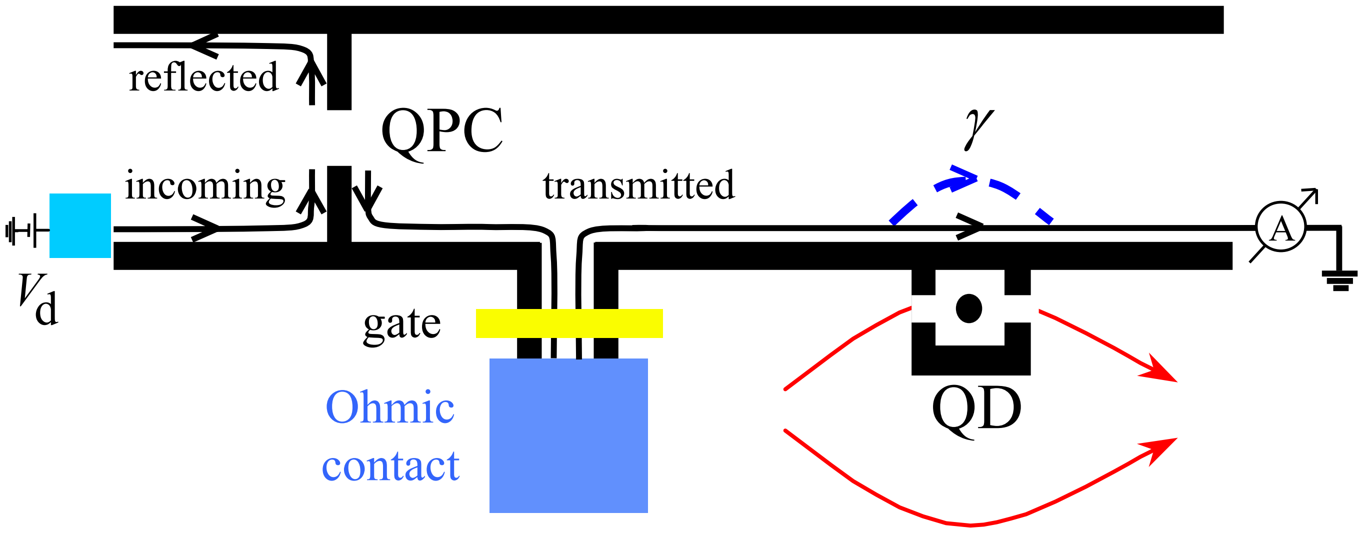
$$\frac{1}{\tau_\varphi} = \frac{2eV_d}{h} \frac{(\Delta T_d)^2}{8T_d}$$

- Y. Imry, to be published in *Proceedings of the 1997 Nobel Symposium on Modern Studies of Basic*

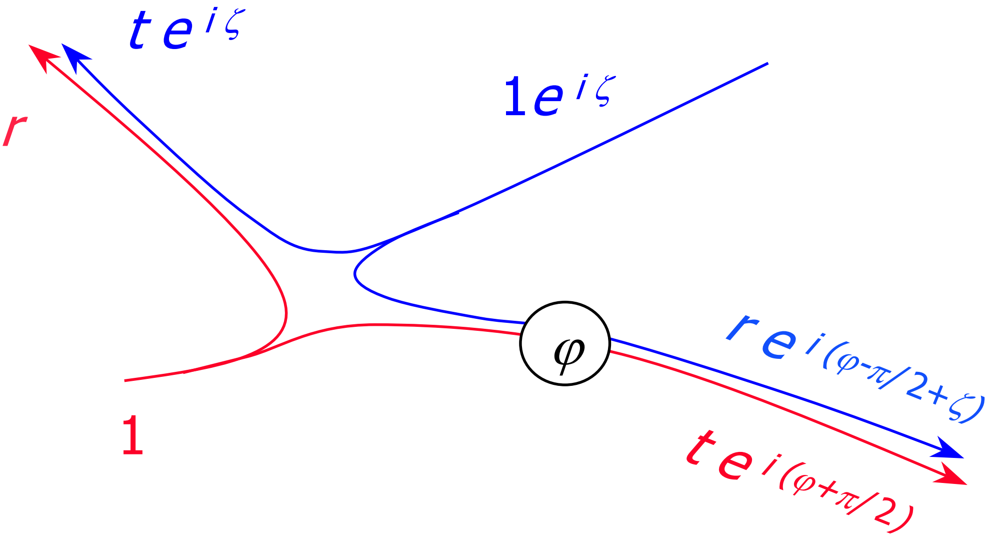
Quantum Concepts and Phenomena.

Peak Height vs. Transmission





look first on information = interference



blue $$2\,\mathrm{Re}\left[te^{i\zeta}\;\, re^{-i(\varphi+\zeta-\pi/2)}\right]=2\,\mathrm{Re}\,tr\left[e^{-i\varphi}e^{i\pi/2}\right]=-2\sin\varphi$$

red $$2\,\mathrm{Re}\left[r\,te^{-i(\varphi+\pi/2)}\right]=2\,\mathrm{Re}\,tr\left[e^{-i\varphi}e^{-i\pi/2}\right]=2\sin\varphi$$

zero interference in detector
no dephasing

two full Fermi seas approach the QPC
partition is impossible

no noise in edge
no dephasing