Determination of the coherence length in the Integer Quantum Hall Regime

Nanoelectronics group & **Phynano team**

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QUANTUM OPTICS	⟷	QUANTUM RF CIRCUITS
FIBERS, BEAMS		TRANSM. LINES, WIRES
BEAM-SPLITTERS		COUPLERS
MIRRORS		CAPACITORS
LASERS		GENERATORS
PHOTODETECTORS		AMPLIFIERS
ATOMS		JOSEPHSON JUNCTIONS

DRAWBACKS OF CIRCUITS: ARTIFICIAL ATOMS PRONE TO VARIATIONS

ADVANTAGES OF CIRCUITS:
- PARALLEL FABRICATION METHODS
- LEGO BLOCK CONSTRUCTION OF HAMILTONIAN
- ARBITRARILY LARGE ATOM-FIELD COUPLING

08-I-38

From M. Devoret, First lecture (May, 13)

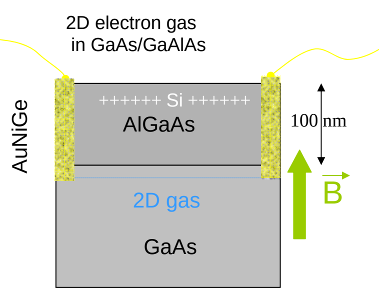
QUANTUM OPTICS ⟷ **QUANTUM ELECTRONICS**
In the IQHE regime

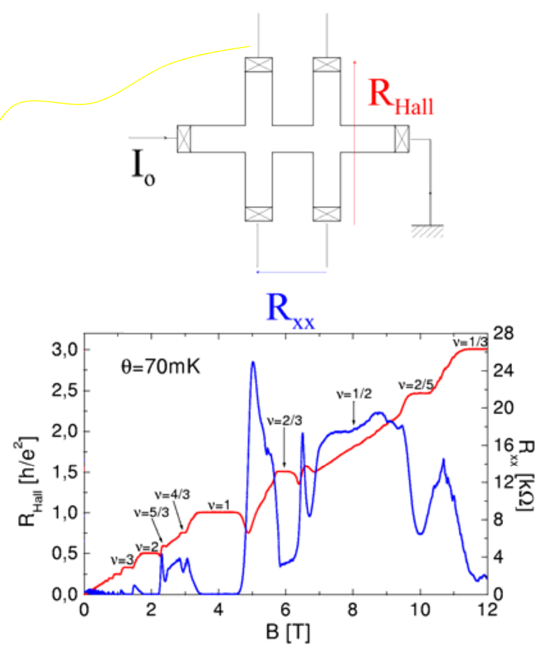
QUANTUM OPTICS	QUANTUM ELECTRONICS
FIBERS, BEAMS	ELECTRON BEAM
BEAM-SPLITTERS	ELECTRON BEAM SPLITTERS
MIRRORS	SAMPLE EDGES
LASERS	GENERATORS

	ENERGY	CHARGE
	BOSONS	FERMIONS
SUB-POISSONIAN SOURCE :	HARD	EASY
INTERFERENCES :	EASY	HARD

Beamlike motion

Transport in the Quantum Hall regime

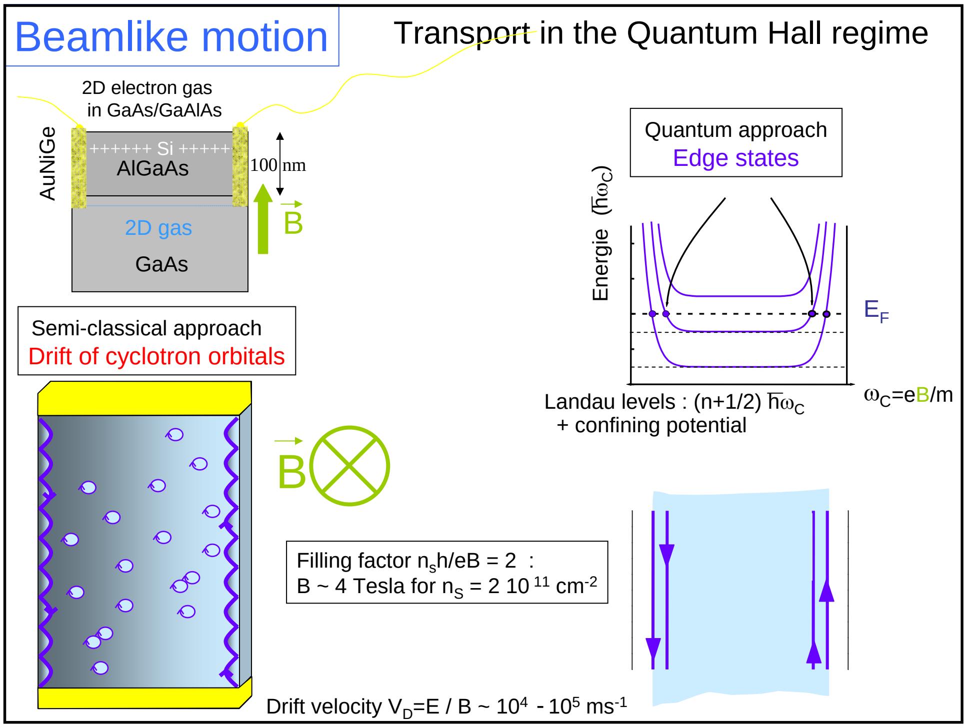


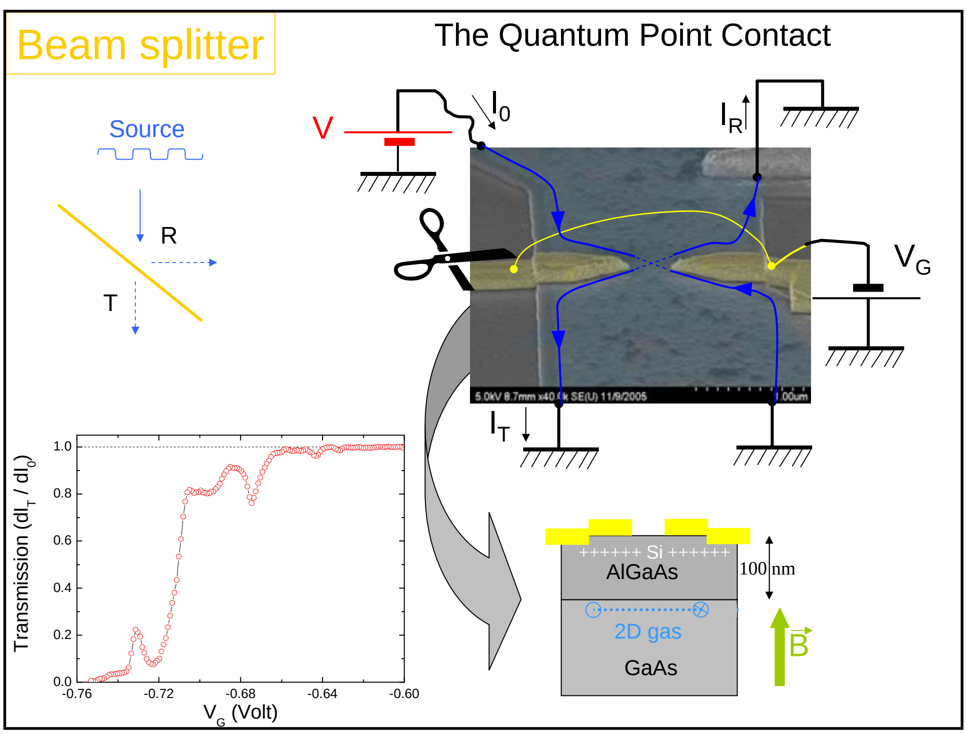


$n_S \sim 10^{11}$ cm-2 ; $\mu \sim 10^6$ cm²/VS

Filling factor $\nu = n_s/n_\Phi$
$n_\Phi = eB/h$

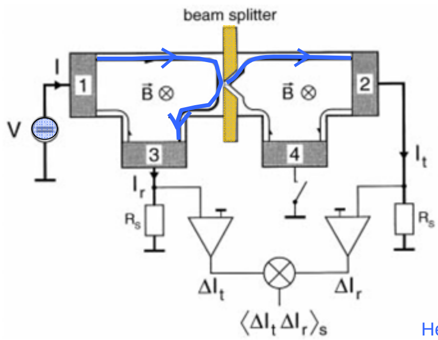
$$R_{Hall} = h / (e^2 \nu)$$

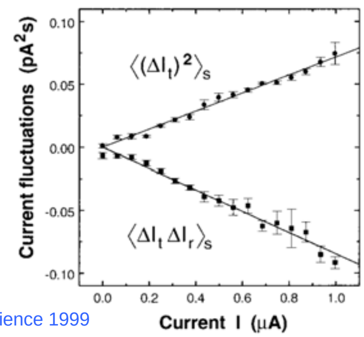

Beamlike motion
Transport in the Quantum Hall regime
2D electron gas
in GaAs/GaAlAs
AuNiGe
++++++ Si +++++
AlGaAs
100 nm
2D gas
GaAs
B
Semi-classical approach
Drift of cyclotron orbitals
B
Quantum approach
Edge states
Energie (ħω_C)
E_F
Landau levels : (n+1/2) ħω_C
+ confining potential
ω_C=eB/m
Filling factor n_sh/eB = 2 :
B ~ 4 Tesla for n_S = 2 10^11 cm^-2
Drift velocity V_D=E / B ~ 10^4 - 10^5 ms^-1


Beam splitter
The Quantum Point Contact
Source
R
T
V
I_0
I_R
V_G
I_T
Transmission (dI_T / dI_0)
V_G (Volt)
++++++ Si ++++++
AlGaAs
100 nm
2D gas
GaAs
B

SUB-POISSONIAN SOURCE

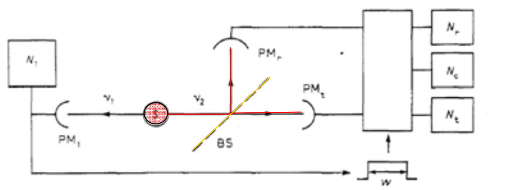
EASY ?

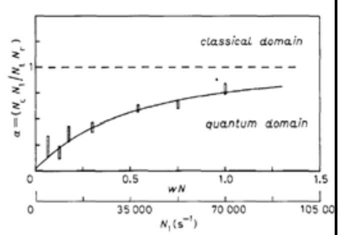




Henny et al., Science 1999

HARD ?

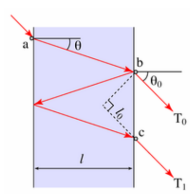




Grangier et al., EPL 1986

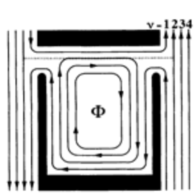
INTERFERENCES

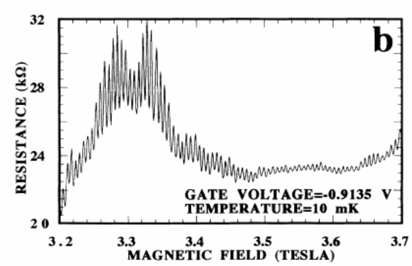
EASY



Fabry-Pérot interferometer

HARD (few μm, few mK, few Tesla & few 10^5 €)

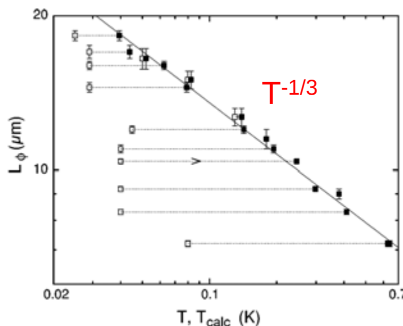




INTRINSIC LIMITATION : FINITE COHERENCE LENGTH

COHERENCE LENGTH $L\varphi$ in diffusive wires

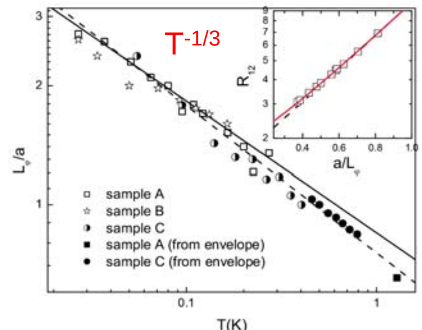
$L\varphi$ is limited by e-e interaction (Altshuler-Aronov-Khmelnitsky 1982)



Diffusive metallic quasi 1D wire (6N Silver)

From Quantronics group, Saclay
F. Pierre et al. (2004)

~ 25 µm @ 25 mK

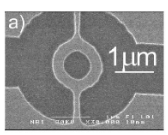


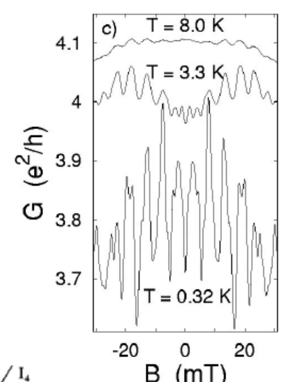
Square network in GaAs/GaAlAs 2DEG

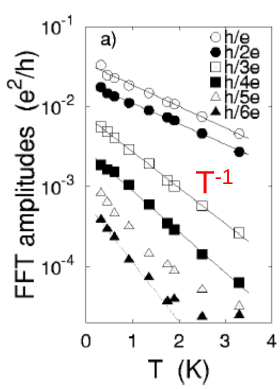
From Ferrier et al. (2004)

~3 µm @ 25 mK

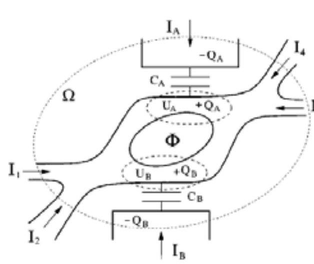
COHERENCE LENGTH $L\varphi$ in quasi 1D ballistic wires







Hansen et al (2001)



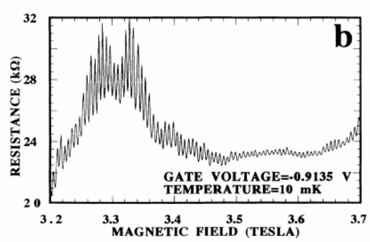
$L\varphi$ is limited by the thermal charge fluctuations

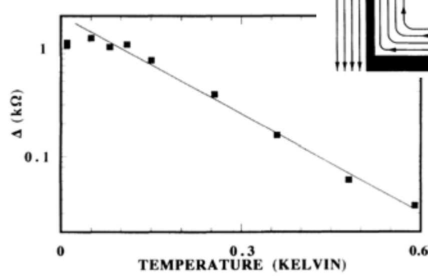
$$L\varphi^{-1} \sim k_B T \, Re(dI_A/dV_A)$$

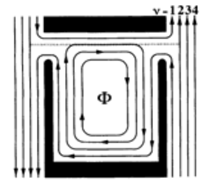
Seelig and Buttiker (2001)

COHERENCE LENGTH in Chiral 1D Wire*

*Edge states of the IQHE





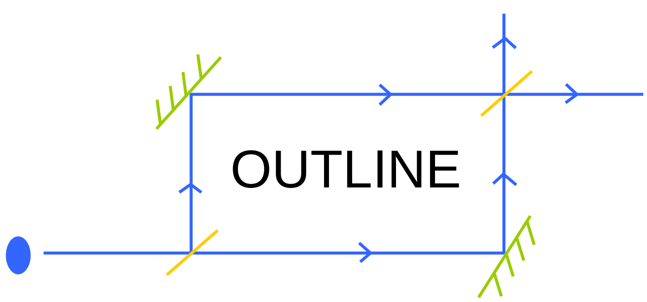


Nonetheless, we note that the exponential decay observed here is not necessarily inconsistent with thermal smearing of the single-particle states and point out, for example, that thermal averaging is known to give rise to the (quasi)exponential decay of Shubnikov–de Haas oscillations.[19]

Thermal Smearing ?*

* Bird et al. (PRB 1994)

TS always present for Fabry-Pérot type interferometer



OUTLINE

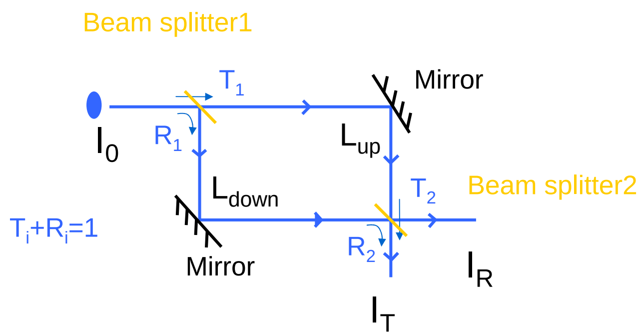
1. Measurement of $L\varphi$ at filling factor 2

2. Dephasing due to Thermal noise in the neighboring edge state

3. (Theory & Comparison with experimental results)

4. Conclusion

Optical Mach-Zehnder Interferometer

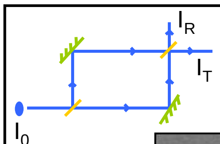


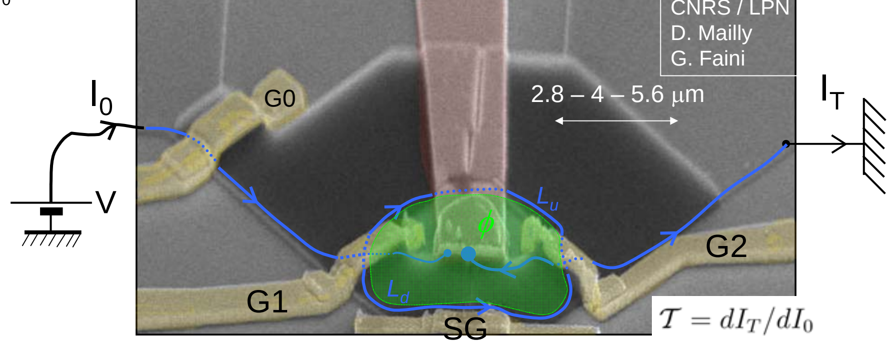
Amplitude : $A \sim (T_1T_2)^{1/2}.\ \exp[i.k.L_{up}] + (R_1R_2)^{1/2}\ \exp[i.k.L_{down}]$

$$I_T \sim A^2 \sim 1 + \mathcal{V}\ .\ \cos\,[k.\ (L_{up} - L_{down})]$$

Visibility : $\mathcal{V} = (T_1T_2R_1R_2)^{1/2} / (T_1T_2+R_1R_2)$

Filling factor $n_s h/eB = 2$
B ~ 4 Tesla for $n_S = 2\ 10^{11}\ cm^{-2}$





$$\mathcal{T} = dI_T/dI_0$$

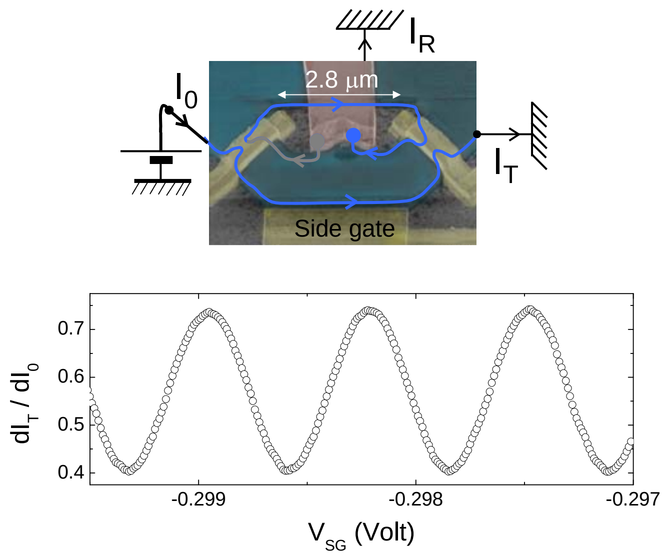
$$\mathcal{T}_1 = \mathcal{T}_2 = 1/2 \qquad \mathcal{T}(eV) = 1/2 \times [1 + \mathcal{V}\sin(\phi(eV))]$$

$$\mathcal{V} \propto e^{-2L/L_\varphi}\ ;\ L_\varphi(T)\ \ ?$$

$$\phi(\epsilon) = 2\pi S(\epsilon) \times eB/h$$

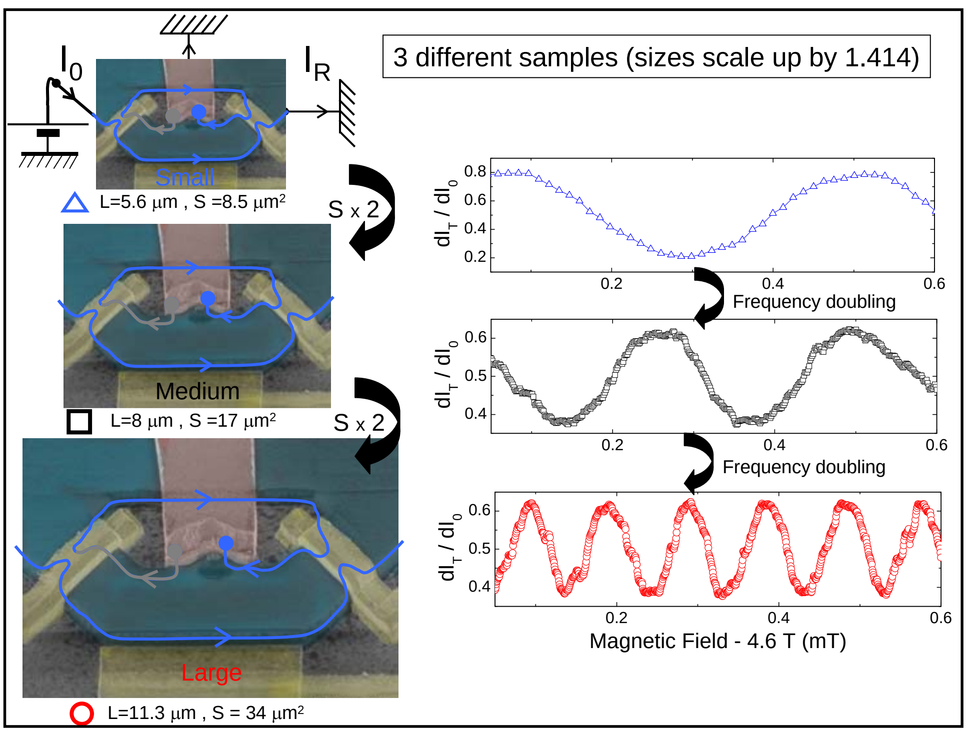
*Note that the inner edge state, fully reflected by all the QPCs is not represented.

Our samples : up to 65 % visibility at 15 mK

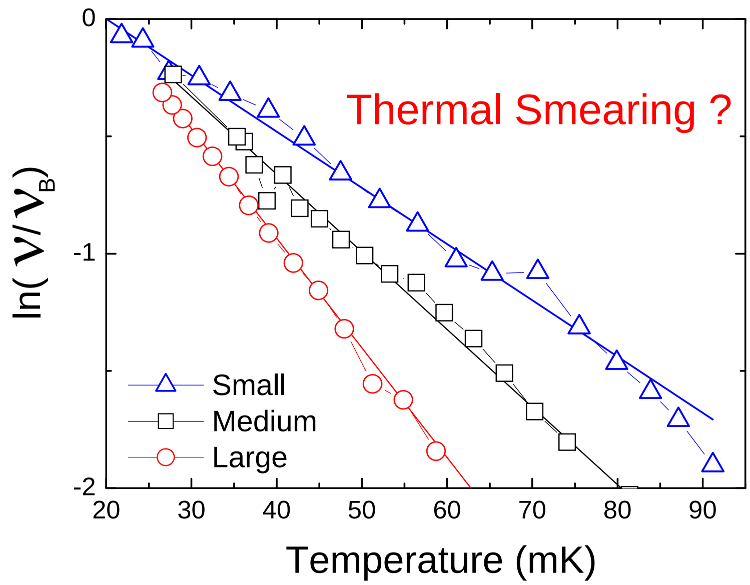


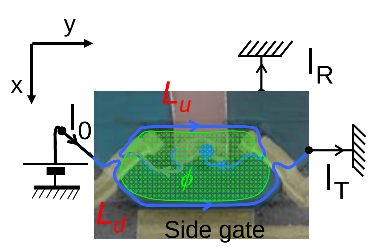
Ji et al. (Nature 2003) – Litvin et al. (PRB 2007) Record : Neder et al. Nature (2007) ~ 90 % @ 10 mK

3 different samples (sizes scale up by 1.414)



TEMPERATURE DEPENDENCE





Thermal Smearing

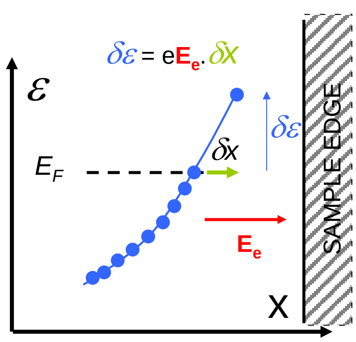
$$\mathcal{V} = \mathcal{V}_0 \pi T/(T_S \sinh(\pi T/T_S))$$

$$k_B T_S = \hbar v_D/\Delta L$$

$$\tau(\epsilon) = 1/2 \times [1 + \mathcal{V} \sin(\phi(\epsilon))]$$

$$\phi(\epsilon) = 2\pi S(\epsilon) \times eB/h$$

$$\phi(\epsilon + E_F) = \phi(E_F) + \epsilon \Delta L/(\hbar v_D)$$



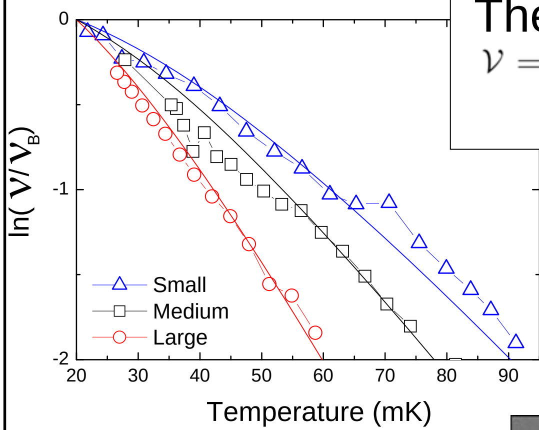
$\Delta\phi = (L_u - L_d).\delta x.B.2\pi e/h = \Delta L.\delta\varepsilon.B/\mathbf{E_e}\, 2\pi/h$

V. S.-W Chung, P. Samuelsson and M. Büttiker (PRB 2005)

Thermal Smearing

$$\mathcal{V} = \mathcal{V}_0 \pi T/(T_S \sinh(\pi T/T_S))$$

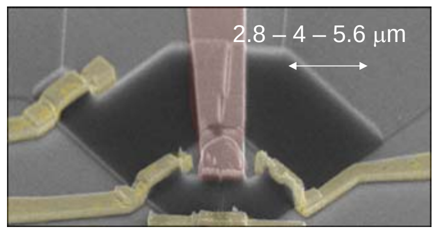
$$k_B T_S = \hbar v_D/\Delta L$$



Fits with Thermal Smearing give :
T_S = 66, 56 , 41 mK

$v_D \sim 5\ 10^4\ ms^{-1}$

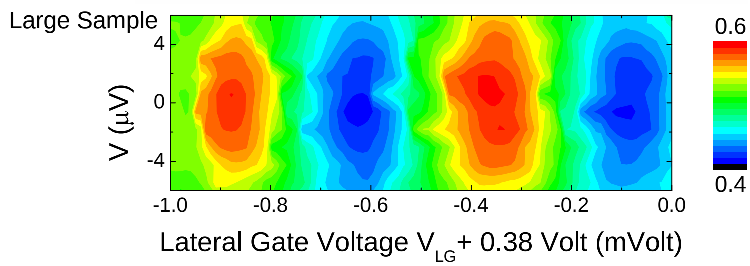
$\Delta L \sim 5$, 6 , 8 μm from Small to Large ?

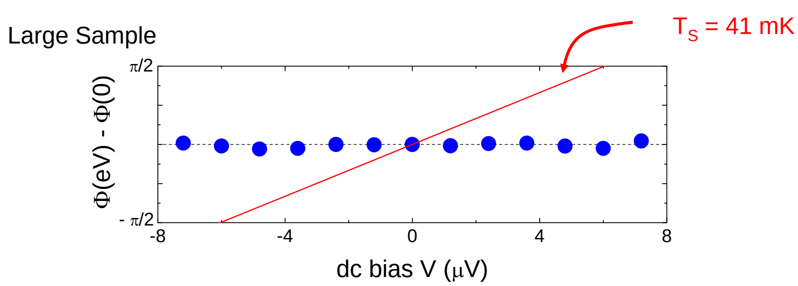


Not compatible with the lithography precision !

PROOF FOR ABSENCE OF THERMAL SMEARING

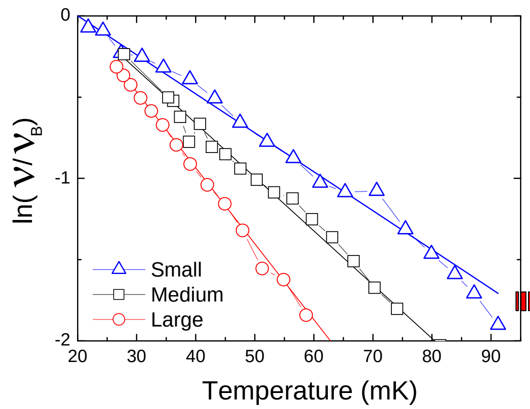
$$\mathcal{T}(eV) \propto 1 + \mathcal{V}(eV)\sin(<\phi(eV)>_{k_BT})$$

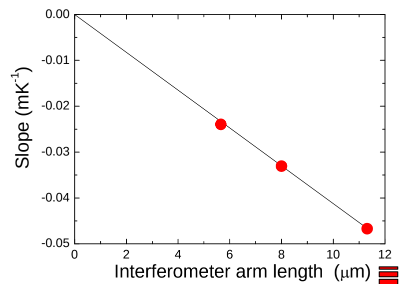




Phase rigidity checked for the 3 studied samples !

1- DETERMINATION OF $L\varphi$





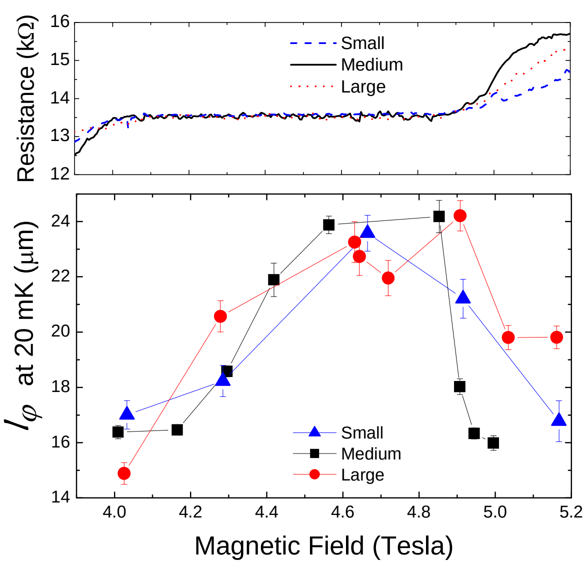
$$\nu \propto e^{-2L/L_\varphi}$$

$$L_\varphi(T) \propto T^{-1}$$

$L\varphi$ = 22 μm at 20 mK

ν ~exp[- T / $T\varphi(L)$] = exp[- 2L / $L\varphi$] $L\varphi$= $2LT\varphi(L)/T_B$

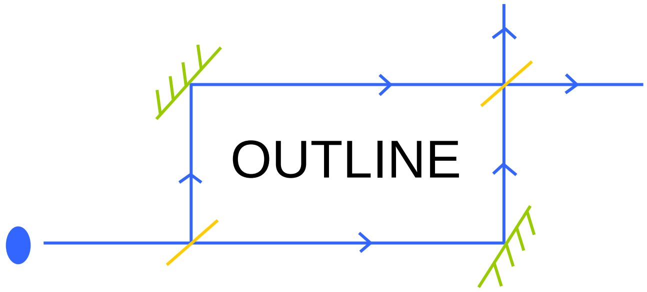
MAGNETIC FIELD DEPENDENCE OF $L\varphi$



$L\varphi$= $2LT\varphi(L)/T_B$

T_B = 20 mK

OUTLINE



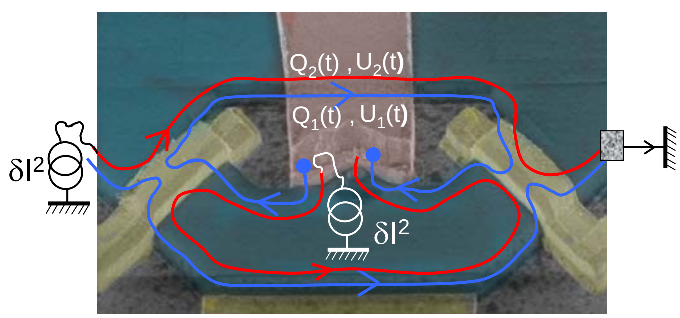
1. Measurement of $L\varphi$ at filling factor 2

2. Dephasing due to Thermal noise in the neighboring edge state

3. (Theory & Comparison with experimental results)

4. Conclusion

2- DECOHERENCE GENERATED BY THERMAL NOISE*



$$\delta\varphi(t) = \frac{1}{\hbar}\int_t^{t+\tau} eU_1(t)dt \qquad \tau = L/v_D$$

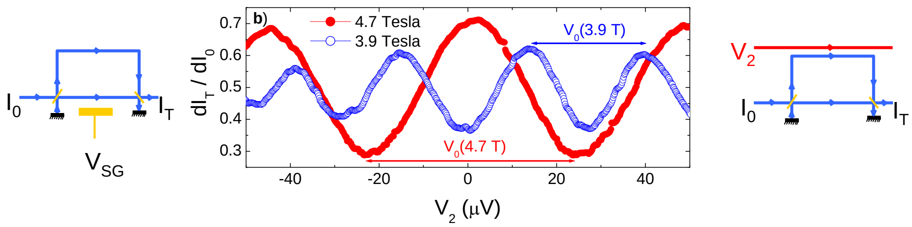
$$\delta I^2 \longrightarrow \delta Q_2^2 \longrightarrow \delta Q_1^2 \longrightarrow \delta U_1^2 \longrightarrow \delta\varphi^2$$

$$\delta I^2 = 4k_B G_Q T \Delta\nu \longrightarrow \mathcal{T} \propto [1 + \mathcal{V}_0 \sin(<\varphi>)e^{-<\delta\varphi^2>/2}]$$

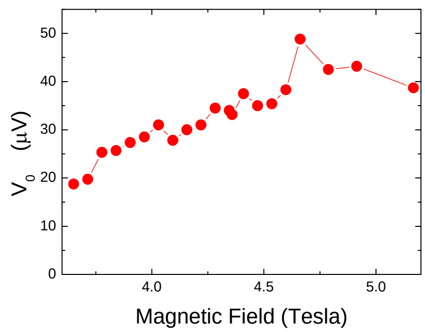
WHITE NOISE & GAUSSIAN NOISE

* Seelig and Buttiker (PRB 2001)

Determination of the coupling : $\varphi = 2\pi V_2 / V_0$ $(T_0=1)$

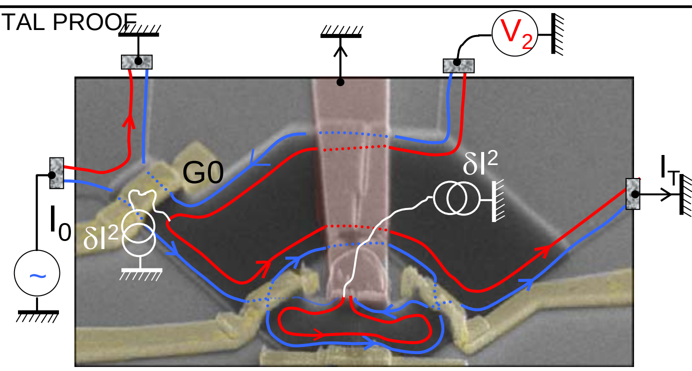


V_0



First coupling exp. in MZI (Neder et al. PRL 2006)

EXPERIMENTAL PROOF



$$\varphi = 2\pi V_2 / V_0 \quad (T_0=1)$$

$$\delta\varphi^2/2 = 2\pi^2 \delta V_2^2 / V_0^2 = 2\pi^2 S_{22}.\Delta\nu/V_0^2$$

Shot noise
$S_{22} = 2eR_Q T_0(1-T_0) V_2$

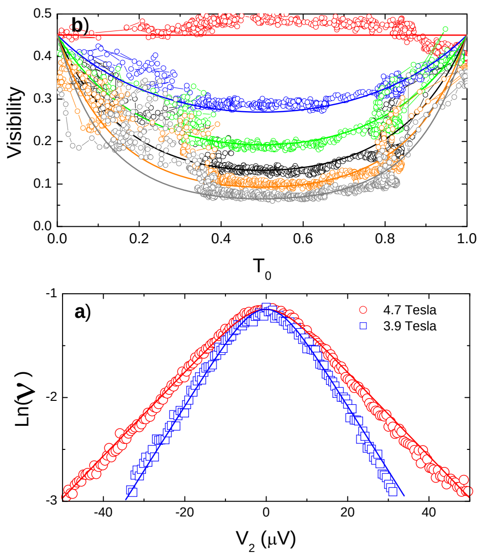
Thermal noise
$S_{22} = 2 \times 4k_BT R_Q$

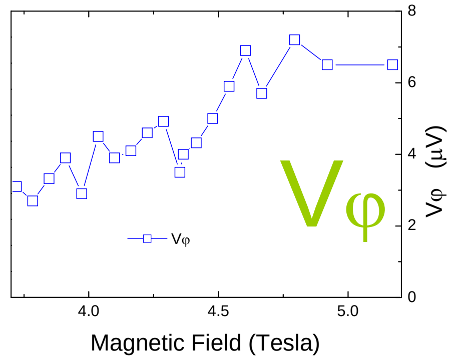
IF $\mathcal{V} \alpha \exp[-V_2T_0(1-T_0) / V\varphi]$

AND IF Thermal noise responsible for $\mathcal{V} \alpha \exp[-T / T\varphi]$

THEN $4k_BT\varphi = eV\varphi$

Exponential decrease of the visibility : $\exp[-V_2 T_0(1-T_0)/V\varphi]$

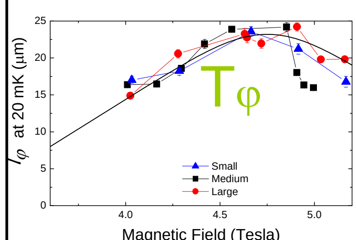




$$V\varphi^{-1} = 4\pi^2\, eR_Q\, \Delta\nu / V_0^2$$

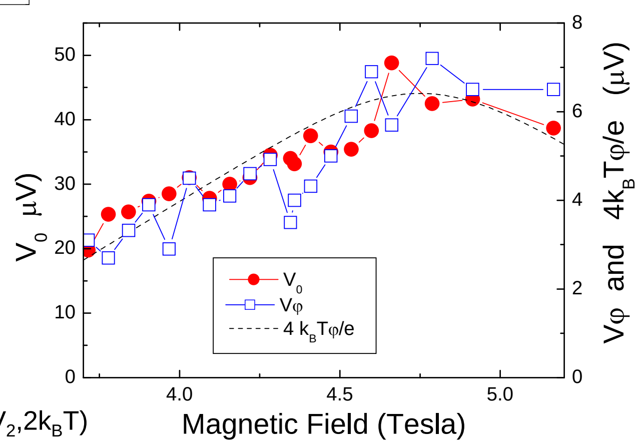
Non-Gaussian noise in Neder et al. (2006)

COMPARISON WITH $\exp[-T / T\varphi]$



$$T\varphi^{-1} = 4\pi^2 . 4k_B R_Q \Delta\nu / V_0^2$$

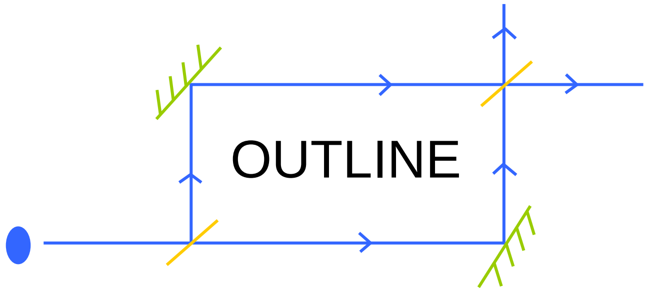
$$4k_B T\varphi = eV\varphi$$



Gaussian approx :

$h\Delta\nu \sim 3$ to $7\ \mu eV < \max(eV_2, 2k_BT)$

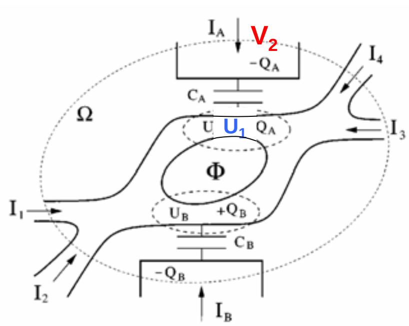
OUTLINE



1. Measurement of $L\varphi$ at filling factor 2
2. Dephasing due to Thermal noise in the neighboring edge state
3. (Theory & Comparison with experimental results)
4. Conclusion

3- Why $eV_0 \sim 4k_BT\varphi$ (which means $h\Delta\nu \propto eV_0$) ?

Seelig and Büttiker approach (2001)



Zero frequency

$\delta\varphi = e\, U_1\, \tau\, 2\pi / h$

$U_1 \sim V_2$

$\delta\varphi = 2\pi$ for $eV_0 \sim h\,\tau^{-1}$

Finite frequency

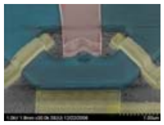
$$\delta\varphi(t) = \frac{1}{\hbar}\int_t^{t+\tau} eU_1(t)dt \;\rightarrow\; \varphi(\omega) = \frac{e}{i\hbar\omega}(e^{i\omega\tau}-1)U_1(\omega)$$

$$<\delta\varphi^2>/2 = \tau/\tau_\varphi = \frac{2e^2}{\hbar^2}\int_0^\infty S_{U_1U_1}(\omega)\frac{\sin^2(\omega\tau/2)}{\omega^2}d\omega/2\pi$$

$S_{U_1U_1}$ generated by δI^2

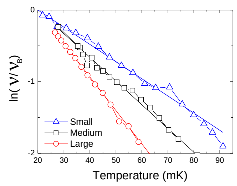
$\Delta\nu \sim \tau^{-1}$

$$<\delta\varphi^2> = \int_0^\infty \varphi(\omega)\varphi(-\omega)d\omega/2\pi$$



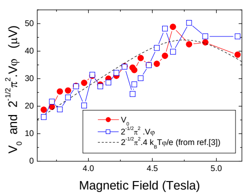
CONCLUSION

High visibility Mach-Zehnder Interferometer. Up to 65 % @ 15 mK on the Hall plateau at $\nu = 2$



Exponential decrease of ν with temperature
Scaling with the sample size

$$L_\varphi(T) \propto T^{-1}$$



Finite L_φ arises from Johnson-Nyquist Noise in the neighboring edge state

B change the coupling

$eV_0 \;\alpha\; k_B T\varphi$

P. Roulleau et al. PRB 76, R161309 (2007)
P. Roulleau et al. PRL 100, 126802 (2008)
P. Roulleau et al. arXiv:0802.2219

THE END