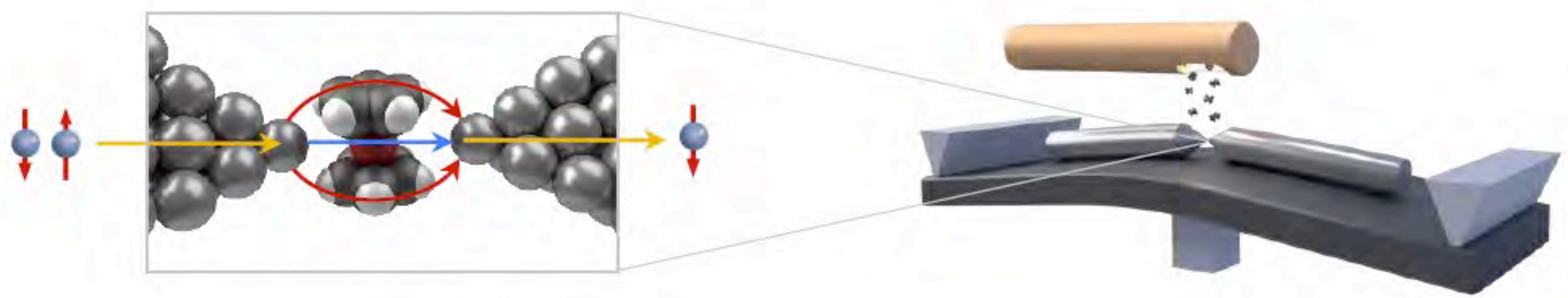
Nonmagnetic spin filter based on single molecular junction

Atindra Nath Pal

S. N. Bose National Centre for Basic Sciences, Kolkata



Nature Comm. **10**, 5565 (2019)

WEIZMANN INSTITUTE OF SCIENCE

מכון ויצמן למדע

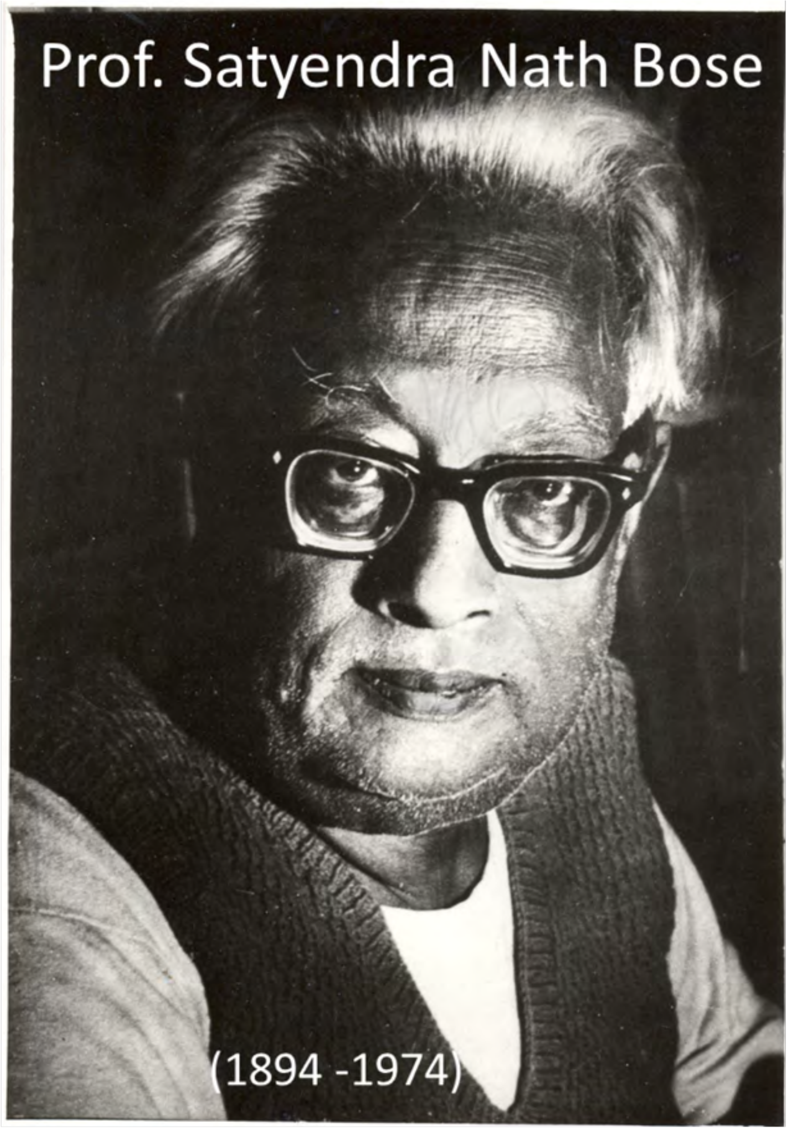
SPICE-Molecular Electro-Opto-Spintronics
Mainz, 15th – 18th October, 2019

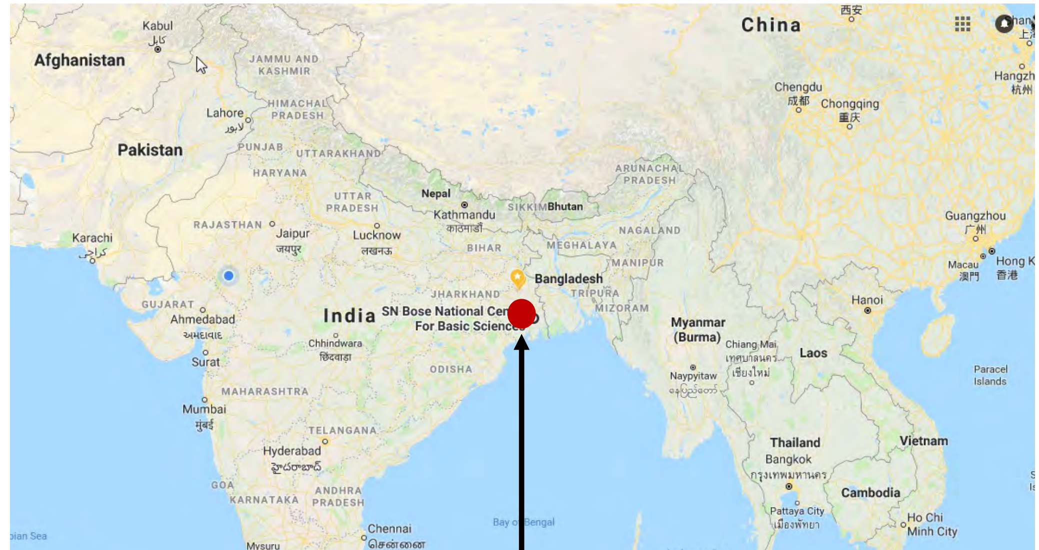
CENTRE FOR BASIC SCIENCES 1986 S. N. BOSE NATIONAL

1894-1974

विज्ञानेन परिपश्यन्ति धीराः

S N Bose National Center for Basic Sciences, Kolkata



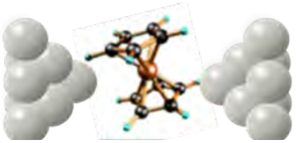


SNNCBS (32 years old)

Today's Plan

- Introduction
- Mechanically Controllable Break Junction (MCBJ)
- Shot Noise: Detecting Spin transport
- Conductance and Shot noise in single molecular junction
- Results & Discussion
- Conclusion
- Group activities

Spin transport at the limit of atomic scale



- What is the smallest component that can control spin transport?

- Can we identify general concepts that will allow efficient control over spin transport at the atomic scale?

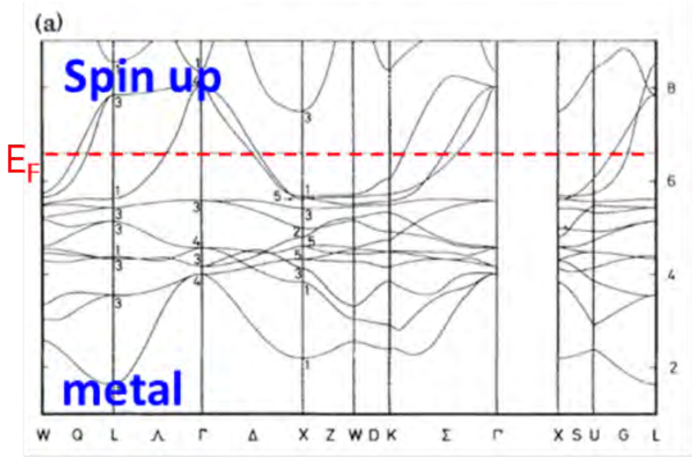
Motivation

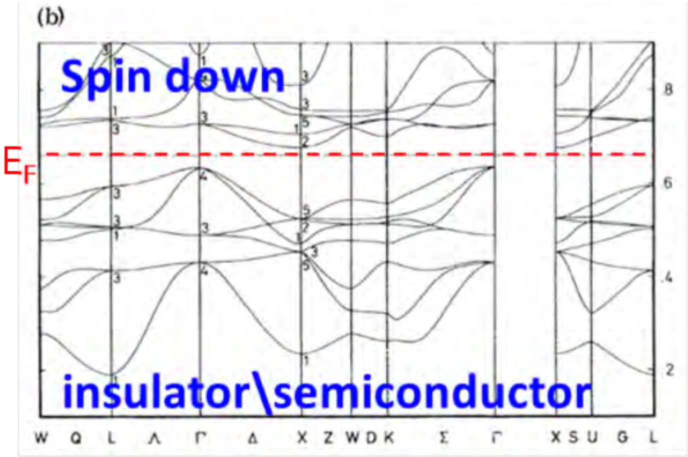
Spintronics: manipulations of electronic spin currents
for electronics and spin transport physics

The most general requirement of spintronics:
high spin polarised current

Current spin polarisation: $$P_I = \frac{I_\uparrow - I_\downarrow}{I_\uparrow + I_\downarrow}$$

Half Metals – Ideal candidate



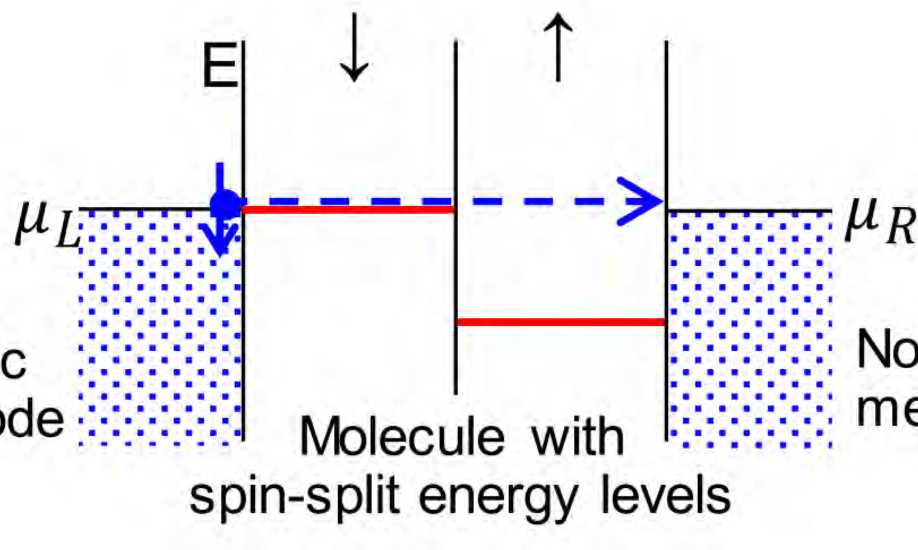


NiMnSb band structure: de Groot, R. A., Mueller, F. M., van Engen, P. G. & Buschow, K. H. J. *Phys. Rev. Lett.* **50**, 2024 (1983)

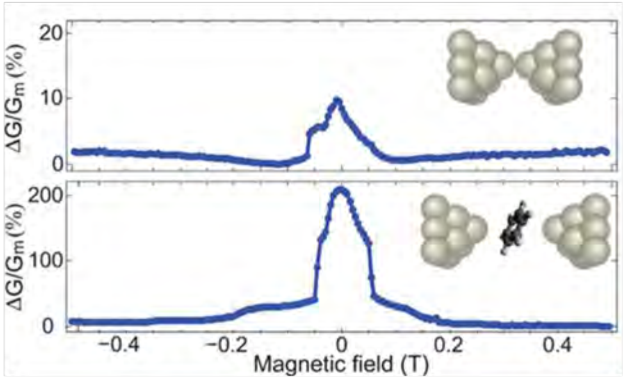
Ideal half metals are ideal materials for spintronics

Full spin polarization of the conducting electrons

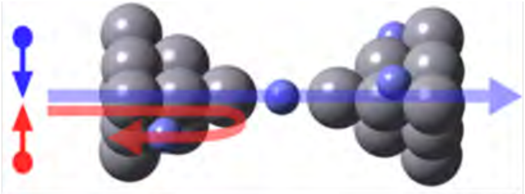
Goal: molecular scale half metallicity



Enhanced magnetoresistance



Ni – Benzene - Ni

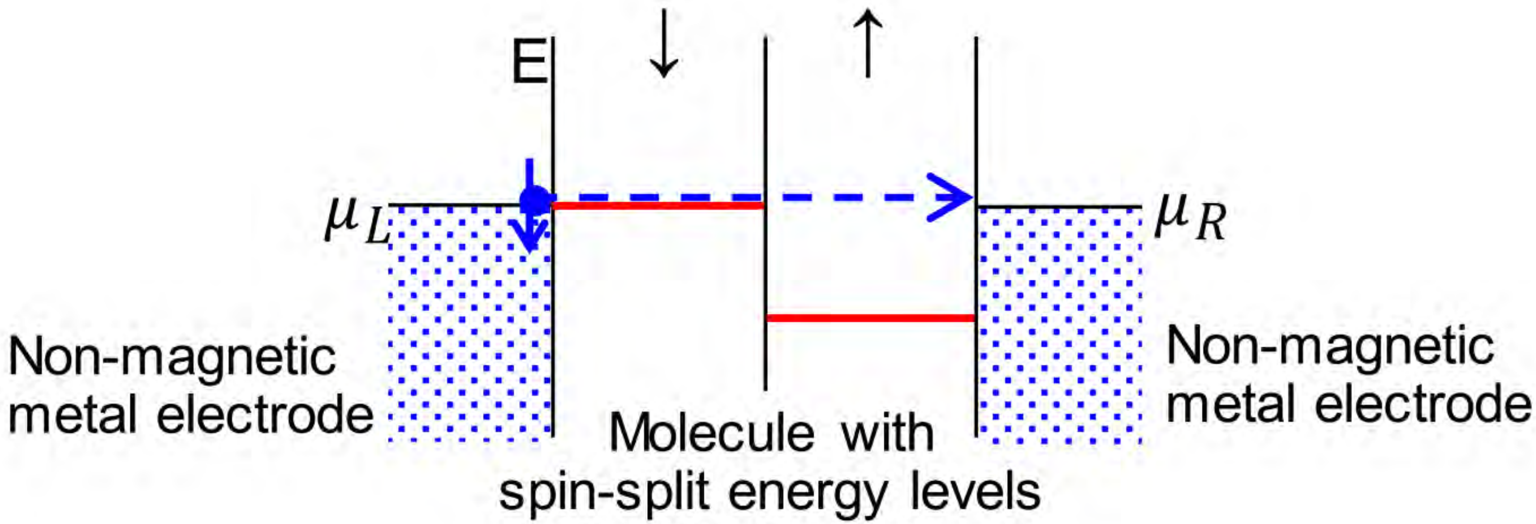


Complete spin filtering in Ni - O - Ni junction

Vardimon, R; Klionsky, M; Tal, O; Nano Letters. **15**:3894-3898

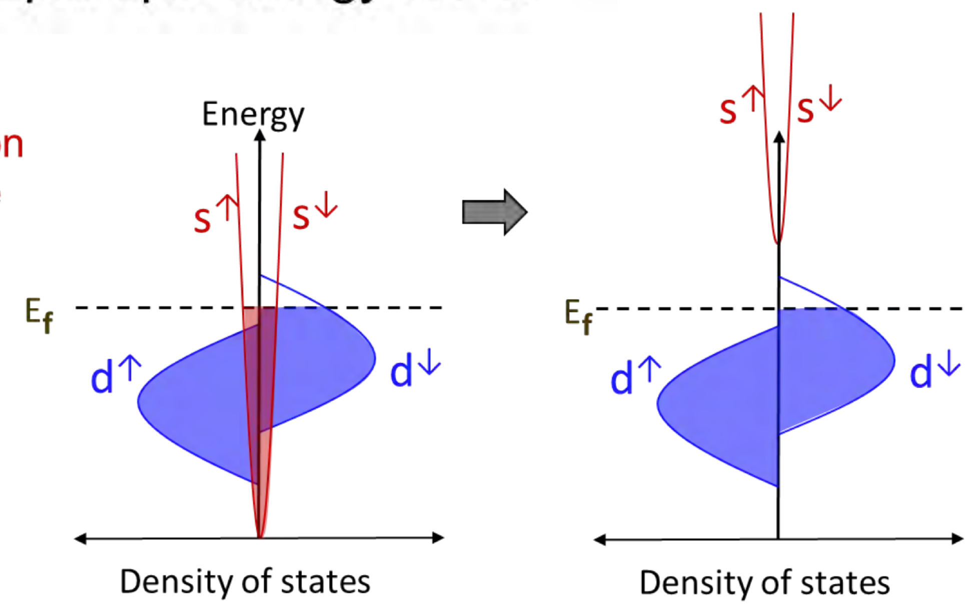
D. Rakhmilevitch, S. Soumyajit. O. Bitton, L. Kronik and O. Tal, Nano Letters. **16**:1741-1745 (2016)

Goal: molecular scale half metallicity



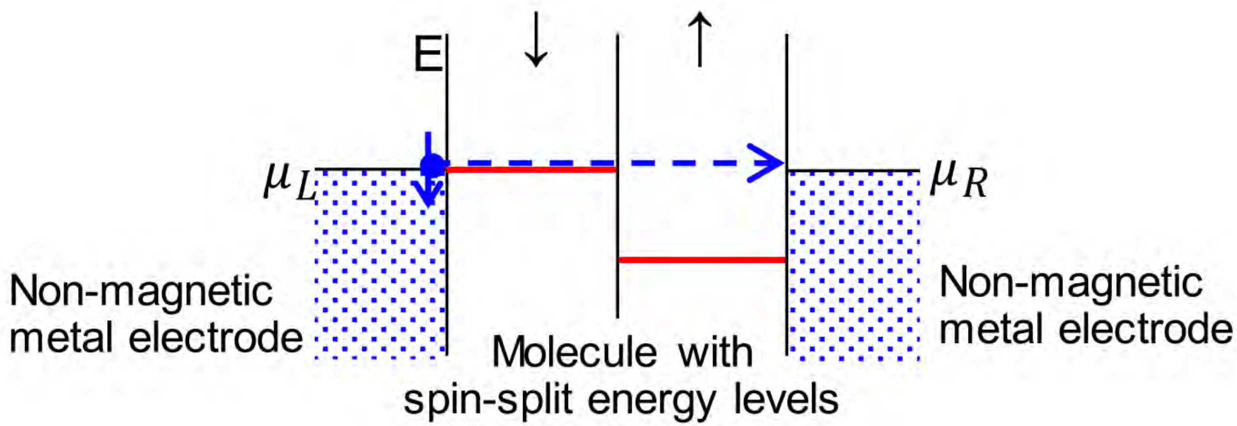
s orbitals:
Small spin polarization but high conductance

d orbitals:
spin polarized but low conductance



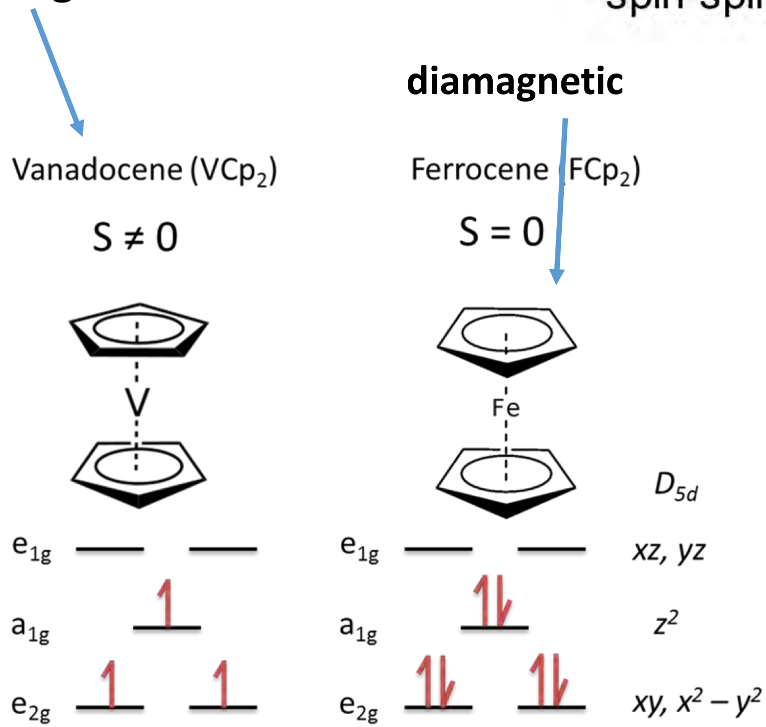
Vardimon, R; Klionsky, M; Tal, O; Nano Letters. **15**:3894-3898

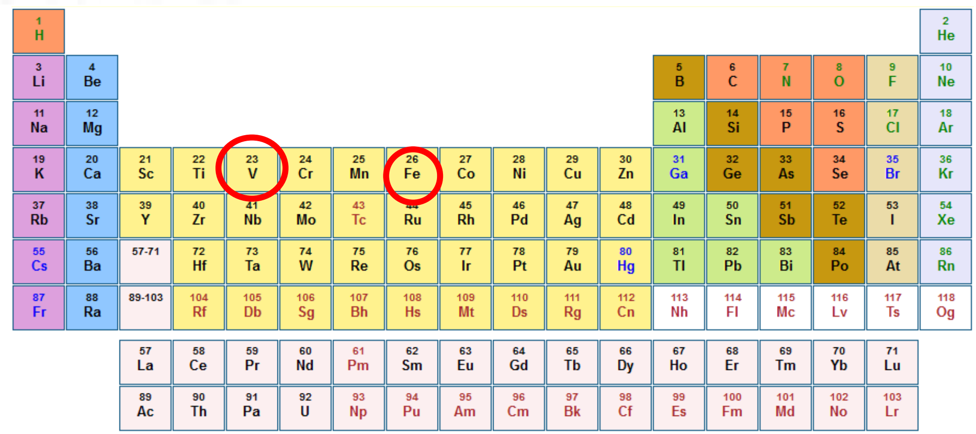
Goal: molecular scale half metallicity



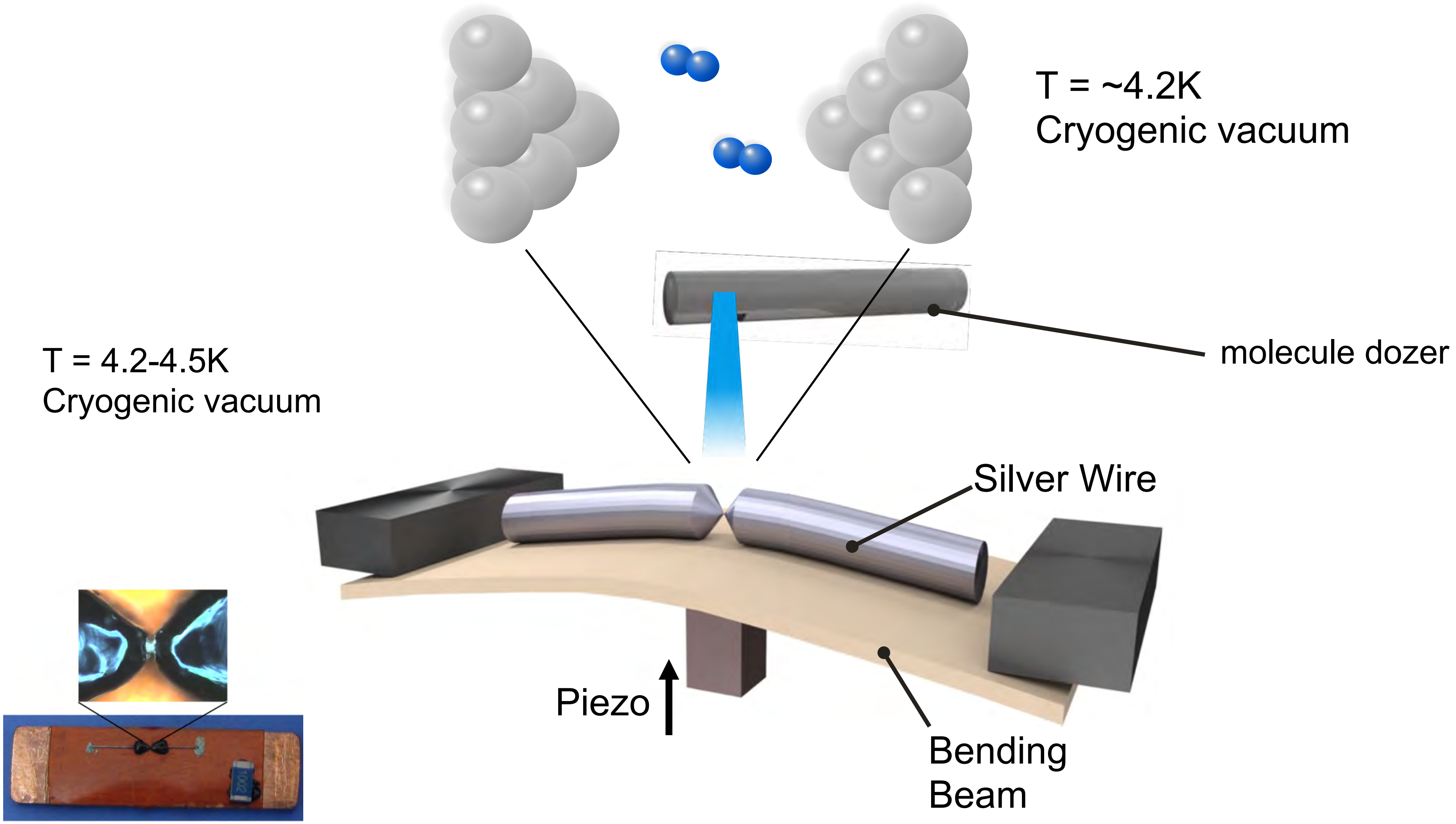
paramagnetic

diamagnetic





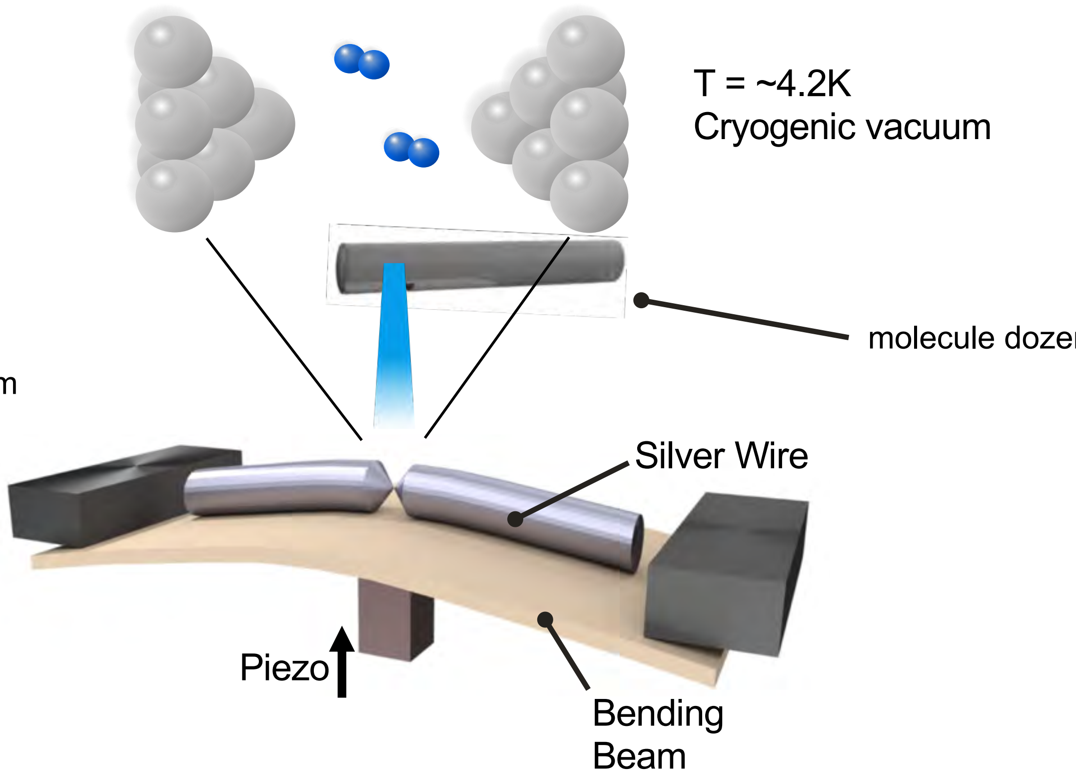
Formation of atomic and molecular junctions by mechanically controllable break junction

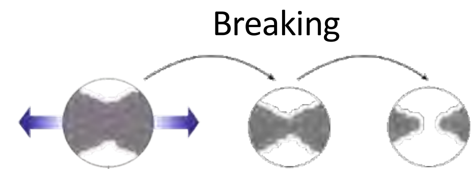


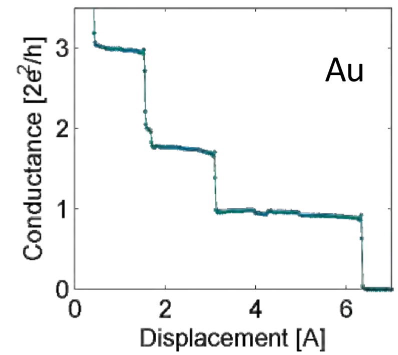
e.g.: T. Yelin, R. Vardimon, N. Kuritz, R. Korytar, A. Bagrets, F. Evers, L. Kronik and O. Tal Nano Letters **13**, 1956 (2013)

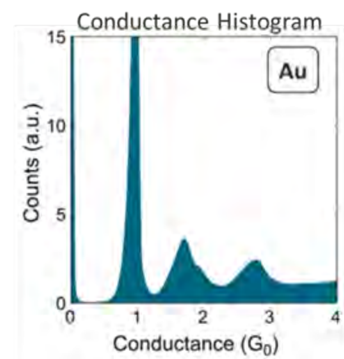
Formation of atomic and molecular junctions by mechanically controllable break junction

T = 4.2-4.5K
Cryogenic vacuum



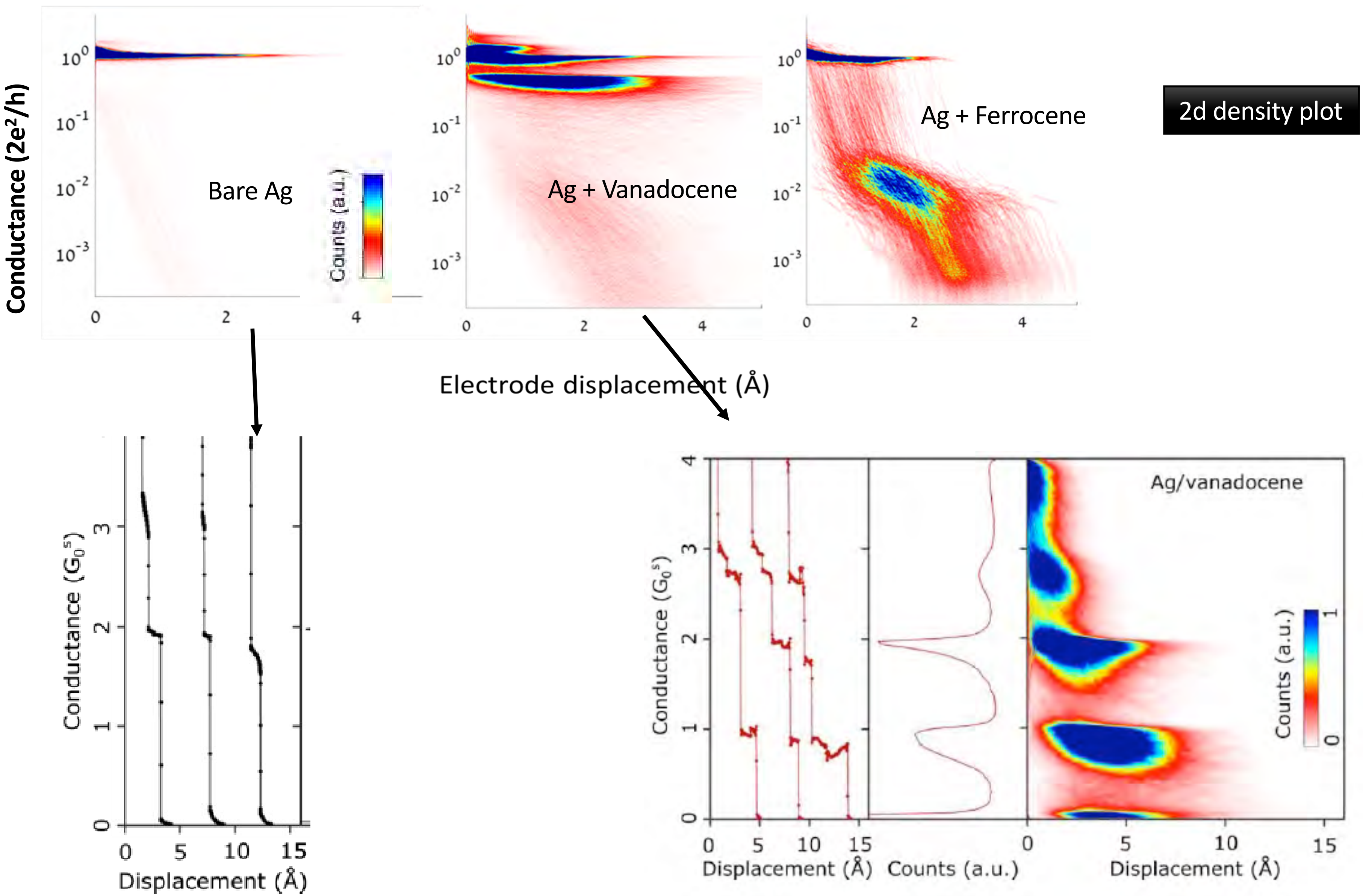




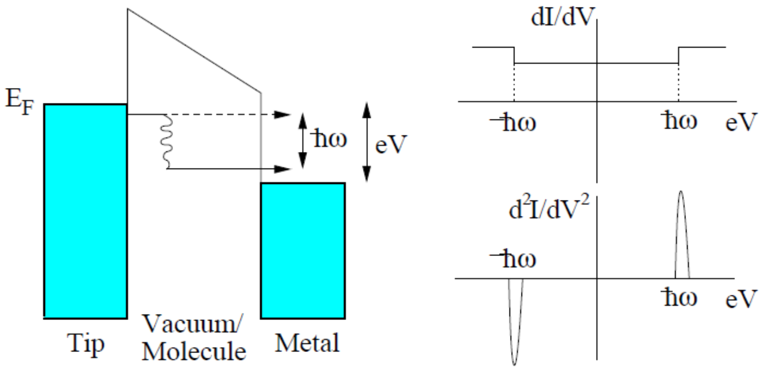


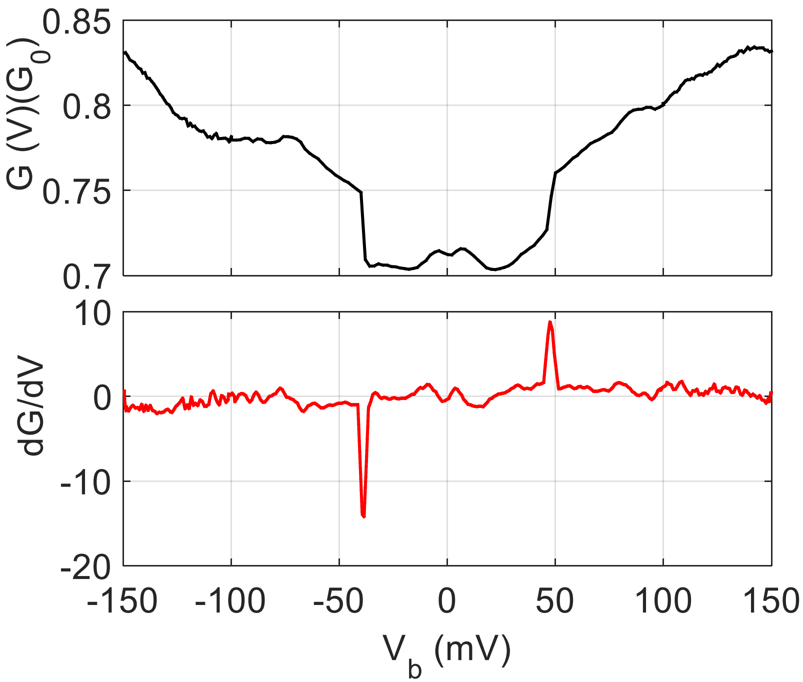
e.g.: T. Yelin, R. Vardimon, N. Kuritz, R. Korytar, A. Bagrets, F. Evers, L. Kronik and O. Tal Nano Letters **13**, 1956 (2013)

Characterization of metal – molecule – metal junction

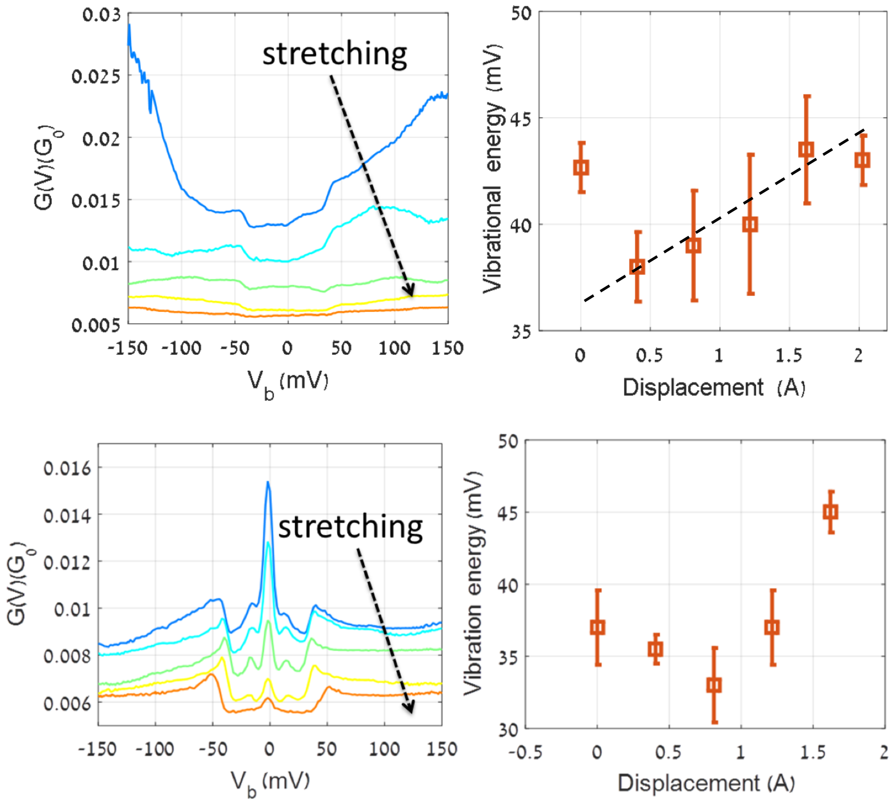


Inelastic spectroscopy: vibrational modes



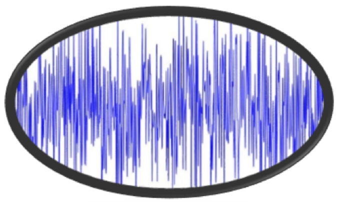


Ag – Vanadocene – Ag junction



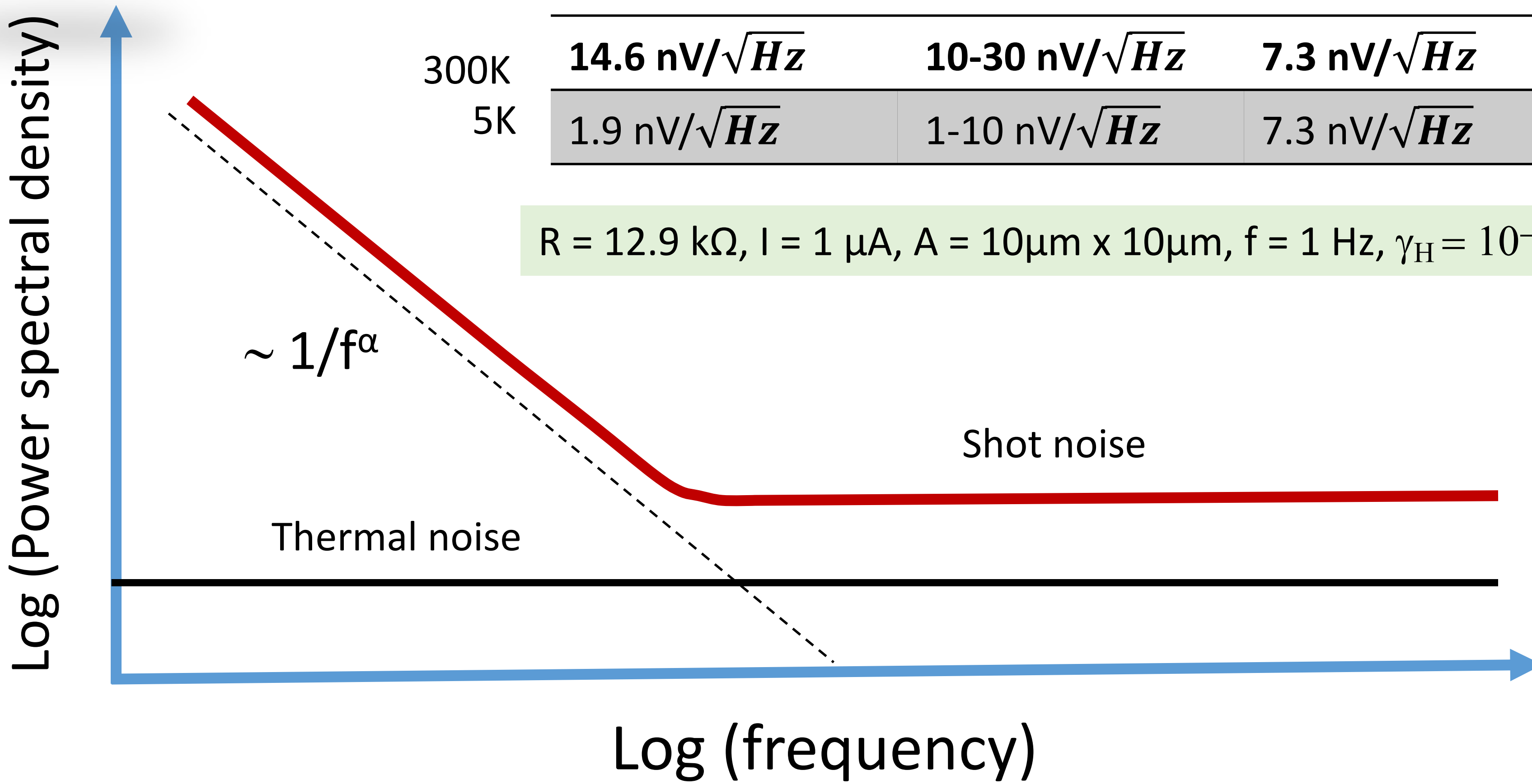
Types of noise

Noise = Thermal noise + 1/f noise + shot noise

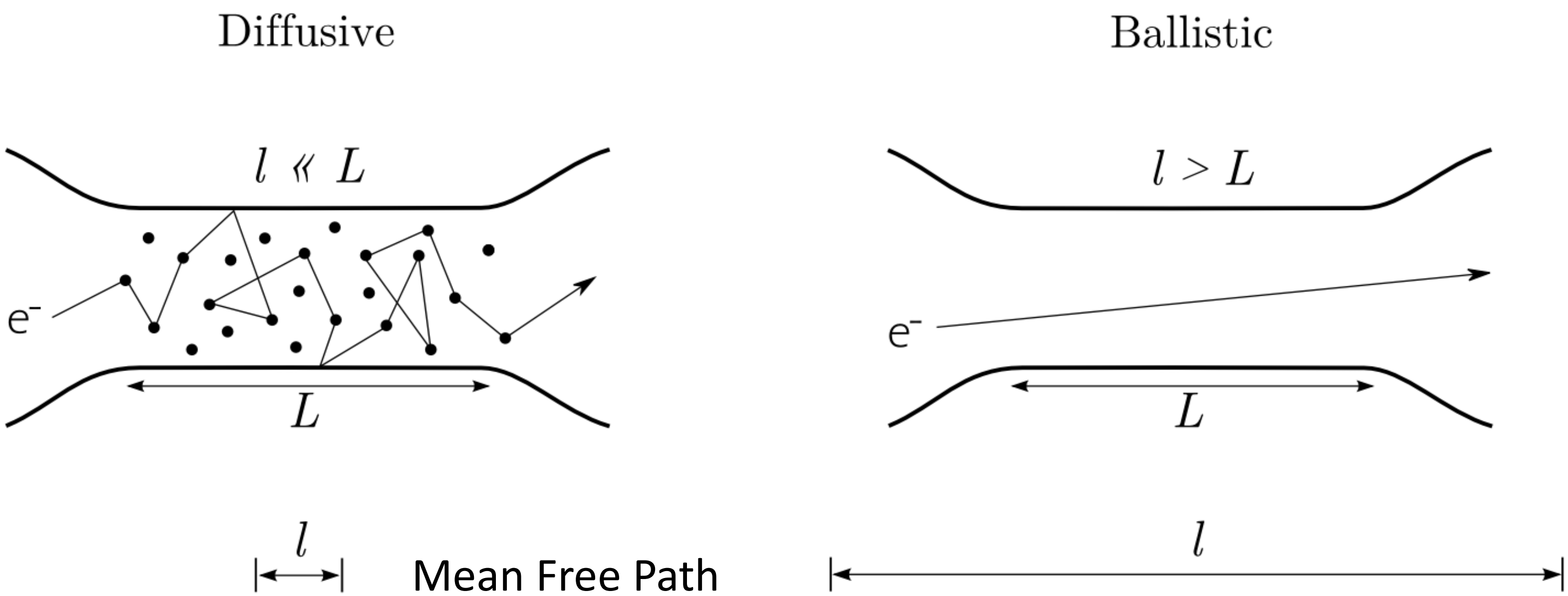


	Thermal noise $(4k_BTR)$	1/f noise $\gamma_H AV^2/f^\alpha$ (Hooge parameter: γ_H)	Shot noise $2e\langle I\rangle F$ (Fano factor: F)
300K	**14.6 nV/$\sqrt{Hz}$**	**10-30 nV/$\sqrt{Hz}$**	**7.3 nV/$\sqrt{Hz}$**
5K	1.9 nV/$\sqrt{Hz}$	1-10 nV/$\sqrt{Hz}$	7.3 nV/$\sqrt{Hz}$

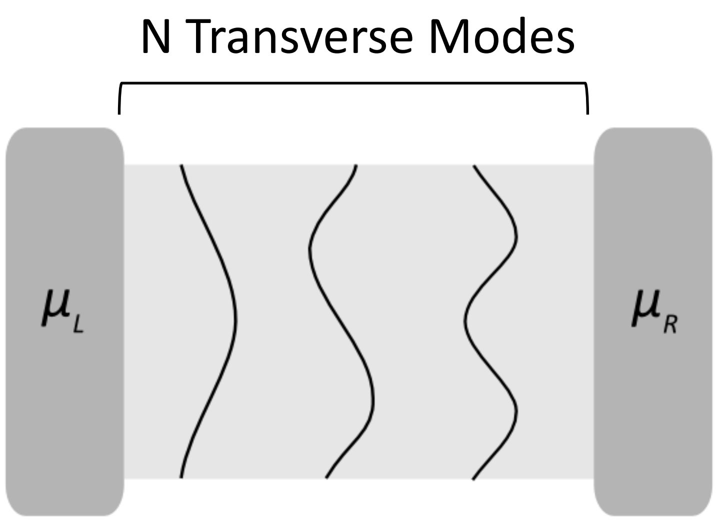
R = 12.9 kΩ, I = 1 μA, A = 10μm x 10μm, f = 1 Hz, $\gamma_H = 10^{-2}$

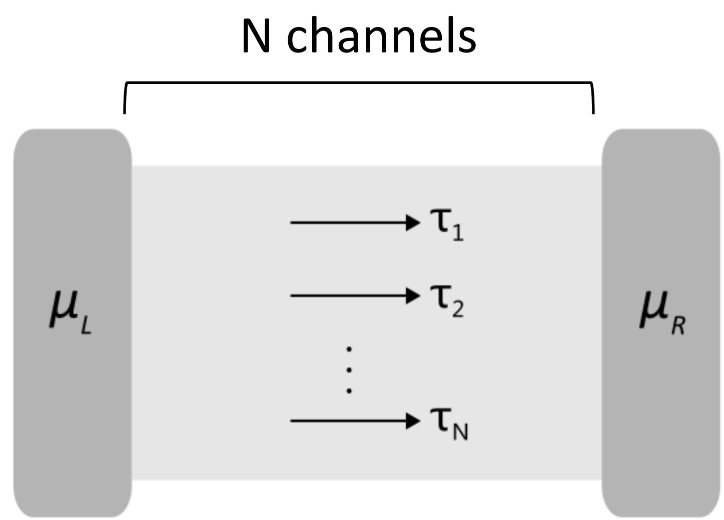


Ballistic Transport



Conduction Channels





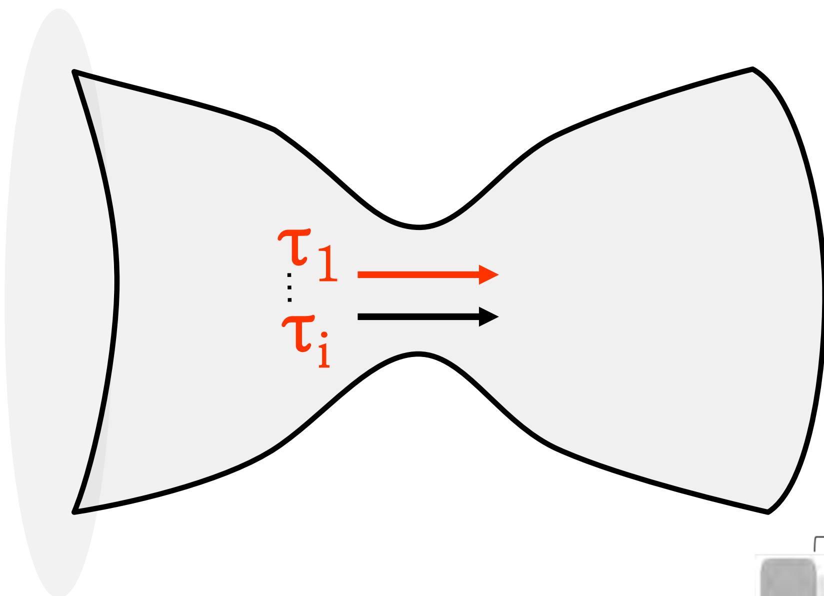
Landauer Formula

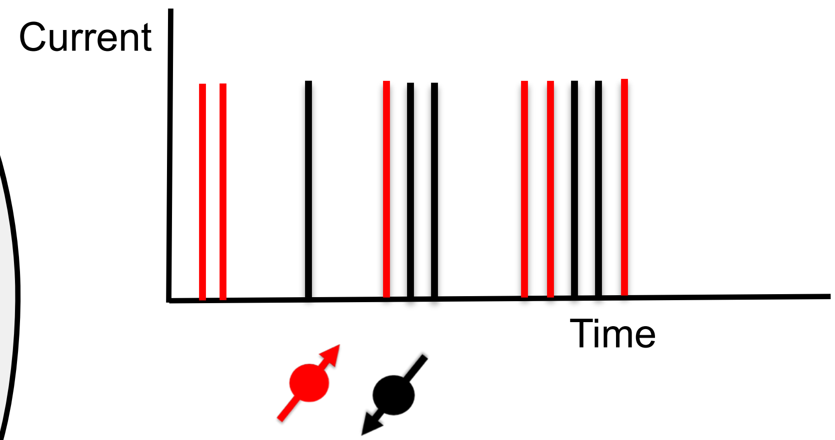
$$G = G_0 \sum_{n=1}^{N} \tau_n$$

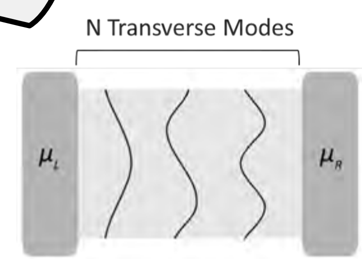
Quantum of conductance

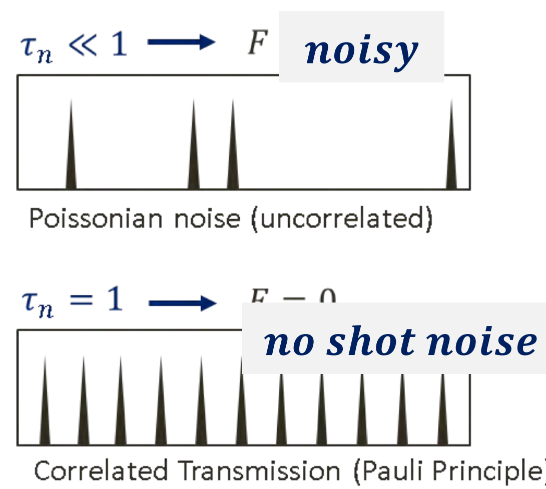
$$G_0 = \frac{2e^2}{h} = (12.9k\Omega)^{-1}$$

Electronic shot noise in point contact









Shot noise Power

$$S = 2eIF$$

Fano Factor

$$F = \frac{\sum \tau_n (1-\tau_n)}{\sum \tau_n}$$

Conductance

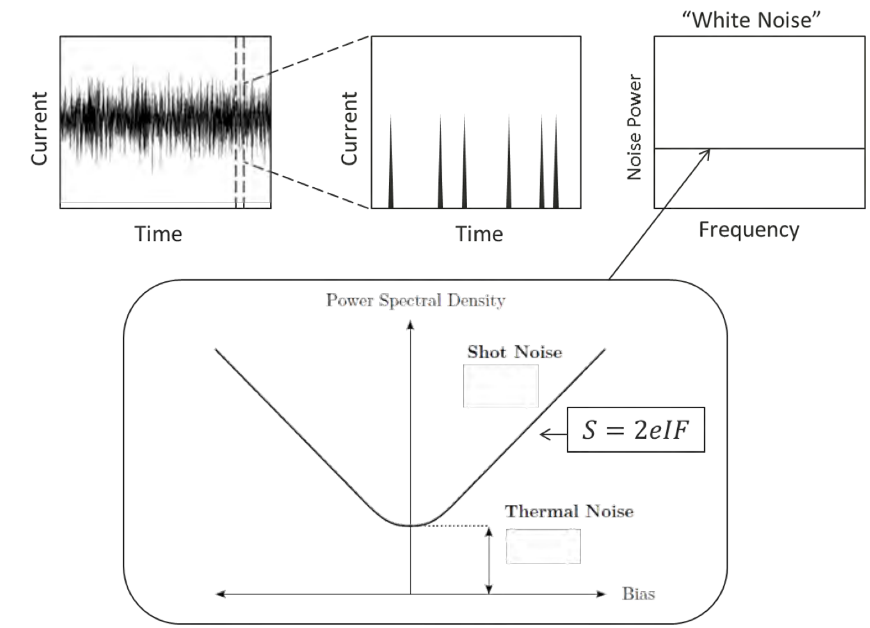
$$G = G_0 \sum \tau_n$$

Conduction Channels

$$\{\tau_n\}$$

R. Vardiman et al, Phys. Rev. B. **88** 161404 (R) (2013).

Shot noise measurement and extraction of Fano factor



Shot noise Power

$S = 2eIF$

Fano Factor

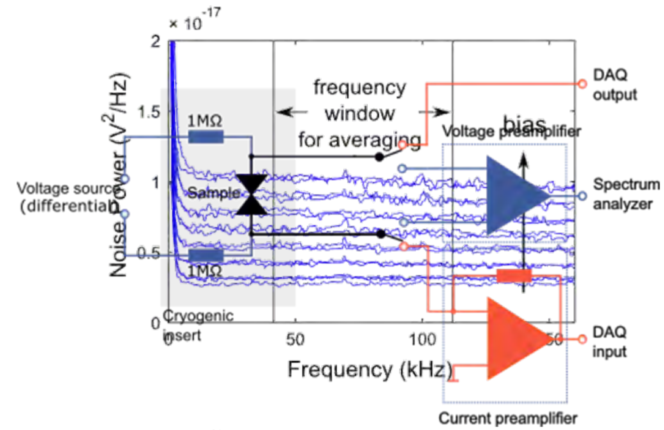
$F = \frac{\sum \tau_n (1-\tau_n)}{\sum \tau_n}$

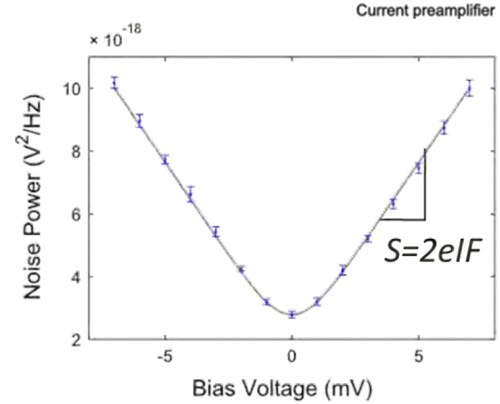
Conductance

$G = G_0 \sum \tau_n$

Conduction Channels

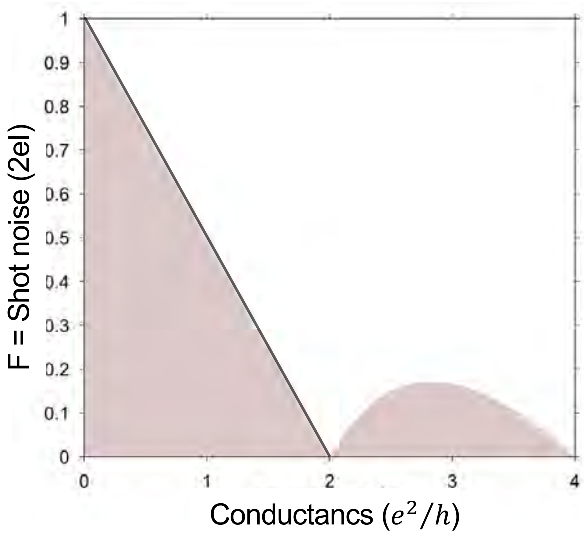
$\{\tau_n\}$





R. Vardiman et al, Phys. Rev. B. **88** 161404 (R) (2013).
M. Kumar et al., Phys. Rev. Lett. **108**, 146602 (2012).

Probing spin polarized conduction by shot noise



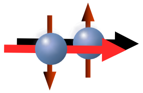
Shot noise Power

$$S = 2eIF$$

Fano Factor

$$F = \frac{\sum \tau_n (1 - \tau_n)}{\sum \tau_n}$$

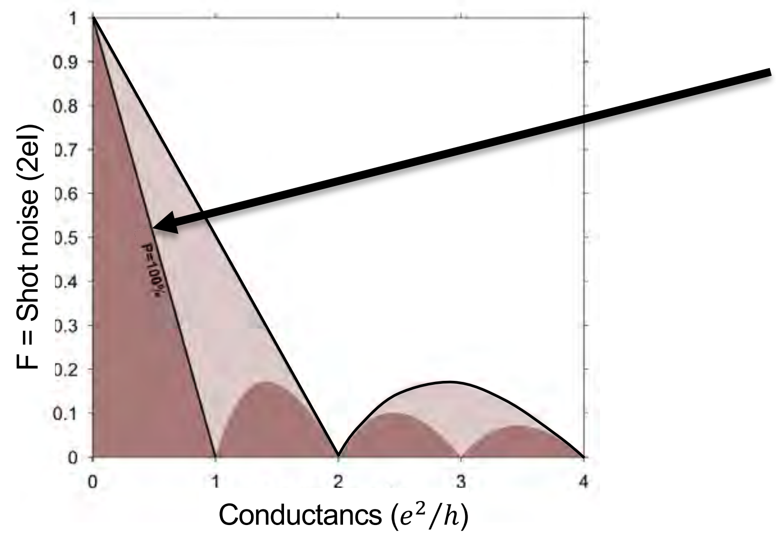
No spin polarized current (**light brown** area is forbidden)



$$S_I = 2eV \coth\left(\frac{eV}{2kT}\right) \frac{2e^2}{h} \sum_i \tau_i (1 - \tau_i) + 4kT \frac{2e^2}{h} \sum_i \tau_i^2$$

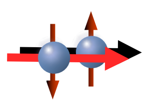
$$G = \frac{2e^2}{h} \sum_i \tau_i$$

Probing spin polarized conduction by shot noise



For one single spin channel
$F = 1 - \tau_1$
Linear

No spin polarized current (light brown area is forbidden)



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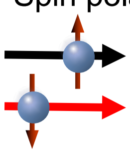
$$G = \frac{2e^2}{h}\sum_i \tau_i$$

Spin polarized current (**dark brown** area is forbidden)



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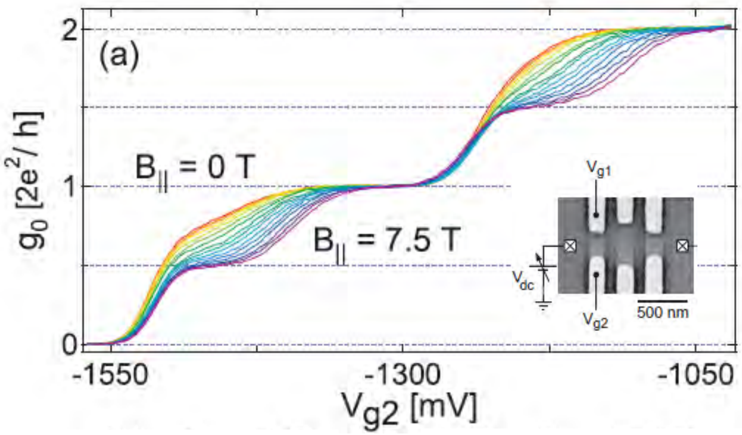
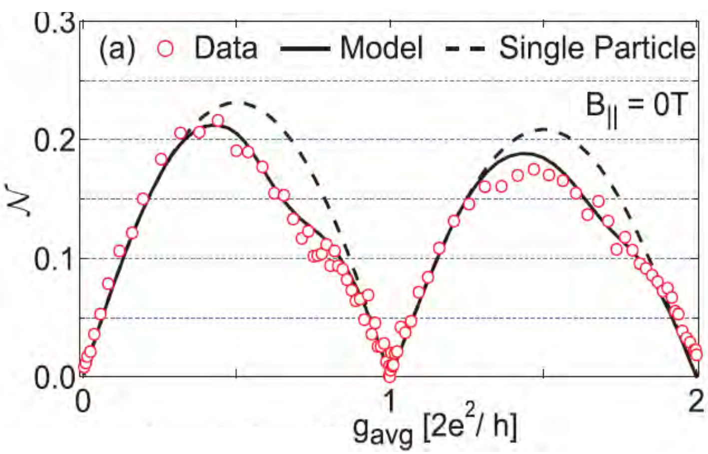
$$G = \frac{e^2}{h}\sum_i \tau_i$$

Spin polarization through Shot noise

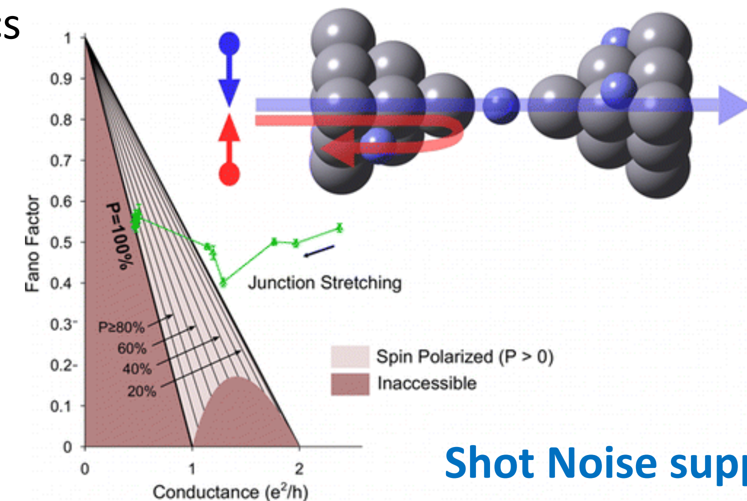
Quantum point contact – Mesoscopic Physics





Suppression of Shot Noise near 0.7 anomaly – Spin origin

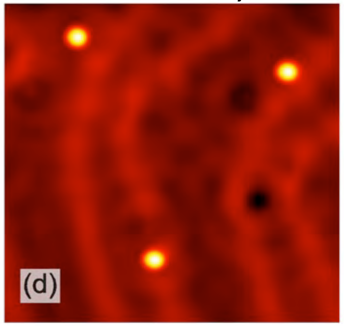
L. DiCarlo et al., PRL 97, 036810 (2006)

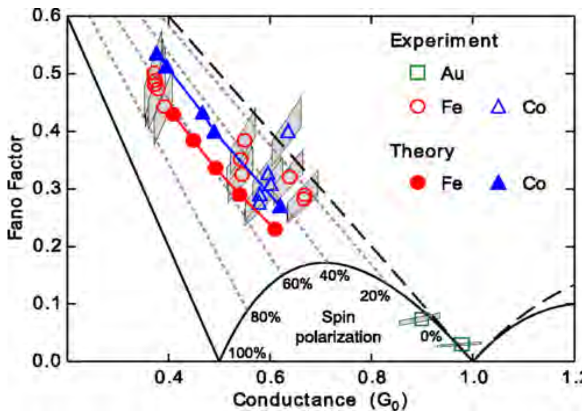


Shot Noise suppression in Ni-O-Ni junction

Vardimon, R et al., Nano Lett. 15, 3894-3898 (2015)

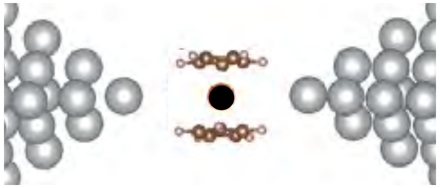
STM : Co, Fe



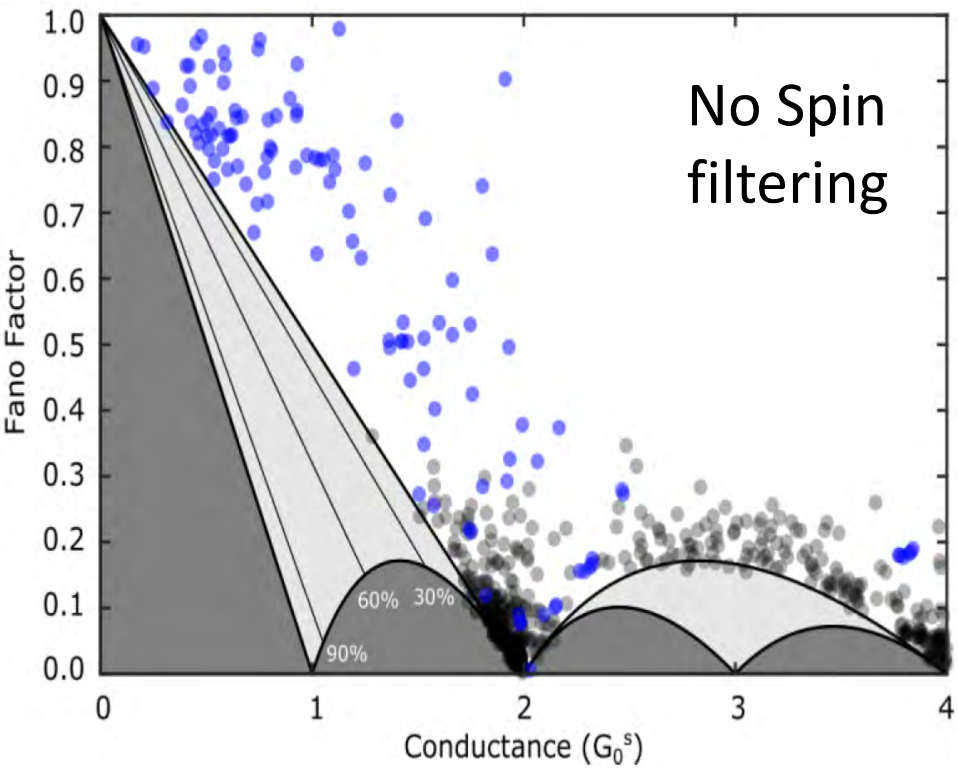


A. Burtzlaff et al., Phys. Rev. Lett. 114, 016602 (2015)

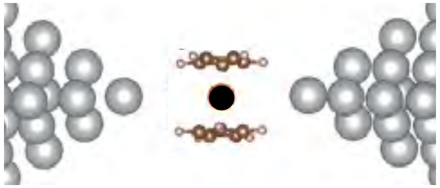
Diamagnetic electrodes and a magnetic molecule (S=3/2)



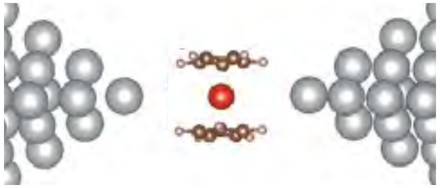
Silver-Ferrocene-Silver
(S=0)



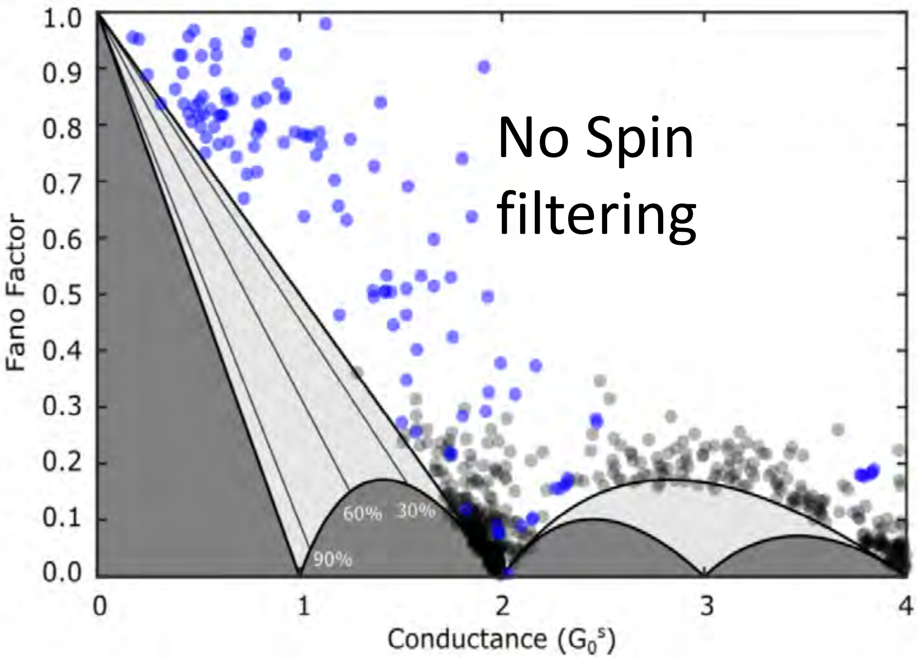
Diamagnetic electrodes and a magnetic molecule (S=3/2)

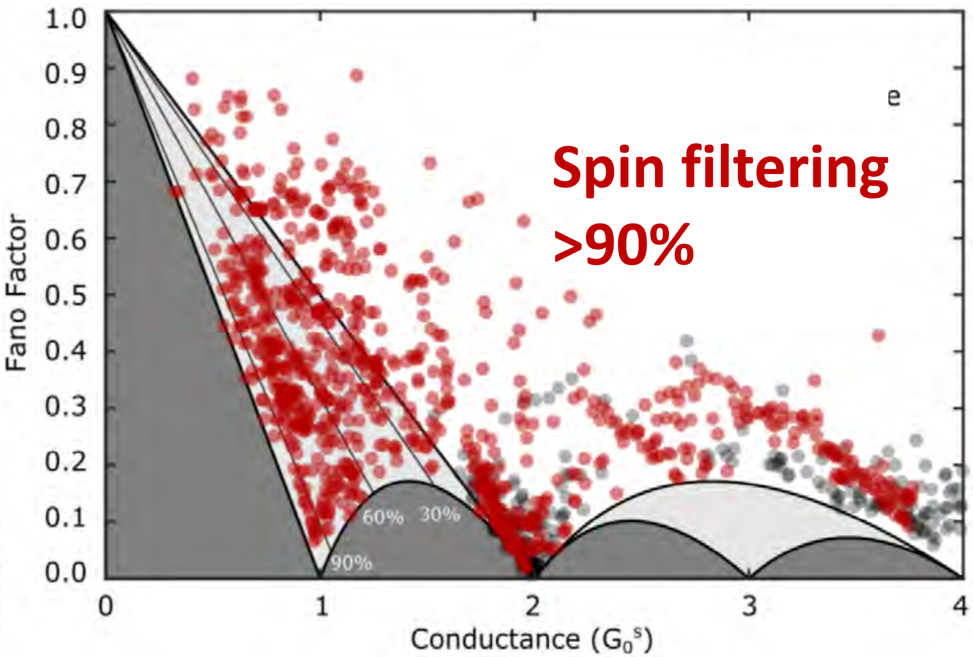


Silver-Ferrocene-Silver (S=0)

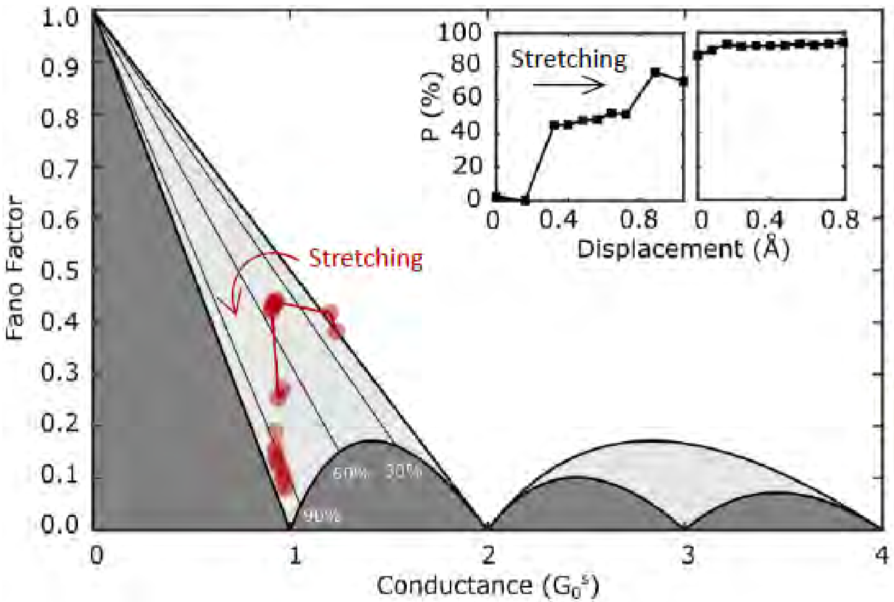


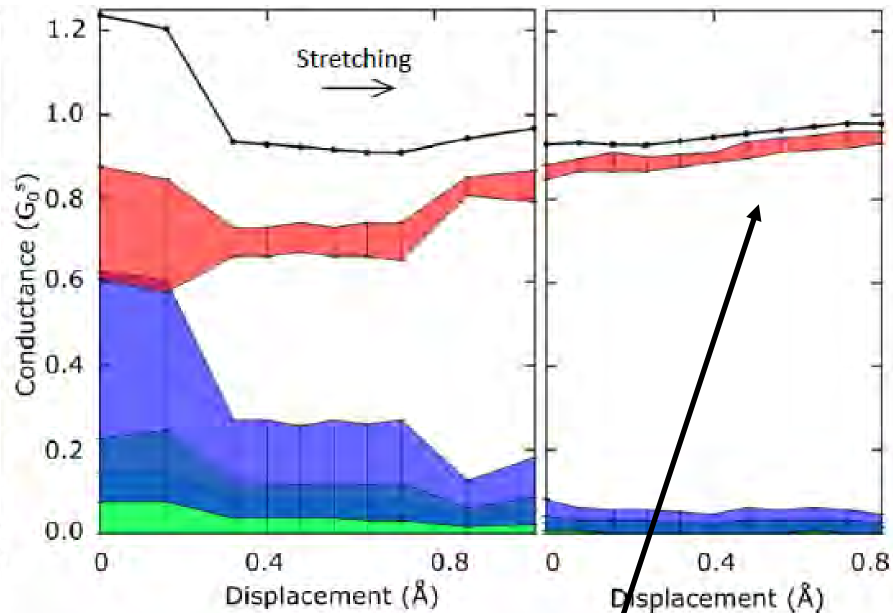
Silver-Vanadocene-Silver (S=3/2)





Stretching dependence of spin polarization Ag-vanadocene-Ag molecular junctions



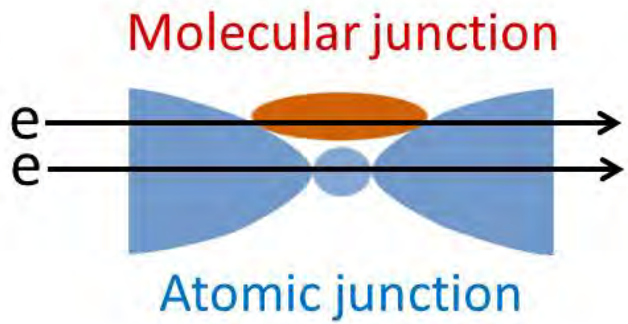


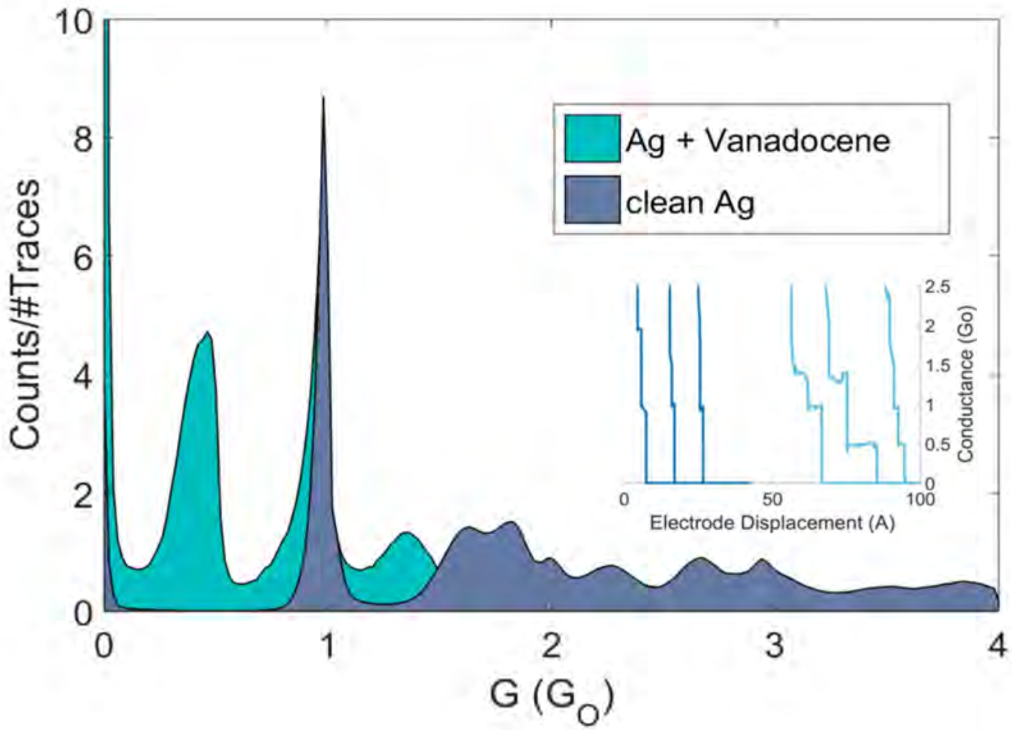
- >90% spin polarized current

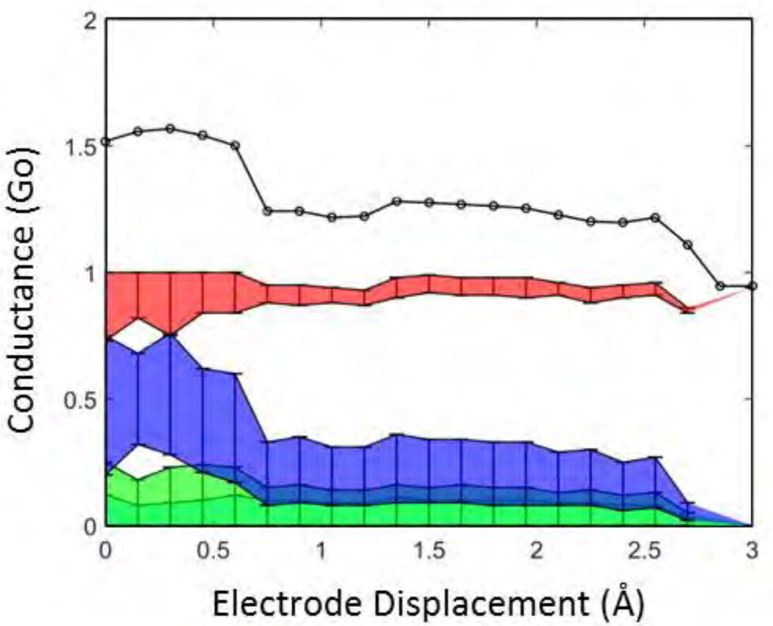
- One dominant spin conduction channel
- Spin transmission probability close to 1

~ballistic spin conductance

Early stage of Formation of molecular junction



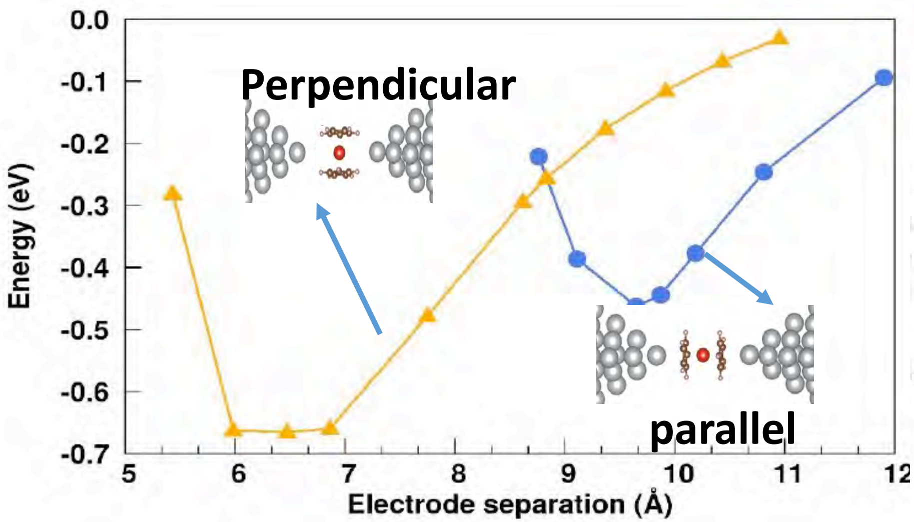


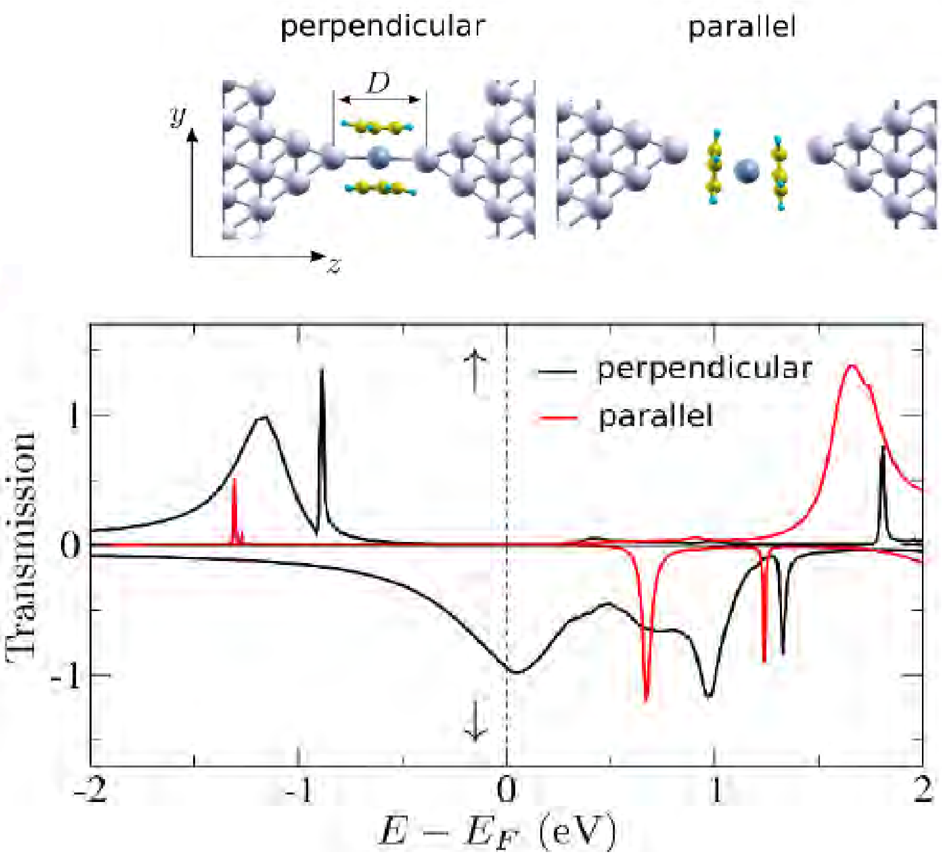


A.N. Pal et al., BJ Nano 9 (1), 1471-1477 (2018)

Orientation of molecule inside the junction

Silver-Vanadocene-Silver



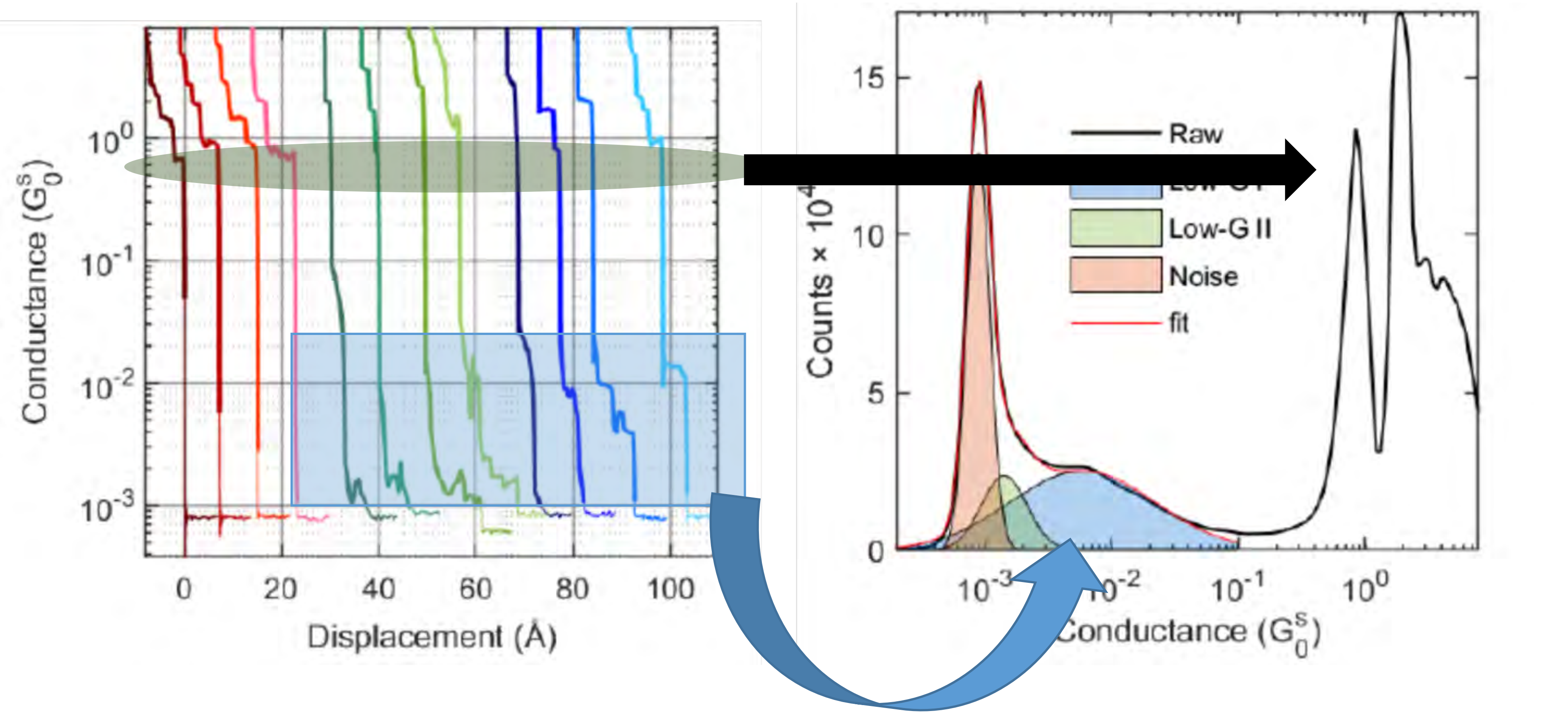


Calculations:

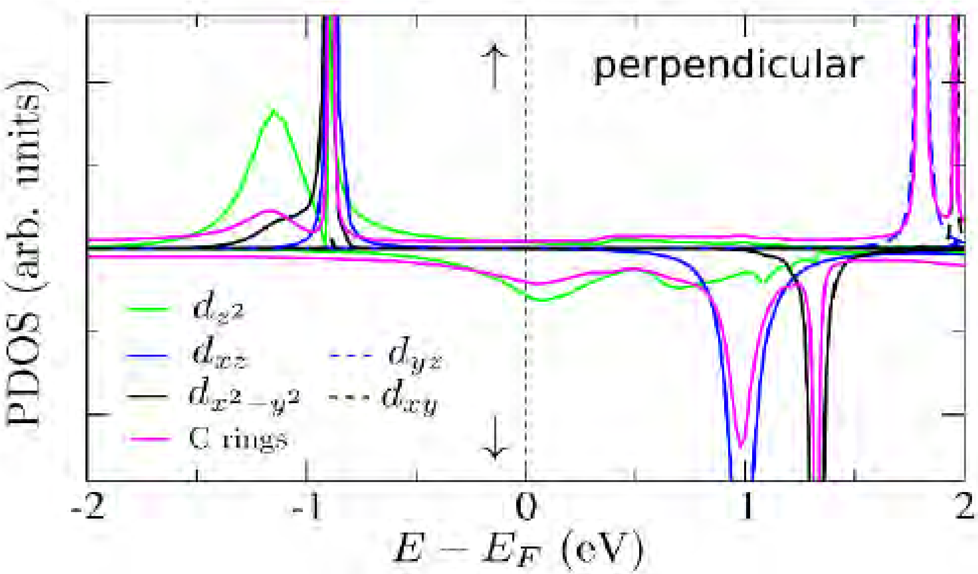
A. Smogunov and D. Li, Université Paris-Saclay, France

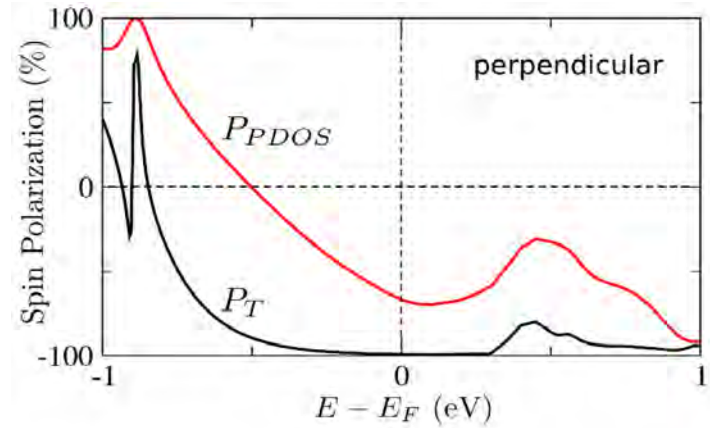
L. Kronik and S. Sarkar, Weizmann Institute

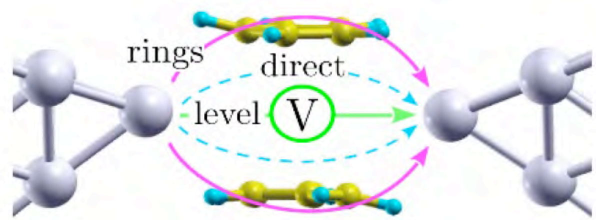
Low and High Conducting states



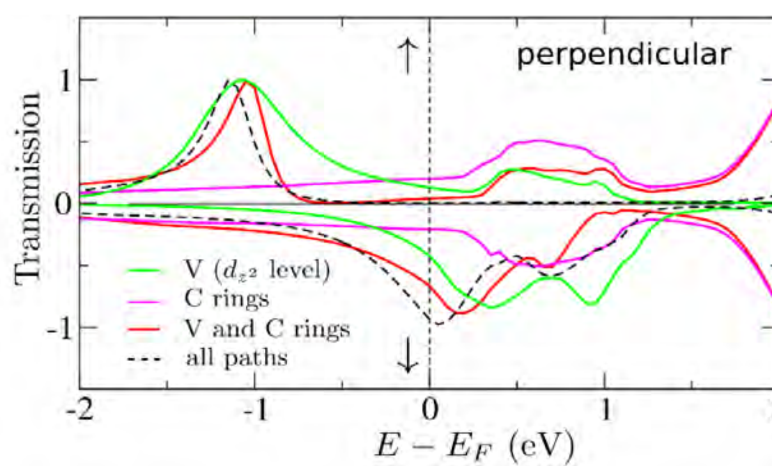
Origin of close to 100% Spin filtering: Spin Polarized DFT







Quantum Interference through Spin Polarized Channels



Calculations:

A. Smogunov and D. Li, Université Paris-Saclay, France

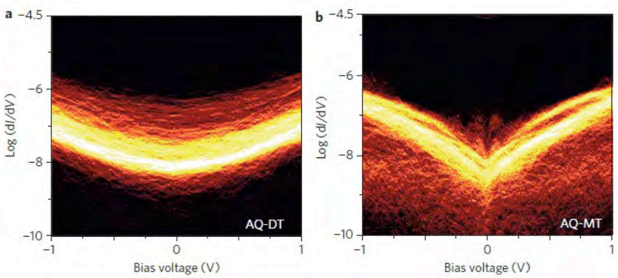
L. Kronik and S. Sarkar, Weizmann Institute

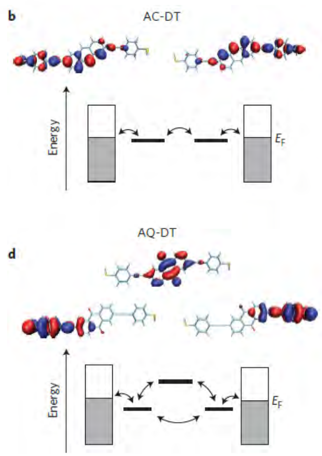
Quantum Interference: Charge transport

nature nanotechnology | LETTERS
PUBLISHED ONLINE: 25 MARCH 2012 | DOI: 10.1038/NNANO.2012.37

Observation of quantum interference in molecular charge transport

Constant M. Guédon[1†], Hennie Valkenier[2†], Troels Markussen[3], Kristian S. Thygesen[3], Jan C. Hummelen[2] and Sense Jan van der Molen[1]*



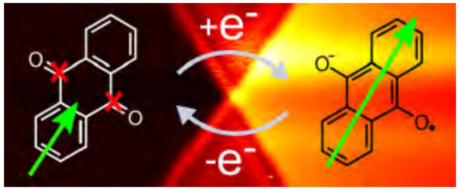


Destructive quantum interference

NANO LETTERS | Letter
pubs.acs.org/NanoLett

Electric-Field Control of Interfering Transport Pathways in a Single-Molecule Anthraquinone Transistor

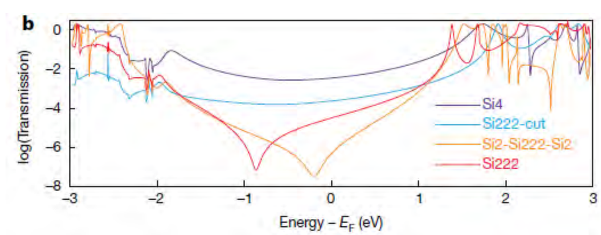
Max Koole,† Jos M. Thijssen,† Hennie Valkenier,‡ Jan C. Hummelen,‡ and Herre S. J. van der Zant*,†
†Kavli Institute of Nanoscience, Delft University of Technology, Lorentzweg 1, 2628 CJ, Delft, The Netherlands
‡Stratingh Institute for Chemistry and Zernike Institute for Advanced Materials, University of Groningen, Nijenborgh 4, 9747 AG, Groningen, The Netherlands



LETTER
https://doi.org/10.1038/s41586-018-0197-9

Comprehensive suppression of single-molecule conductance using destructive σ-interference

Marc H. Garner[1,9], Haixing Li[2,6,9], Yan Chen[3,9], Timothy A. Su[4,7], Zhichun Shangguan[3,8], Daniel W. Paley[4,5], Taifeng Liu[3], Fay Ng[4], Hexing Li[3], Shengxiong Xiao[3]*, Colin Nuckolls[3,4]*, Latha Venkataraman[2,4]* & Gemma C. Solomon[1]*

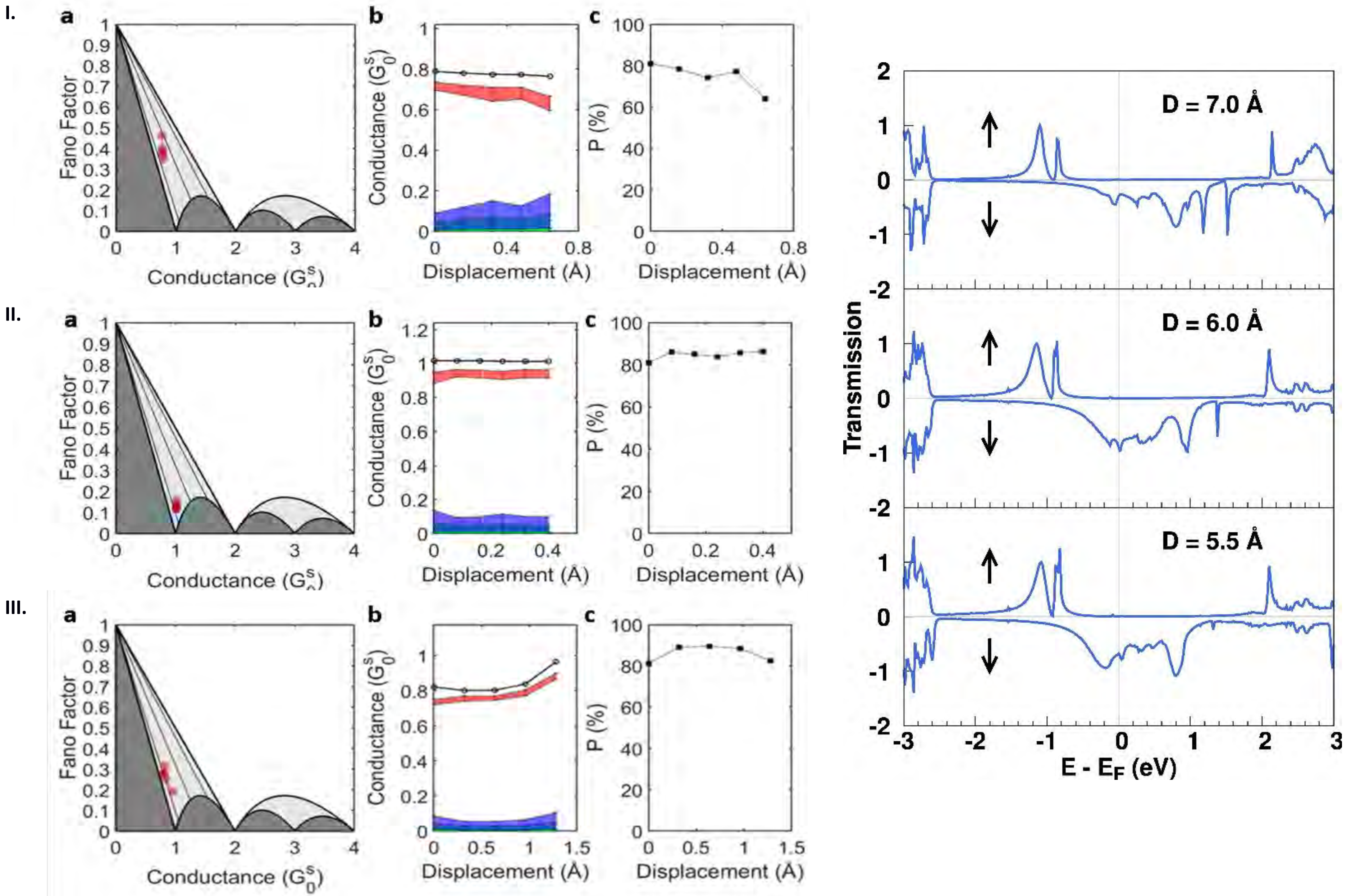


LETTERS | nature nanotechnology
https://doi.org/10.1038/s41565-018-0258-0

Mechanically controlled quantum interference in graphene break junctions

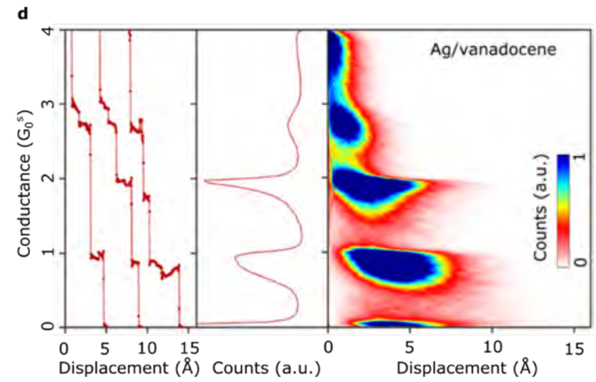
Sabina Caneva[1], Pascal Gehring[1], Víctor M. García-Suárez[2,3], Amador García-Fuente[2], Davide Stefani[1], Ignacio J. Olavarria-Contreras[1], Jaime Ferrer[2,3]*, Cees Dekker[1] and Herre S. J. van der Zant[1]*

Non monotonic stretching dependence

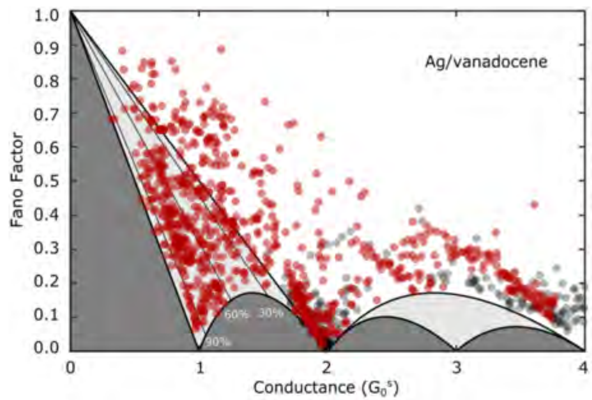


Conclusions

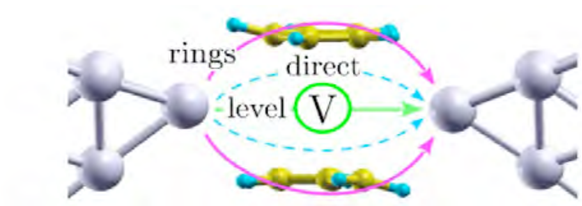
- Ag-Vanadocene-Ag junction
  Conductance ~ $1e^2/h$



- Suppression of Shot Noise
  Spin filtering ~ 100%, Ballistic Spin channel



- Spin dependent quantum interference

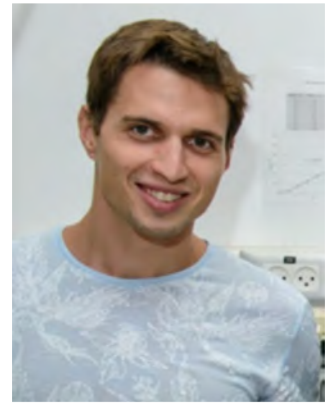


Acknowledgments

Oren Tal

Sudipto Chakraborti

Nadav Genossar



Lev Khmelnitsky

Ran Vardiman

Collaborators

Calculations:

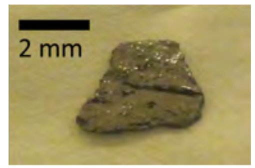
A. Smogunov and D. Li, Université Paris-Saclay, France

L. Kronik and S. Sarkar, Weizmann Institute

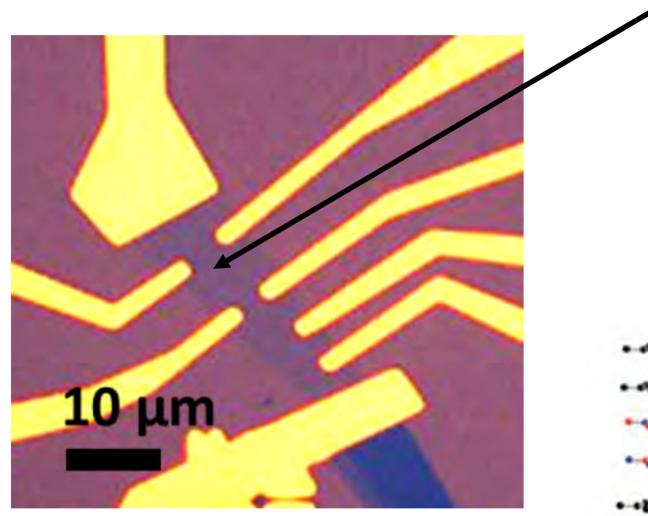
Ref. Nature Communication (Accepted for publication)

Current Research

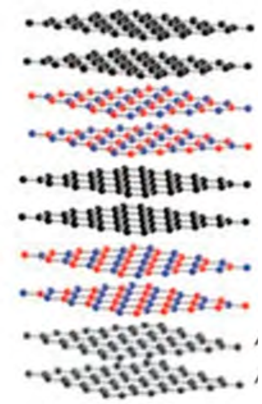
- 2D materials: Graphene, MOS_2, WSe_2, Carbon Nanotube and nanowires.
- Low temperature Physics
- Topological Insulator
- Charge and spin transport
- Molecular electronics
- Noise Measurements
- Quantum Hall effect
- Bio electronics

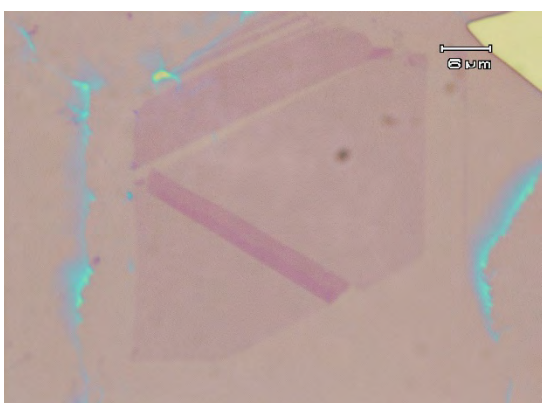


Monolayer graphene

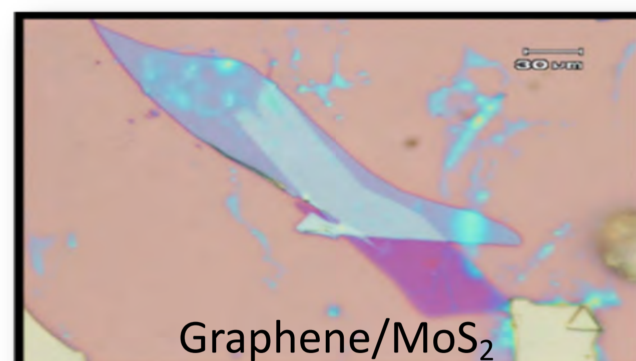


Example of a Graphene Field Effect Transistor



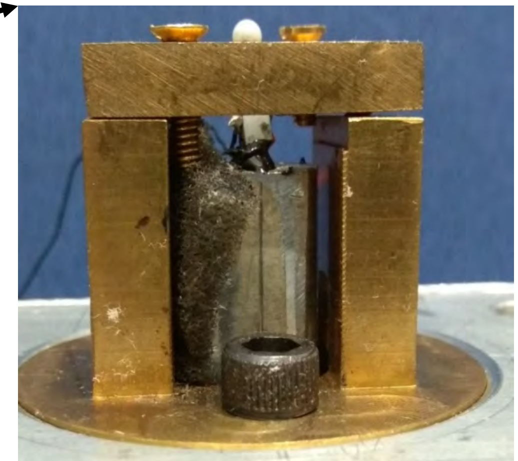


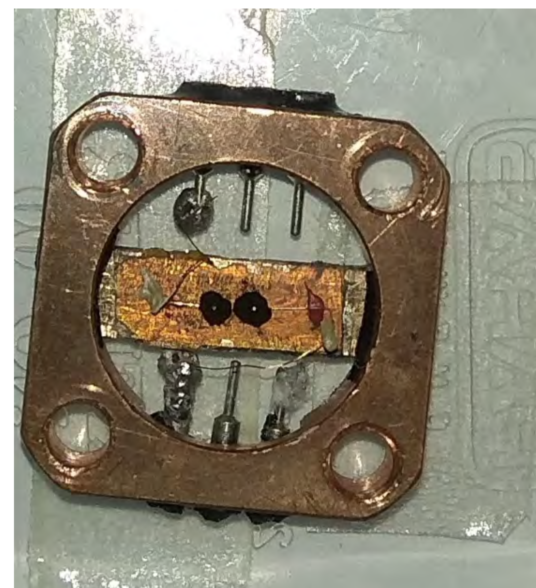
Graphene



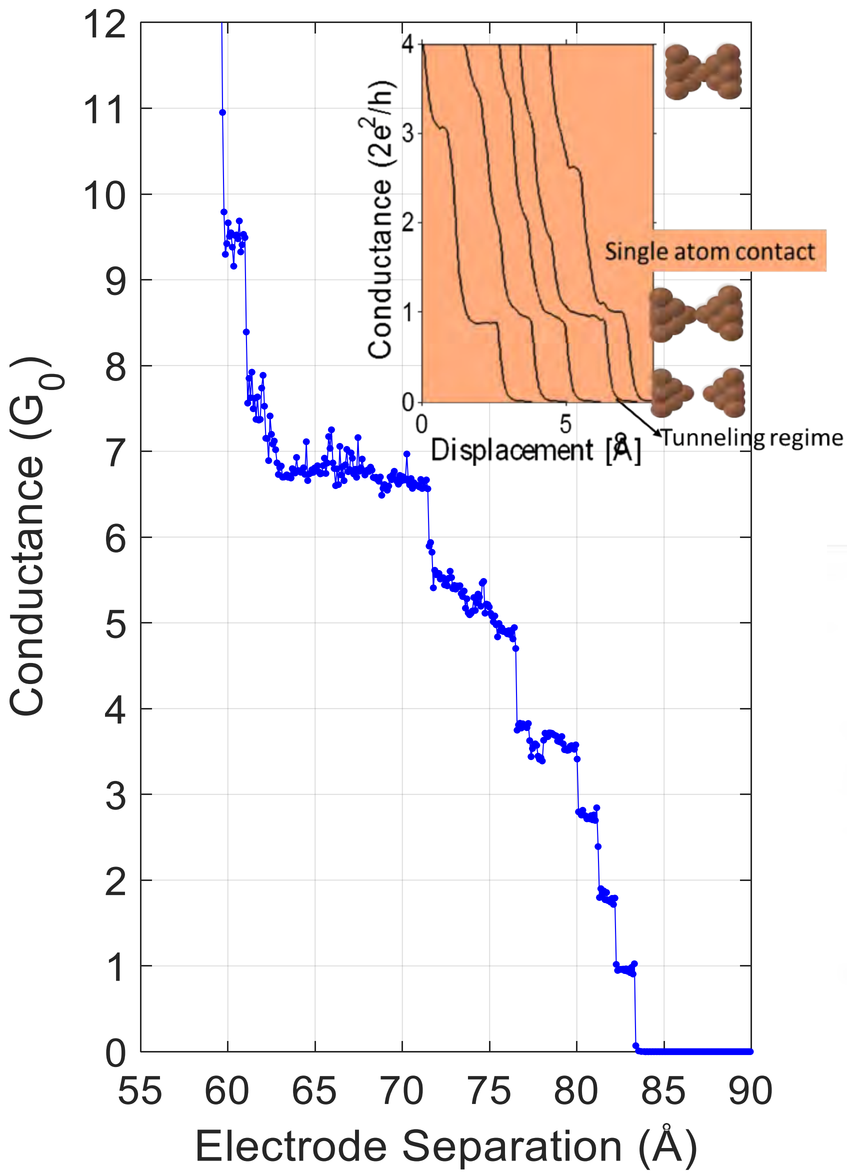
Graphene/MoS_2

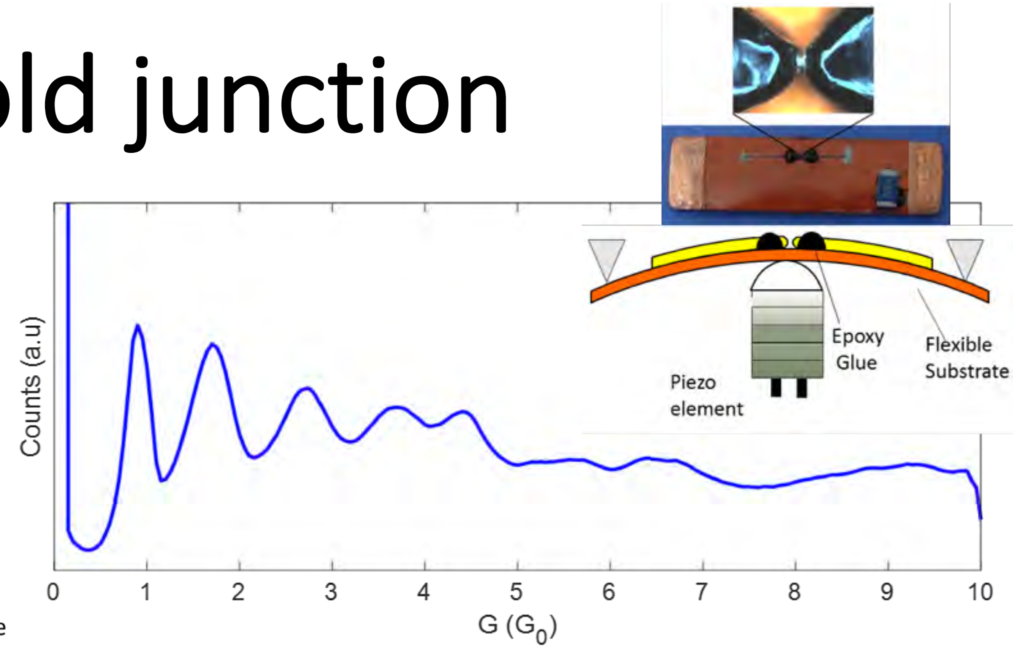
Room temperature MCBJ set up at SNBNCBS



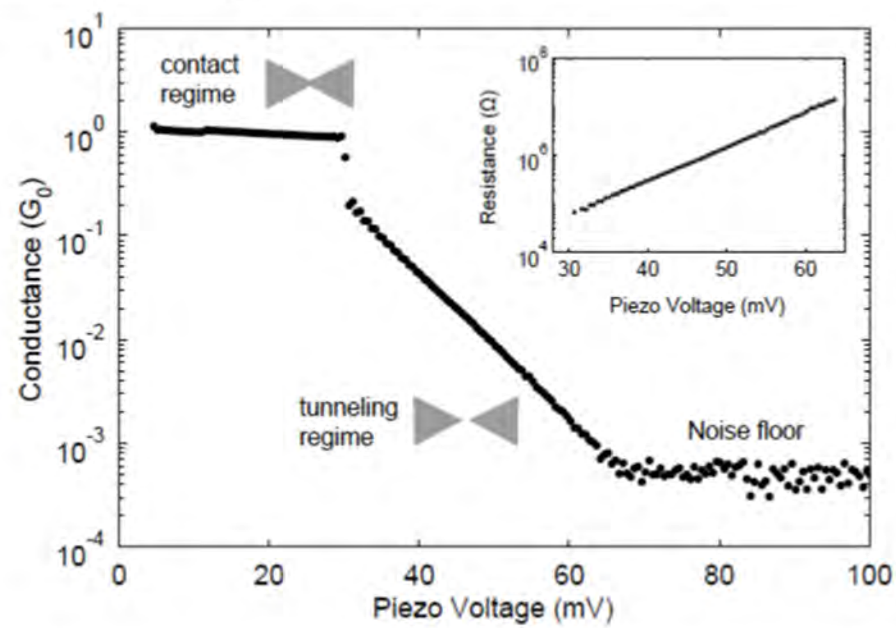


Atomic Gold junction

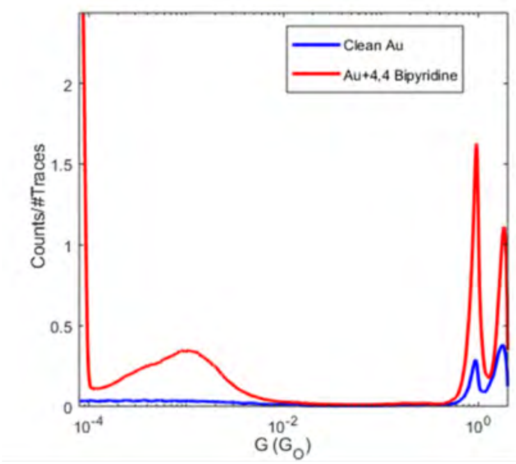


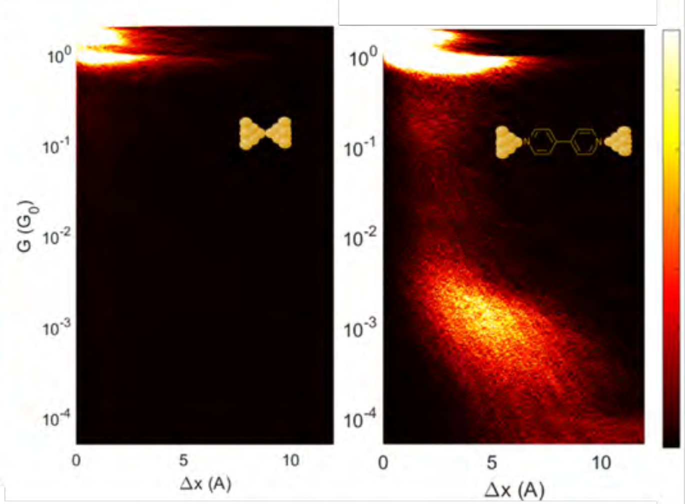


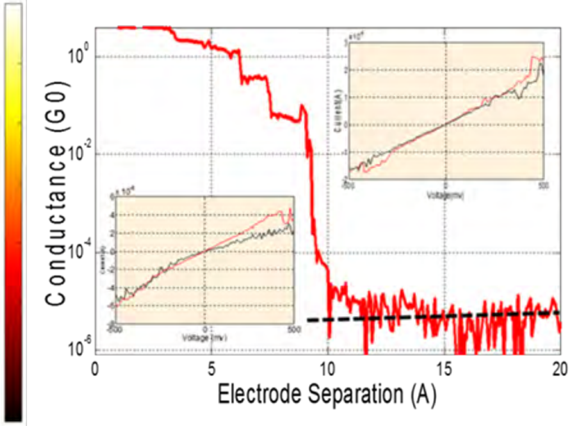
Length Calibration

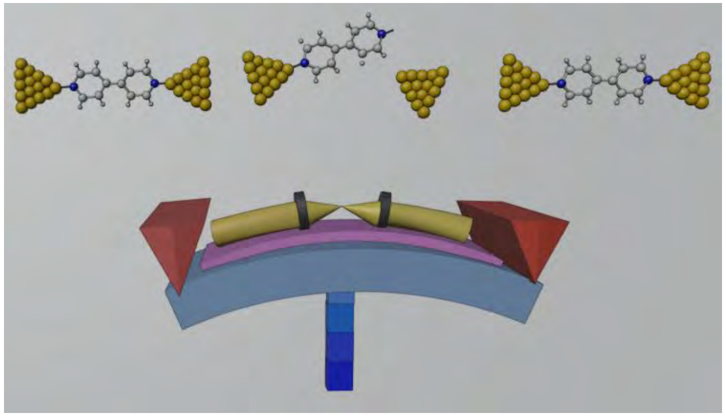


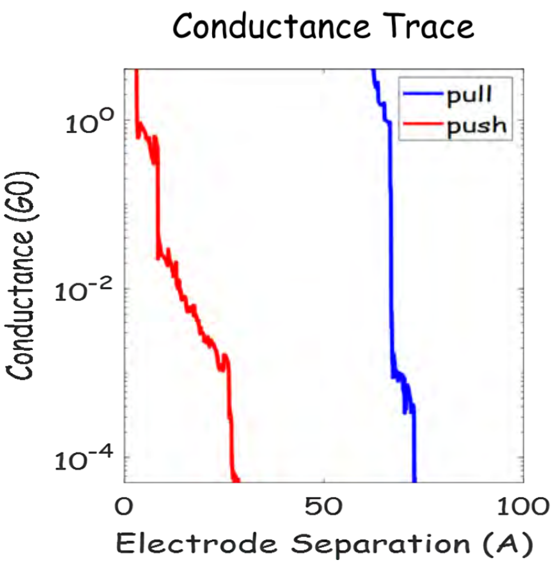
Gold-4,4 BiPyridine junction











Breaking and making process?

Biswajit Pabi & ANP (in preparation)

Group Members

Shubhadip
Moulick

Shubhrasish
Mukherjee

Hybrid 2D devices

Biswajit
Pabi

Single Molecular
transport

Rafiqul
Alam

Transport in
Topological
Materials

Riju Pal

Spintronics with
2D materials

Post Doc
Buddhadeb Pal

Superconductor-
Ferromagnet
junction

Visiting Fellow
Aditya N Roychoudhury

Vortex dynamics

Tousif
Project Student

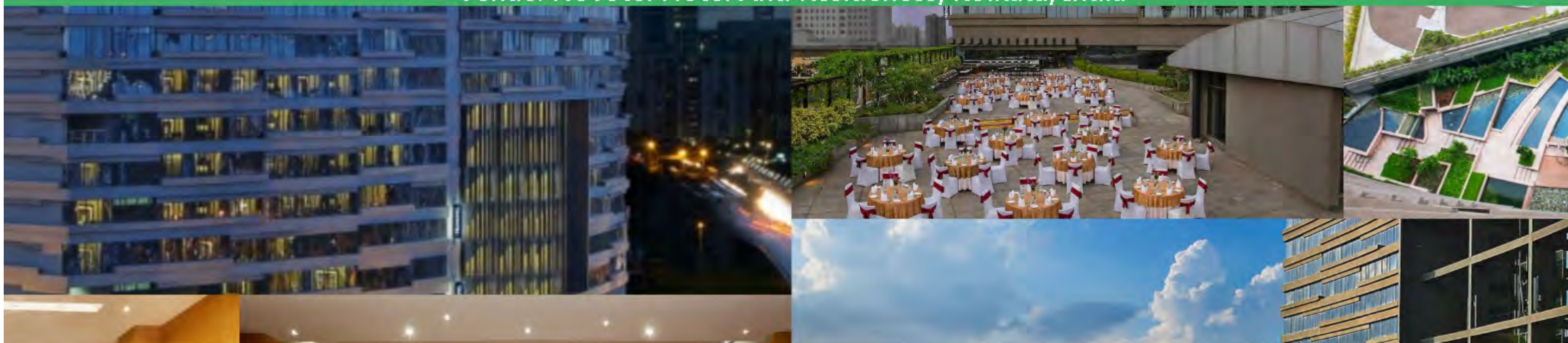
Taniya Basu
Technical assistant
Clean Room

IWPSD 2019

XXth International Workshop on Physics of Semiconductor Devices: IWPSD 2019

December 17-20, 2019

Venue: Novotel Hotel And Residences, Kolkata, India



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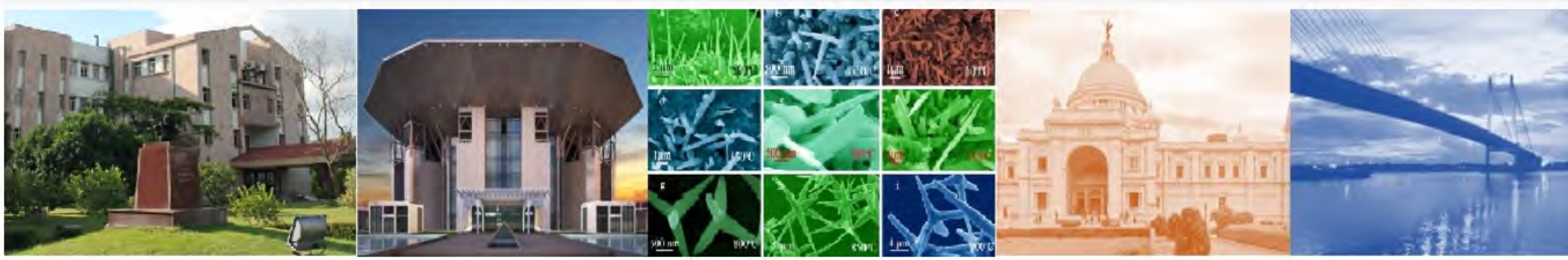

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International Conference on Nano Science and Technology

March 5-7, 2020

under the aegis of DST Nanomission, Govt. of India

Venue: Biswa Bangla Convention Centre, New Town, Kolkata