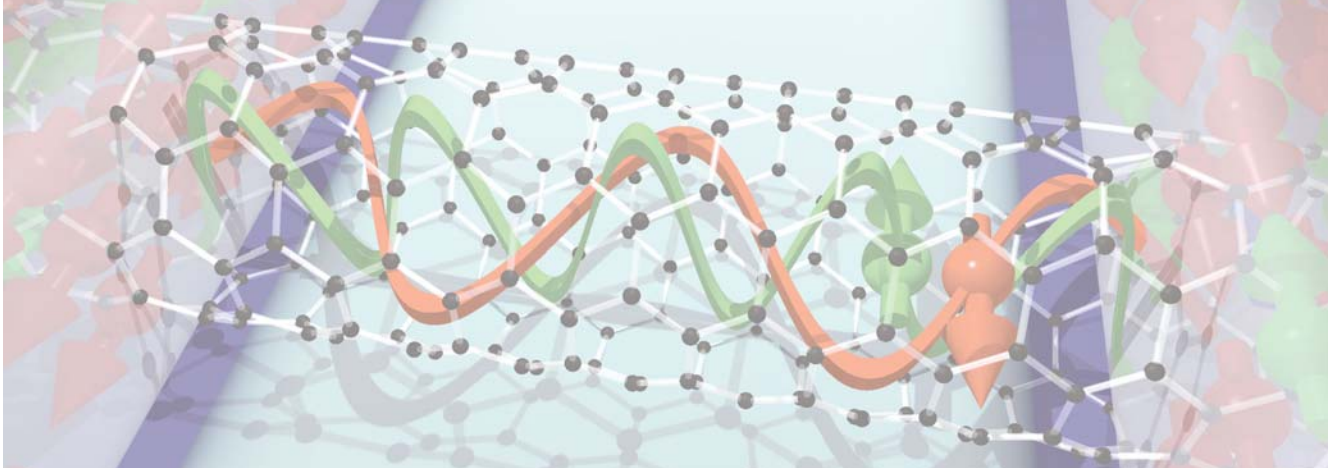
# Gated Magnetoresistance in Carbon Nanotubes



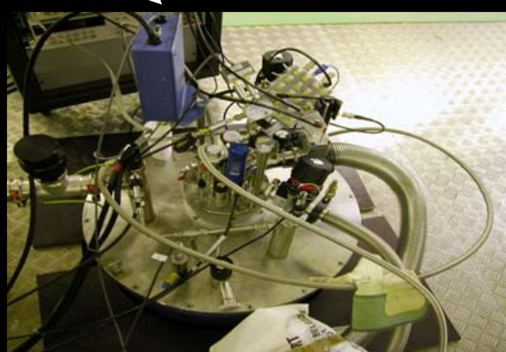
Matthias Gräber, Markus Weiss, Bill Coish, Daniel Loss,
Sangeeta Sahoo, Takis Kontos, Audrey Cottet, Wolfgang Belzig,
Christoph Bruder and Christian Schönenberger

NT06, Nagano, 18-23 June 2006

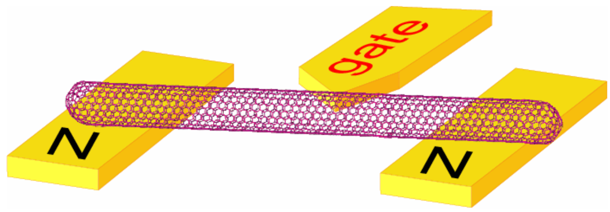
## low-T quantum transport

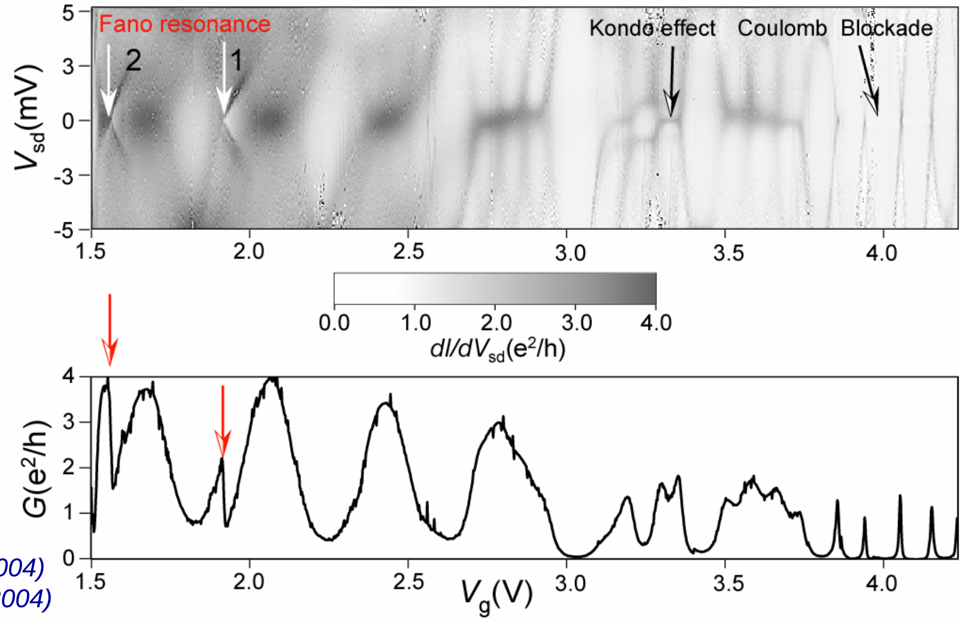
- we are users of CNTs


↘ 20 mK



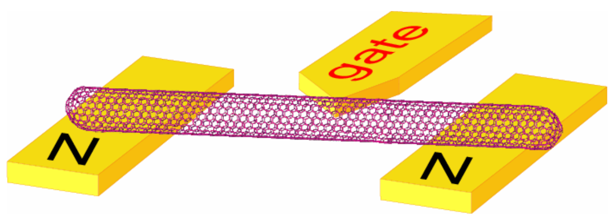
# Carbon Nanotube Devices




*B. Babic, T. Kontos and CS*
*Phys. Rev. B 70, 235419 (2004)*
*Phys. Rev. B, 70, 195408 (2004)*

# Carbon Nanotube Devices




for fundamental transport studies, CNTs are e.g. good for:

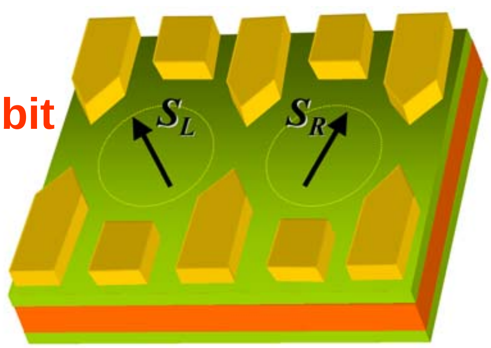
► strong interaction ➔ LL-type behavior

► additional degeneracies ➔ unconventional Kondo physics

► very small spin-orbit int. ➔ expect large spin coherence times

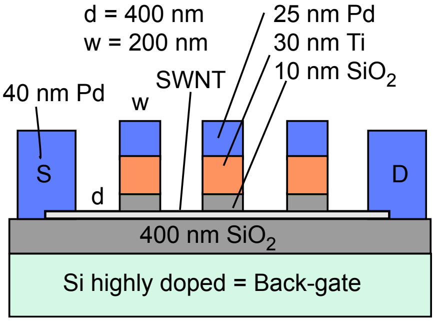
- Local gate control of electronic transport in nanotubes
- Probing and controlling quantum effects including spin degree of freedom

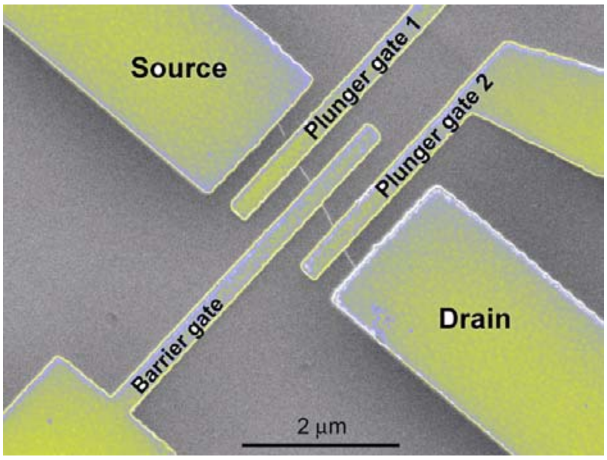
**spin qubit**




*D. Loss and D. P. DiVincenzo*
*Phys. Rev. A* ***57****, 120-126 (1998)*

# Carbon Nanotube Devices

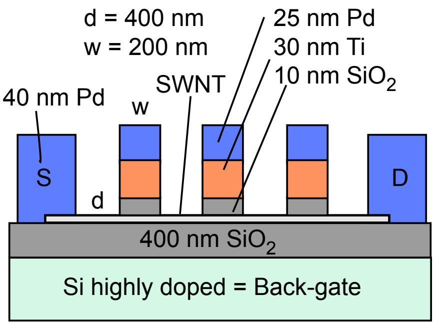


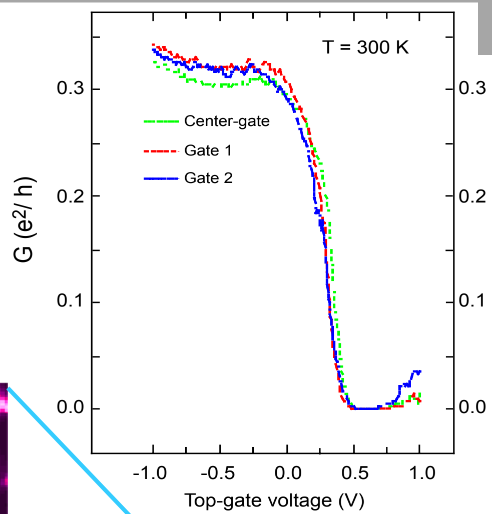



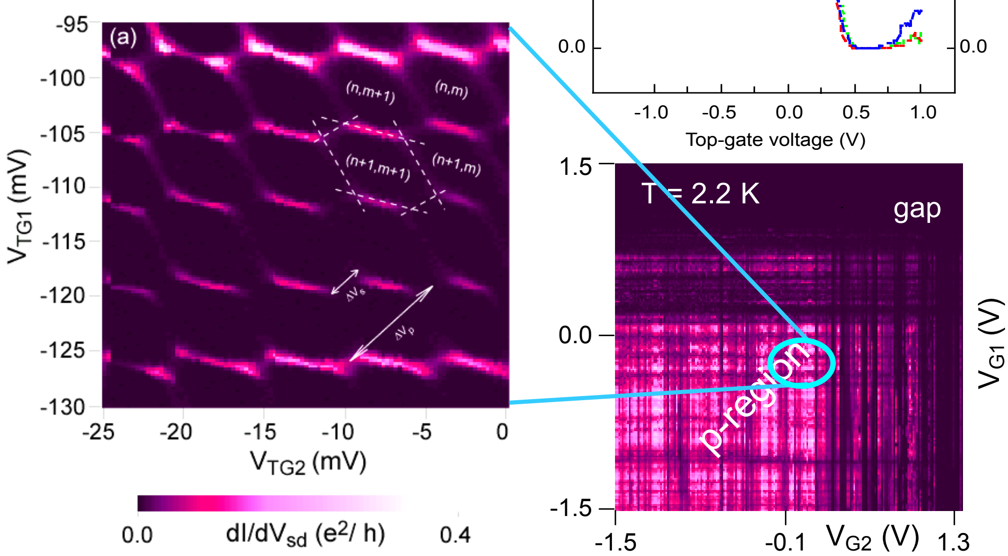

*see: cond-mat/0603367 and cond-mat/0605220*

*Mason et al. Science 303 (2004)*

# Carbon Nanotube Devices

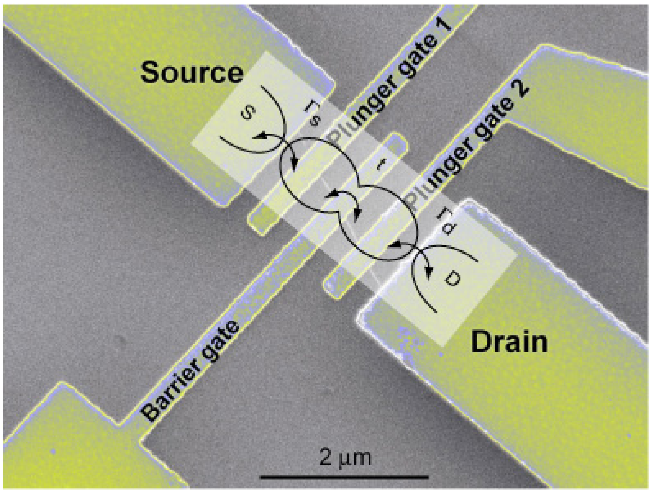


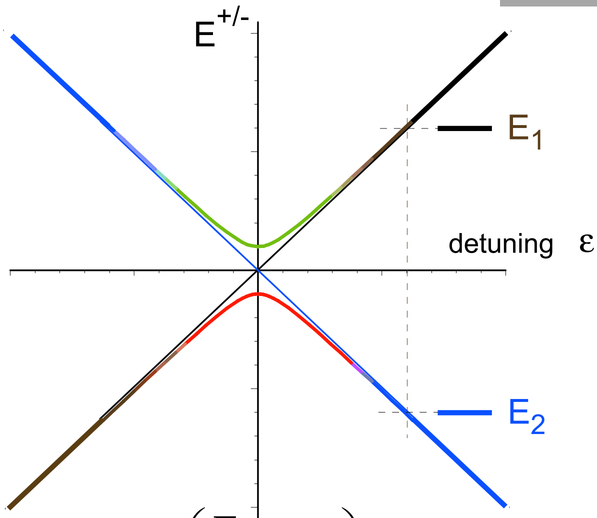



# molecular states (hybridization)

## „hydrogen molecule“




$$H\psi = \begin{pmatrix} E_1 & t \\ t^* & E_2 \end{pmatrix}\psi$$

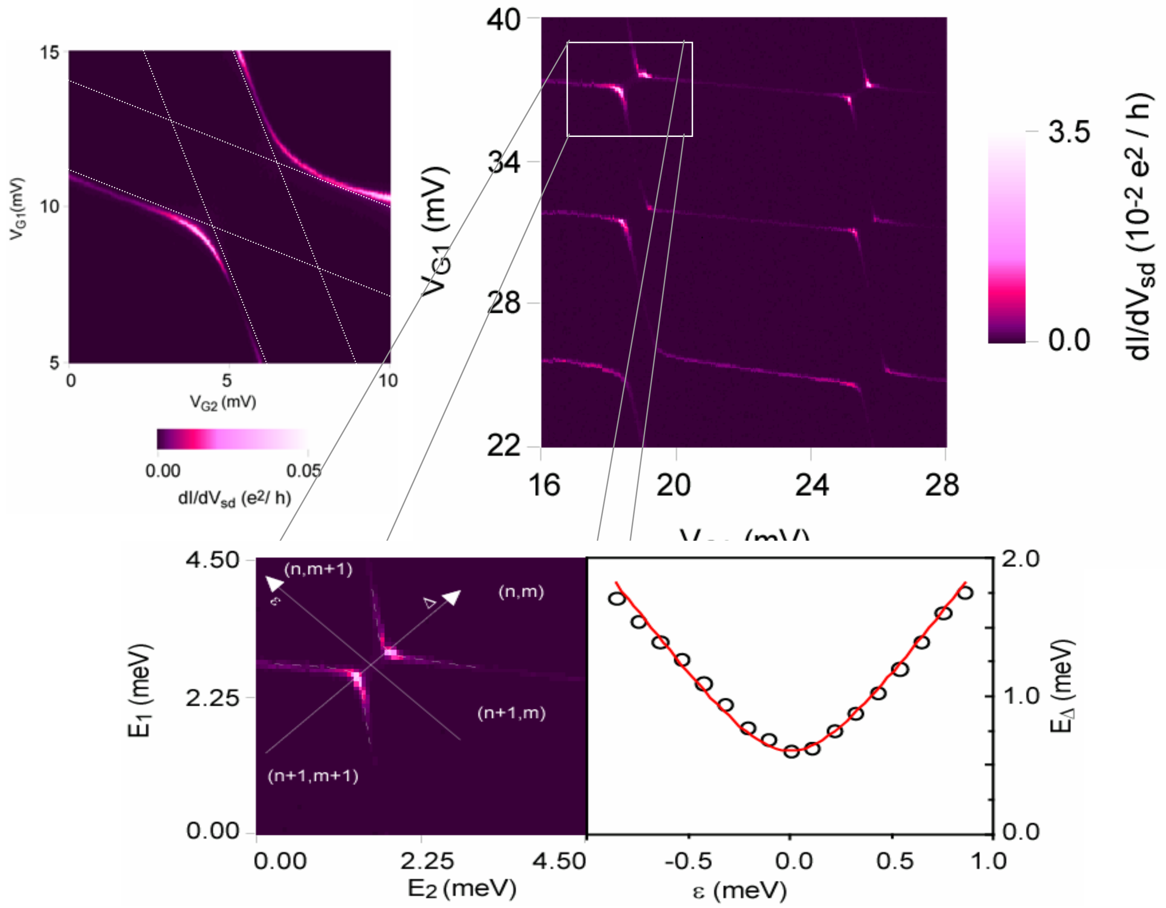
$$\Delta = \frac{E_1 + E_2}{2} \qquad \varepsilon = \frac{E_1 - E_2}{2}$$

$$E^{+/-} = \Delta \mp \sqrt{\varepsilon^2 + |t|^2}$$

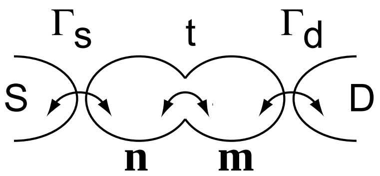
**$C_{100'000}$ ➔ $(C_{100'000})_2$**

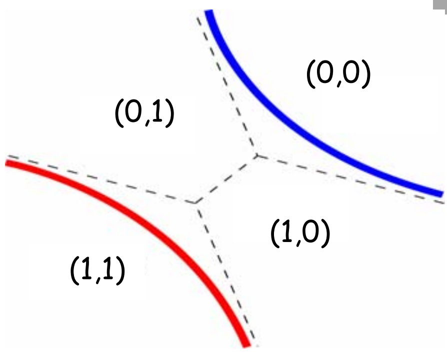
*M. Gräber et al. cond-mat/0603367 and cond-mat/0605220*

# molecular states



# mapping of molecular states

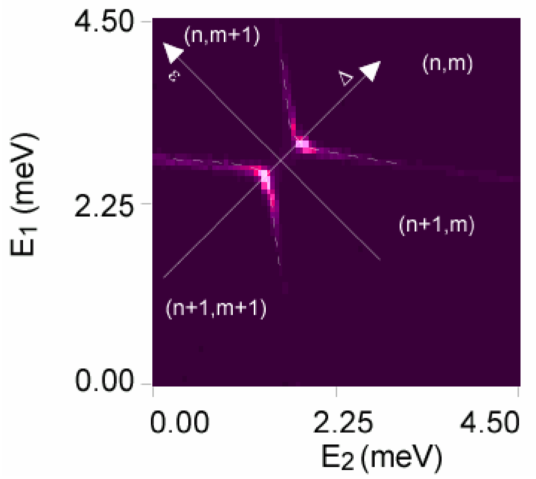


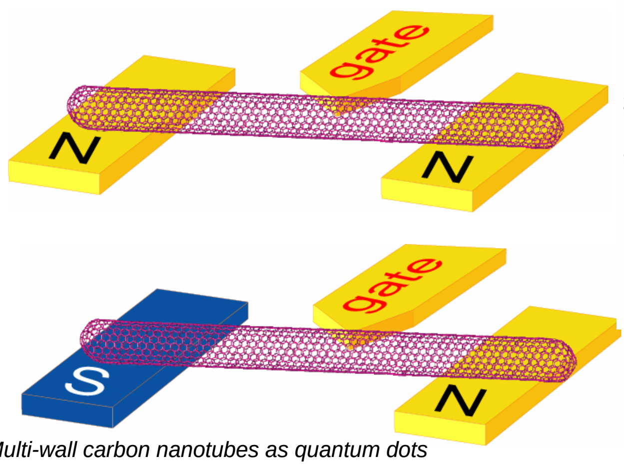

$$\psi = \alpha\left|n+1,m\right\rangle + \beta\left|n,m+1\right\rangle$$

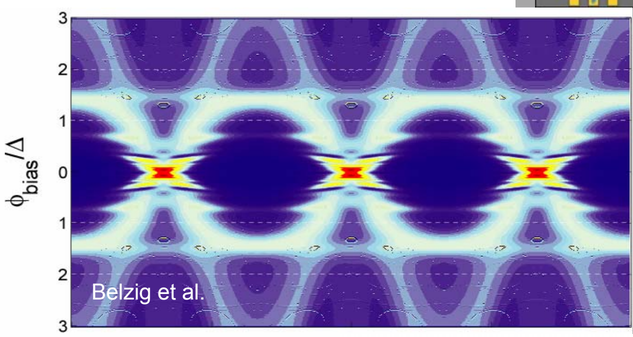
$$\alpha,\beta(\varepsilon) = \frac{|t|^2}{|t|^2 + \left(\varepsilon \pm \sqrt{\varepsilon^2 + |t|^2}\right)^2}$$

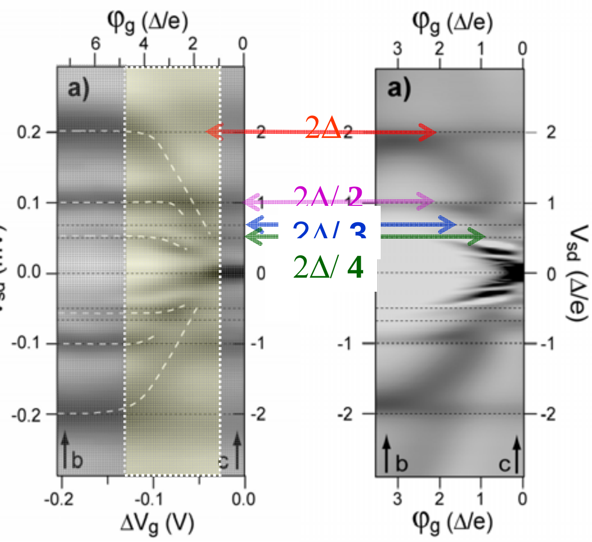
$$G = e\Gamma\left|\alpha(\varepsilon)\cdot\beta(\varepsilon)\right|^2$$




# Carbon Nanotube Devices



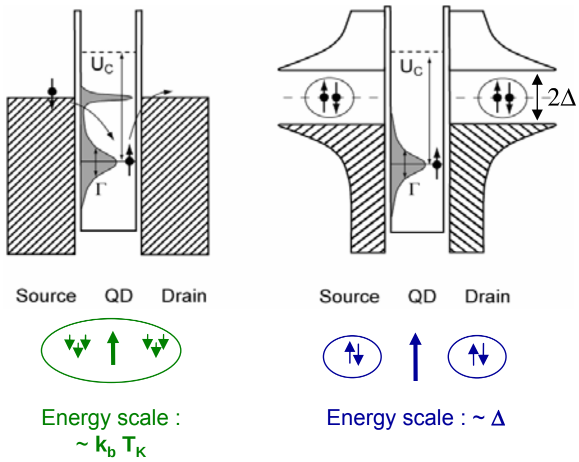



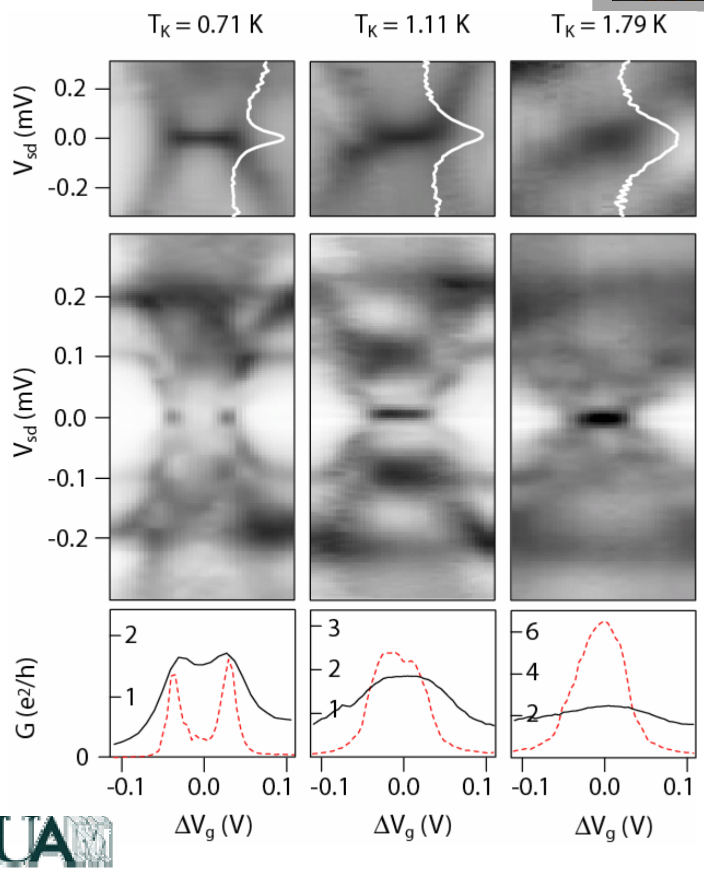

1. *Multi-wall carbon nanotubes as quantum dots*
**M. R. Buitelaar**, A. Bachtold, T. Nussbaumer, M. Iqbal and C.S.,
Phys. Rev. Lett. 88, 156801 (2002).
2. *A quantum dot in the Kondo regime coupled to* ***superconductors***,
**M. R. Buitelaar**, T. Nussbaumer, and C.S.,
Phys. Rev. Lett. 89(25):256801 (2002).
3. ***Multiple Andreev Reflections*** *in a Carbon Nanotube Quantum Dot*,
**M. R. Buitelaar**, **W. Belzig**, T.N., B. Babić, B. Bruder, and C.S.,
Phys. Rev. Lett. 91:057005 (2003).
4. *Quantum dot coupled to a* ***normal and a superconducting lead***
M. Gräber, T. Nussbaumer, W. Belzig and C.S.
Nanotechnology 15, S479 (2004)
5. *Cond. properties of* ***nanotubes coupled to superconducting leads***
E. Vecino, M. Buitelaar, A. Martin-Redero, C.S. and A. Levy Yeyati
Solid State Comm. 131, 625 (2004)

# Carbon Nanotube Hybrid Dots

Kondo effect & Superconductivity



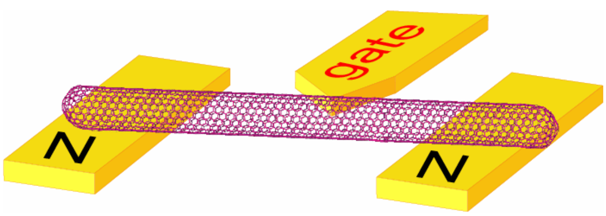

A cross-over at $k_B T_K \sim \Delta$

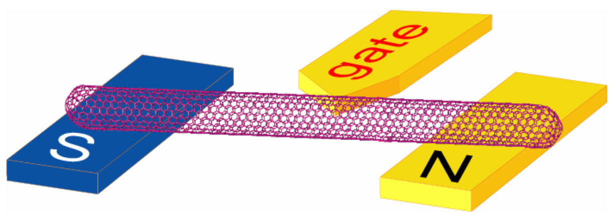


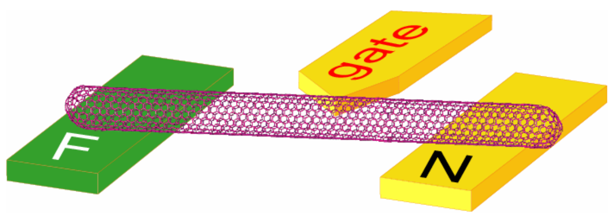

*Phys. Rev. Lett. 89, 256801 (2002)*

*Solid-State Communications **131**, 625 (2004)*

# Carbon Nanotube Hybrid Devices



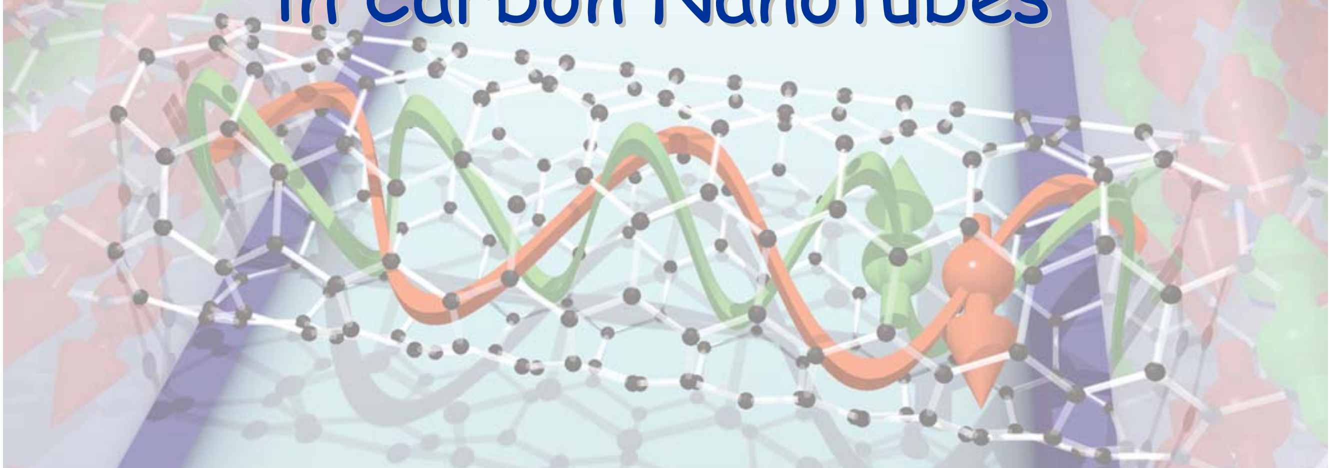




**Using carbon nanotubes - novel quantum effects that (only) appear in low-dimensional hybrid devices - can be studied -**

**...**
**many of which can not be studied in „conventional“ quantum dots**

# Gated (gate tunable) Magnetoresistance in Carbon Nanotubes



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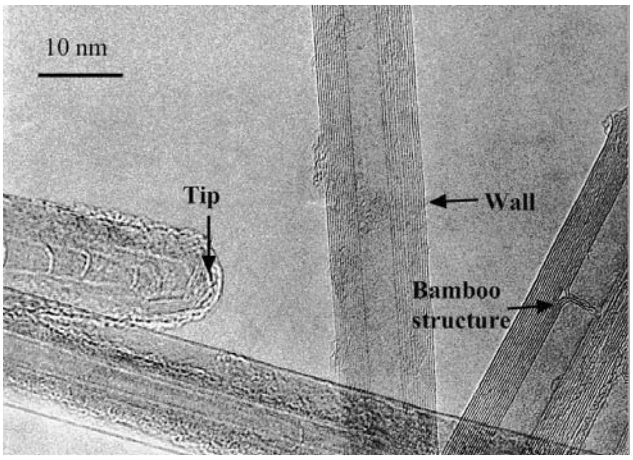
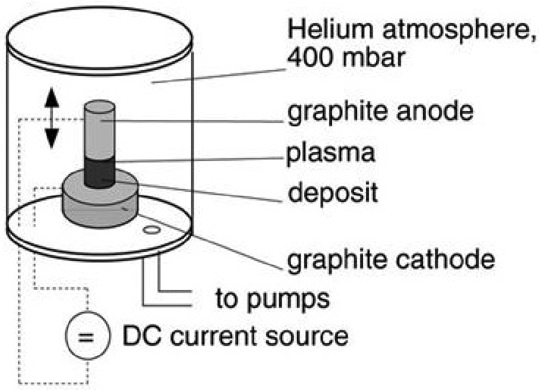
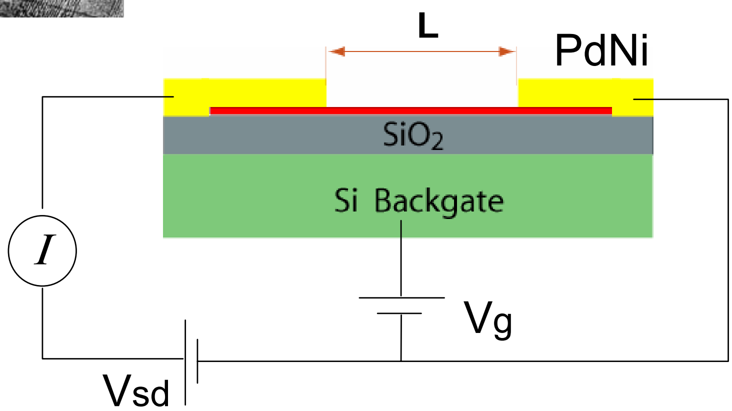
NT06, Nagano, 18-23 June 2006

## Multi-Wall Carbon Nanotubes



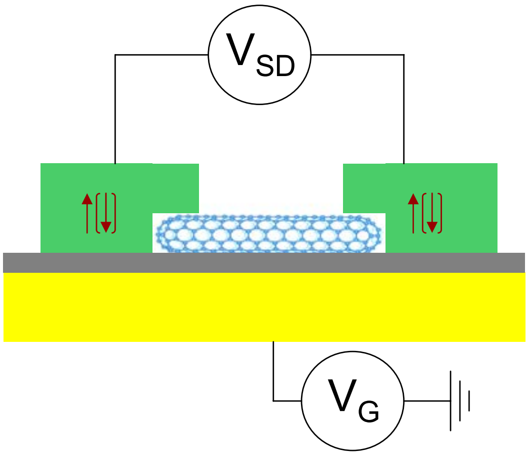




EPFL

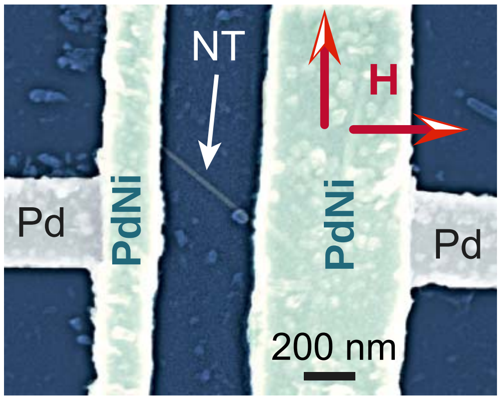
NN research group

**Laszlo Forró EPFL**

# an actual device (MWNT)

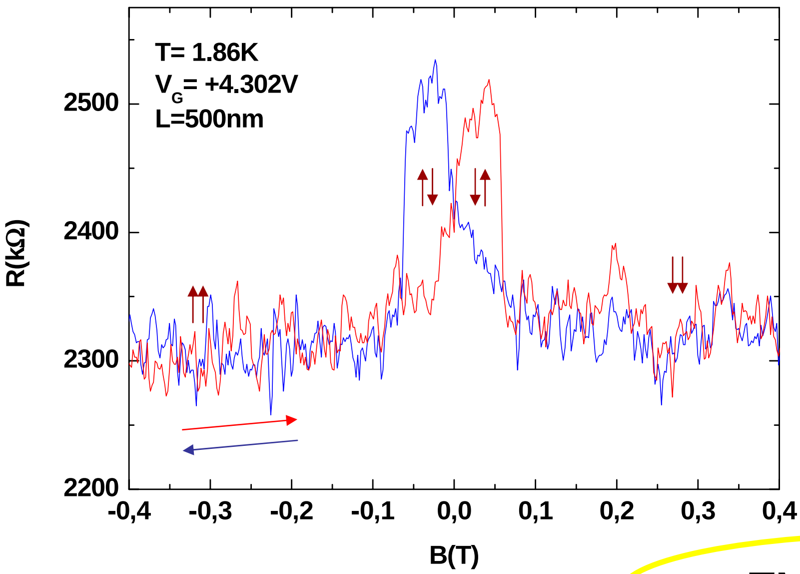



**Spin valve geometry**




- Transparent contacts using a new contacting scheme with $Pd_{0.3}Ni_{0.7}$
- Shape anisotropy to control switching of magnetizations.

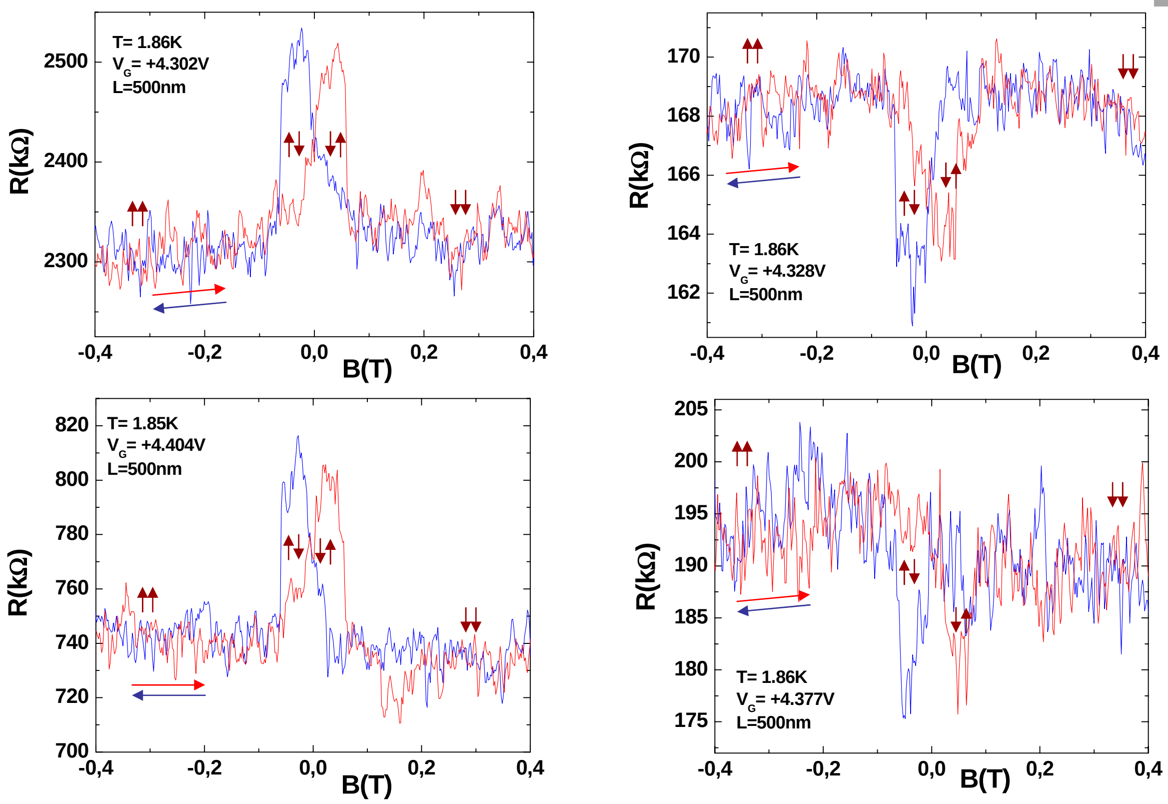
# Spin signal for a CNT-device



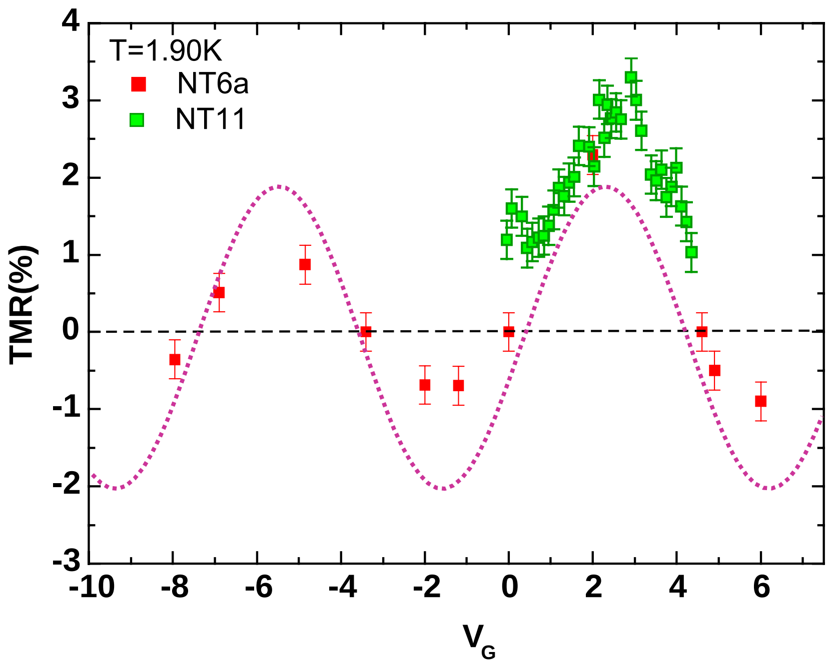

$TMR=(R_{AP}-R_P)/R_P$

- Hysteresis ~ 5-10 %
- Sharp switching for ~ 100mT
- TMR ~ $2P^2$ with P~0.2

# Gate dependence of TMR



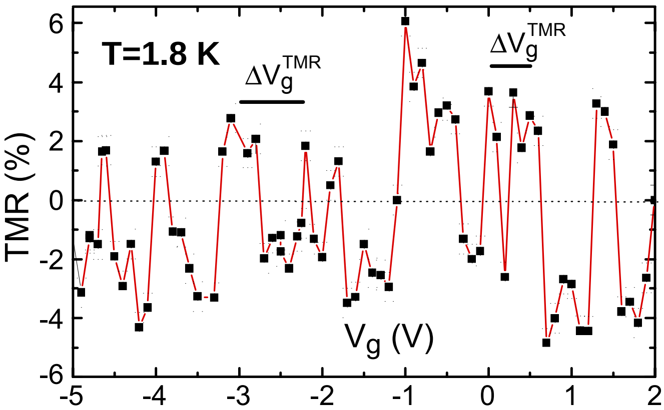

# TMR Gate Dependence

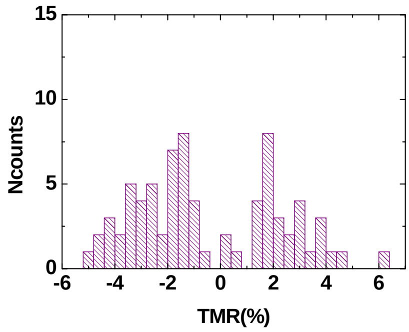


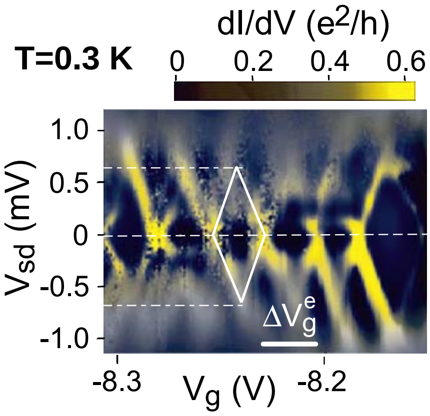

speculation

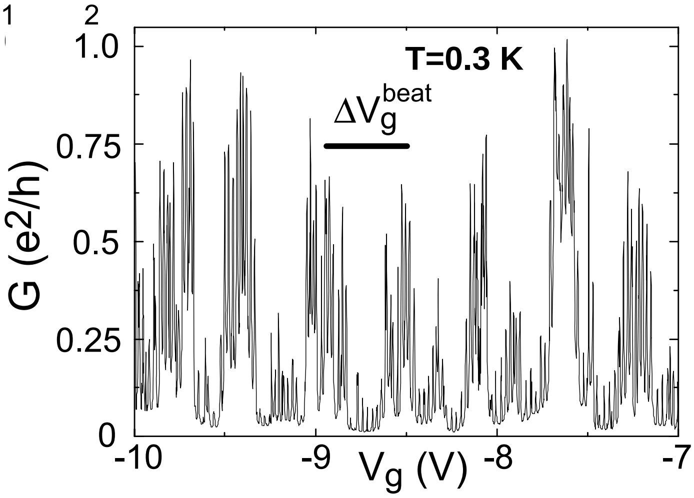
- ❑ Oscillations of TMR between +3% and approx. ±1% ?

# TMR „oscillation": what causes it?

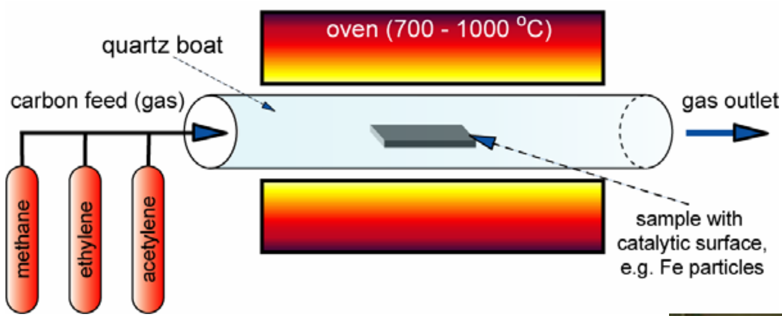


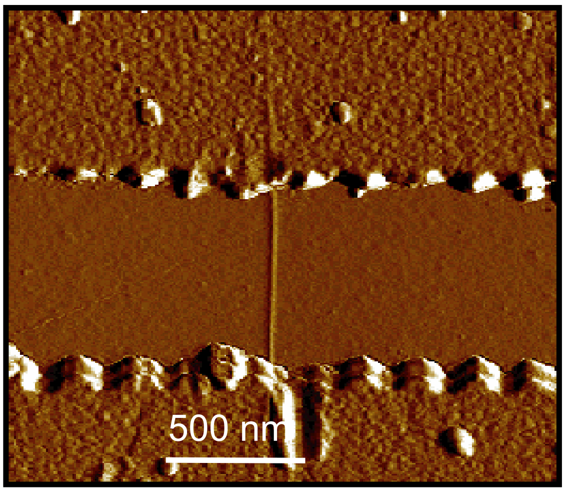




# Single-Wall Carbon Nanotubes



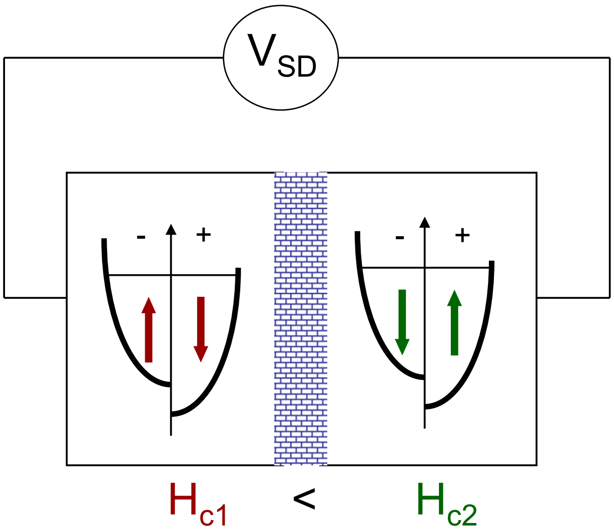

Bakir Babic

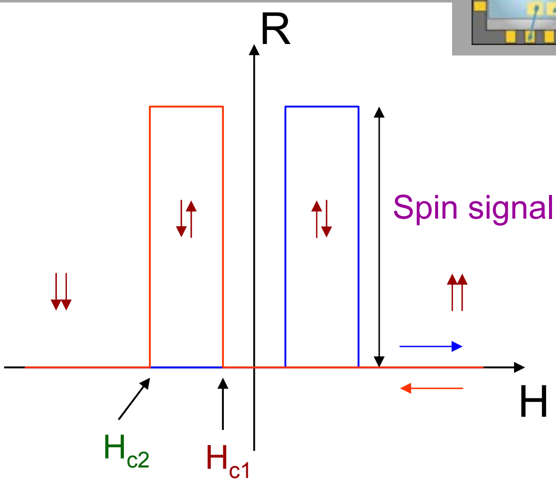
Jürg Furer




acknowledgment:
Jing Kong and
Herre van der Zant !

# Introduction: Spin Valve Effect




assume spin and energy independent transmission ➔ Jullière's model

$$G_P \propto |t|^2 \left(N_+{}^2 + N_-{}^2\right)$$

$$G_{AP} \propto |t|^2 2N_+N_-$$

$$G_P > G_{AP} \quad because \quad N_+{}^2 + N_-{}^2 > 2N_+N_-$$

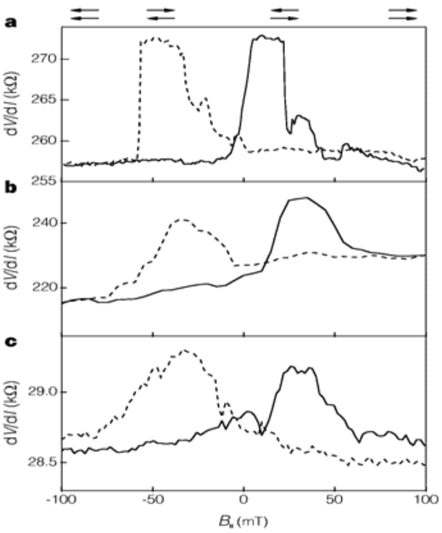
$$P = \frac{N_+ - N_-}{N_+ + N_-}$$

$$TMR = 2\frac{G_P - G_{AP}}{G_P + G_{AP}} = 2P^2$$

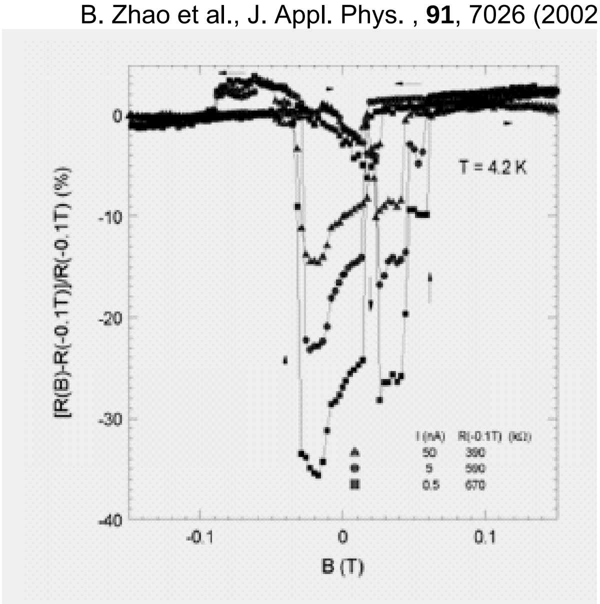
# Previous work

Co contacts

K. Tsukagoshi et al., Nature, **401**, 572 (1999)




B. Zhao et al., J. Appl. Phys. , **91**, 7026 (2002)

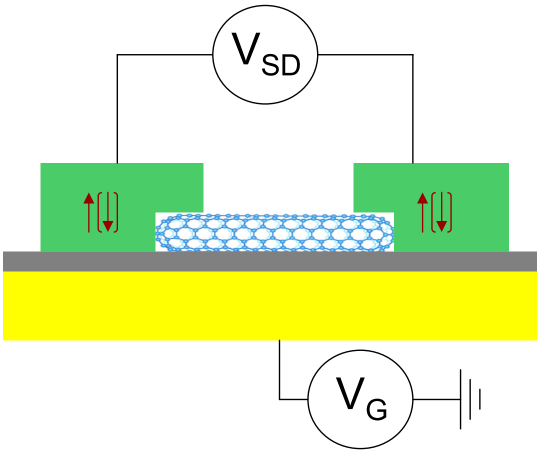



- ❑ Positive TMR ~5%
- ❑ No gate !

- ❑ Negative TMR ~ -30%
- ❑ No gate !

➔ Normal as well as anomalous TMR...?

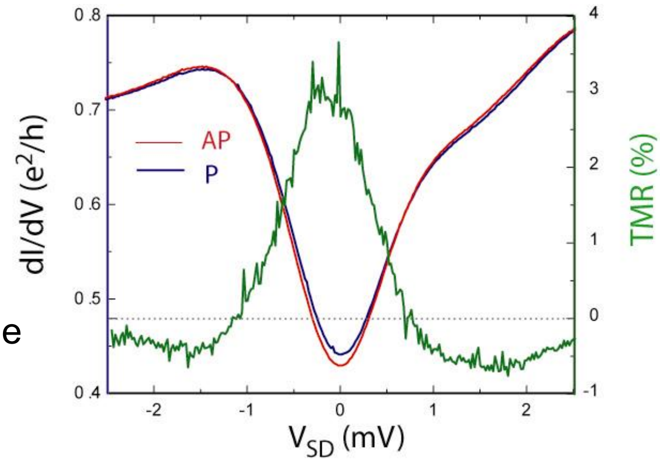
# Spin Injection in NTs




**Spin valve geometry**
**with gate shows ...**

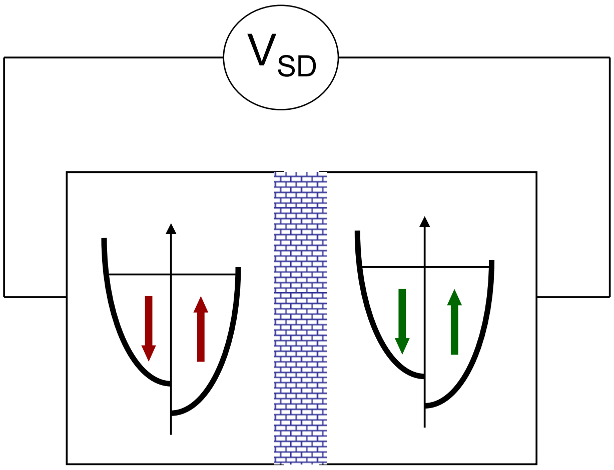
.. that the **magnetoresistance depends on gate voltage**

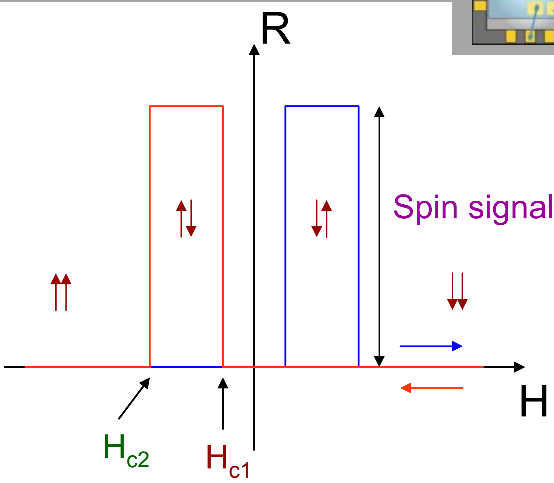
also depends on bias voltage
and temperature




*S. Sahoo, T. Kontos, J. Furer, C. Hoffmann, M. Gräber, A. Cottet and CS, Nature Physics* ***1,*** *99 (2005)*

# Introduction: Spin Valve Effect




$H_{c1}$ < $H_{c2}$

Jullière's model $P = \frac{N_\uparrow - N_\downarrow}{N_\uparrow + N_\downarrow}$

$$G_{AP} \propto |t|^2 2N_\uparrow N_\downarrow$$

$$G_P \propto |t|^2 (N_\uparrow{}^2 + N_\downarrow{}^2)$$

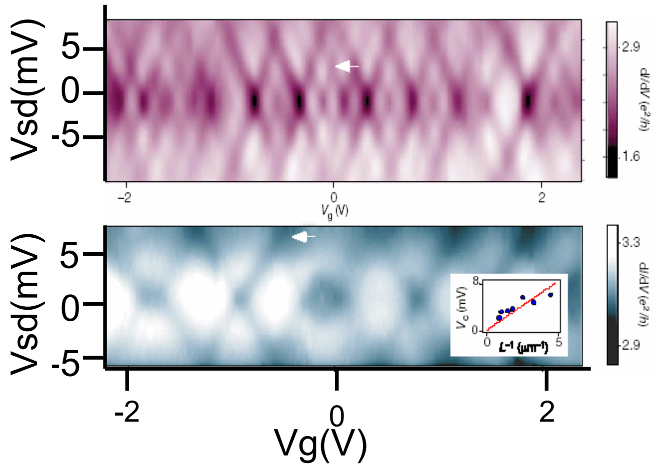
$$TMR = 2\frac{G_P - G_{AP}}{G_P + G_{AP}} = 2P_L P_R$$

$$G_P > G_A \quad because \quad N_\uparrow{}^2 + N_\downarrow{}^2 > 2N_\uparrow N_\downarrow$$

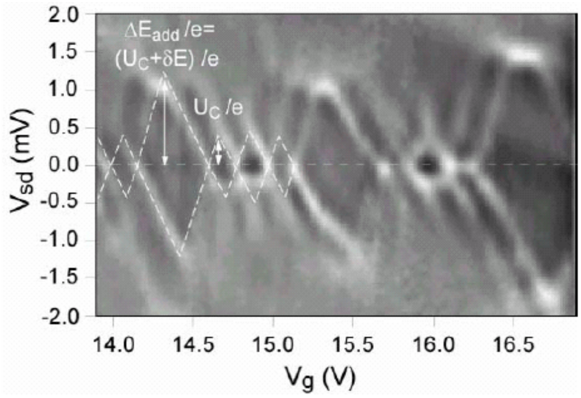
**Assumes spin and energy independent transmission !**

# quantum interference and charging

W. Liang et al., Nature **411**, p 665 (2001)




Mark Buitelaar et al., PRL **88**, 156801 (2002)

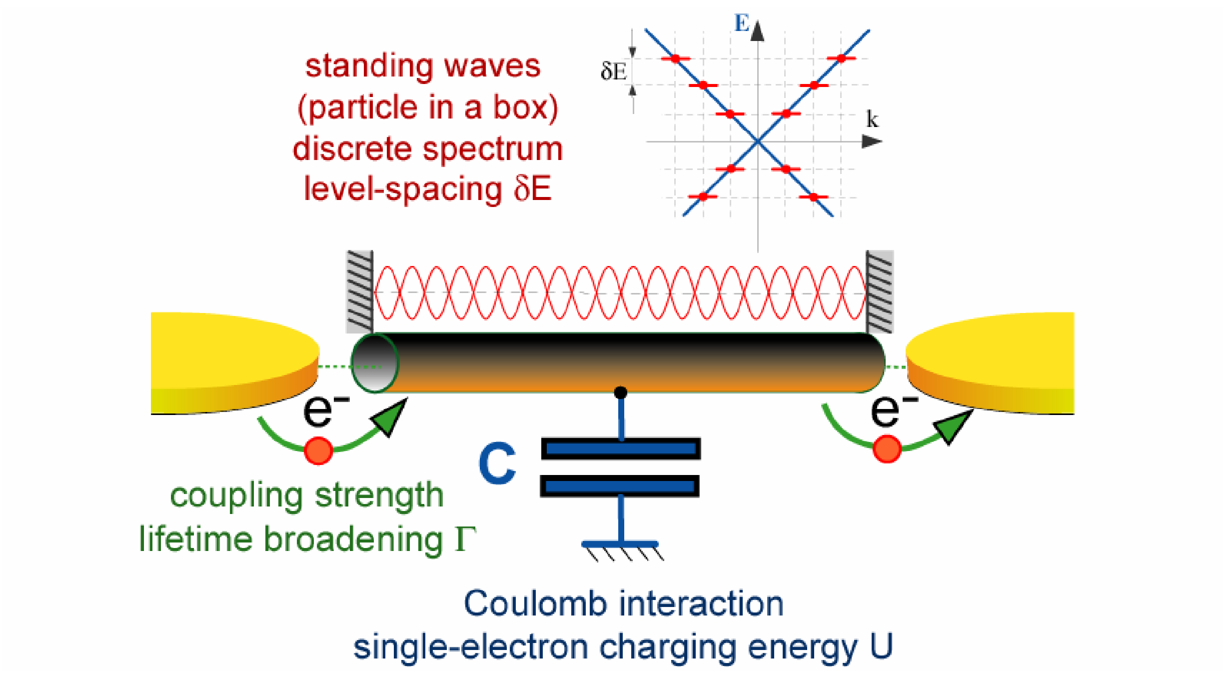



- Fabry-Perot in SWNTs
- Quantum dot in MWNTs

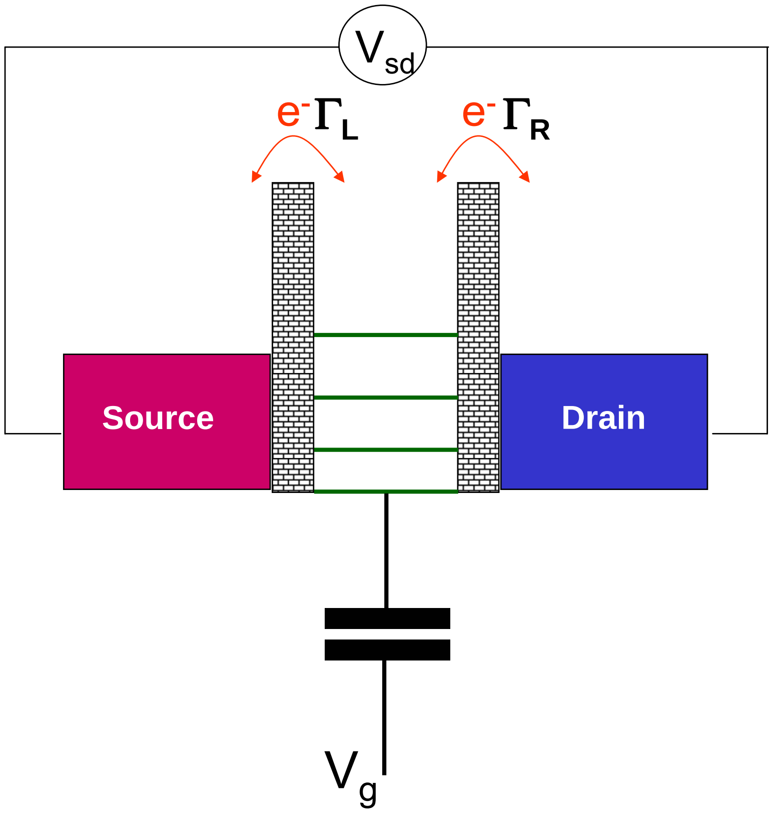
$E = hv_F/2L$ ⟶ 1.67 meV/µm

➡ Energy dependent transmission in NTs…

# Nanotubes as quantum dots

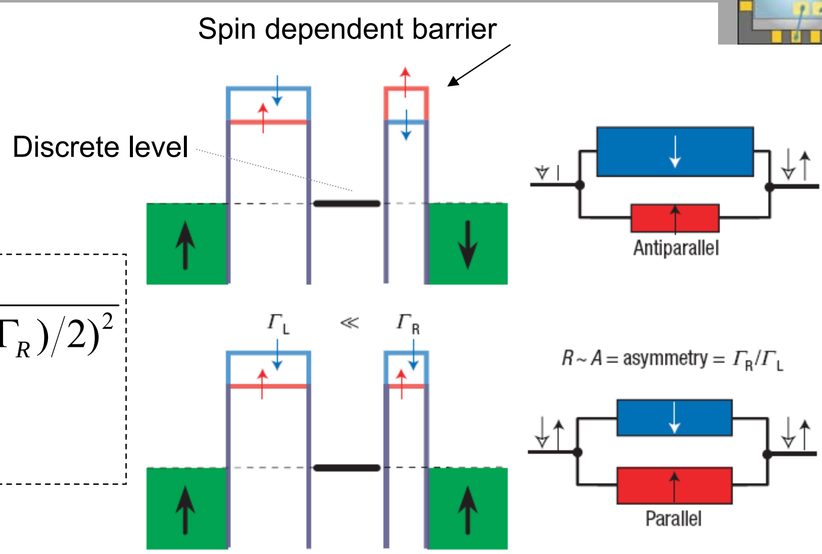


# Nanotubes as quantum dots




→ Energy dependent transmission in NTs…

# TMR and quantum interference




$$T(E) = \frac{\Gamma_L \Gamma_R}{(E-E_0)^2 + ((\Gamma_L+\Gamma_R)/2)^2}$$
$$\Gamma_L = \Gamma_L(1 \pm P_L)$$
$$\Gamma_R = \Gamma_R(1 \pm P_R)$$

Off-resonance,

$$T(E) \propto \Gamma_R \Gamma_L, TMR = \frac{2P_L P_R}{1-P_L P_R}$$

On resonance with asymmetry,

$$\Gamma_R >> \Gamma_L \Rightarrow T(E) = 4\Gamma_L / \Gamma_R, TMR = \frac{-2P_L P_R}{1+P_L P_R}$$

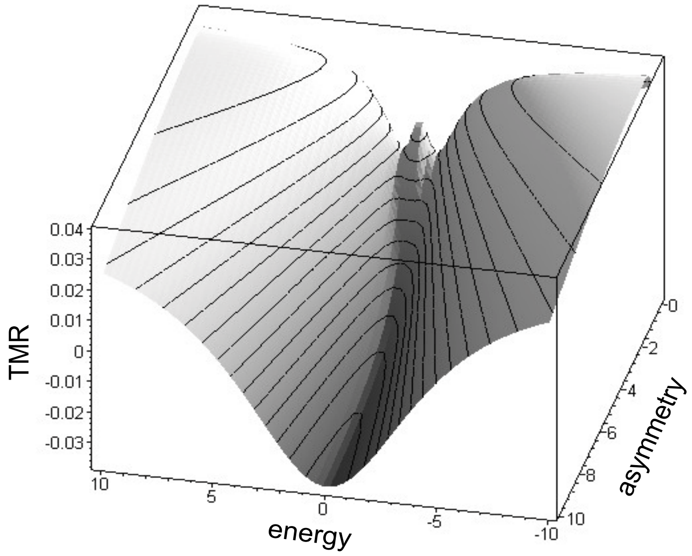
→ SpinFET behavior because $E_0$ controlled by gate.

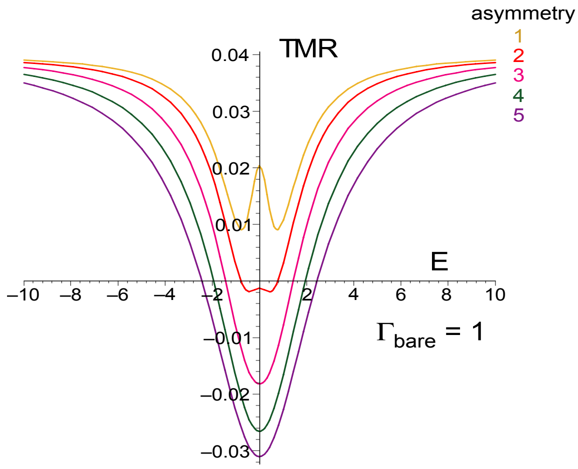
*S. Sahoo, T. Kontos, J. Furer, C. Hoffmann, M. Gräber, A. Cottet and CS, Nature Physics **1,** 99 (2005)*

*See also E.Y. Tsymbal et al. PRL 90, 186602 (2003) in Ni/NiO/Co nanojunctions*

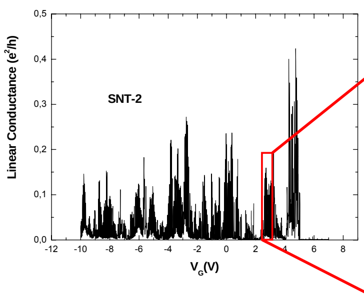
# RT yields a symmetric TMR

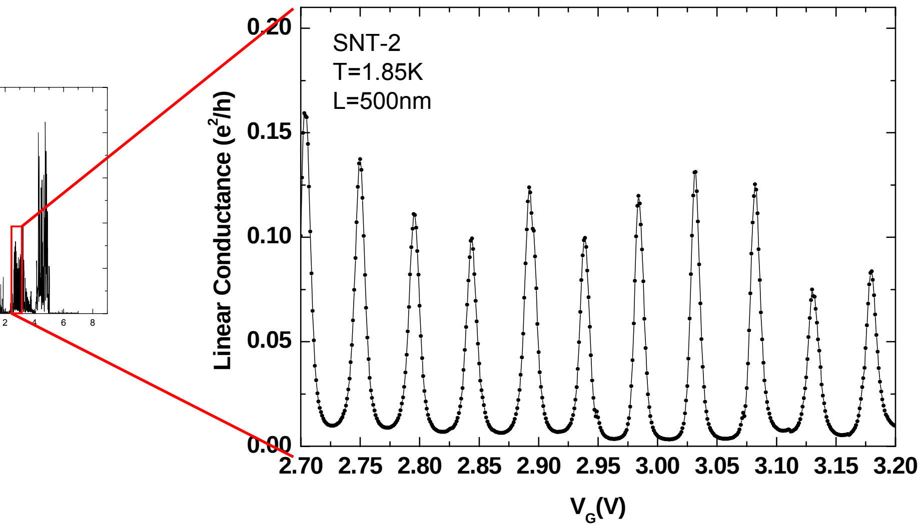
Γ=1 and P=0.2, one resonance



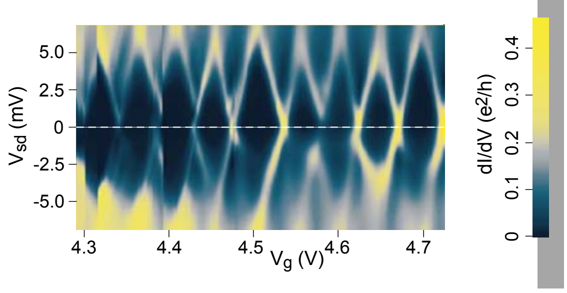




# Linear conductance of SWNT device



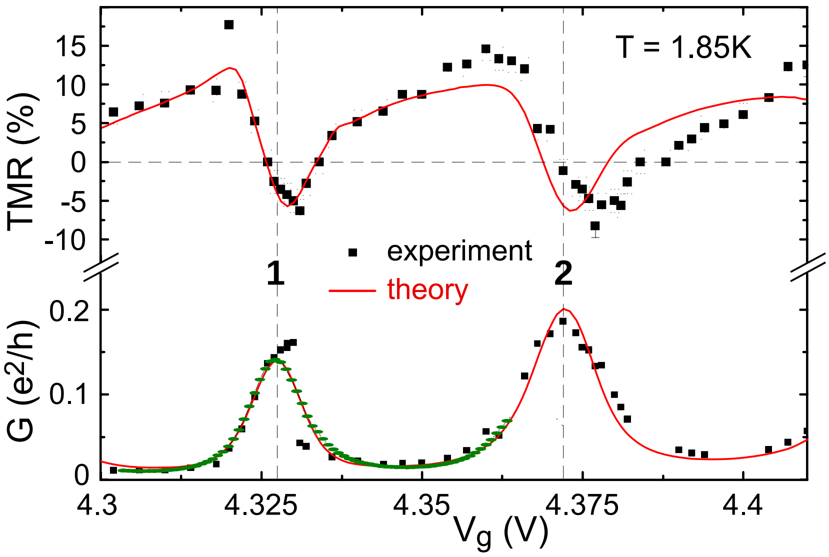



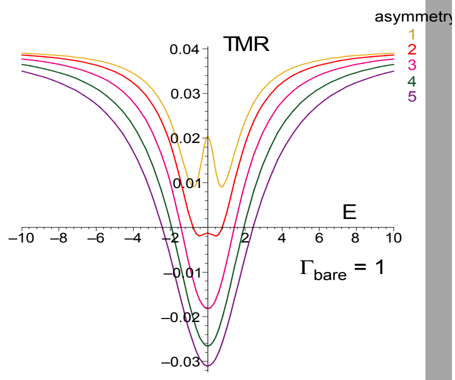

- Resonances in conductance at 1.85K
- Peaks always symmetric about maximum

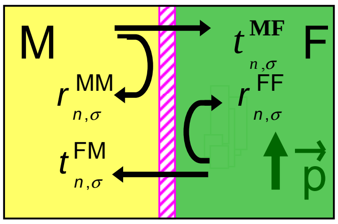


# Comparison G and TMR vs Gate

S. Sahoo, T. Kontos, J. Furer, C. Hoffmann M. Gräber, A. Cottet and C.S., Nature Phys., **2,** 99 (2005)



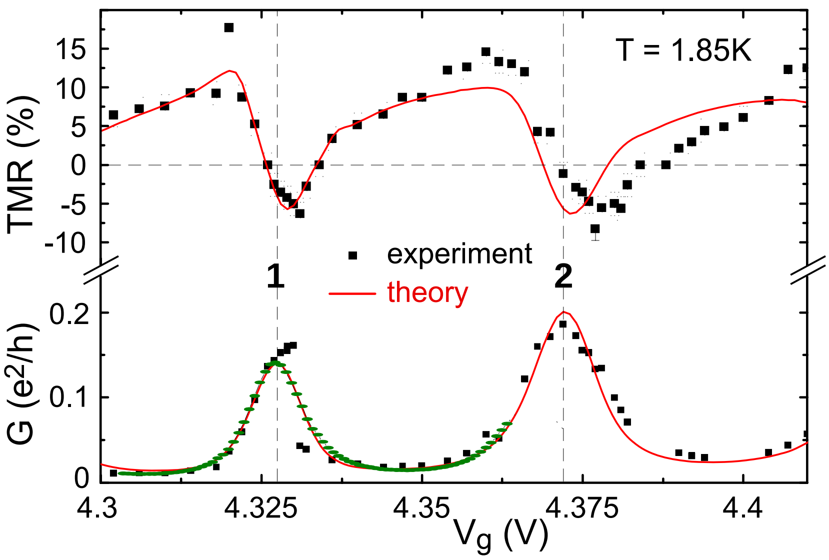




**S**pin-**D**ependence **I**nterfacial **P**hase **S**hifts (SDIPS) ➔ **spin-dependent dot eigenstates**

$$\varepsilon_{\sigma}^{m_1,m_2} := \varepsilon_0(V_g) + \kappa\sigma\left(P_1 m_1 + P_2 m_2\right)$$

*A. Cottet, T. Kontos, W. Belzig, CS, and C. Bruder, Europhys. Lett.* ***74,*** *320 (2006)*

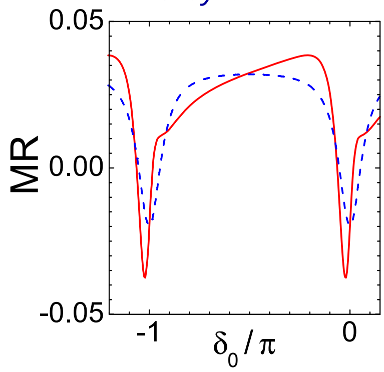
# Comparison G and TMR vs Gate




Asymmetry in TMR

$$E_{\uparrow} - E_{\downarrow} = 0.26meV$$

*Audrey Cottet et al.*




- Oscillations of TMR between -8% and +17%.
- Spin dependent resonant tunneling mechanism.
- Direct measurement of spin imbalance ~ 2.2 T.

S. Sahoo, T. Kontos, J. Furer, C. Hoffmann M. Gräber, A. Cottet and C.S., Nature Phys., **2,** 99 (2005)

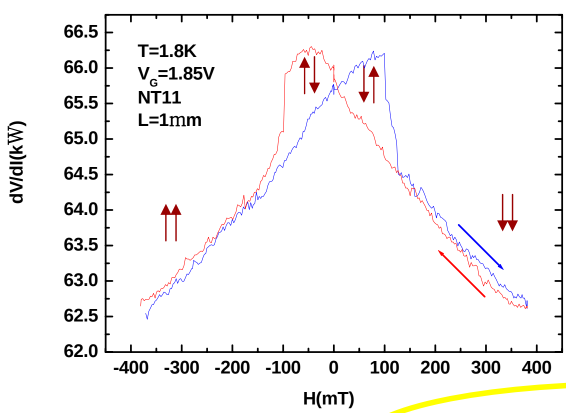
## Problems…?

**have we really measured spin signal in transport ?**

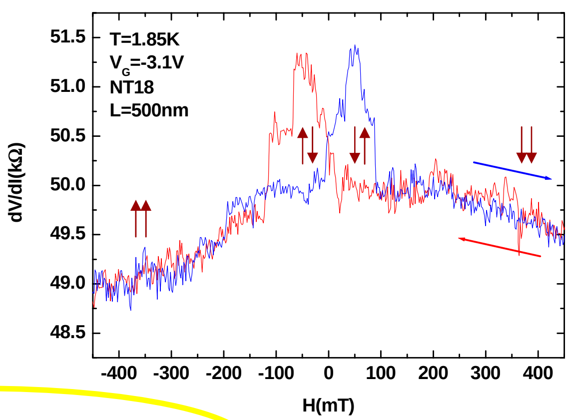
1. ***stray-field*** effects ?
2. ***magneto-Coulomb*** effect (through Zeeman effect)
3. ***magnetostrictive*** effects very locally on the contacts
4. how large is the *„**true“ spin polarization*** in the current
5. how large is the „***spin accumulation“*** in the CNT dot?

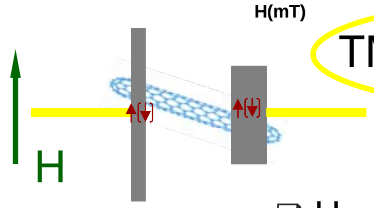
## Background and MR

H parallel to leads axis

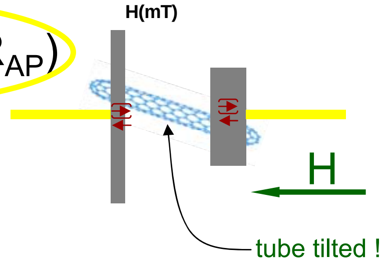



H perpendicular to leads axis



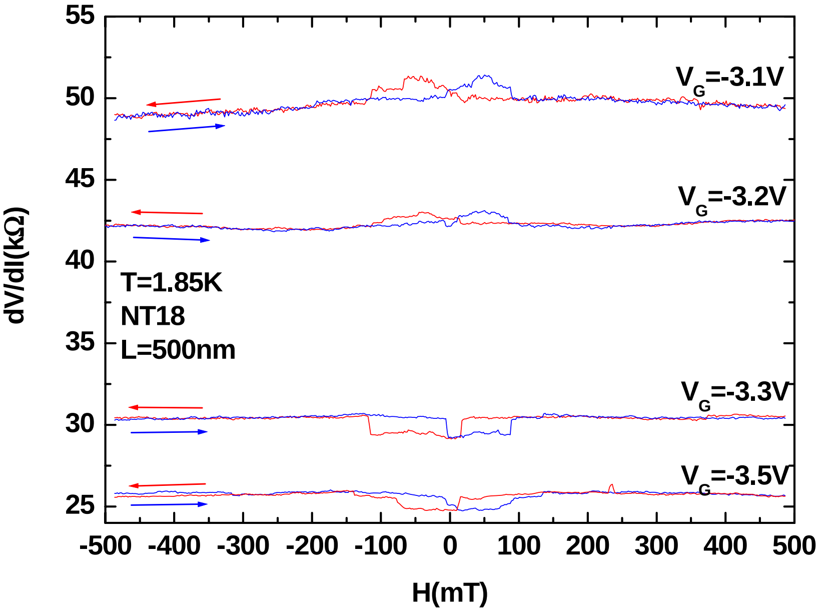




$$TMR=2(R_{AP}-R_P)/(R_P+R_{AP})$$

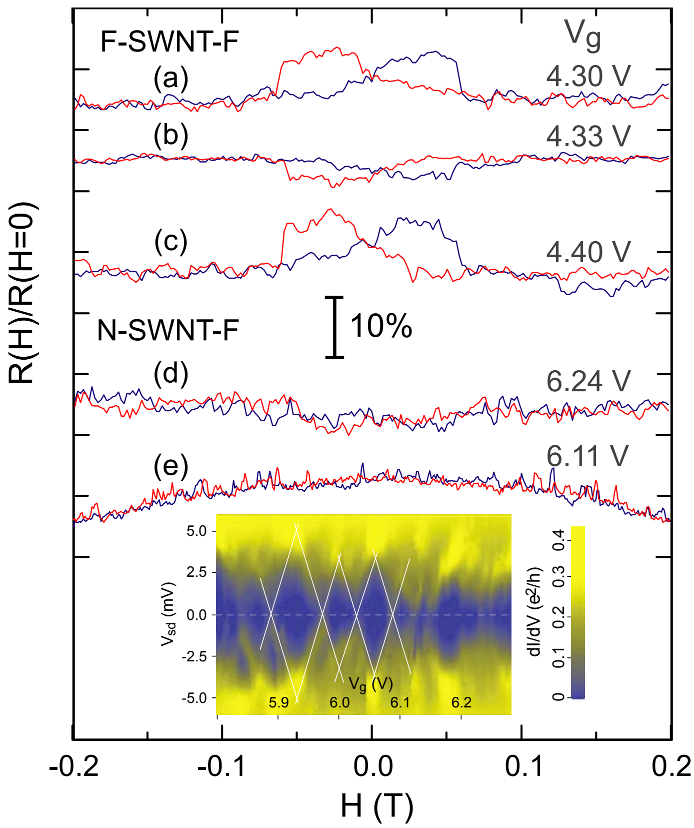



- Hysteresis with TMR ~ +3%
- Sharp switching for ~ 100mT
- Sharper switching for ~ 0mT for perpendicular H

# Background and MR

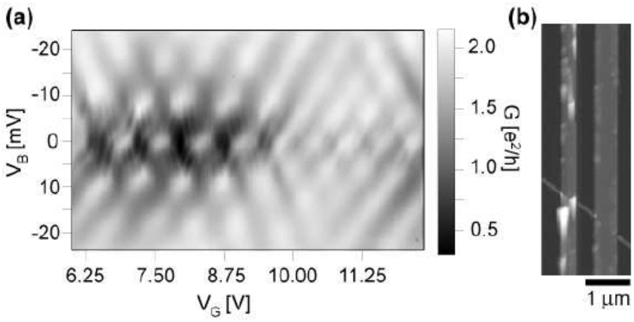


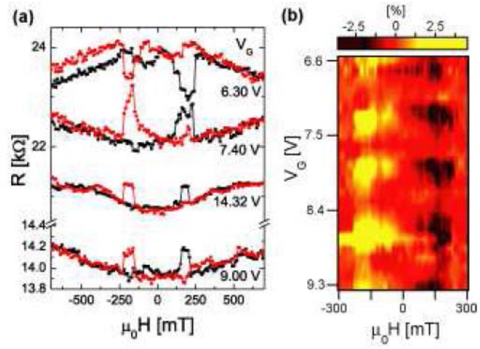

# Control Experiment

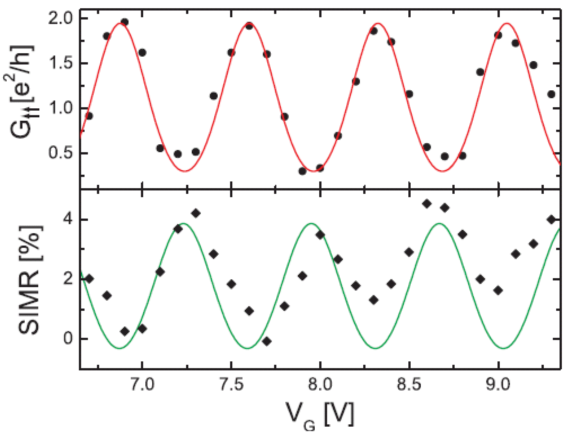


# Morpurgo et al.

*H.T. Man, I.J.W. Wever, and A.F. Morpurgo, condmat 0512505*




# Alphenaar et al.

APPLIED PHYSICS LETTERS **88**, 023503 (2006)

## Gated spin transport through an individual single wall carbon nanotube


B. Nagabhirava, T. Bansal, G. U. Sumanasekera, and B. W. Alphenaar[a)]
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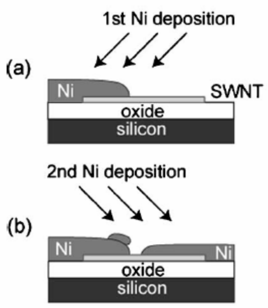
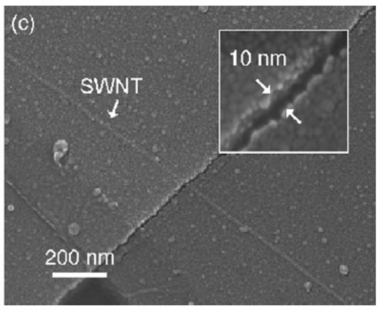
L. Liu
*Department of Physics, McGill University, Montreal, Quebec H3A 2T8, Canada*


(Received 19 October 2005; accepted 21 November 2005; published online 10 January 2006)

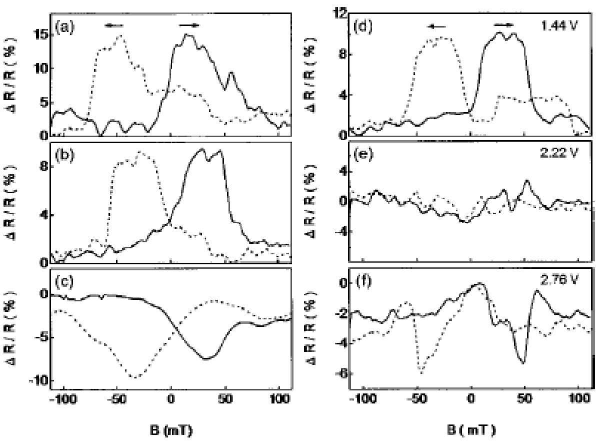
Hysteretic switching in the magnetoresistance of short-channel, ferromagnetically contacted individual single wall carbon nanotubes is observed, providing strong evidence for nanotube spin transport. By varying the voltage on a capacitively coupled gate, the magnetoresistance can be reproducibly modified between +10% and −15%. The results are explained in terms of wave vector matching of the spin polarized electron states at the ferromagnetic / nanotube interfaces. © 2006 *American Institute of Physics*. [DOI: 10.1063/1.2164367]

some non-trivial gate-effect, but not (yet) periodic




very short channel



# Conclusion

- Spin injection in carbon nanotubes TMR ~10% (SWNTs)
- Spin FET-like behavior in spin valves with nanotubes due to quantum dot behavior

→ Importance of spin dependent quantum interference

- How much spin injection ?
- Can one make effective spin FETs ?
- Direct control of spin possible ?
- Effect of e-e interactions ?

***Refs:***

*S. Sahoo, T. Kontos, CS and C. Sürgers, Appl. Phys. Lett.* ***86****, 112109 (2005)*
*S. Sahoo, T. Kontos, J. Furer, C. Hoffmann, M. Gräber, A. Cottet and CS, Nature Phys.* ***2,*** *99 (2005)*
*A. Cottet, T. Kontos, W. Belzig, C.S and C. Bruder, Eur. Phys. Lett.* ***74****, 320 (2006)*

*H.T. Man, I.J.W. Wever, and A.F. Morpurgo, cond-mat 0512505*

*B. Nagabhirava, T. Bansal, G. U. Sumanasekera, B. W. Alphenaar, Appl. Phys. Lett. 88, 023503 (2006)*

*N. Tombros, S.J. van der Molen, B.J. van Wees, cond-mat/0506538*

# many thanks to