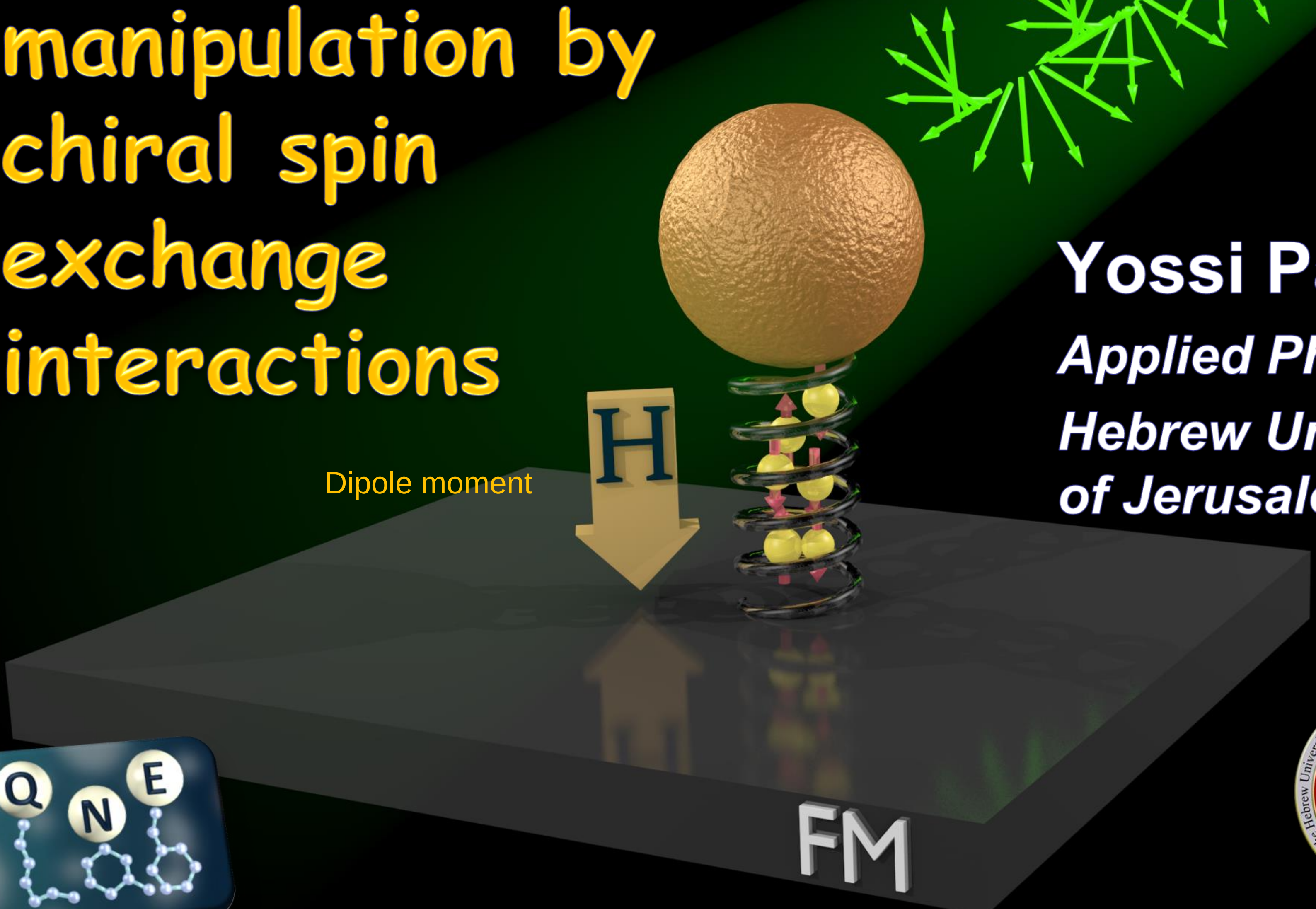
The Harvey M. Krueger Family Center for Nanoscience and Nanotechnology

Magnetic impurities manipulation by chiral spin exchange interactions



Yossi Paltiel

Applied Physics, Hebrew University of Jerusalem

Quantum Nano-Engineering Lab

THANKS

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Dr. Oren Ben Dor, Dr. Eran Katzir, Dr. Guy Koplovitch

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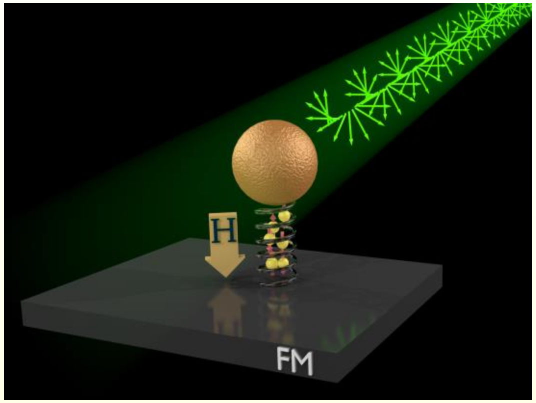
Claire gay
Universite-paris-saclay

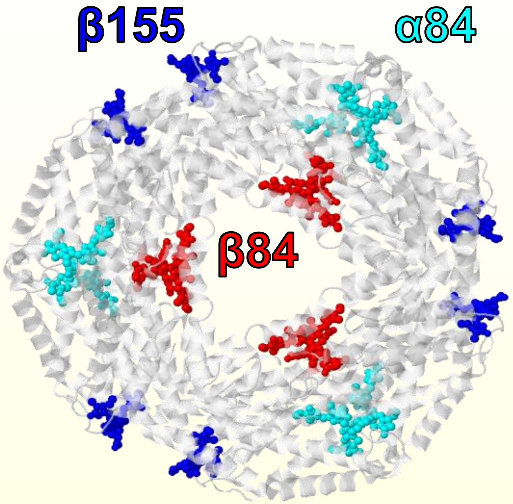
Collaborators; Ron Naaman, Dave Waldack, Oded Millo, Nir Keren

Quantum Nano Engineering Laboratory

Chiral induced spin selectivity effect

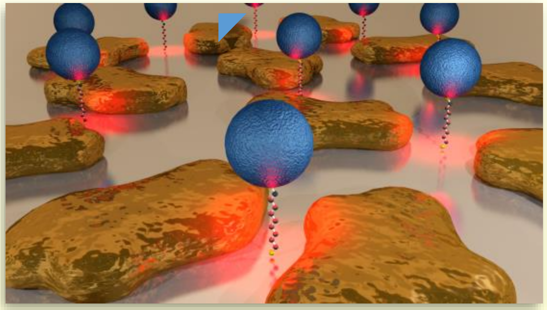


Quantum Biology



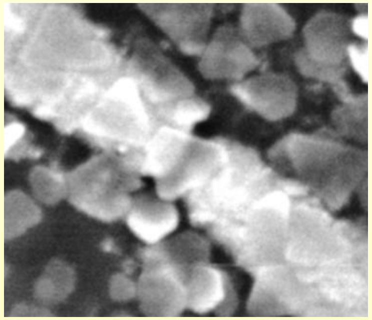
β155 is exposed to the environment

Quantum photon sensors

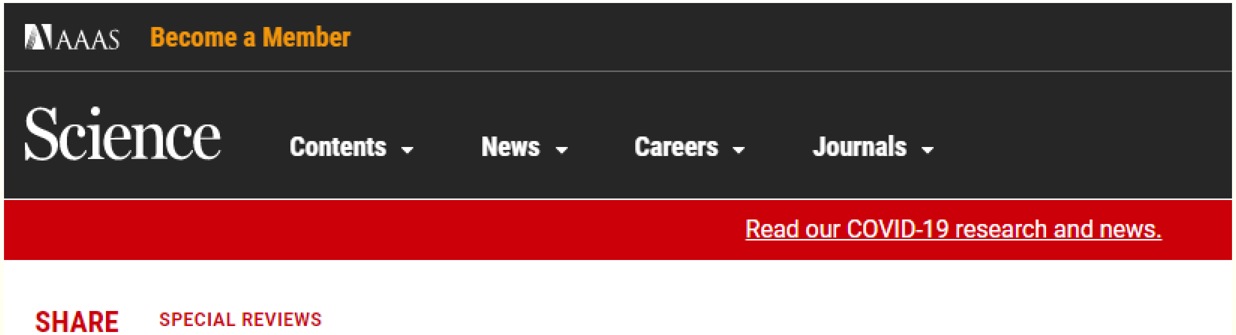


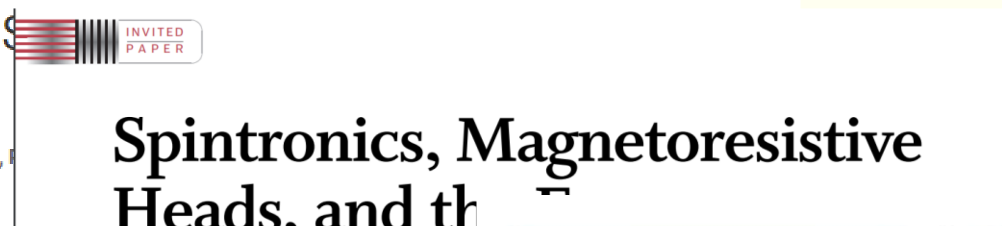
Surface superconductivity

Spintronics



Motivation





Spintronics

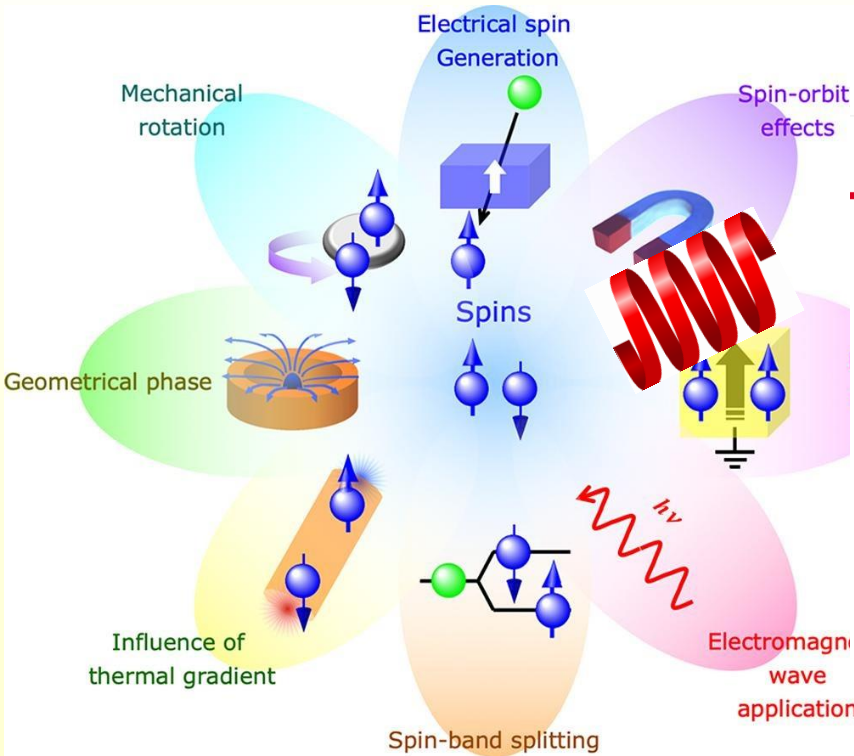
Spintronics is the area of condensed-matter physics that studies the properties of the electron spin, with a view to improve the efficiency of electronic devices and to enrich them with new functionalities.

Such a broad definition implies that the range of subjects that fall under the umbrella of spintronics is inevitably very wide. In one extreme, researchers explore the control of single localized spins, realized on single atomic sites in crystals — such as nitrogen-vacancy centres in diamond — or in semiconductor quantum dots. These are regarded as spin qubits, ideal for quantum

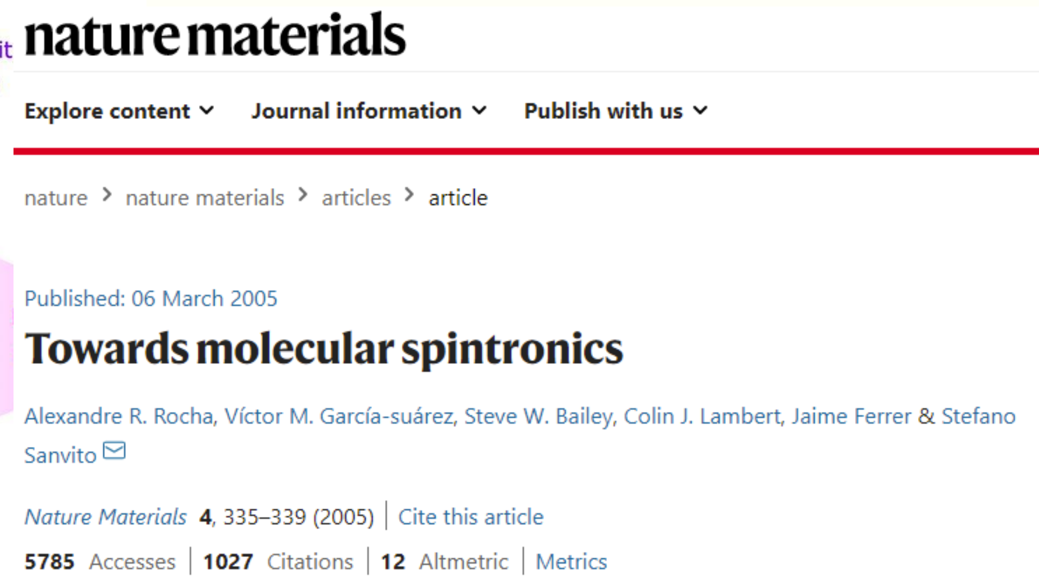
Spintronics studies the properties of the electron and spin.

In principle, for spintronics one expect less scattering and higher frequency operation.

Motivation



A. Hiroata, et al. Journal of Magnetism and Magnetic Materials 2020, 509.



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Published: 06 March 2005

Towards molecular spintronics

Alexandre R. Rocha, Víctor M. García-suárez, Steve W. Bailey, Colin J. Lambert, Jaime Ferrer & Stefano Sanvito

Nature Materials **4**, 335–339 (2005) | Cite this article

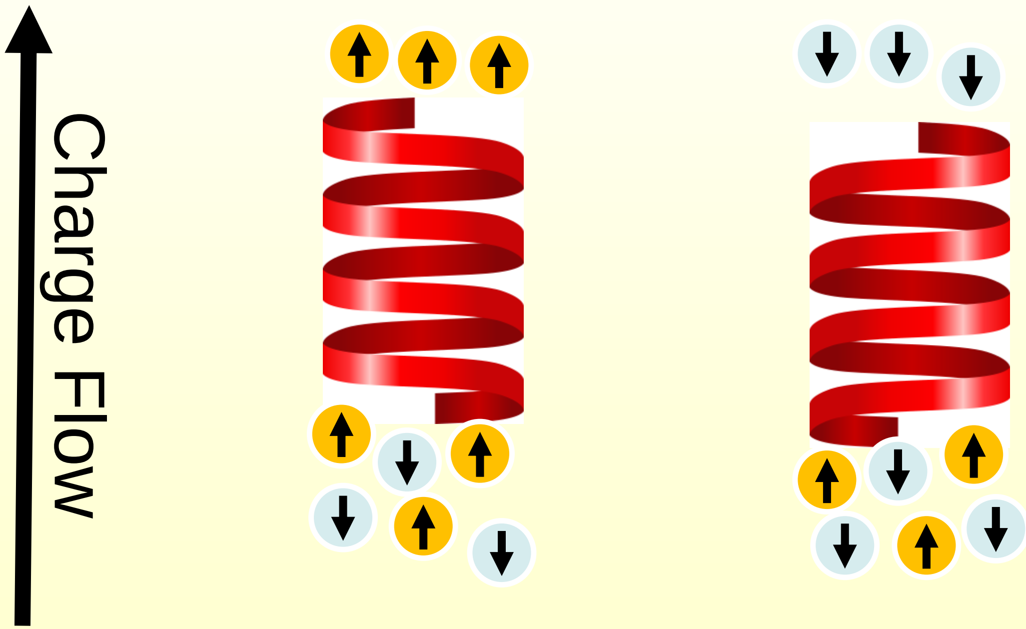
5785 Accesses | **1027** Citations | **12** Altmetric | Metrics

- Easily reproducible
- Inexpensive
- Symmetry breaking in the nano scale

The CISS Effect

What about the electron spin?

CISS – **C**hiral **I**nduced **S**pin **S**electivity



$$\bar{B}_{eff} = \frac{\bar{E} \times \bar{P}}{mc^2}$$

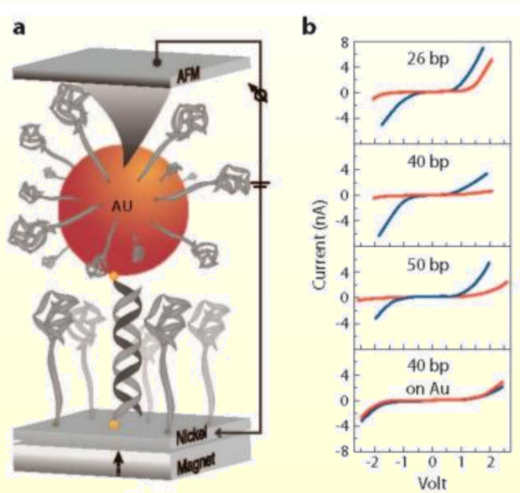
$$H_{SO} = \mu_B \left(\frac{\bar{E} \times \bar{P}}{mc^2} \right) \cdot \bar{\sigma}$$

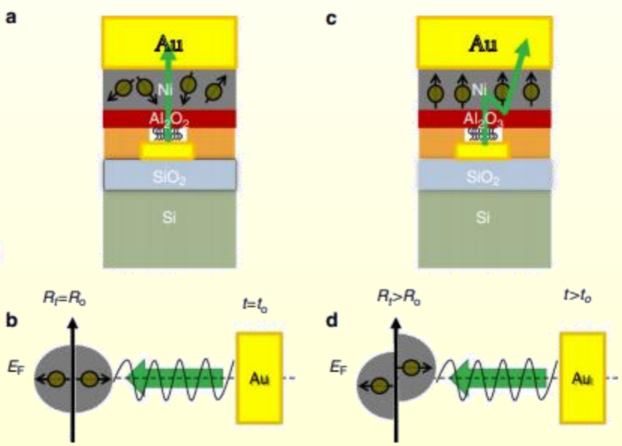
Chiral molecules as spin filters.

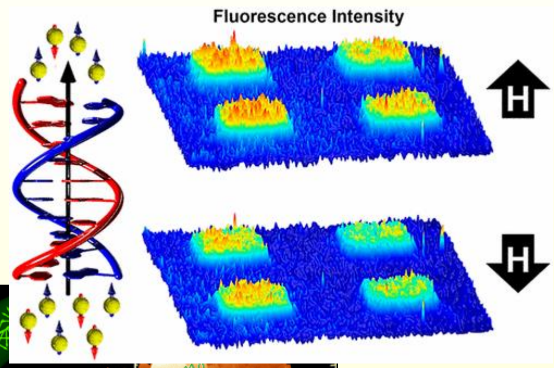
The CISS Effect

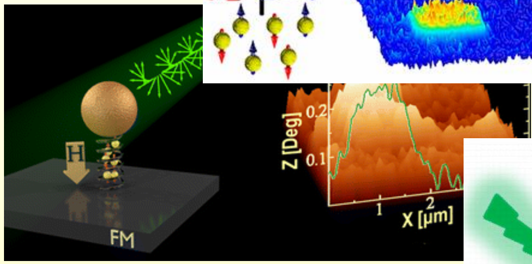
What about the electron spin?

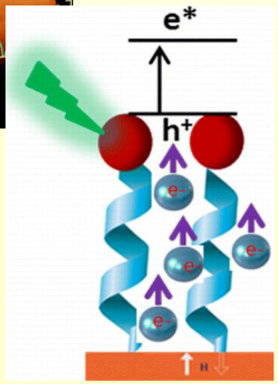
CISS – Chiral Induced Spin Selectivity





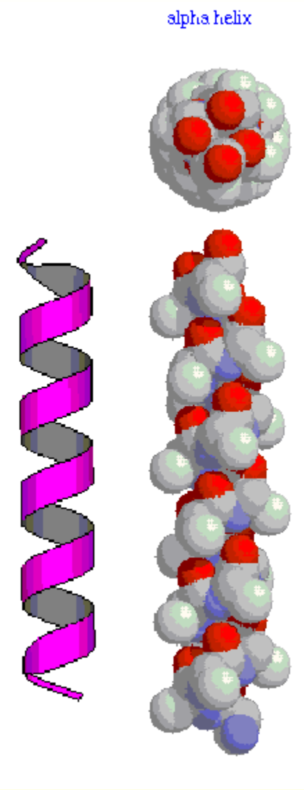


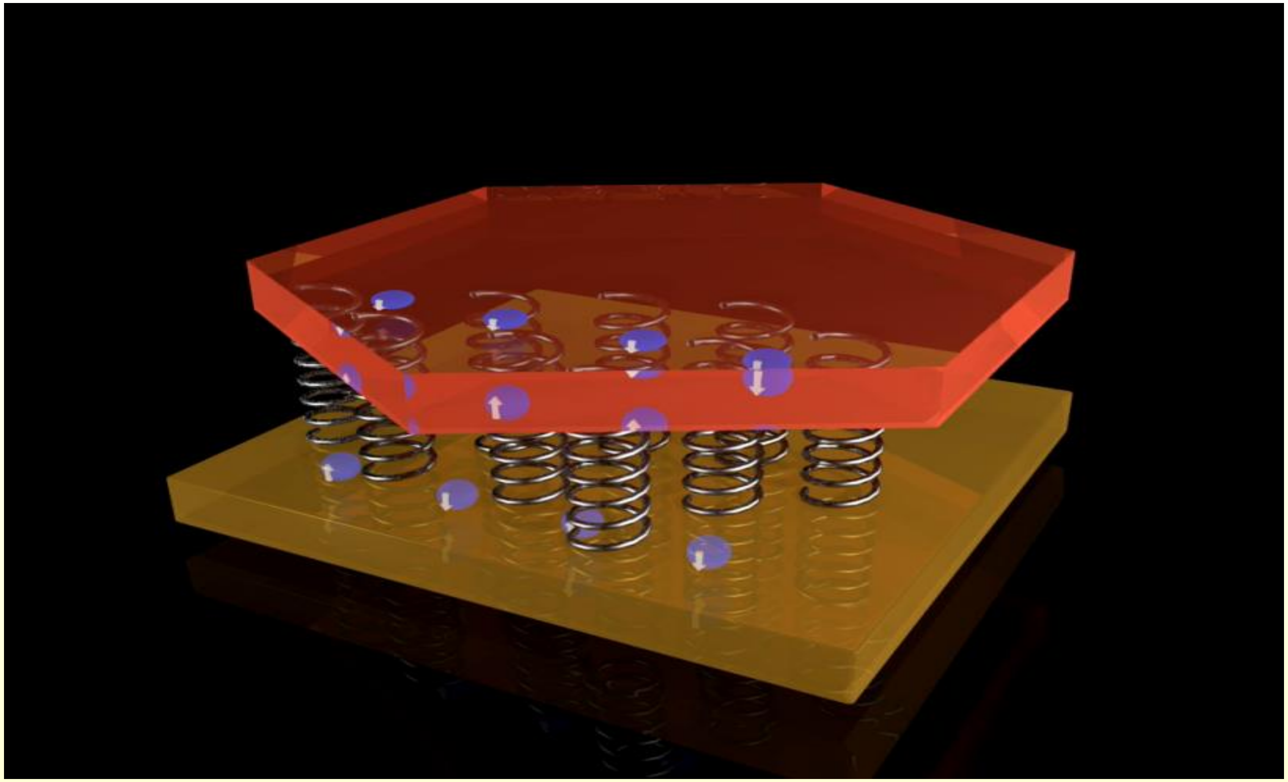




Z. Xie, et al., Nano Lett., 2011, 11
O. Ben Dor, et al. Nat. Commun. 2013, 4
O. Ben Dor, et al. Nano Lett. 2014, 14; P. C. Mondal, et al. Nano Lett. 2016, 16; J. M. Abendoth, et al. ACS Nano 2017, 11

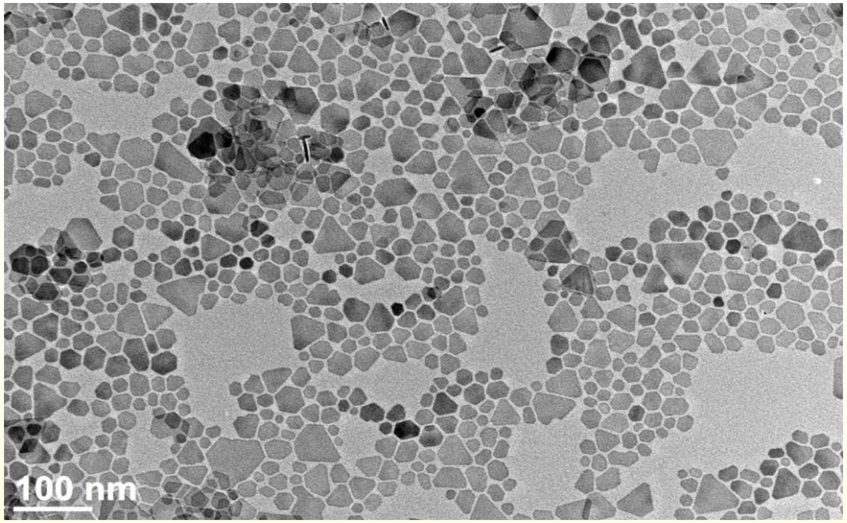
Electrical CISS Nano Memory

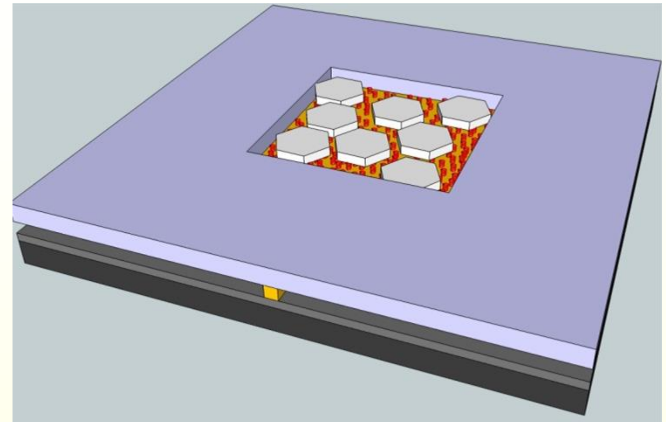




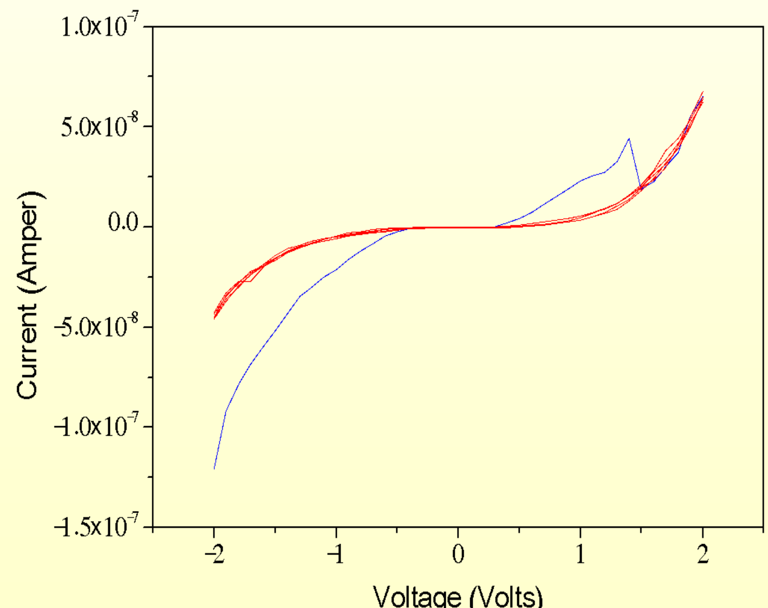
L or D PAL (polyalanine), thiolated α-helix -
CAAAAKAAAAKAAAAKAAAAKAAAAKAAAAKAAAAK-SH
C, A, and K represent cysteine, alanine, and lysine

Vertical Memristor Device

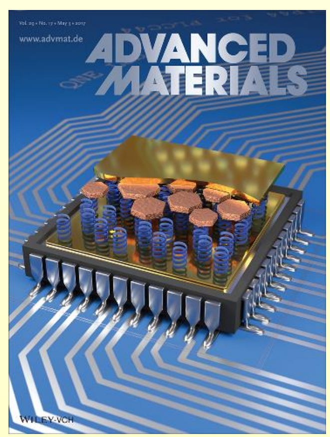




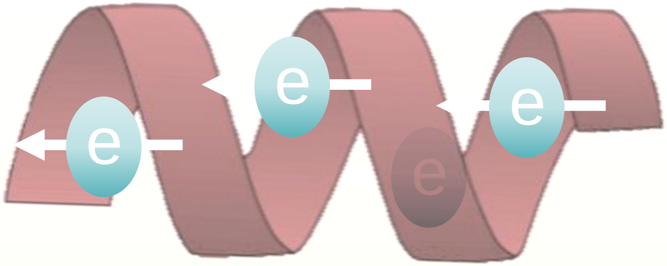
- Bottom electrode
- Adsorb AHPA-L or AHPA-D and multiple FMNPs
- Al_2O_3 tunnel barrier
- Top electrode



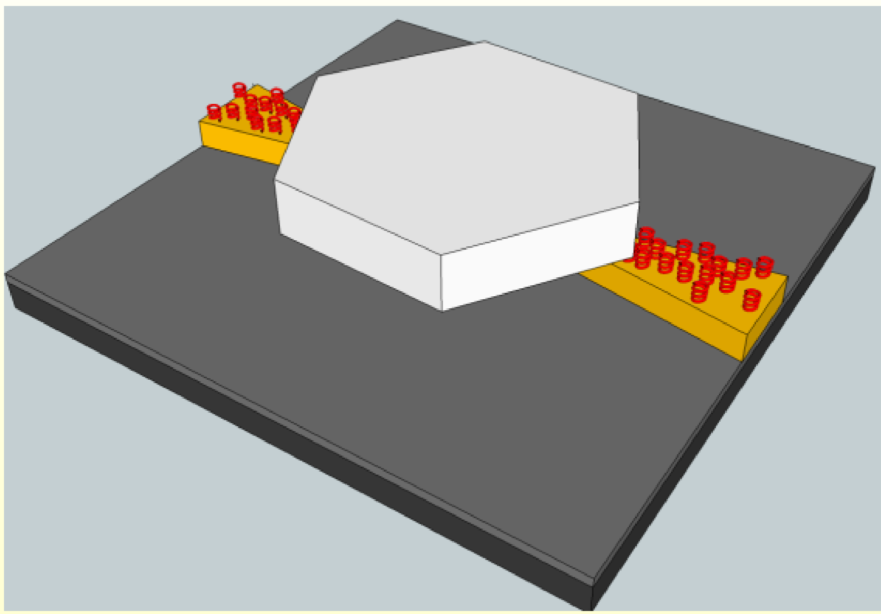
AHPA chiral molecules-
[H]-CAAAAKAAAAKAAAAKAAAAKAAAAK AAAAKAAAAK-[OH]



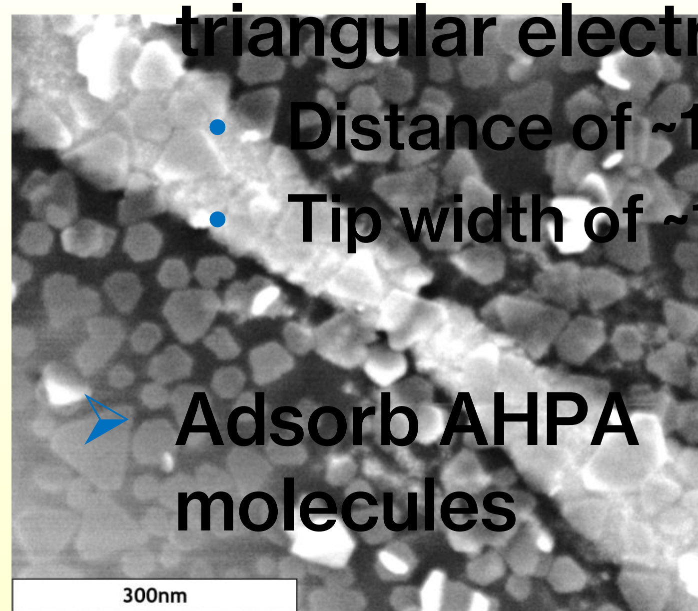
Single FMNP device

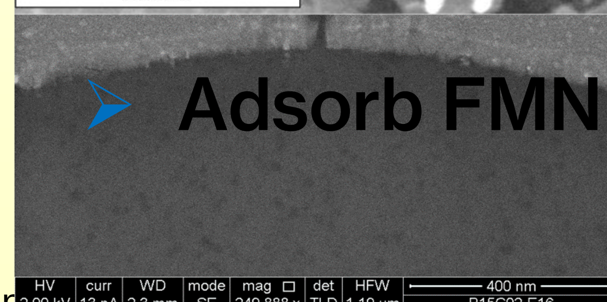


- Fabricating metal triangular electrodes
  - Distance of ~10nm
  - Tip width of ~10nm
- Adsorb AHPA molecules
- Adsorb FMNPs

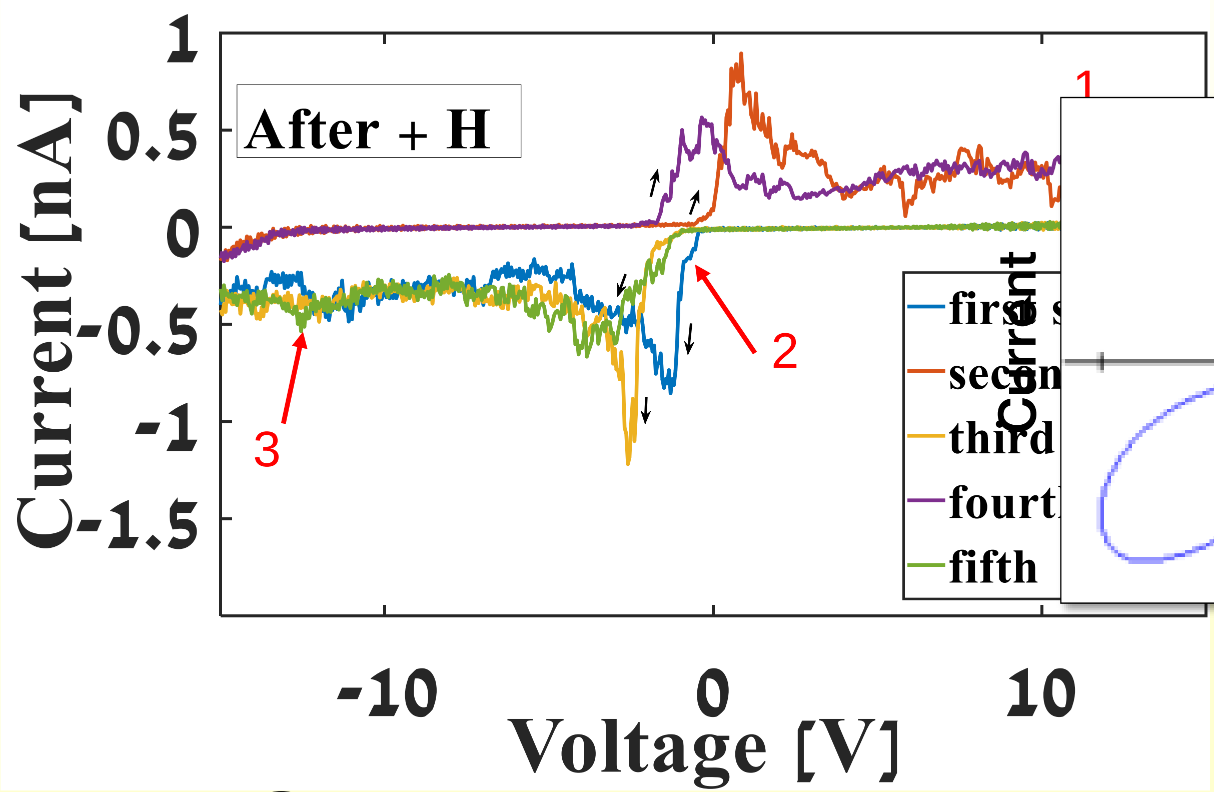


Single nanoparticle magnetic spin memristor
H. Al Bustami, G. Koplovitz, D. Primc, S.Yochelis, E. Capua, D. Porath, R. Naaman, and Y. Paltiel
Small 1801249 (2018).

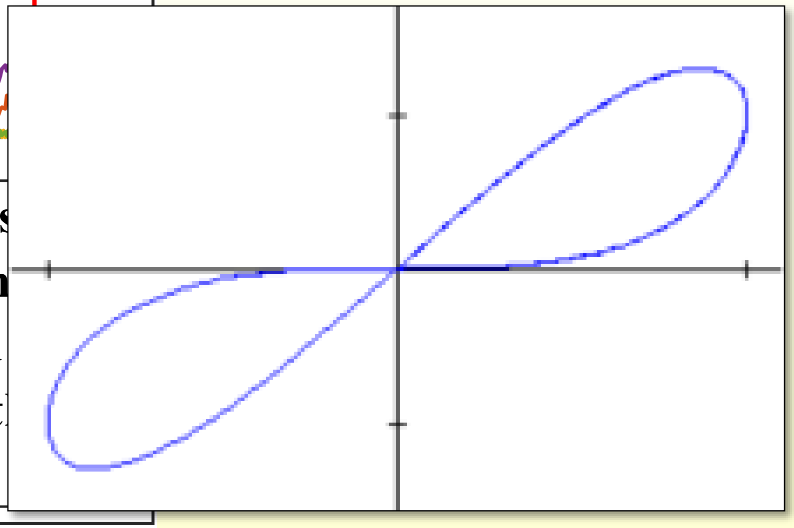




Single FMNP device
Results – 2 states logic device

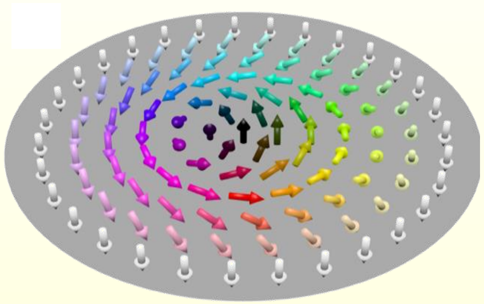


Memristor IV curve



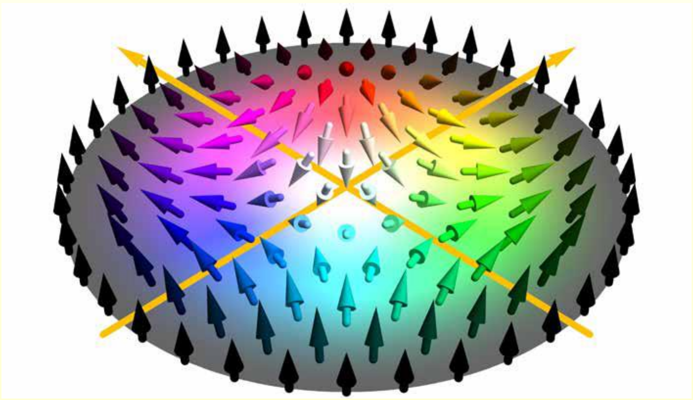
Magnetic impurities

- Skyrmions chiral impurities….



Sketch of chiral "Bloch skyrmion"
Scientific Reports **10**, 8657 (2020) .
Nature communication **11**, 1115 (2020) .

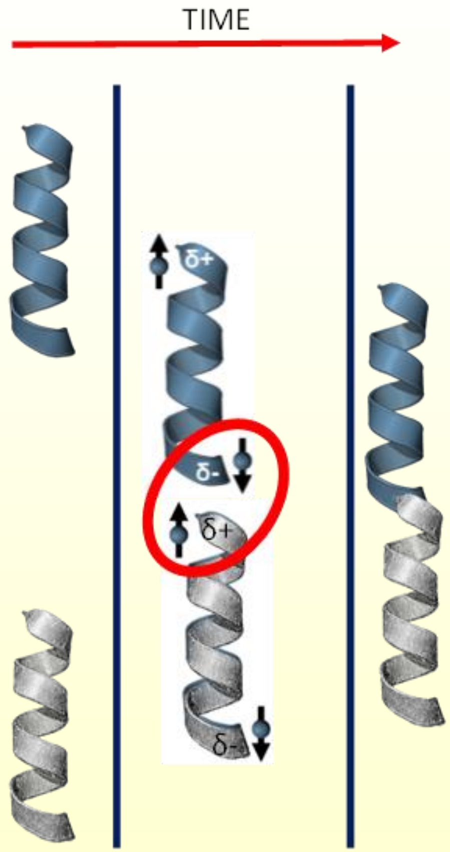
Hybrid chiral domain walls and skyrmions in magnetic multilayers
William Legrand , Jean-Yves Chauleau*, Davide Maccariello , Nicolas Reyren, Sophie Collin, Karim Bouzehouane, Nicolas Jaouen , Vincent Cros, Albert Fert

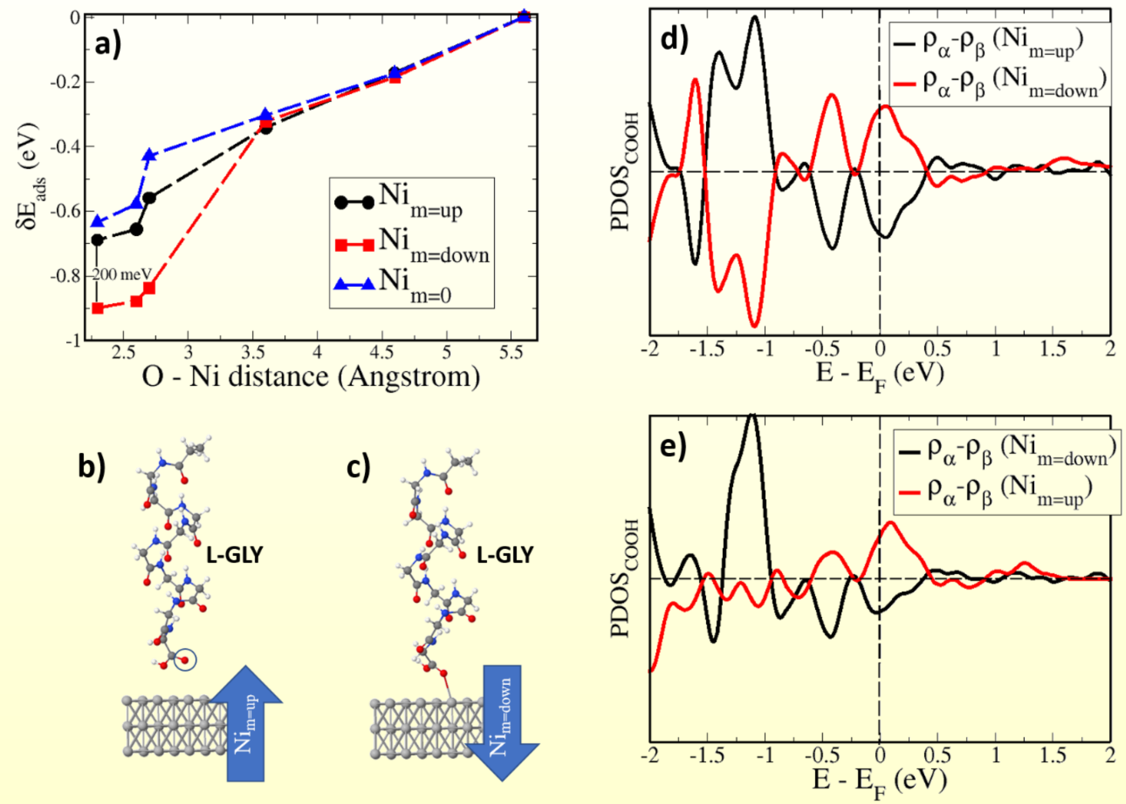


Chiral spintronics S … P. Parkin; *Nature Reviews Physics* , 3 …

Can the CISS be utilized
To control, and manipulate magnetic impurities?

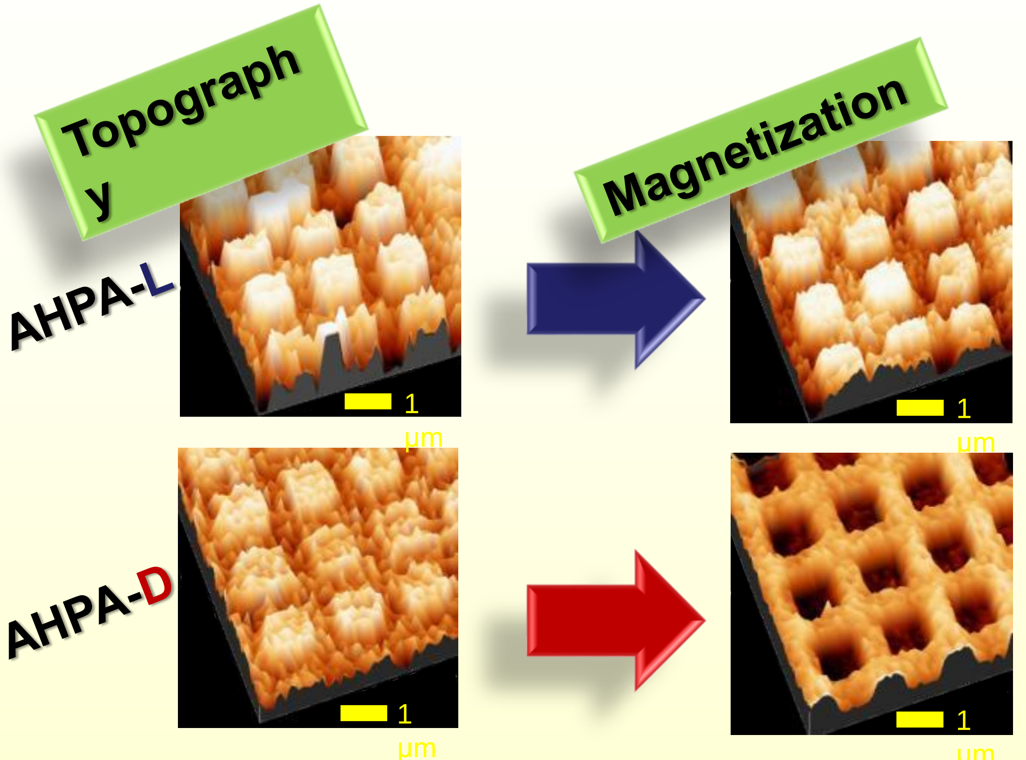
Exchange Interactions

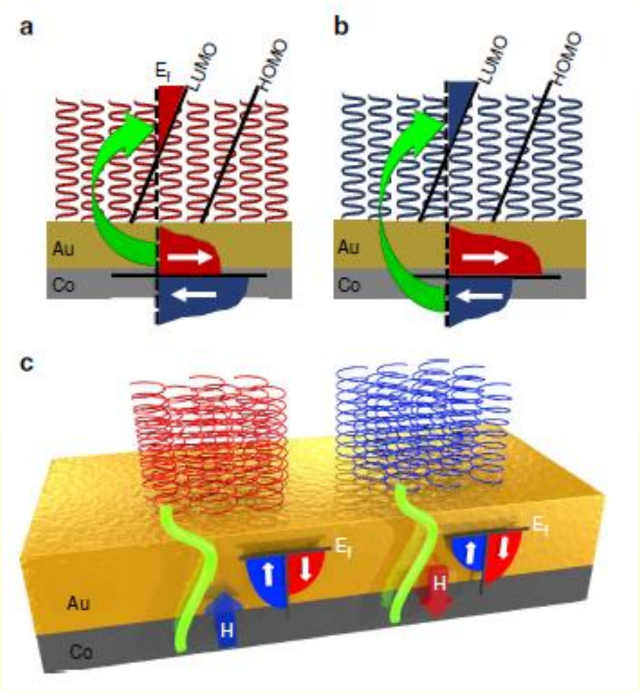




The Role of Exchange Interactions in the Magnetic Response and Inter-Molecular Recognition of Chiral Molecules, Nano Letters, **10**, 7077–7086 (2020).

Selective adsorption -> Selective magnetization



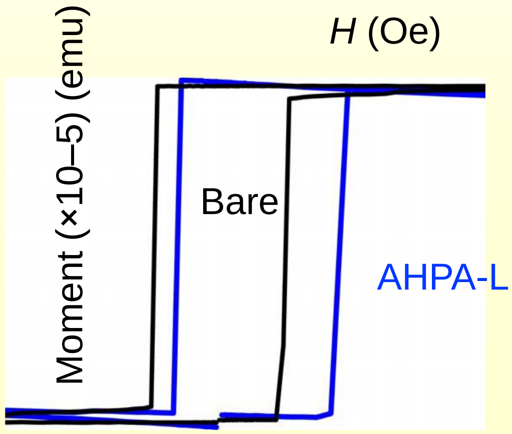


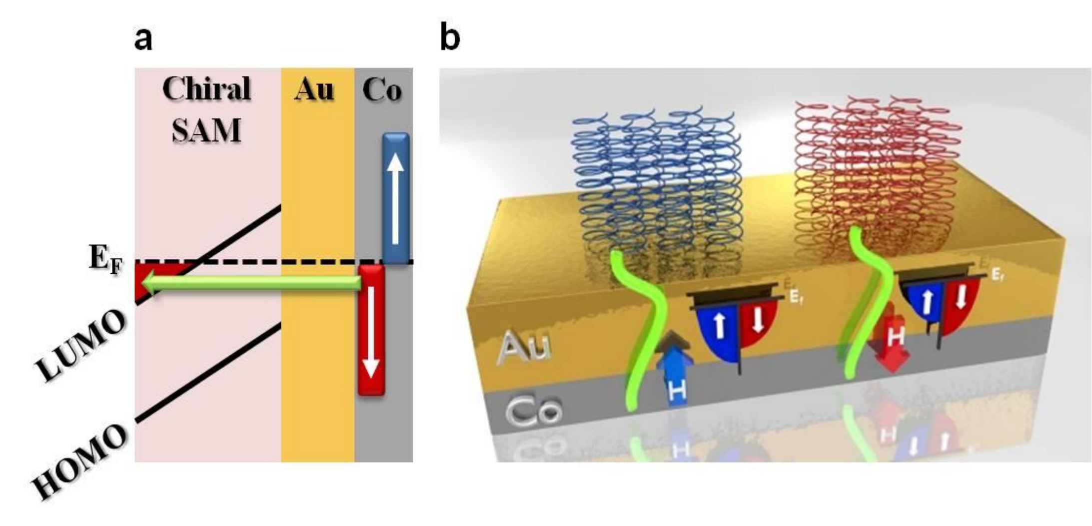
Selective adsorption of α helix polyalanine
results in selective magnetization of a ferromagnet

O. Ben Dor, et al. Nat. Commun. 2017, 8.

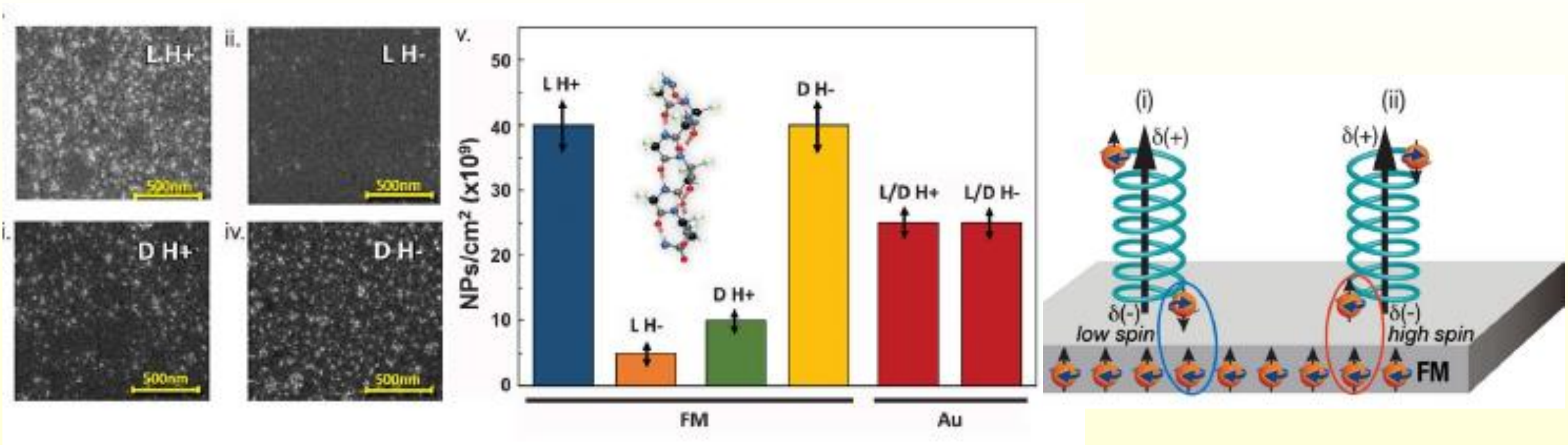
Magnetization with no current

- The current density required for the spin-transfer torque (STT) is of the order of 10^6 A/cm^2
- STT – current density equals10^{25} electrons/ s cm^2
- Adsorption of molecules 10^{13} molecules/cm^2
- Here if 1 electron is transfer per molecule10^{13} molecules/cm^2





Magnetize substrate enantio-selectivity



Magnetization of a ferromagnet

results in selective adsorption of α helix polyalanine

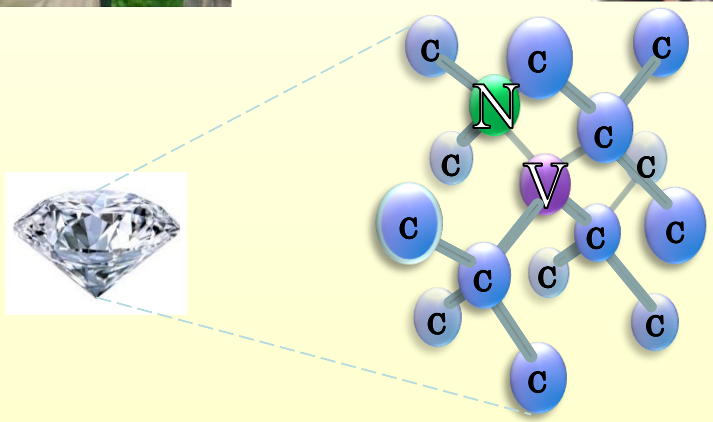
Banerjee-Ghosh et al. Science. 2018, 360.

Does this brake time reversal?!

NV centres

- NV centers- Local highly sensitive magnetic sensor
- Can measure both direction and magnitude
- Consists of a substitutional nitrogen atom and a vacancy on adjacent lattice sites


In collaboration with
Nir Bar-Gill lab @ HUJI

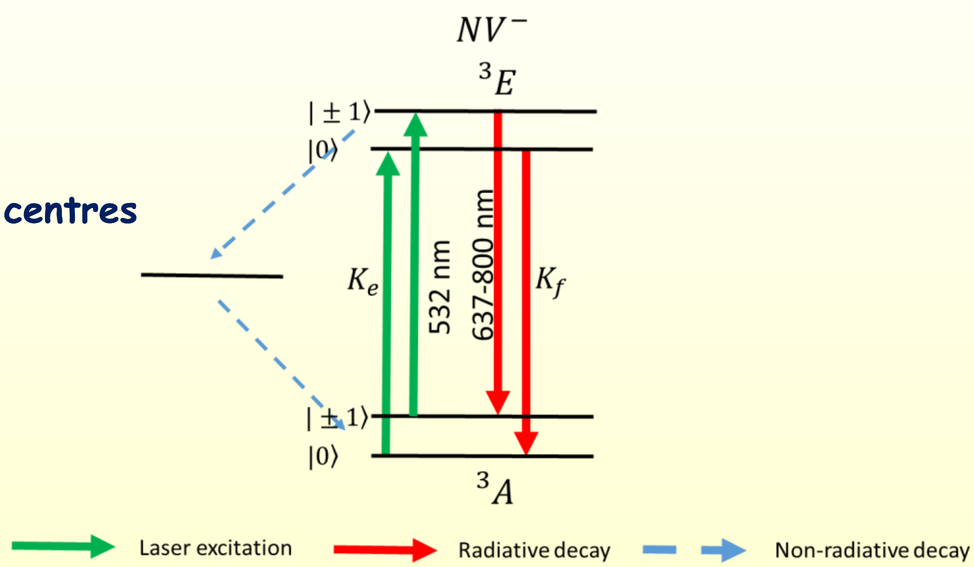



NV centres manipulation

- Optical absorption (532 nm)
- Fluorescence 600-800 nm
- Spin manipulation with microwave ~3GHz

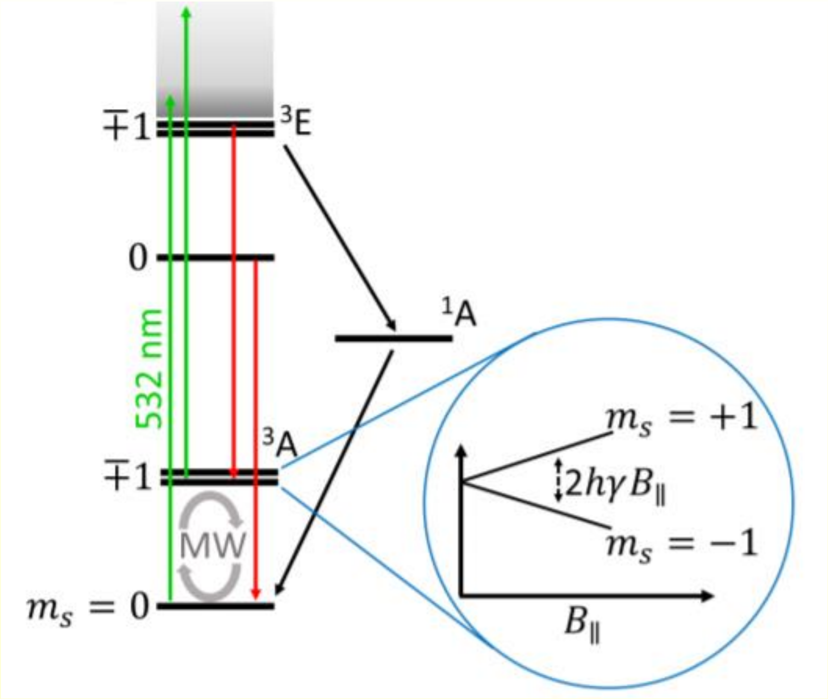
Initialization in 0 state

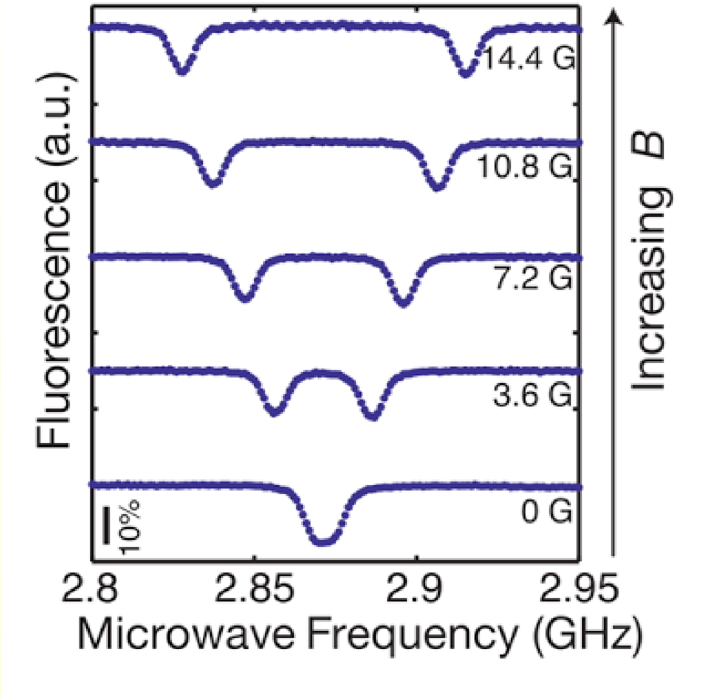
NV centres



NV centres magnetization measurement

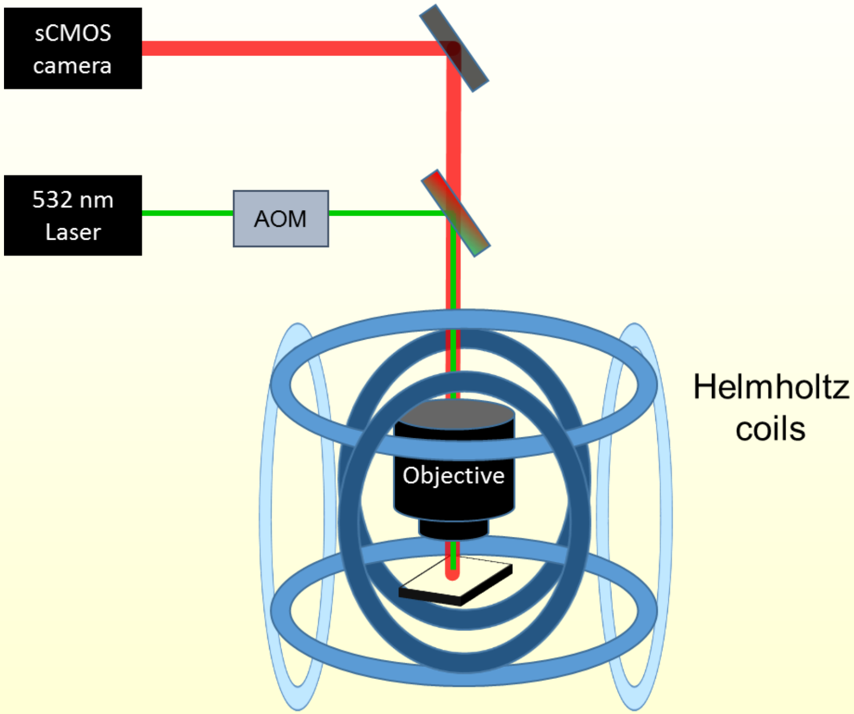
A decrease in fluorescence in the resonance MW frequency

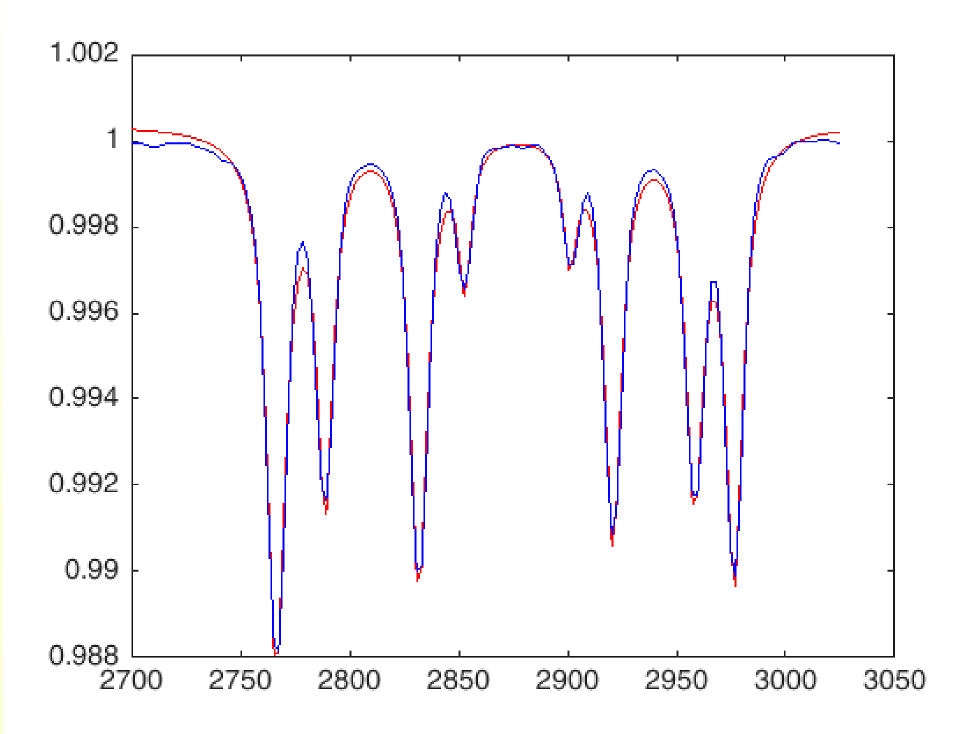




Zeeman Splitting- proportional to external magnetic field

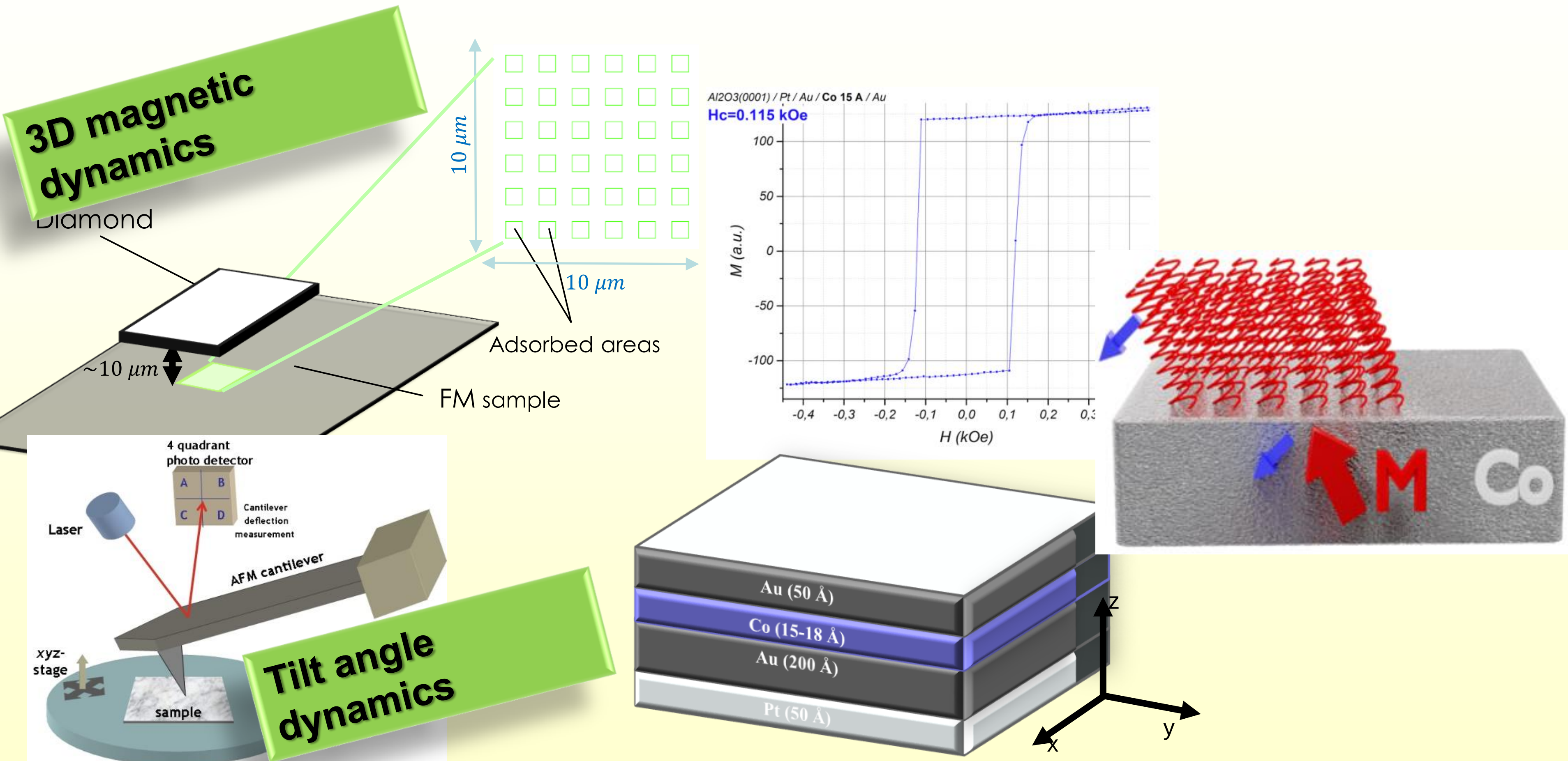
NV centres magnetization measurement





Using NV centers can give us the magnitude & direction of magnetization

Time evolution of the magnetization reorientation



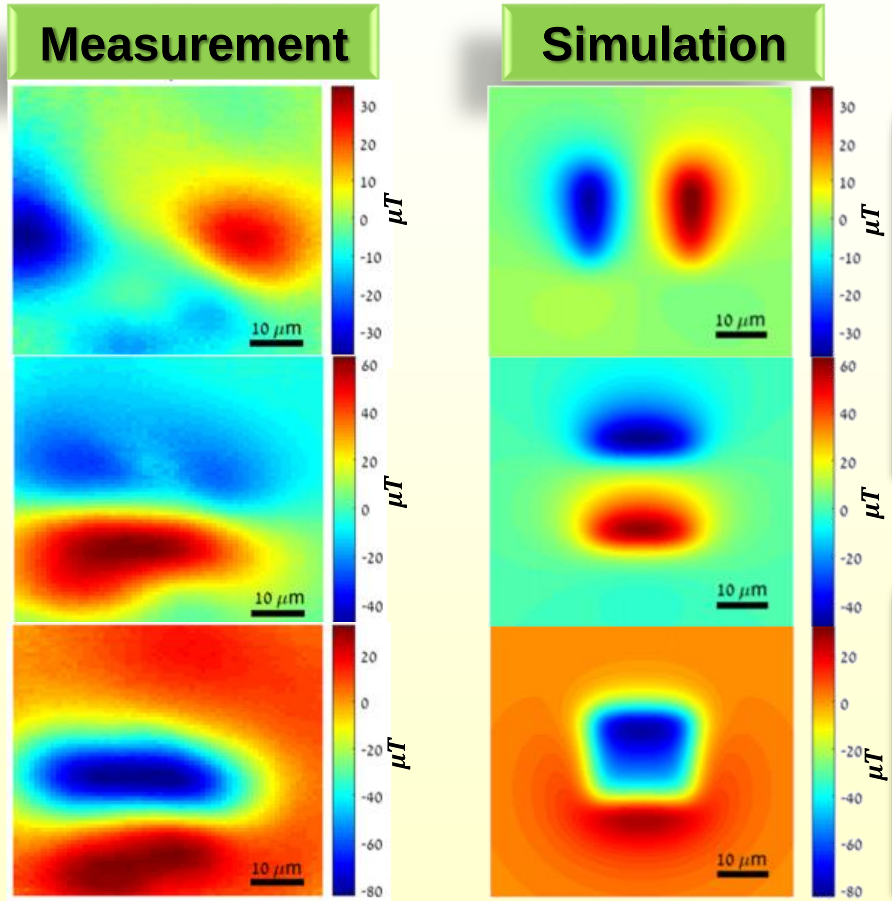
I. Meirzada[∇], N. Sukenik[∇] et al. 'Long-Timescale Magnetization Ordering Induced by an Adsorbed Chiral Monolayer on Ferromagnets' **ACS Nano**. 2021, 15.

Time evolution of the magnetization reorientation

X

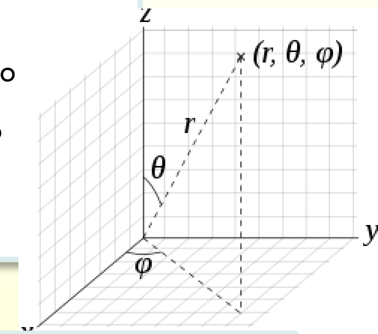
Y

Z



Magnetization angles:

$$\Theta = 40^\circ \pm 10^\circ$$
$$\bar{\phi} = 90^\circ \pm 3^\circ$$



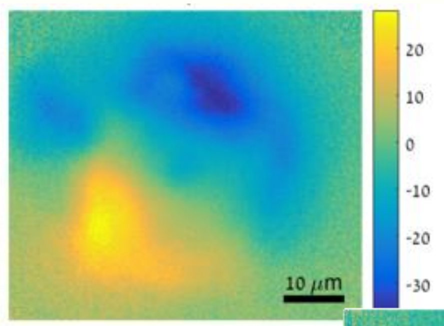
- **Magnetization angle compatible with monolayer tilt angle**
- **$\bar{\phi}$ is not random**

I. Meirzada$^\nabla$, N. Sukenik$^\nabla$ et al. 'Long-Timescale Magnetization Ordering Induced by an Adsorbed Chiral Monolayer on Ferromagnets' **ACS Nano**. 2021, 15.

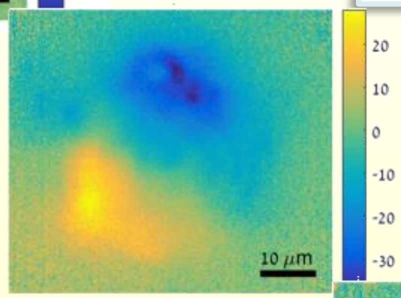
Magnetization time evolution

- **Magnetization weakens over time**
- **Magnetization angle increases over time**

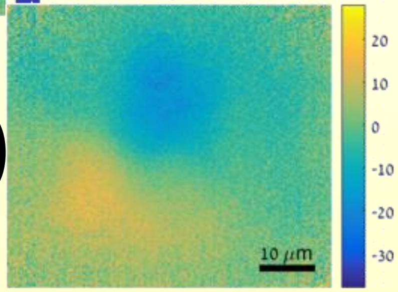
Z (t=4hr)



Z (t=8hr)

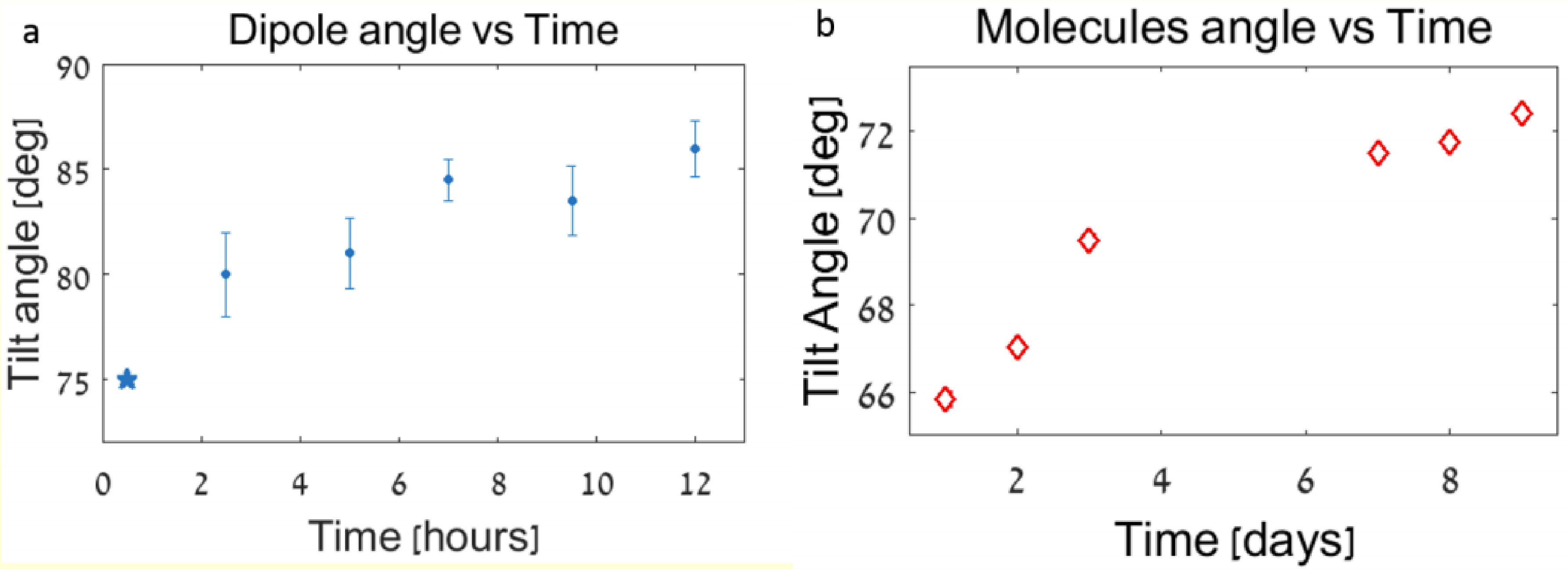


Z (t=12hr)



I. Meirzada[∇], N. Sukenik[∇] et al. 'Long-Timescale Magnetization Ordering Induced by an Adsorbed Chiral Monolayer on Ferromagnets' **ACS Nano**. 2021, 15.

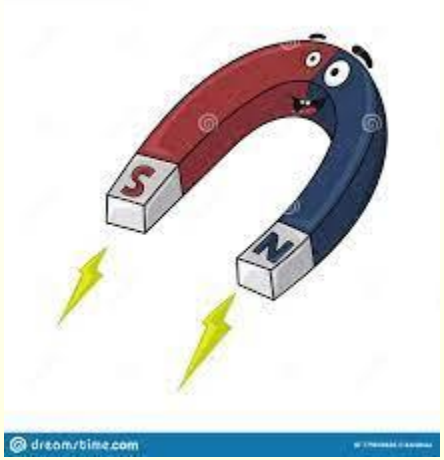
Time evolution of the magnetization reorientation



Both tilt angle and magnetization angle increase over time

I. Meirzada∇, N. Sukenik∇ et al. 'Long-Timescale Magnetization Ordering Induced by an Adsorbed Chiral Monolayer on Ferromagnets' **ACS Nano**. 2021, 15.

The magnetization is metastable and seems to break T due to thermal fluctuations !!!

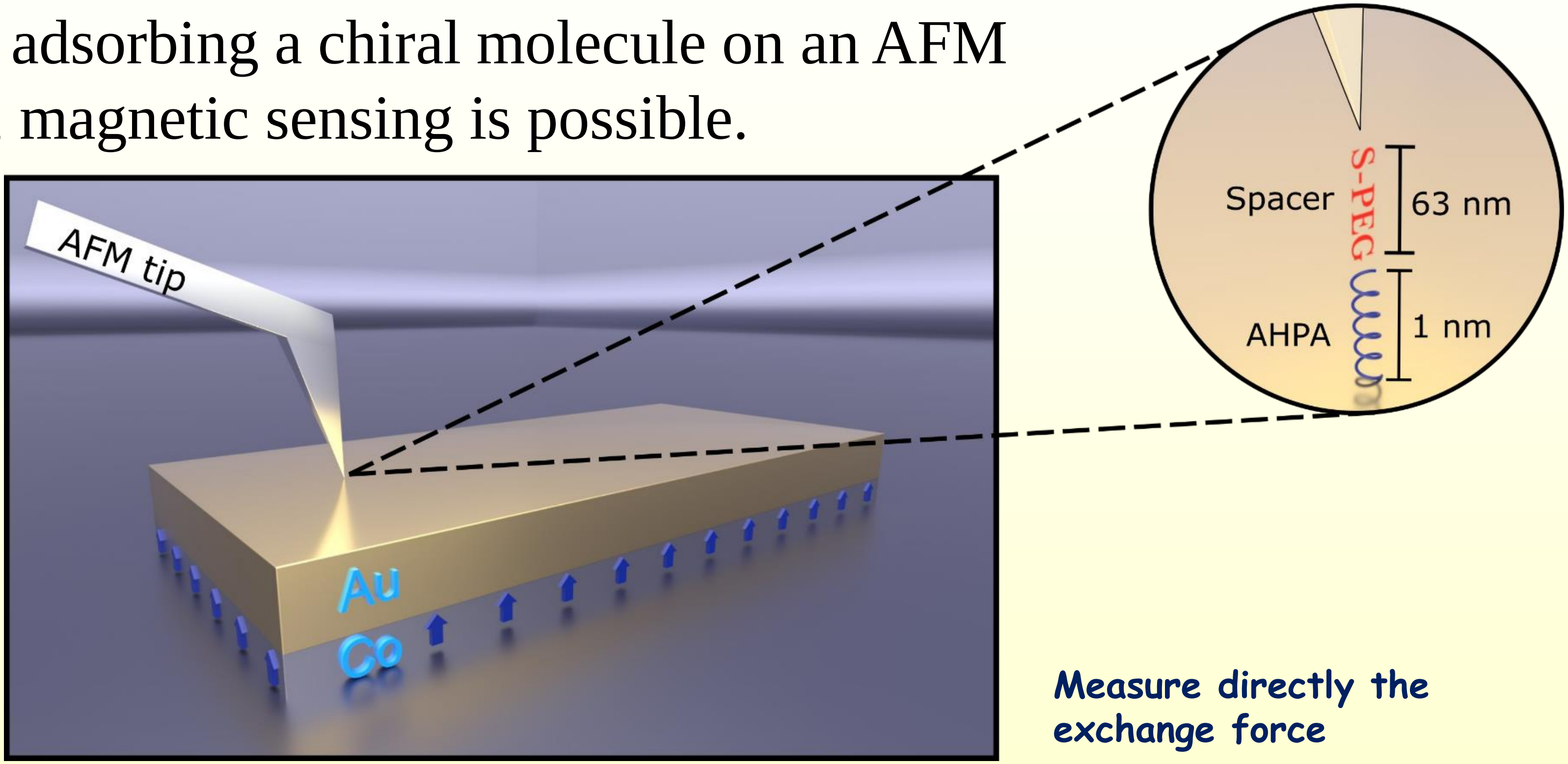


But we are on a magnet - does break T in any case and we have dissipation

Artem G. Volosniev, Hen Alpern, Yossi Paltiel, Oded Millo, Mikhail Lemeshko, and Areg Ghazaryan, *Interplay between friction and spin-orbit coupling as a source of spin polarization;* Phys. Rev. B **104**, 024430 (2021).

AFM-Based Spin-Exchange Microscopy Using Chiral Molecules

By adsorbing a chiral molecule on an AFM tip, magnetic sensing is possible.



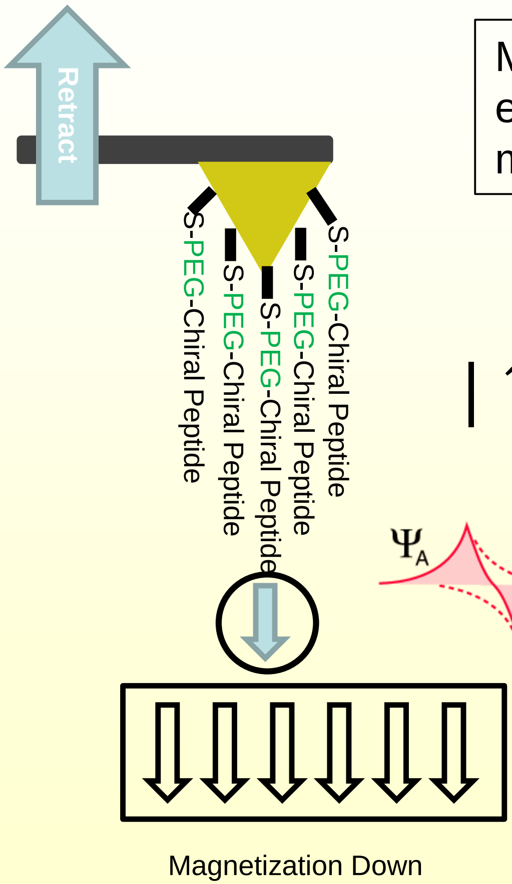
Measure directly the exchange force

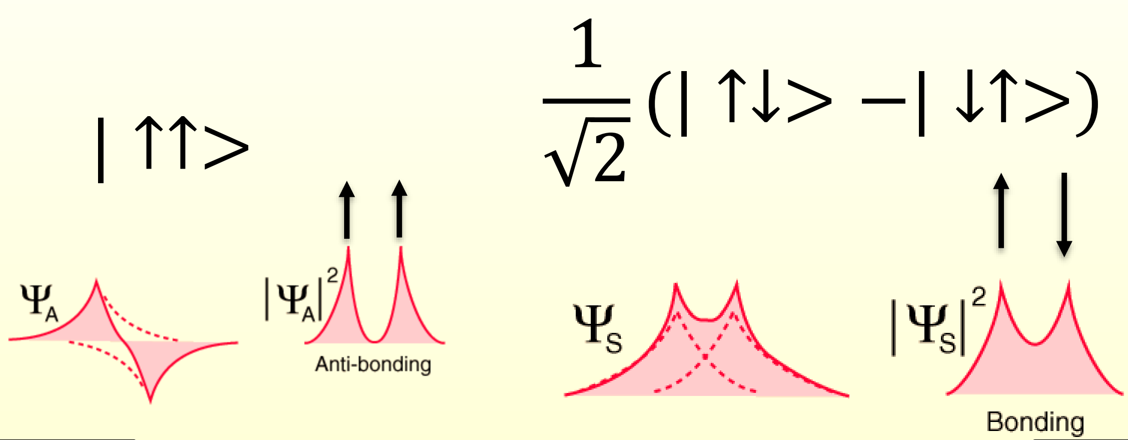
Amir Ziv, Abhijit Saha, Hen Alpern, Nir Sukenik, Lech Tomasz Baczewski, Shira Yochelis, Meital Reches,* and Yossi Paltiel*; *AFM-Based Spin Exchange Microscopy Using Chiral Molecules*, Advanced Materials (2019).

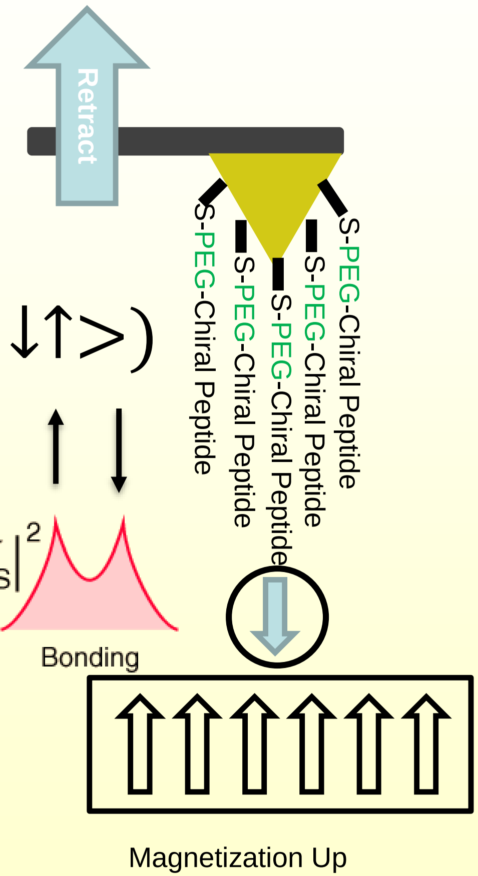
Chiral spin AFM

Measure directly the exchange force

Magnetic imaging is achieved due to exchange interaction and **not** by magnetic dipole interaction

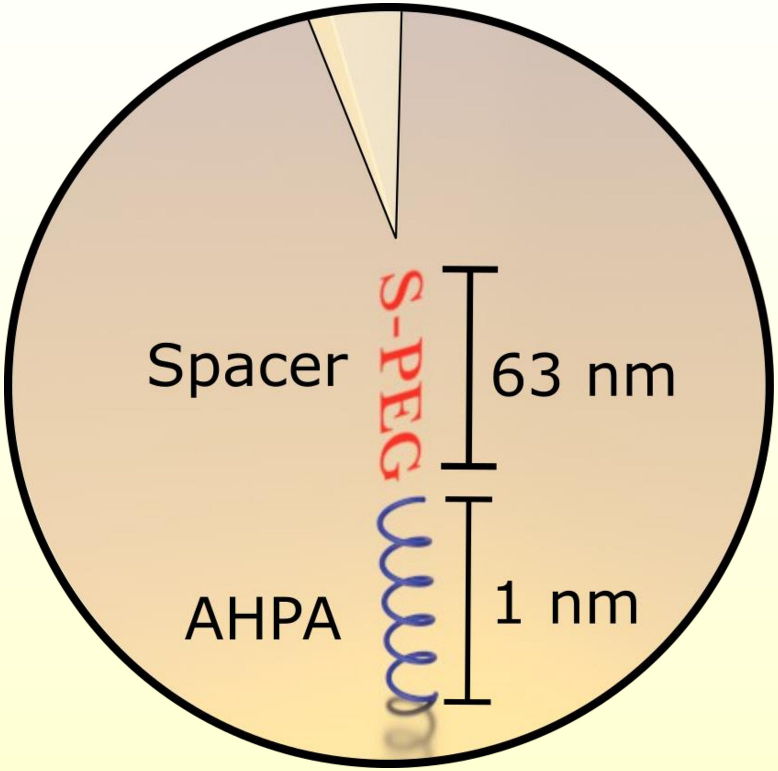






Atomic resolution of magnetic mapping!!!!

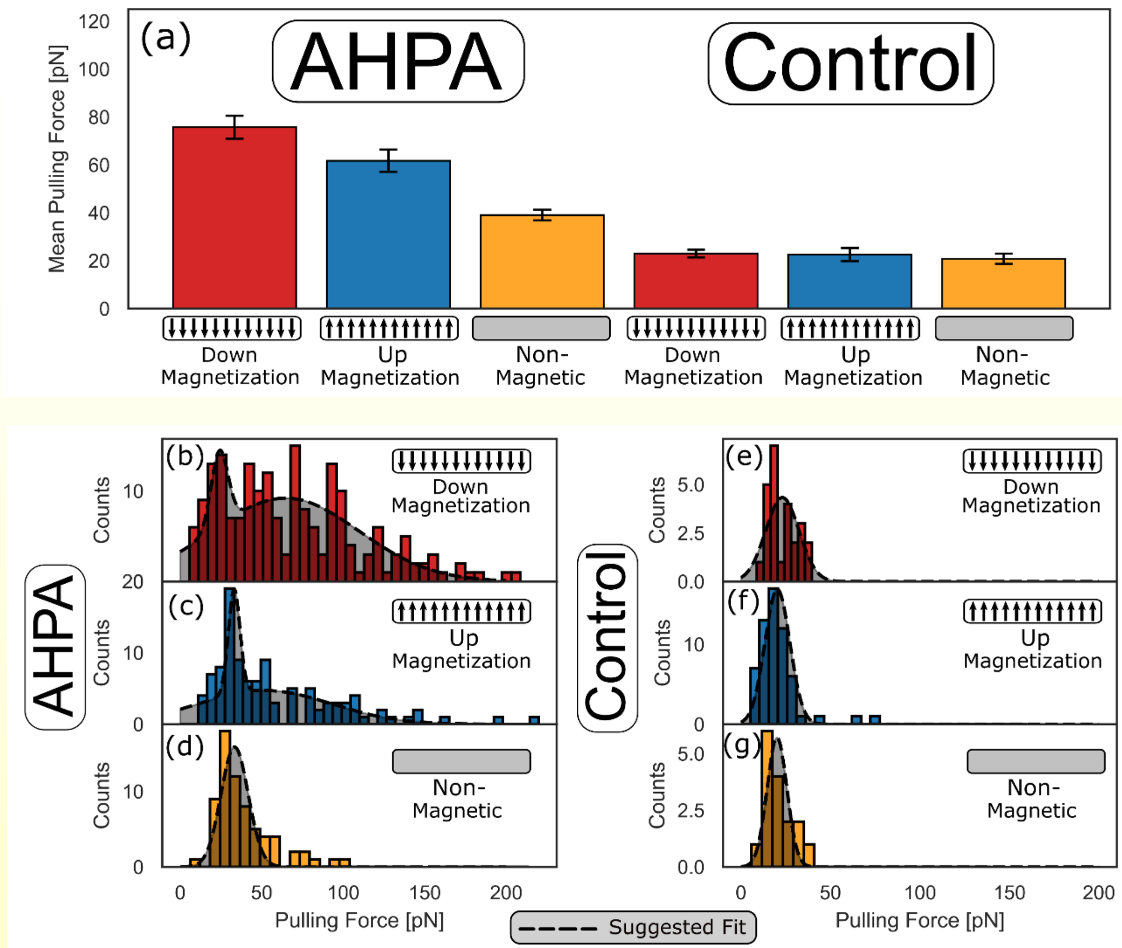
CISS on Tip



In order to isolate the specific interface-molecule interaction:

- A spacer molecule is placed between the tip and the molecule of interest, to reduce VDW and electrostatic interaction.
- The measurement if perform in a liquid environment to avoid capillary forces
- The measured sample is an MBE grown sample to avoid discrepancies between the composition and topography.

Results

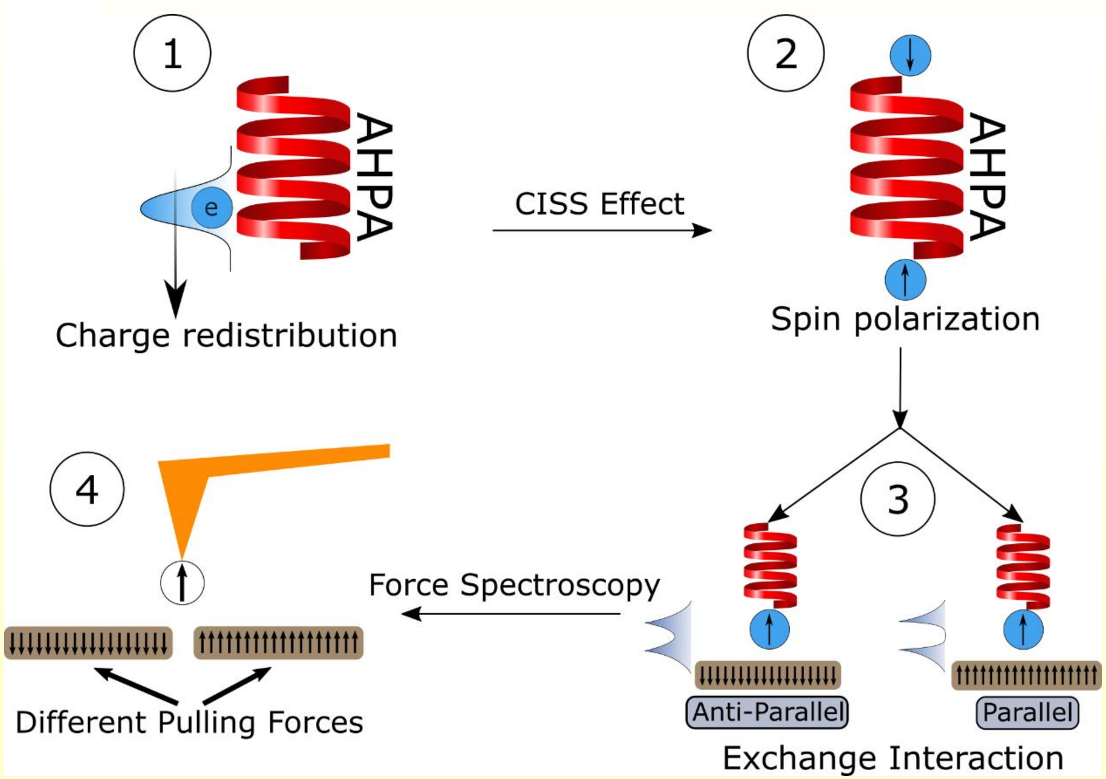


Control experiments were made with gold alone and with an achiral molecule with the same linkers.

A force difference of 13.98 $\pm$ 6.67 $[pN]$ was measured.

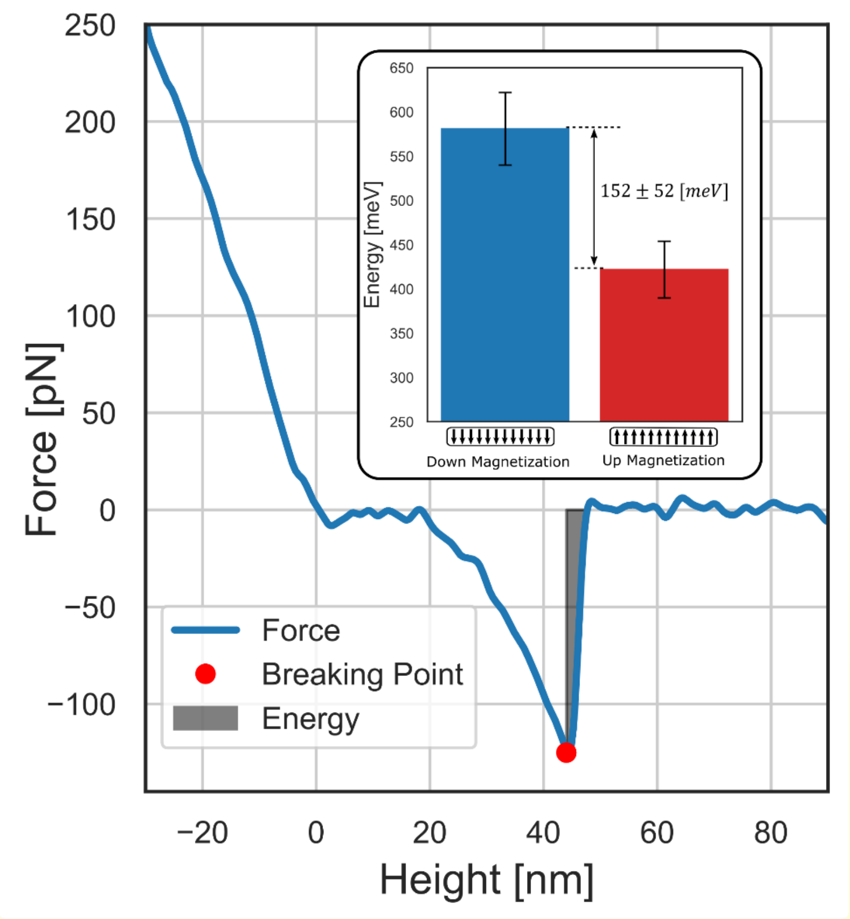
Ziv, A, Saha, A. et al. AFM-Based Spin-Exchange Microscopy Using Chiral Molecules. Advanced Materials 0, 1904206

Suggested Mechanism



Ziv, A, Saha, A. et al. AFM-Based Spin-Exchange Microscopy Using Chiral Molecules. Advanced Materials 0, 1904206

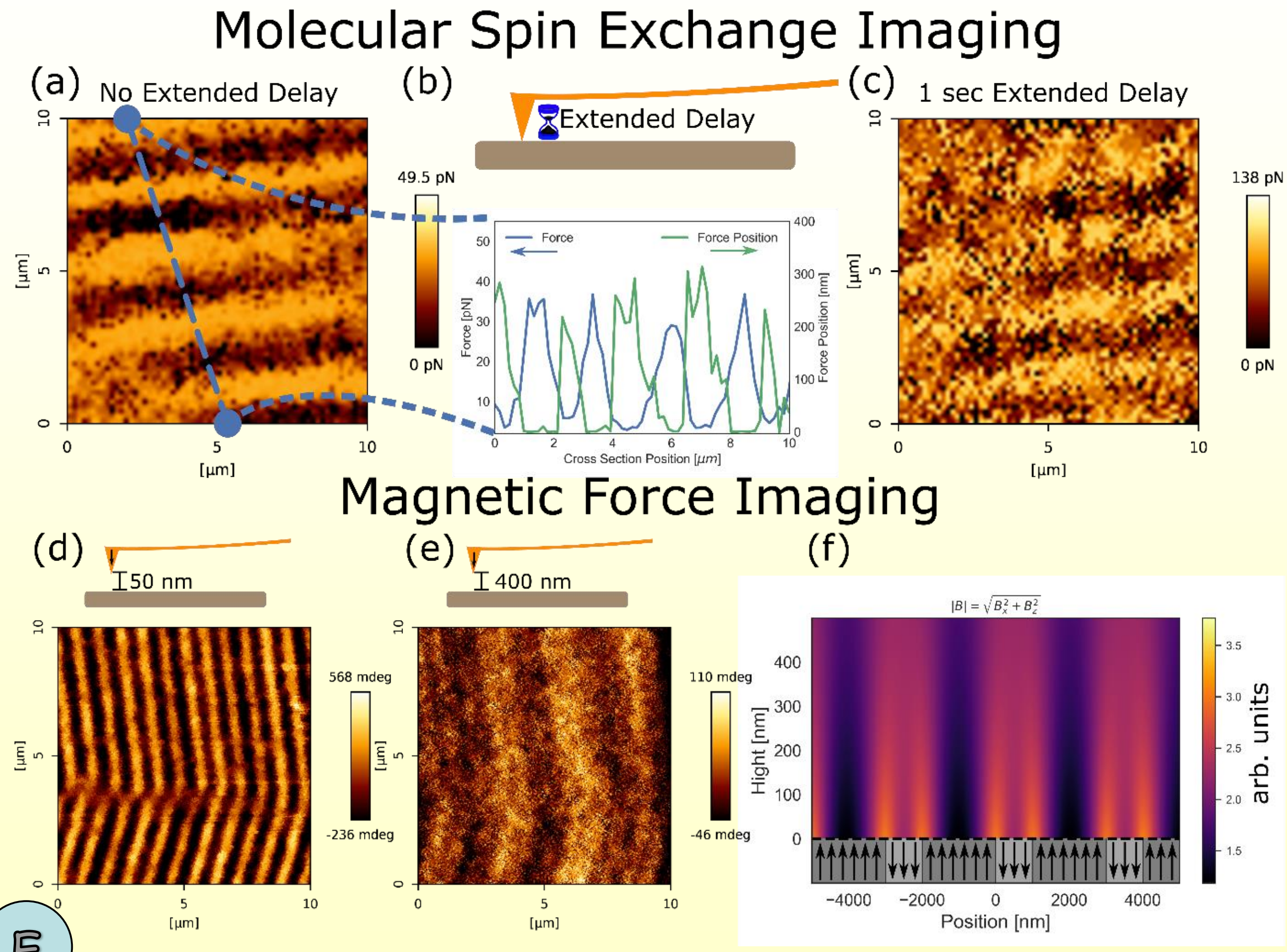
Interaction Energy



Calculating the energy difference between the down and up magnetization yielded a difference of $152 \pm 52[meV]$ which corresponds to first principle calculations.

Amir Ziv, Abhijit Saha, Hen Alpern, Nir Sukenik, Lech Tomasz Baczewski, Shira Yochelis, Meital Reches,* and Yossi Paltiel*; *AFM-Based Spin Exchange Microscopy Using Chiral Molecules*, Advanced Materials (2019).

Using Chiral molecules to achieve nano scale magnetic mapping

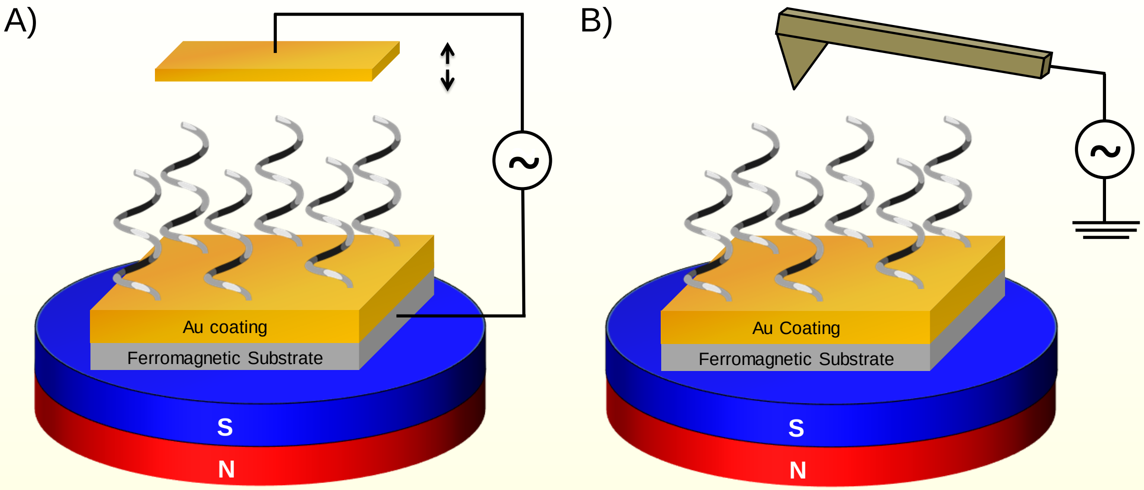


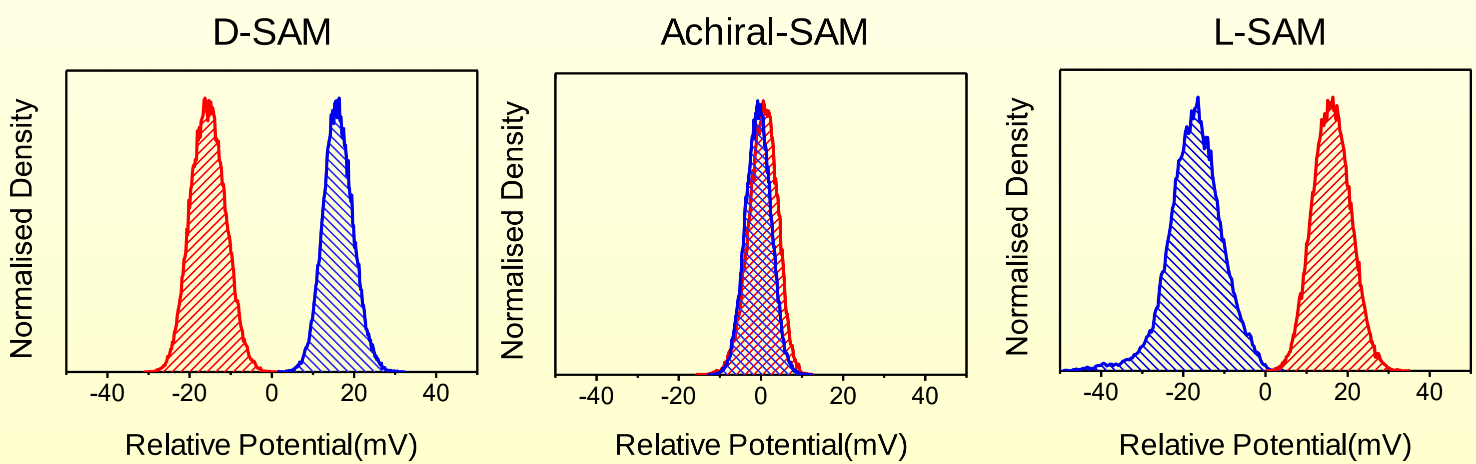
Quantum Nano Engineering Lab

9/2/2021

Work function results

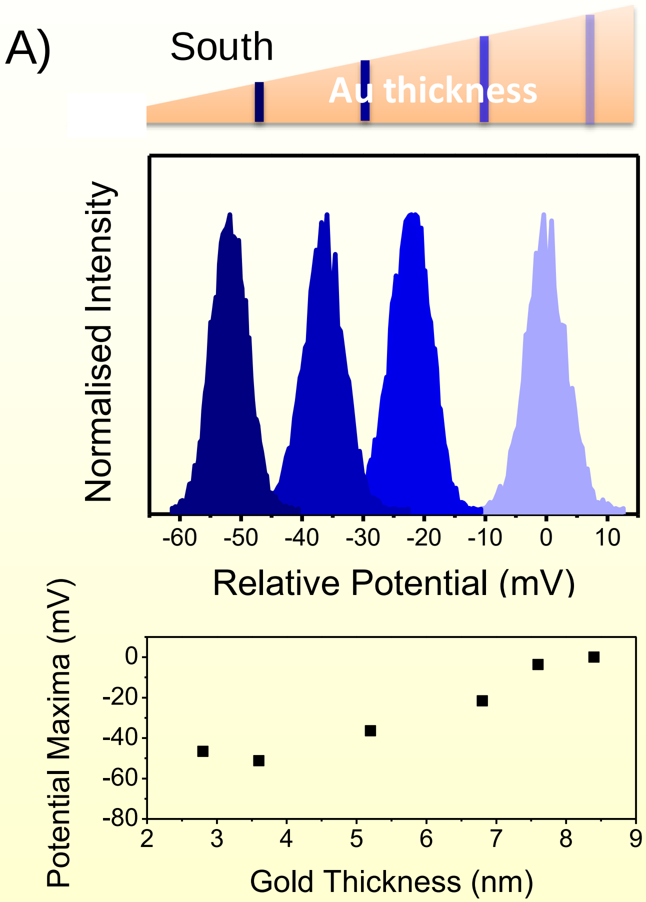
Ni or Co Ferromagnetic substrate

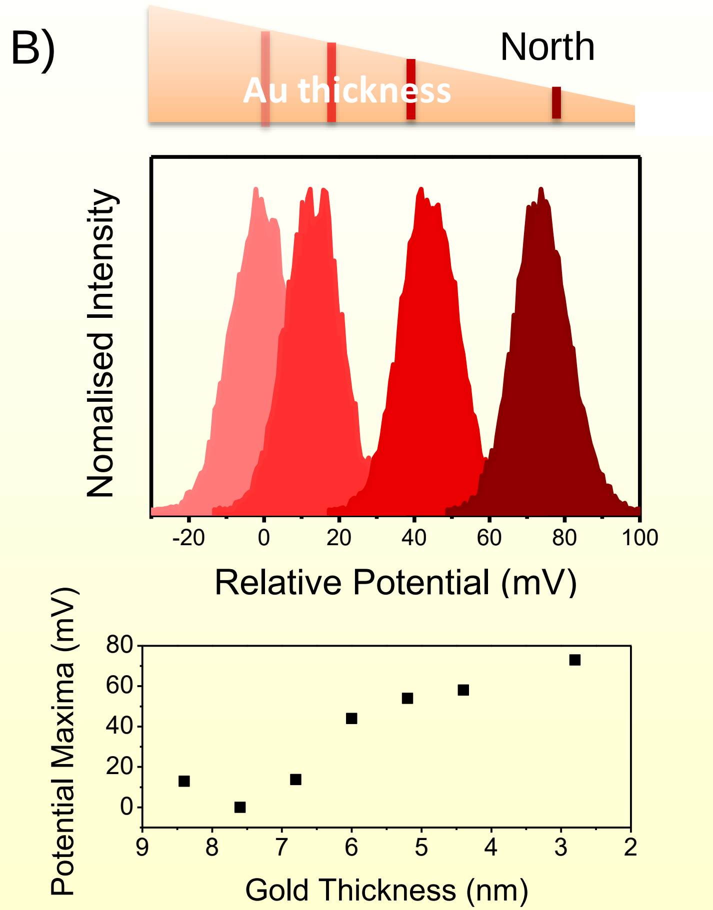




Effect of Chiral Molecules on the Electron's Spin Wavefunction at Interfaces, J. Phys. Chem. Lett., **11,** (4), 1550 (2020).

Spin exchange delocalization





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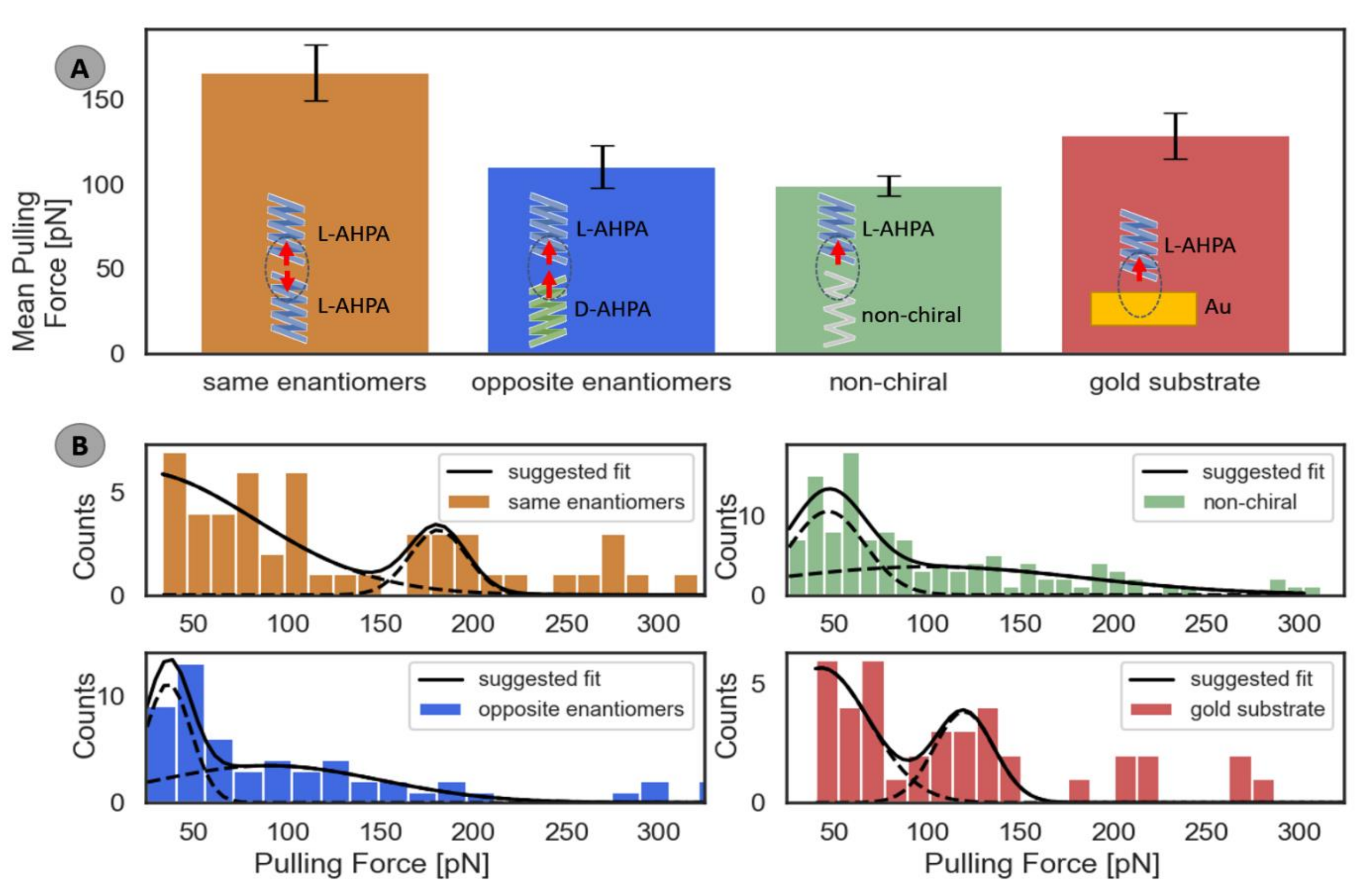
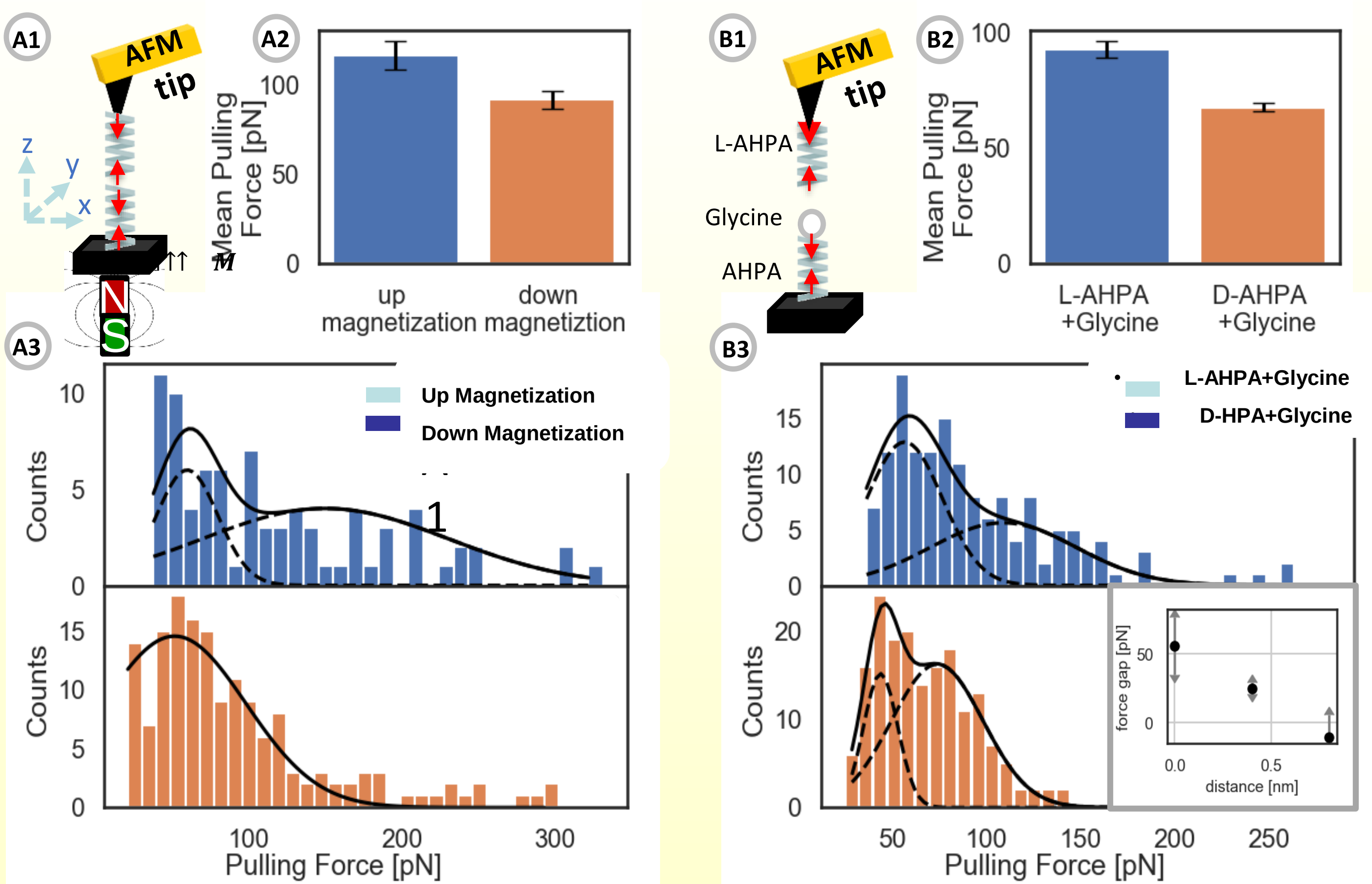
Bio recognition forces

Protein folding and bio recognition

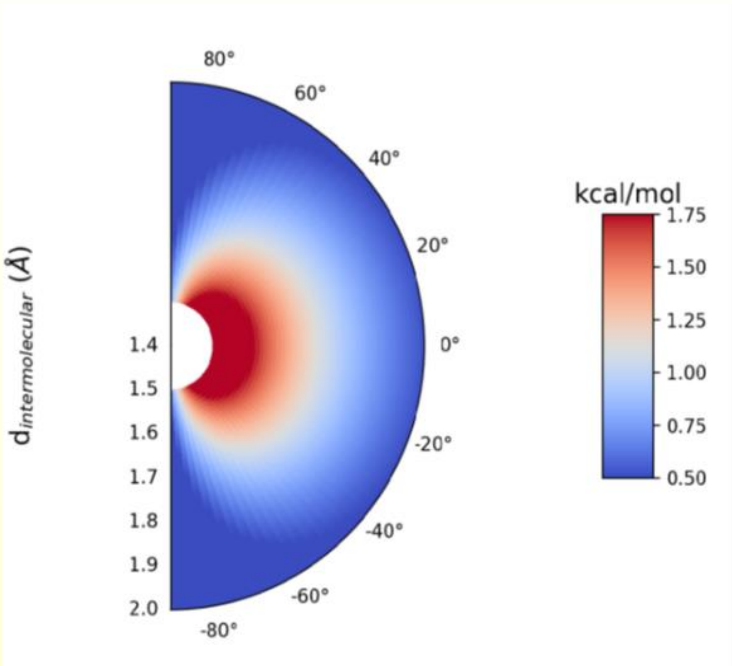
Evident for New Enantiospecific Interaction Force in Chiral Biomolecules Yael Kapon,+ Abhijit Saha,+ Thijs Stuyver, Amir Ziv, Shira Yochelis, Sason Shaik, Ron Naaman,* Meital Reches,* and Yossi Paltiel*

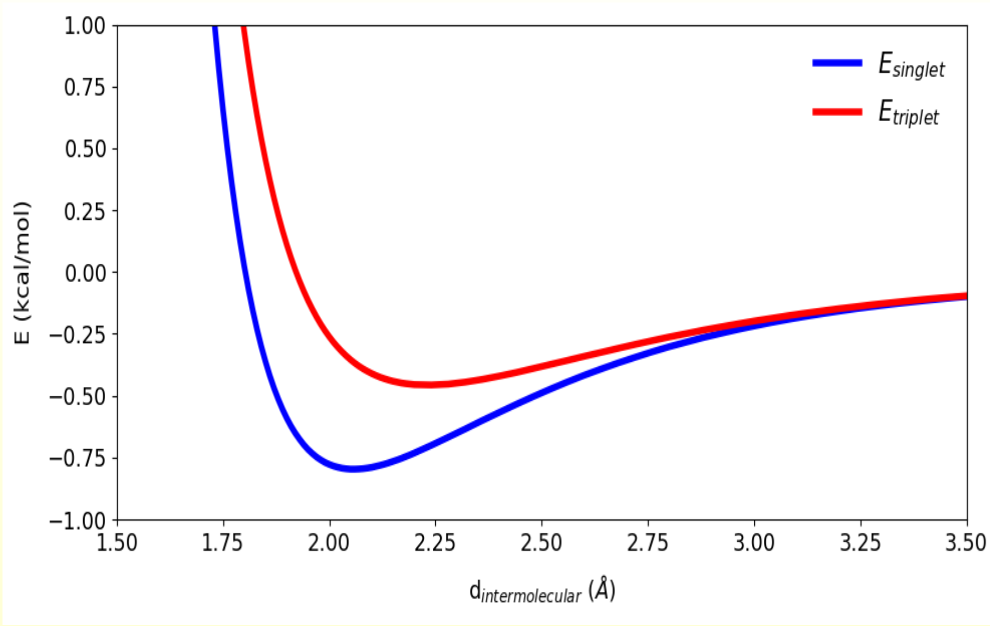


Relation to spin



Protein folding and bio recognition

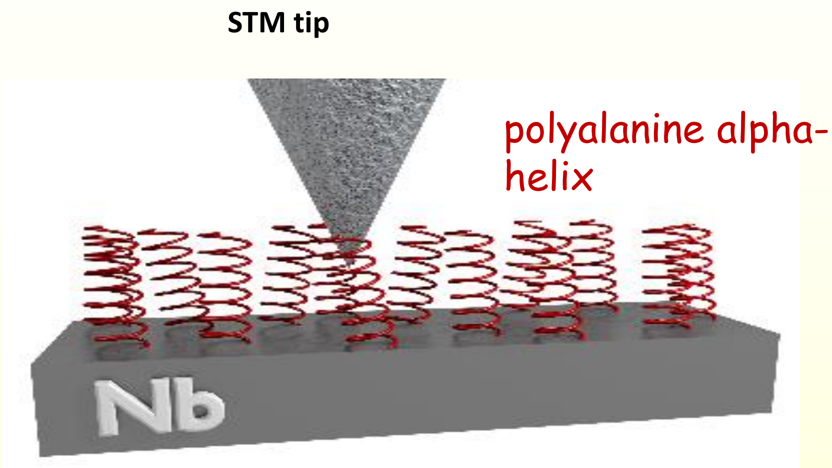


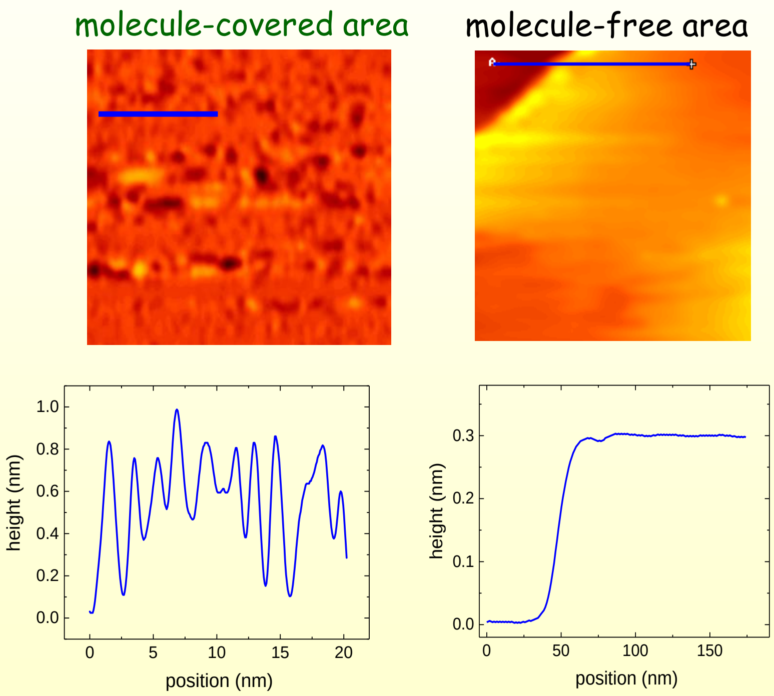


The calculated potential energies from the toy model for interaction of two molecules with spin polarized either antiparallel (blue) or parallel (red) to each other

Can chiral molecules alter an s-wave superconductor

Not a magnetic system!!!



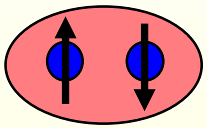


D wave and P wave spectra

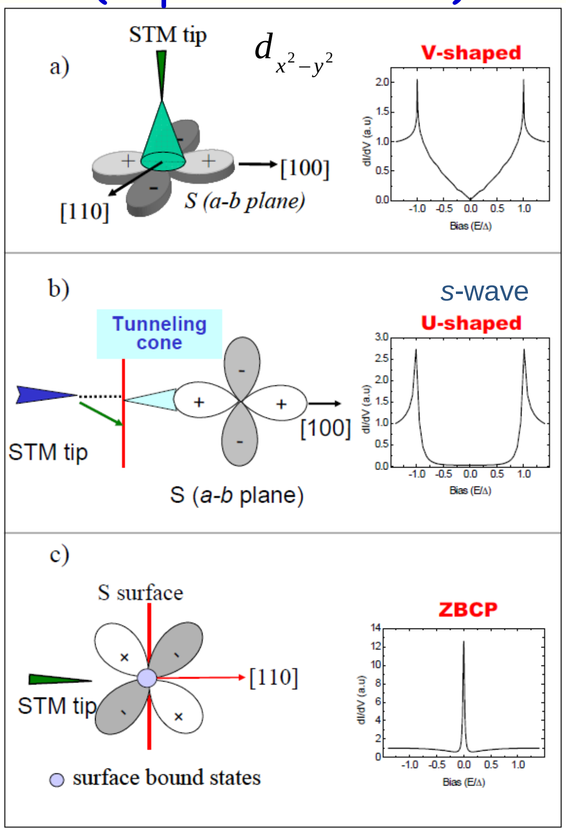
d-wave
(cuprate HTSCs)

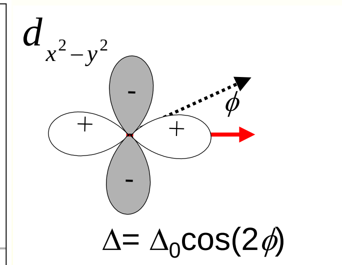
p-wave
(triplet superconductors)

Spin Singlet



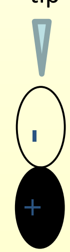
$|\uparrow\downarrow\rangle - |\downarrow\uparrow\rangle$

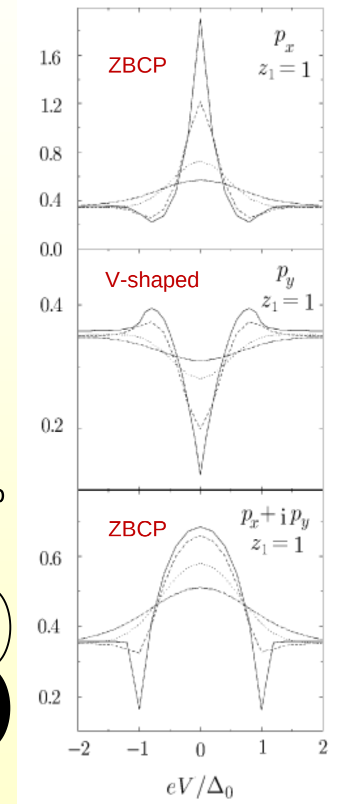




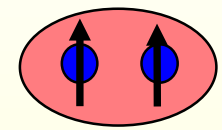
Note:

1. (split) ZBCPs
2. V-shaped gaps





Spin triplet



$|\uparrow\uparrow\rangle$
$|\uparrow\downarrow\rangle + |\downarrow\uparrow\rangle$
$|\downarrow\downarrow\rangle$

QNE Lab

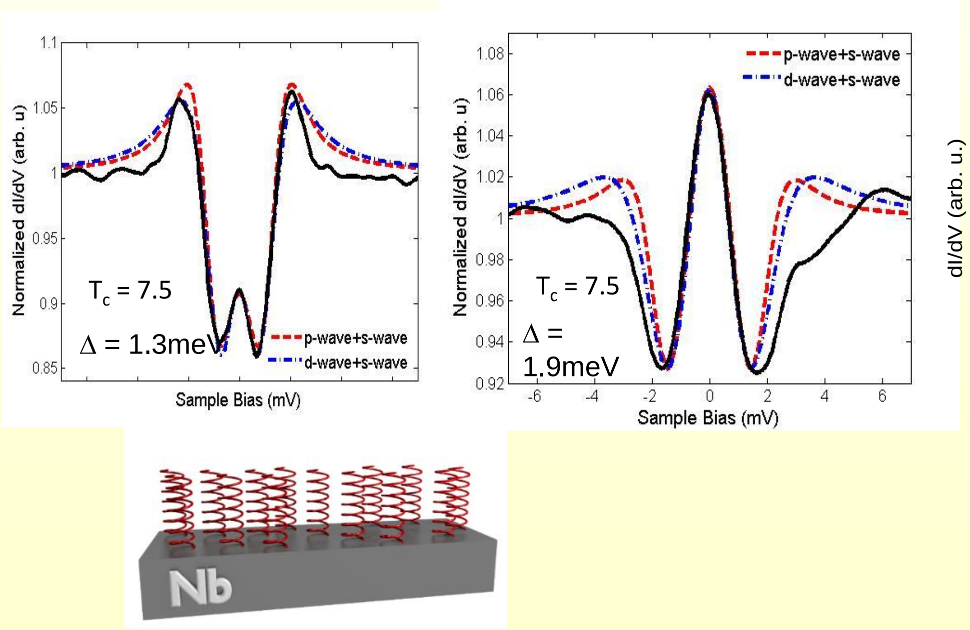
Fits to the three types of spectra

Combination of *s*-wave, *d*-wave and chiral *p*-wave pairing potentials.

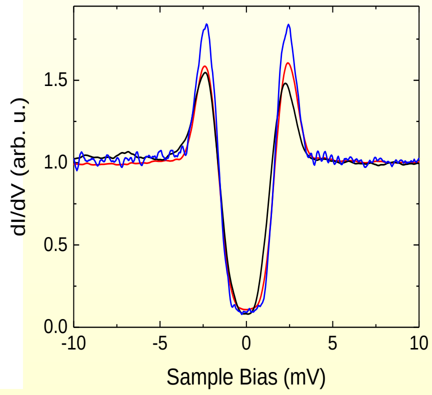
chiral *p*-wave : $\Delta_{\uparrow\uparrow} = \Delta_0 \sin\theta(\cos\phi + i\sin\phi)$ ($p_x + ip_y$, triplet)

d-wave ($d_{x^2-y^2}$) : $\Delta = \Delta_0 \cos(2\theta)$ (singlet or odd-frequency triplet)

After Adsorption

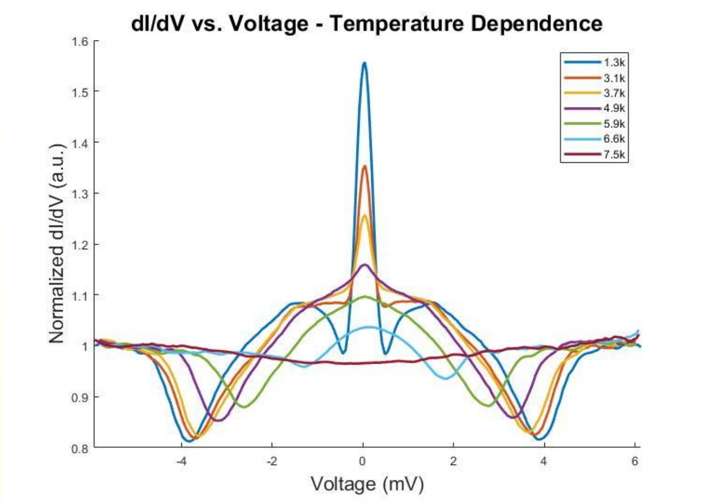


Pristine Sample

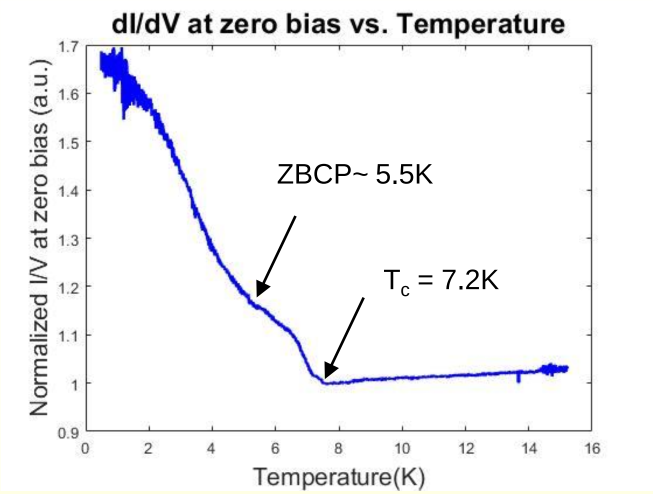


Alpern, et al., *New J. Phys. 18, 113048 (2016)*

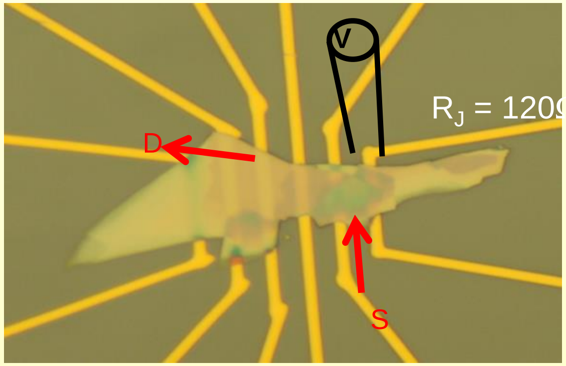
Non Splitting ZBCP



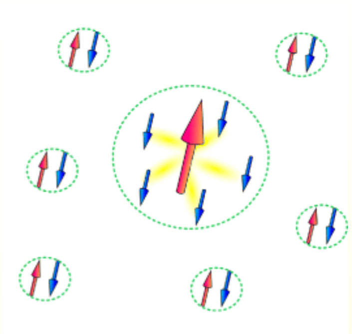
low resistance junction, T-dependence

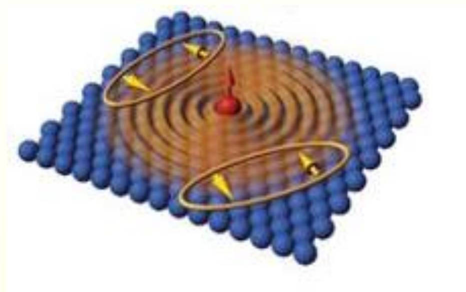


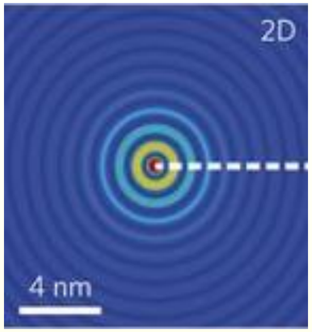
The induced component decreases with temperature.



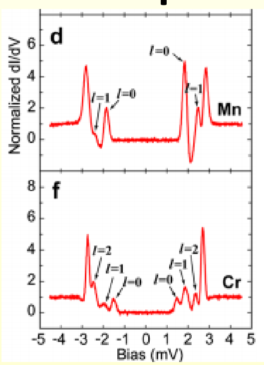
Yu – Shiba – Rusinov (YSR) States



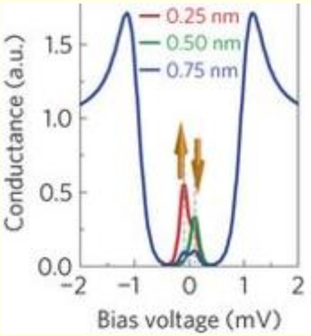




magnetic impurities form discrete low energy spin-polarized bound states within the superconducting gap



In-gap states

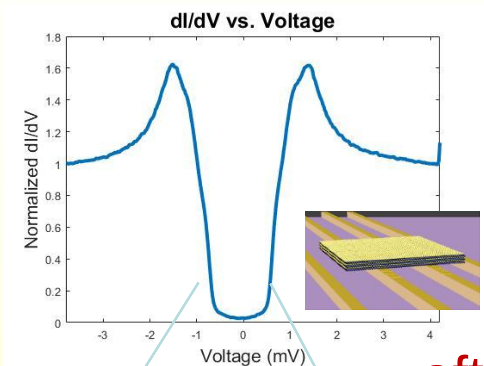


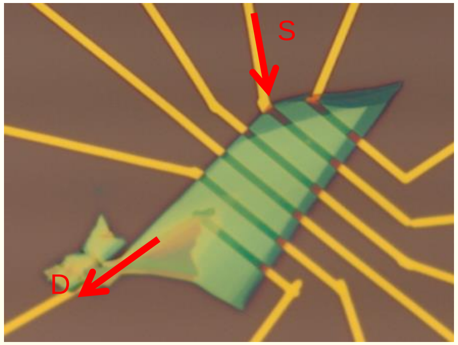
Ménard, G. C. *et al.* Coherent long-range magnetic bound states in a superconductor. *Nat. Phys.* **11**, 1013–1016 (2015).

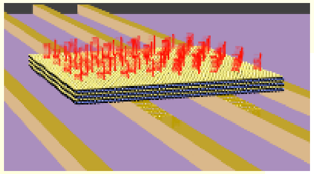
Ji, S.-H. *et al.* High-Resolution Scanning Tunneling Spectroscopy of Magnetic Impurity Induced Bound States in the Superconducting Gap of Pb Thin Films. *Phys. Rev. Lett.* **100**, 226801 (2008).

Sub gap states (YSR-like) which diverge with applied magnetic field

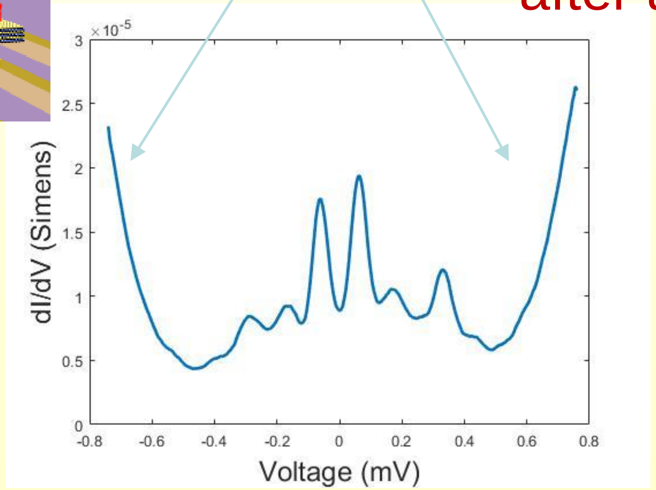
Before adsorption







after adsorption



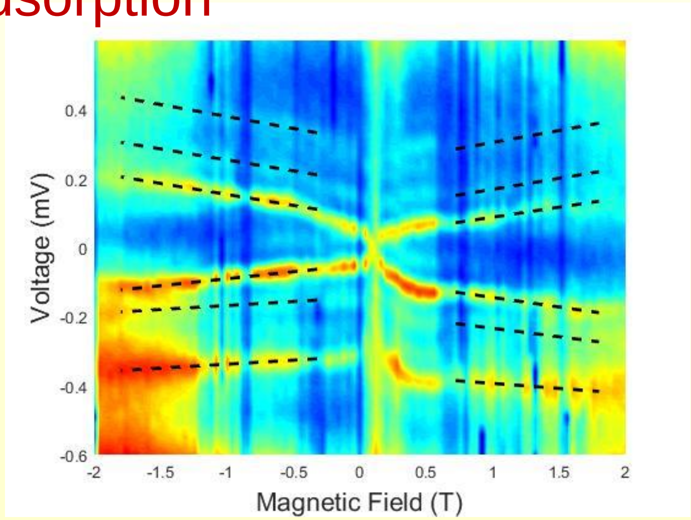
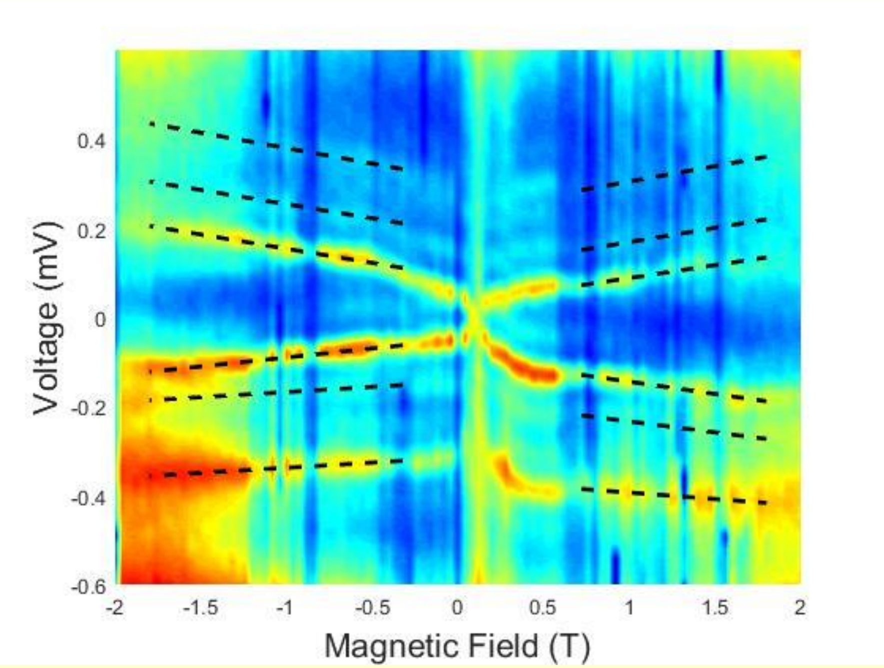
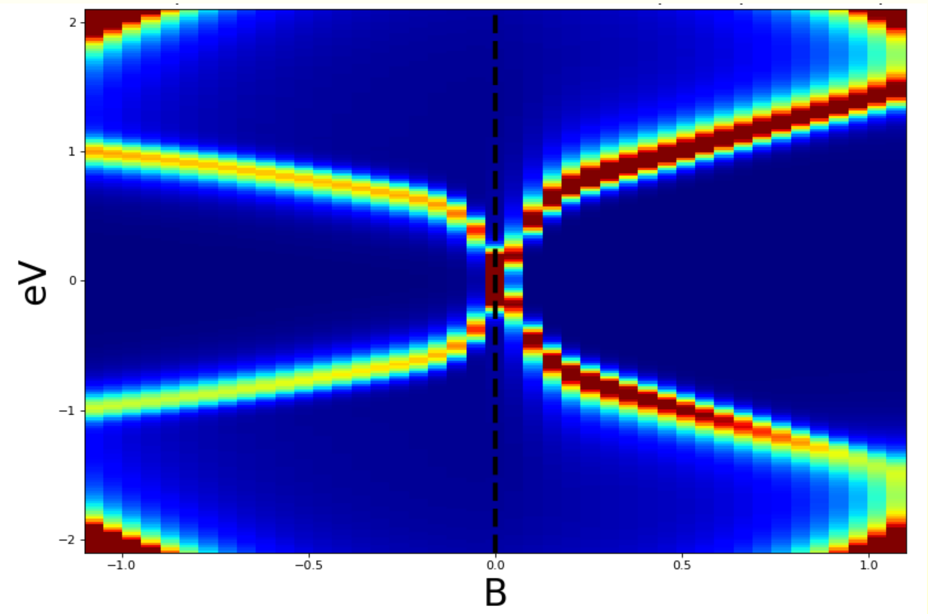


Figure 3: high junction resistance

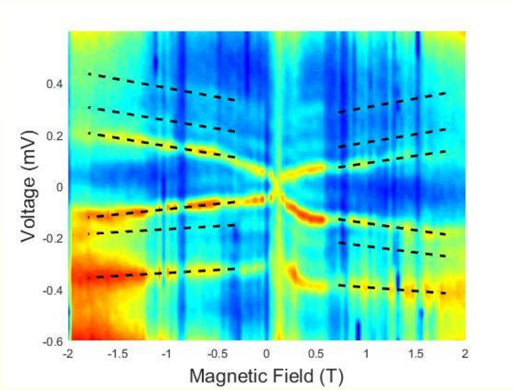
Comparison between measurement and simulation of an array of YSR states





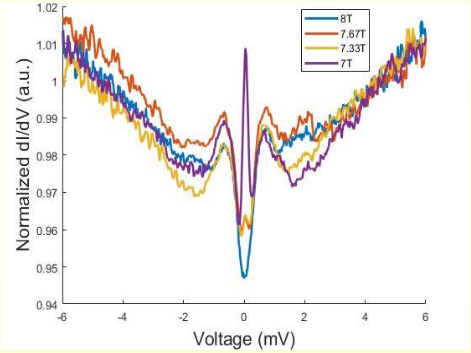
Simulated ….

Possible Scenario



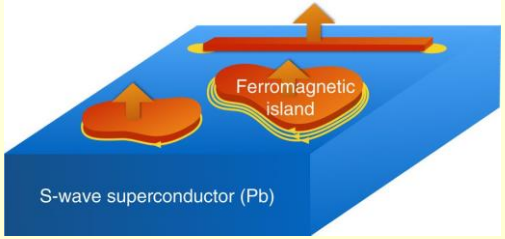
discrete YSR states

Low density adsorption



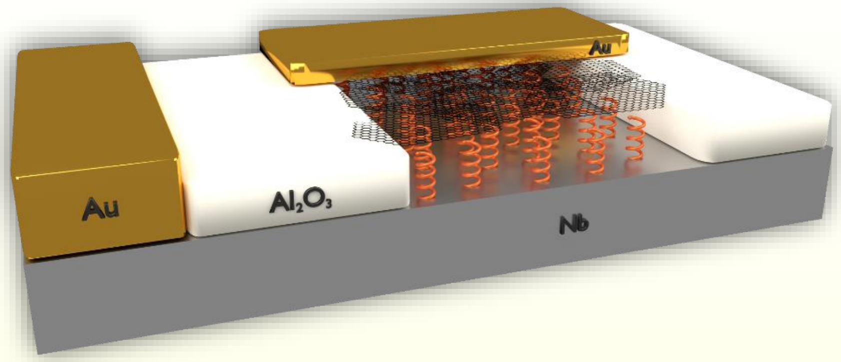
chiral p-wave

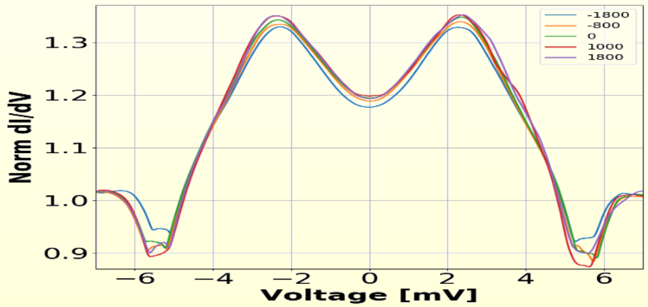
High density adsorption

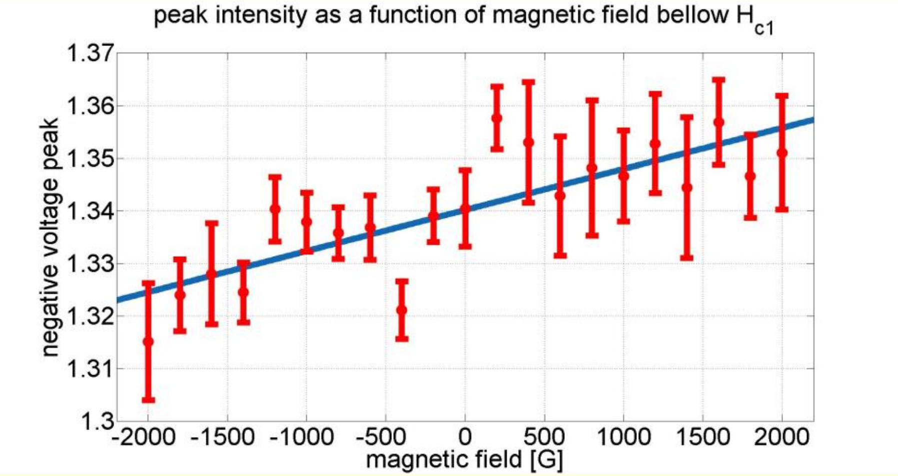


Li, J. et al. *Two-dimensional chiral topological superconductivity in Shiba lattices. Nat. Commun. 7, 12297 (2016).*

SC order parameter change by chiral molecules







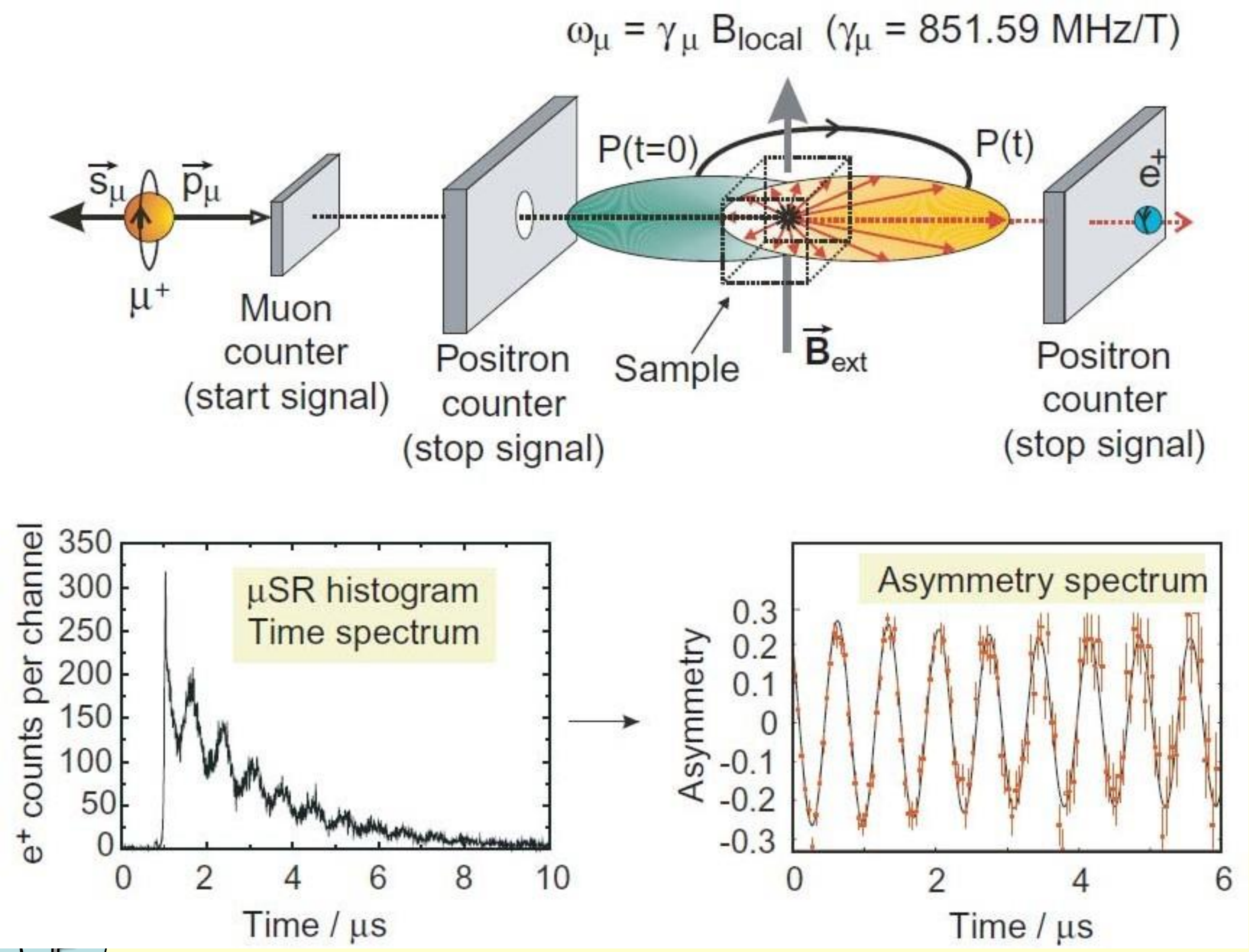
the junction measured consists of a Nb substrate, chiral polyalanine molecules, conductive graphene flakes and a top gold electrode. The measurement is done between the gold electrodes.

Proximity Effect through Chiral Molecules in Nb–Graphene-Based Devices
Nir Sukenik, Hen Alpern, Eran Katzir, Shira Yochelis, Oded Millo, and Yossi Paltiel
Adv. Mater. Technol. 2018, 1700300

μSR Muon Spin Rotation/Relaxation

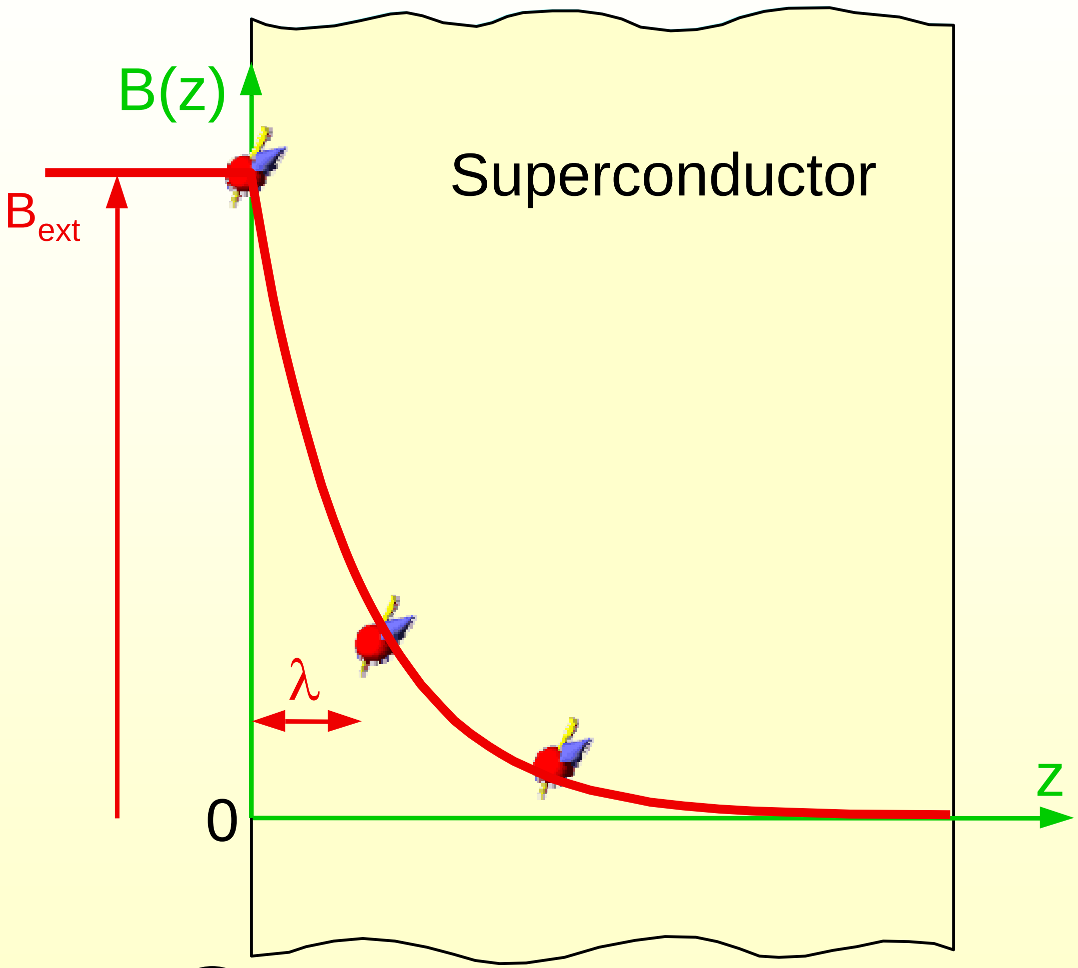
Paul Scherrer Institute

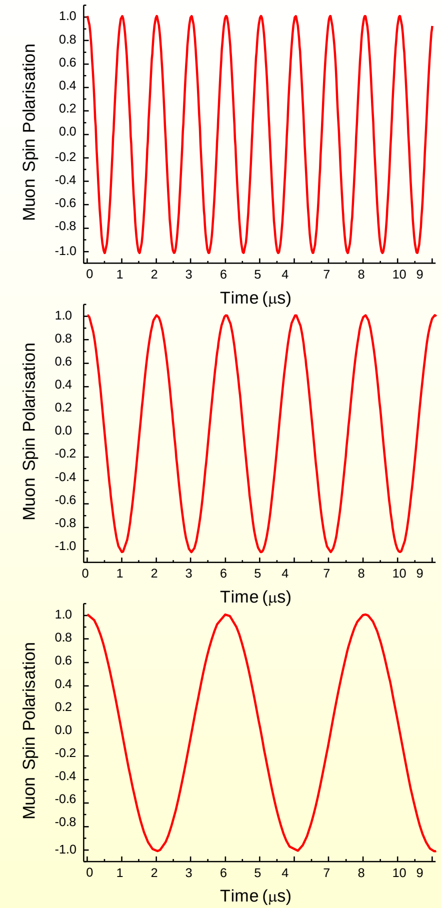
Principle of a μSR experiment



Depth dependent µSR measurements

→ Magnetic field profile B(z) over nm scale



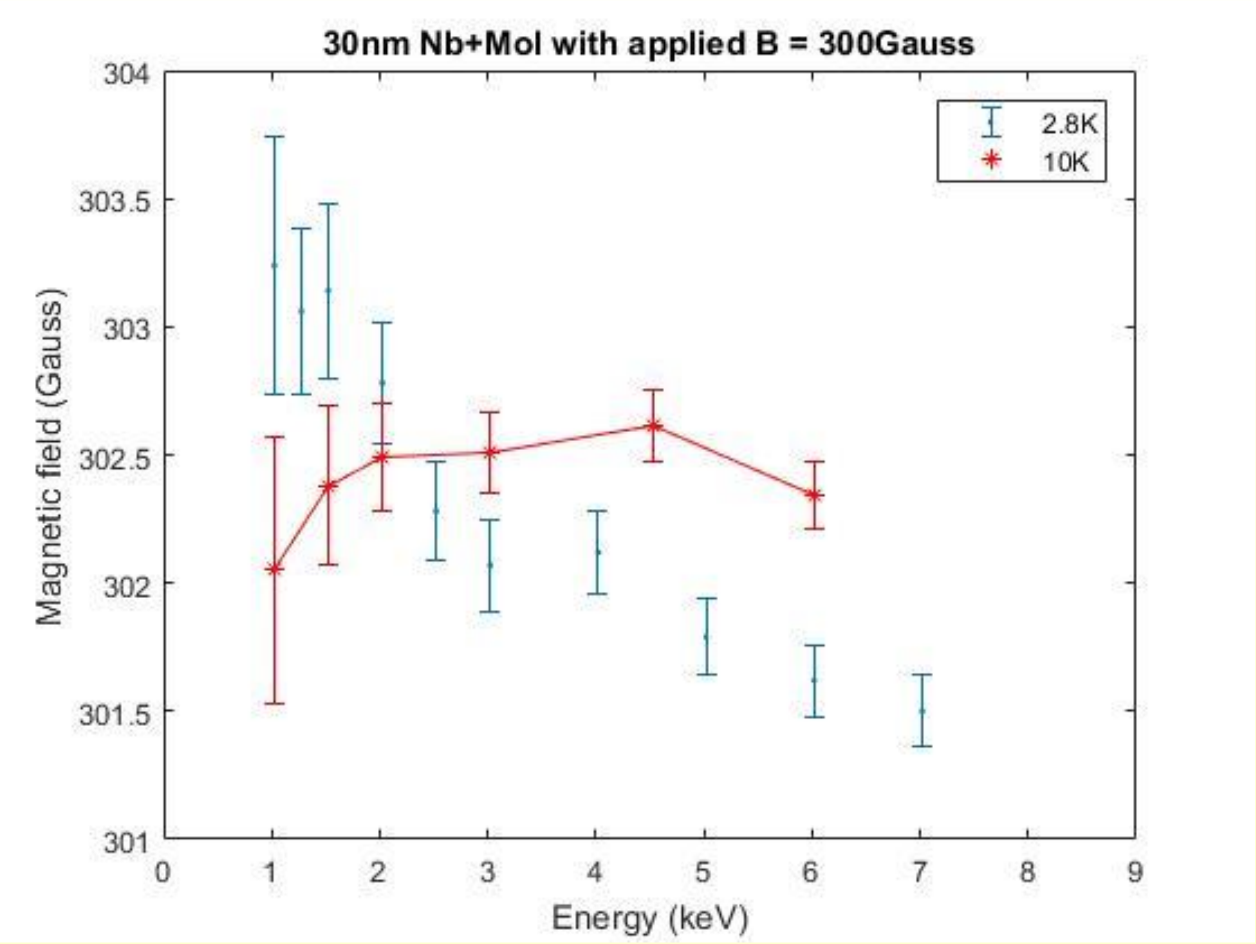


$$\omega_\mu(z) = \gamma_\mu B_{loc}(z)$$

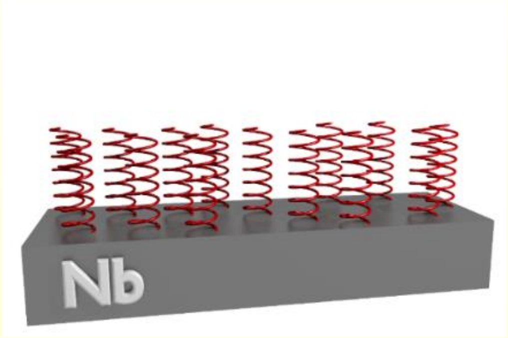
→ Characteristic lengths of the sc λ, ξ

<B> vs <z> ⇒ B(z)

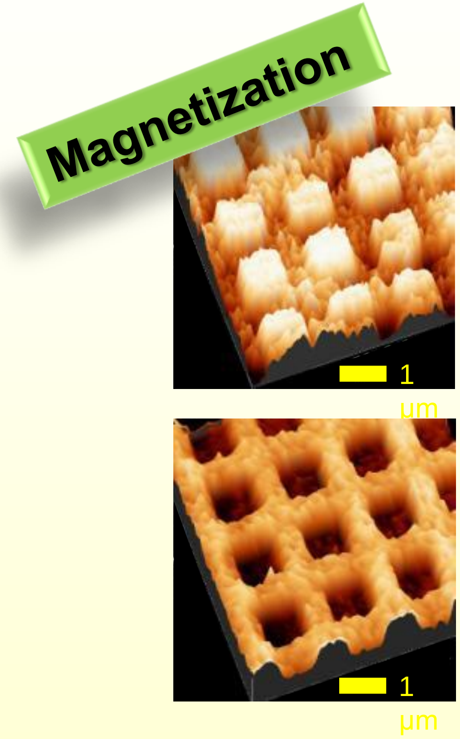
30nm Nb sample under 300G



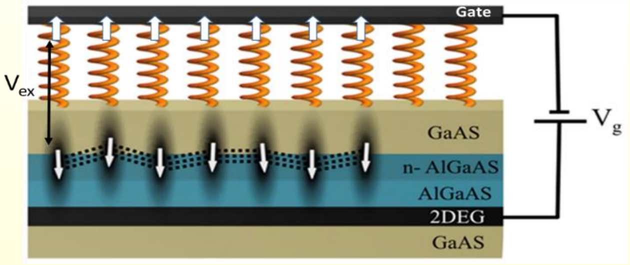
Inducing magnetic impurities



New Journal of Physics 2016



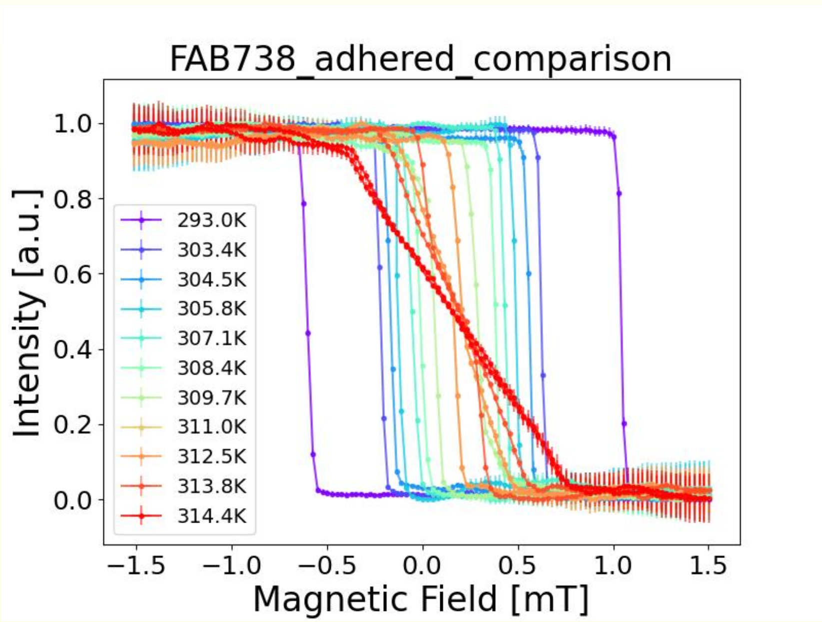
Nature Communication 2017

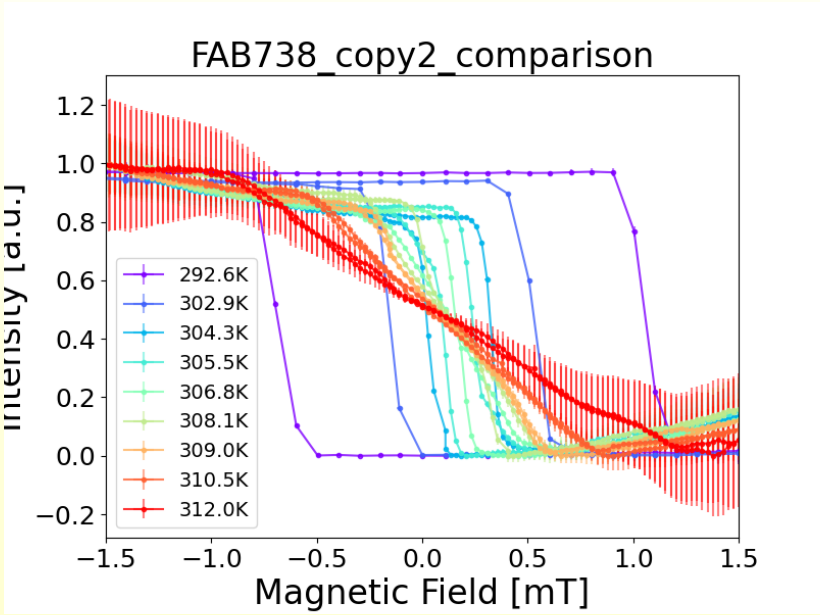


JPC letters 2019

Manipulation of Skyrmions

Pt (3) / Au (5)
Ta (2)
MgO (2)
CoFeB (0.9)
Ta (5)

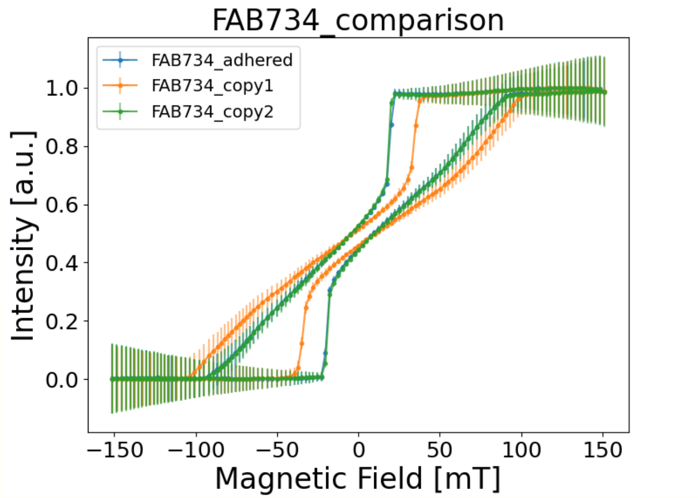


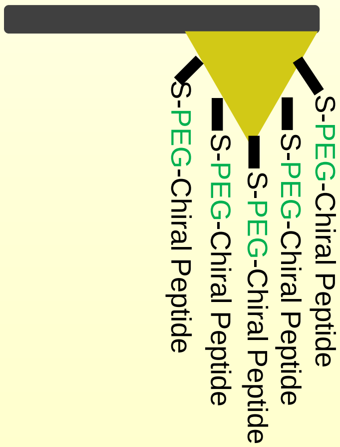


In collaboration with
Mathias Kläui

Future ideas

- Paramagnets
- Ferromagnets
- Anti-ferromagnets
- Superconducting and magnetics
- Multi-gated devices





Long Range Spin exchange interactions in chiral molecules can be used to control measure and manipulate quantum magnetic impurities.

Ron Naaman, Yossi Paltiel, David H. Waldeck;
Chiral molecules and the electron spin;
Nature Review Chemistry
DOI: 10.1038/s41570-019-0087-1 (2019).