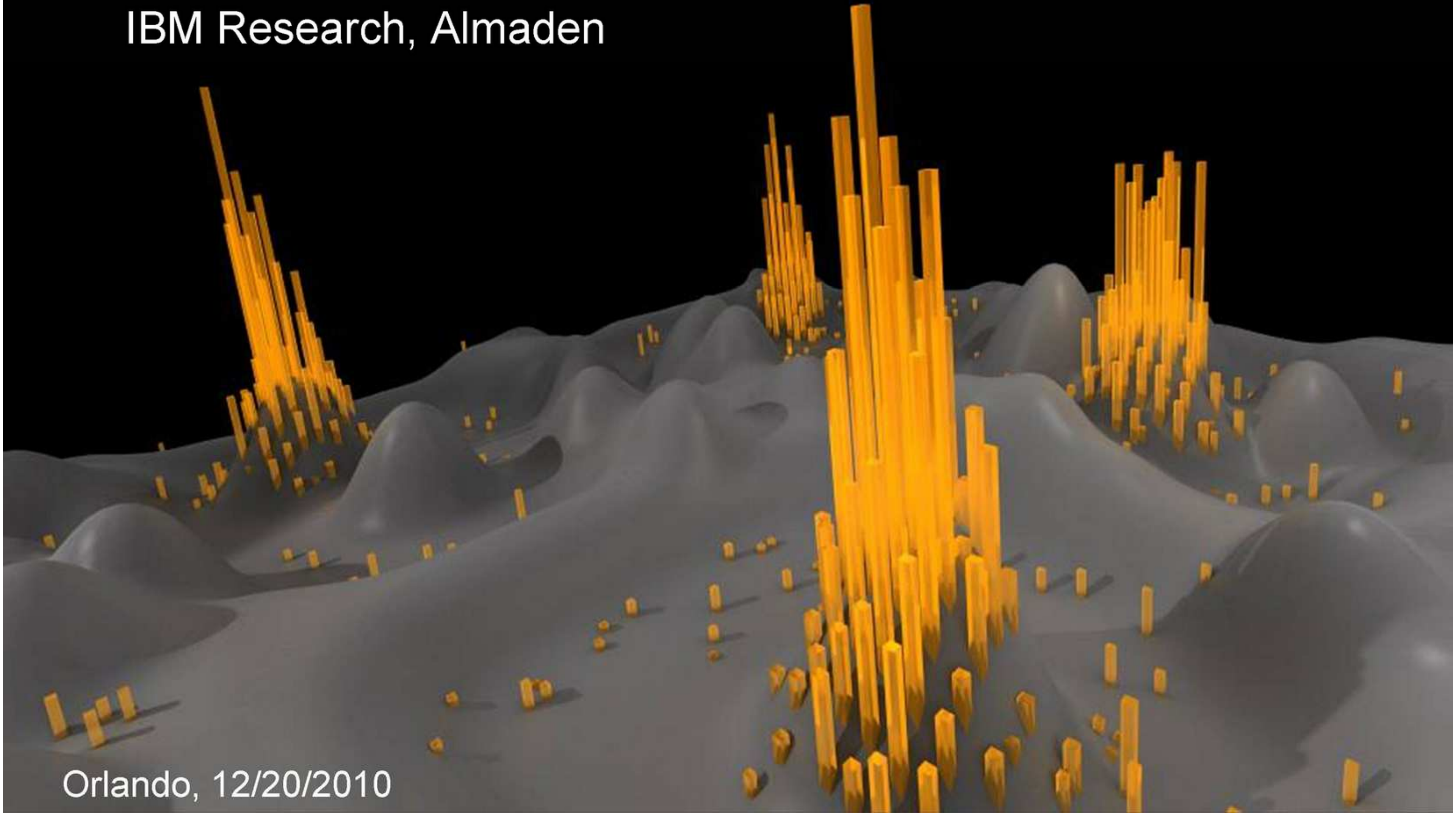
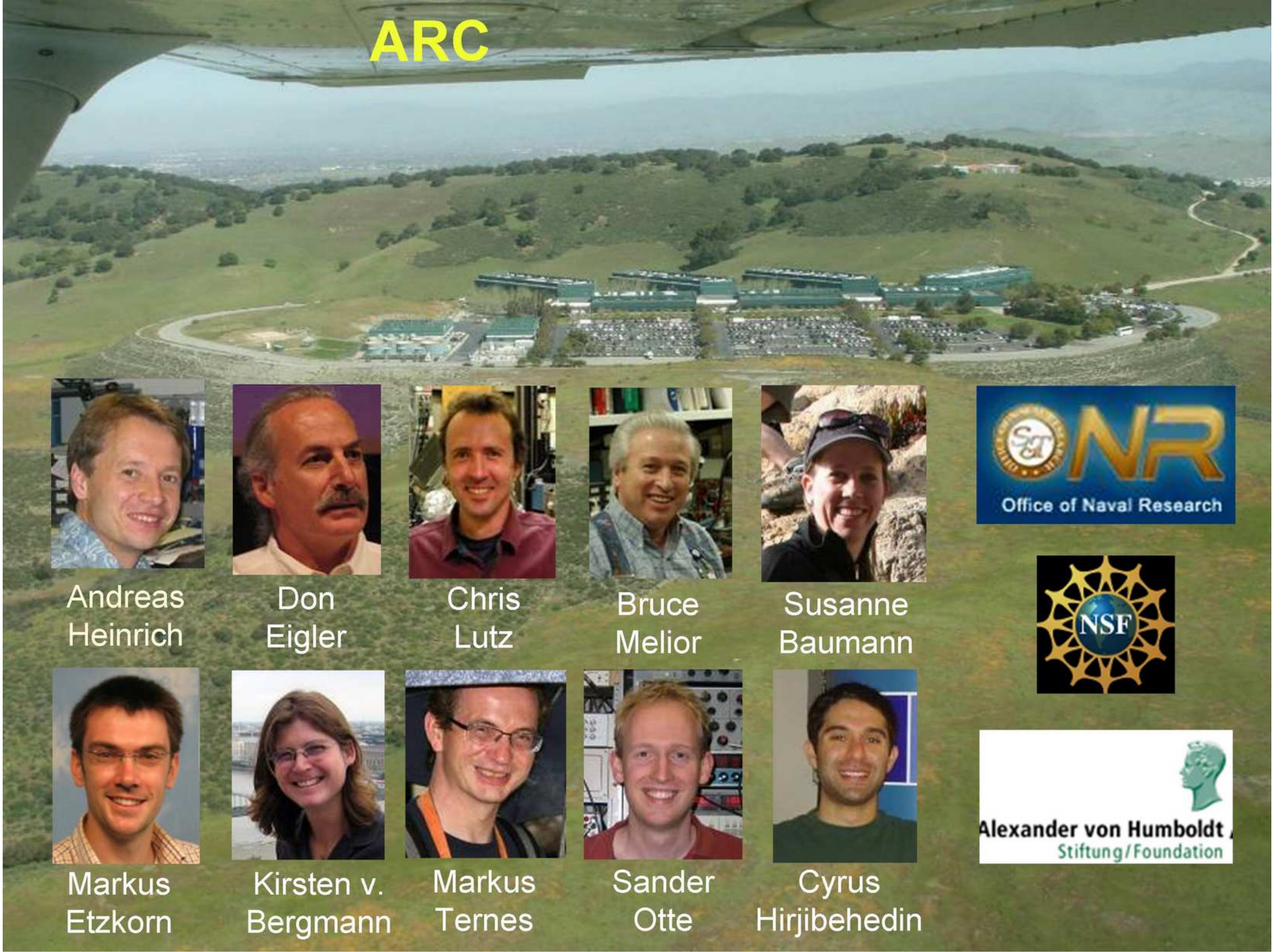
Quantum Tunneling of Magnetization in individual atoms

Sebastian Loth
IBM Research, Almaden



Orlando, 12/20/2010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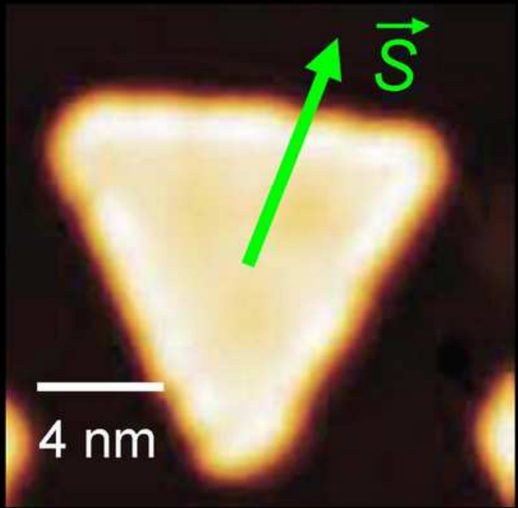
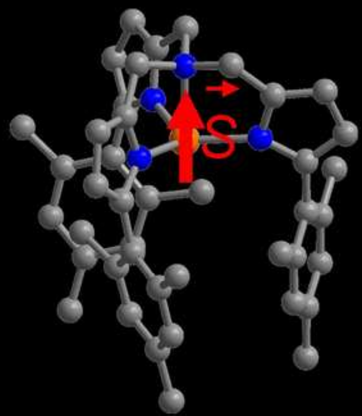
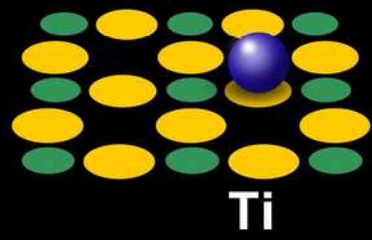
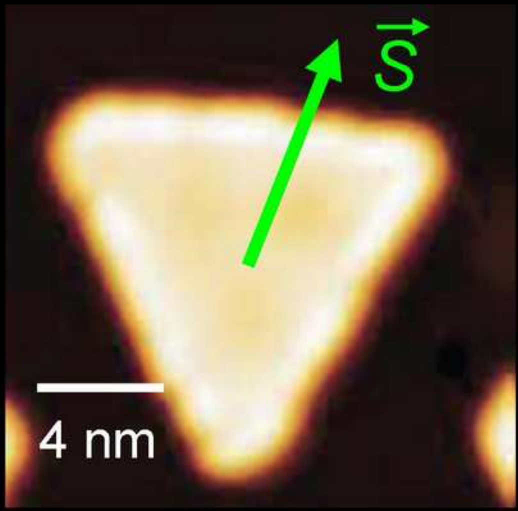
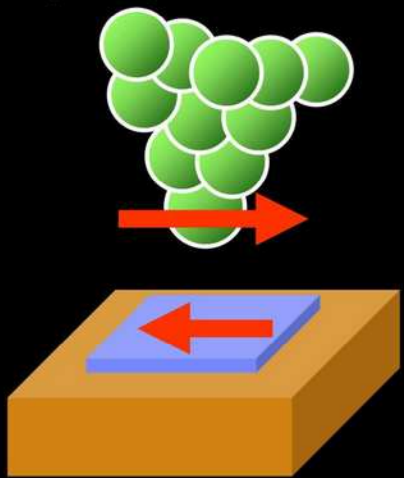
Classical Magnets	Quantum Magnets	Spins
		
Co island on Cu(111)	$[(tpa^{Mes})Fe]^-$ molecule	Ti atoms on Cu_2N / Cu(100)
~ 3000 atoms S > 1000	1 magnetic atom **$S \approx 2$**	1 atom S = ½
Classical Magnetization	Magnetic Tunneling	Kondo effect
Oka *et al.* Science (2010)	Freedman *et al.* JACS (2010)	Nature Physics (2008)

Magnetism in STM: Magnetic Islands



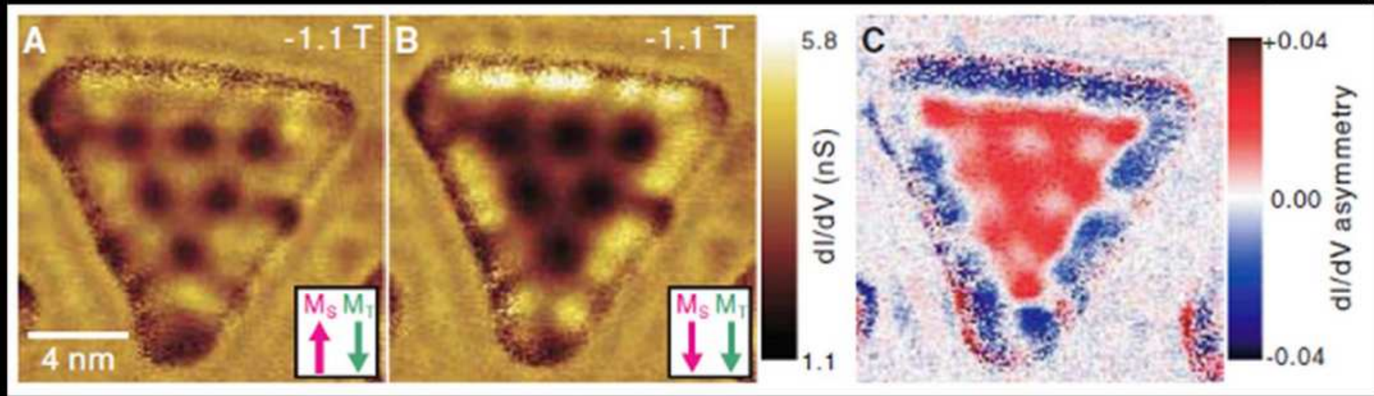
Oka *et al.* Science (2010)

Spin-polarized tip



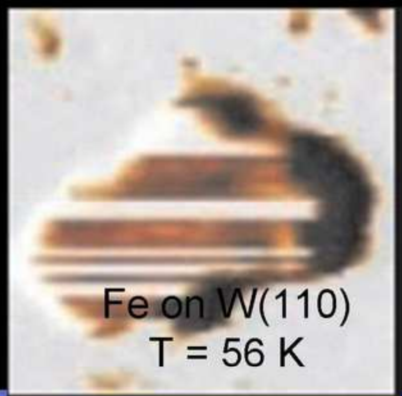
- **Spin-polarized STM tips resolve the magnetric orientation**
  - Single domain magnets: One Macro-'Spin'

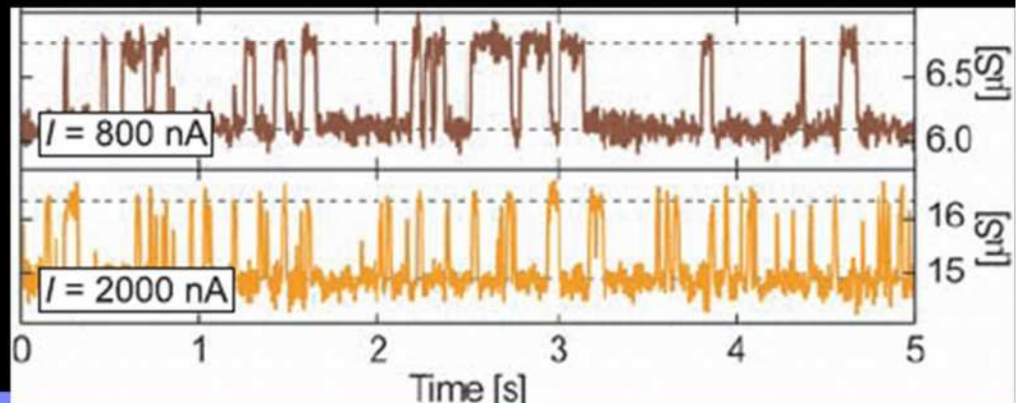
Oka *et al.* Science (2010)



  - Thermally-induced or Spin-torque assisted switching observable.

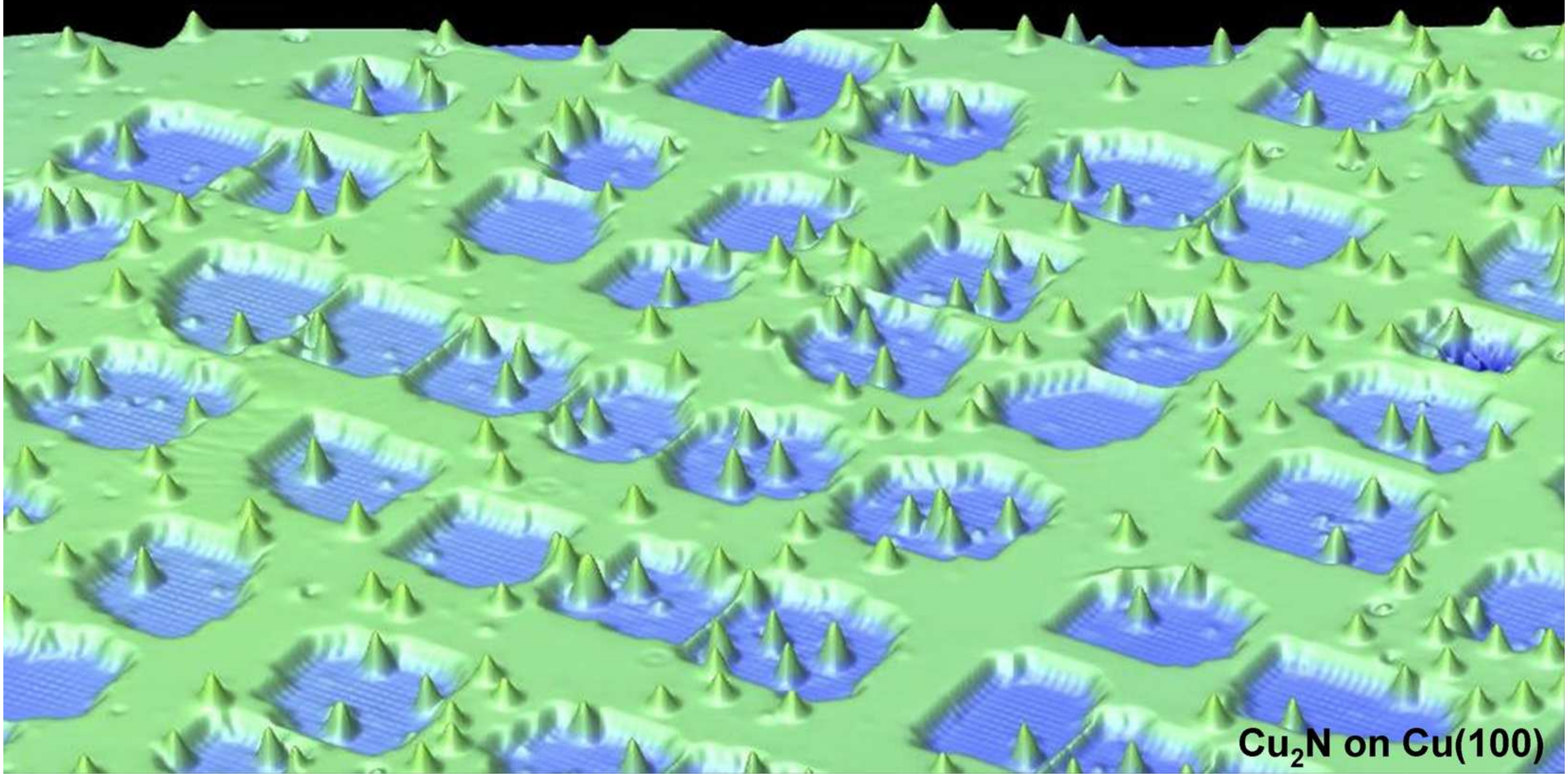
Krause *et al.* Science (2007)





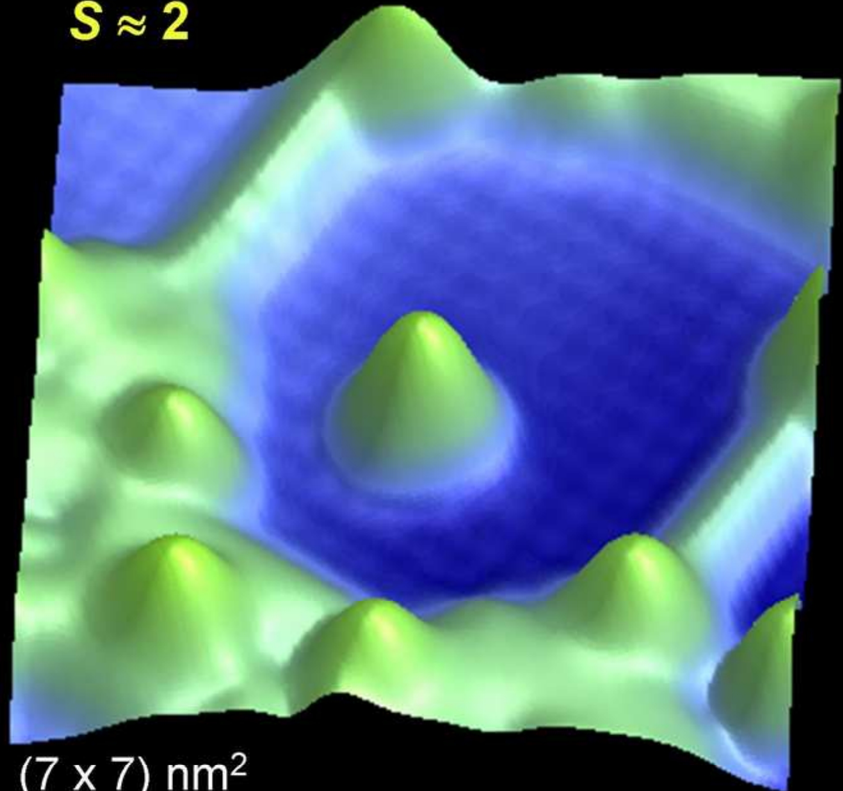
Magnetism in STM: Individual atoms

- Transition metal atoms (Fe, Mn, Cu)
- Substrate Cu_2N on Cu(100)
- Quantum mechanical description of spins necessary

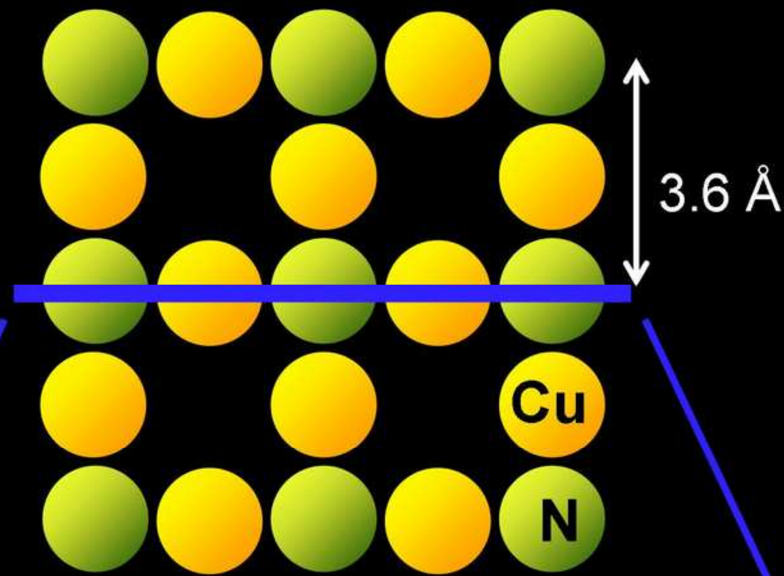


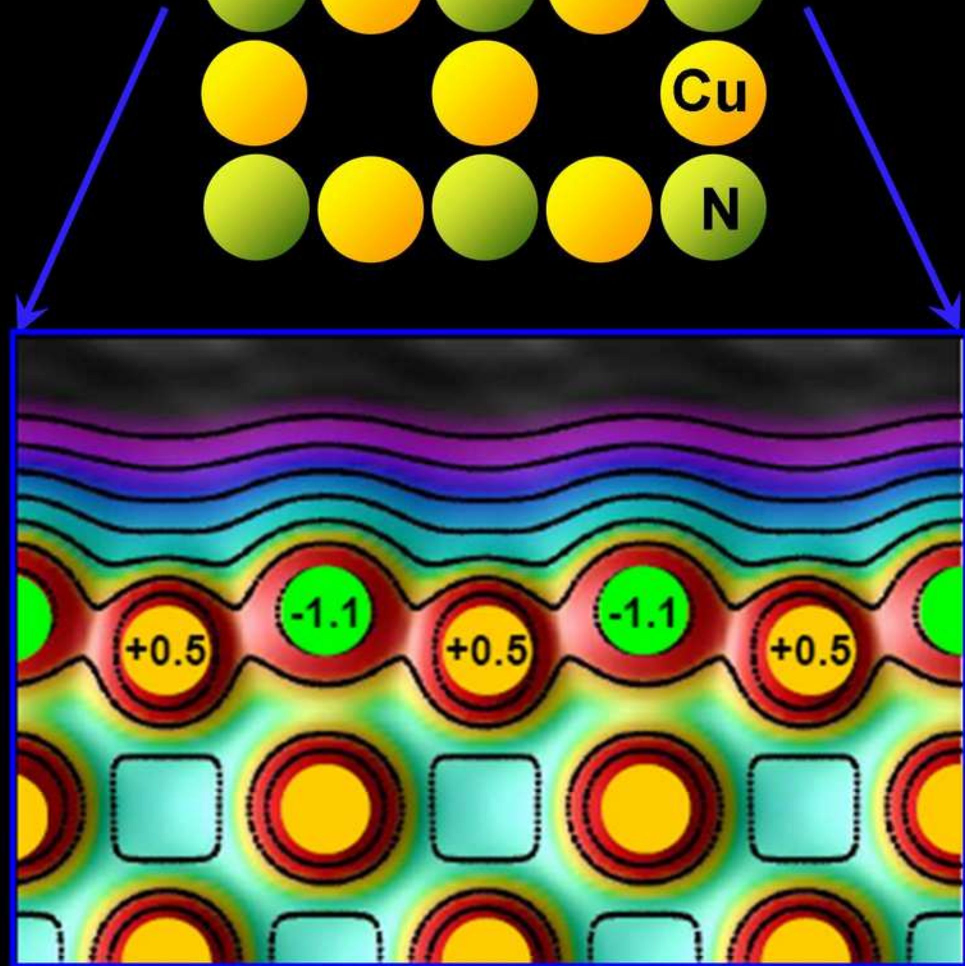
Transition metal atoms on Cu_2N

Mn − Cu_2N
1 magnetic atom
***S* ≈ 2**



(7 x 7) nm²

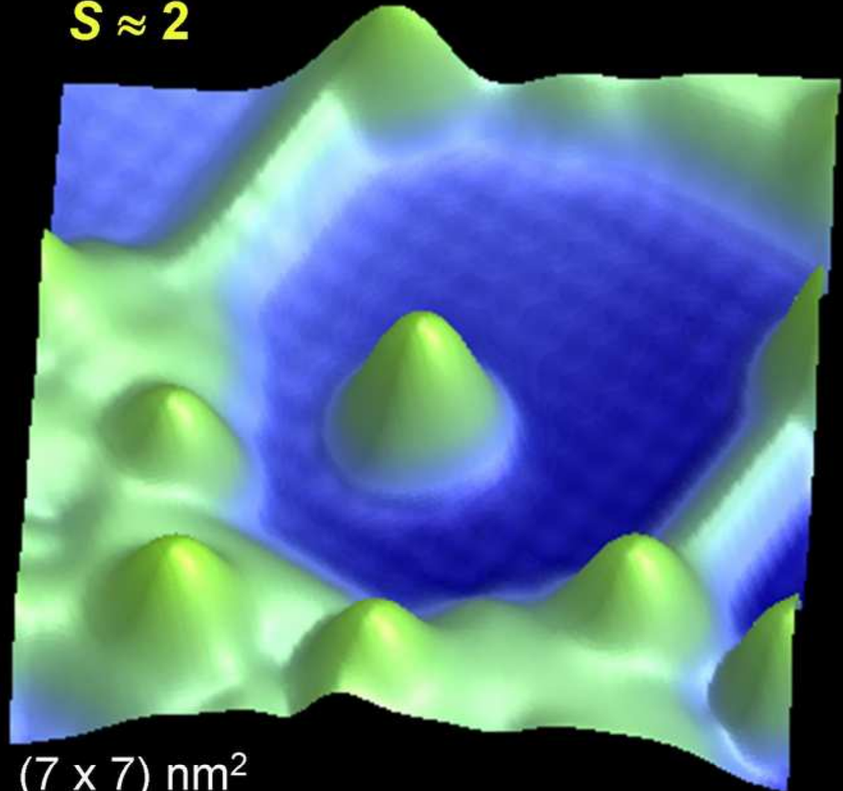




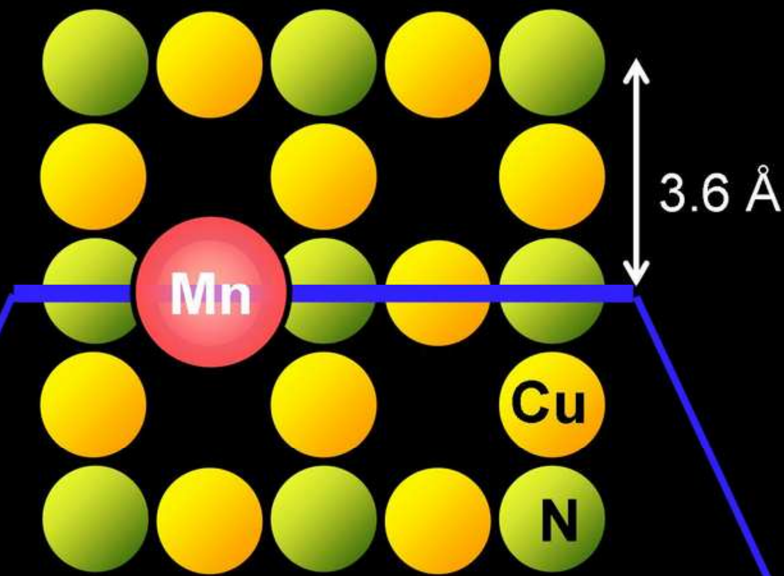
- **N forms planar molecular network**

Transition metal atoms on Cu_2N

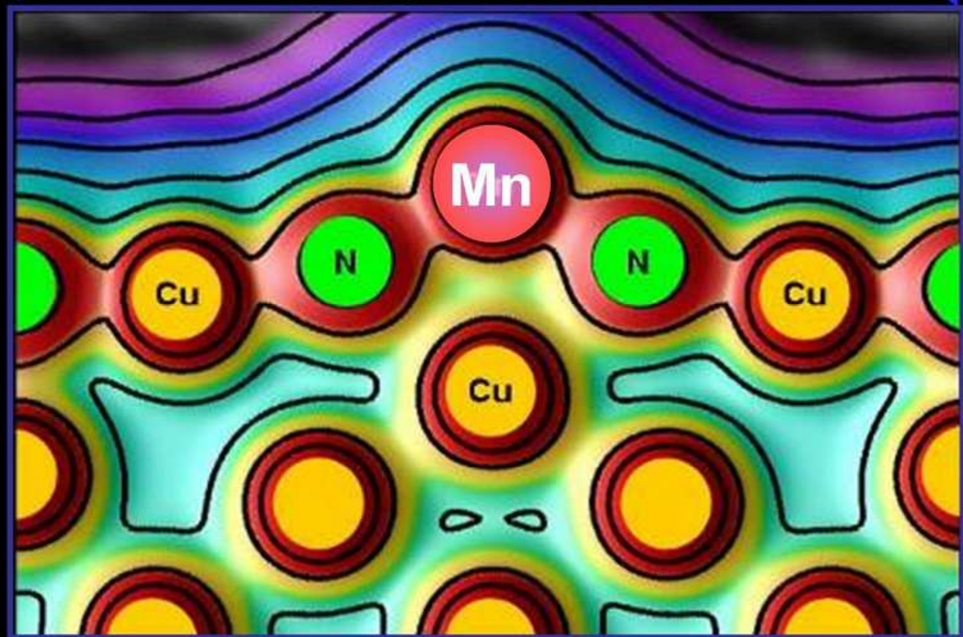
$Mn - Cu_2N$
1 magnetic atom
***S* ≈ 2**



(7 x 7) nm^2

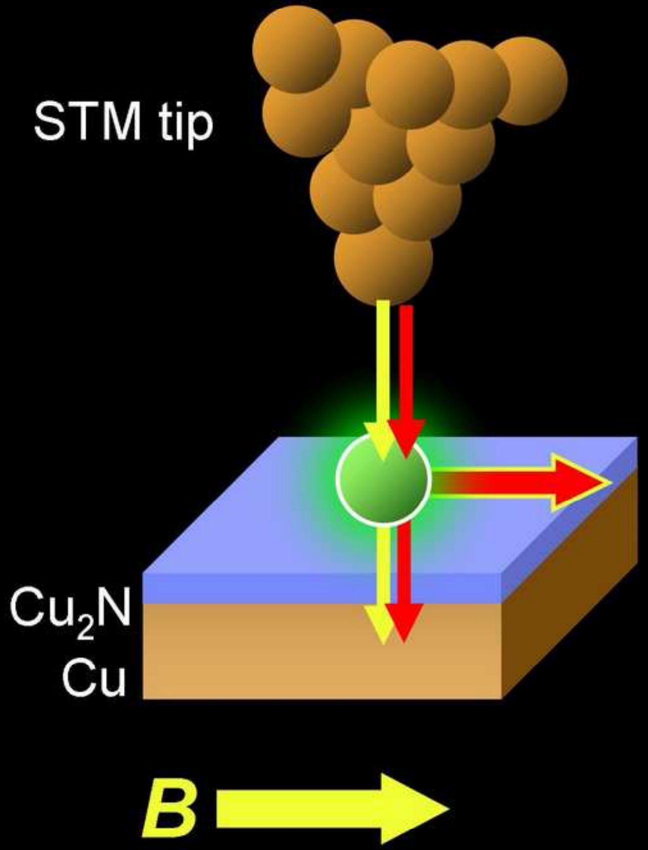


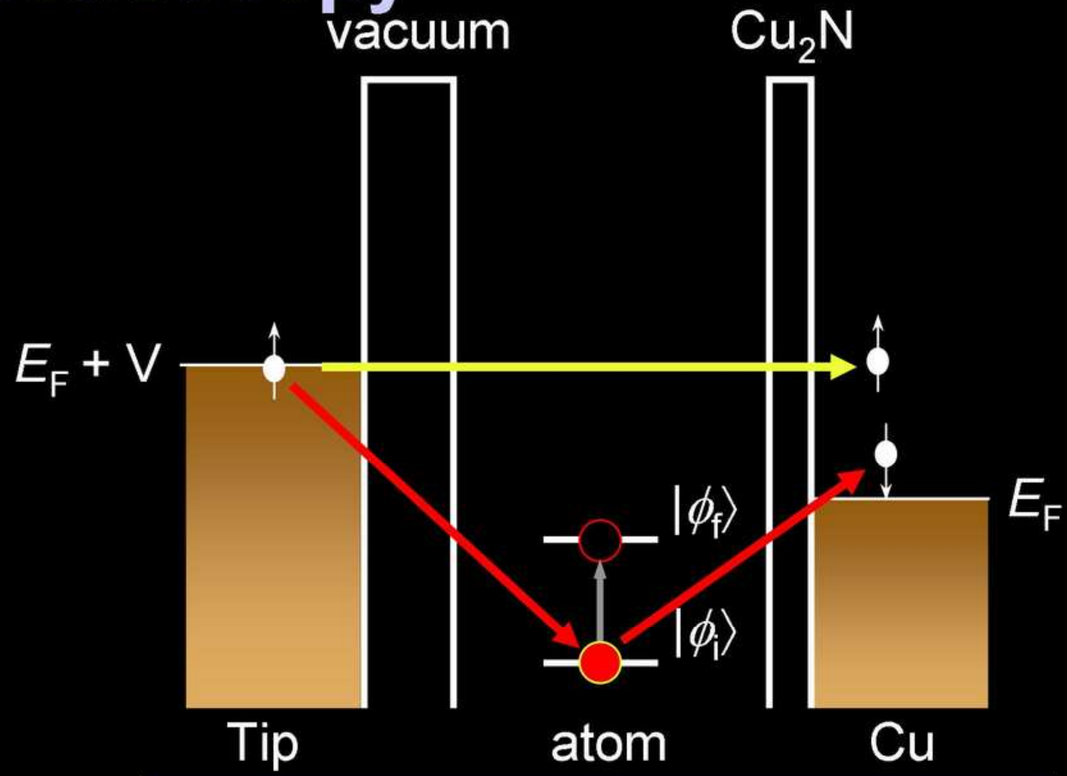
DFT calculations by C.-Y. Lin and B.A. Jones



- **N forms planar molecular network**
- **Mn is held in this network**

Spin excitation spectroscopy



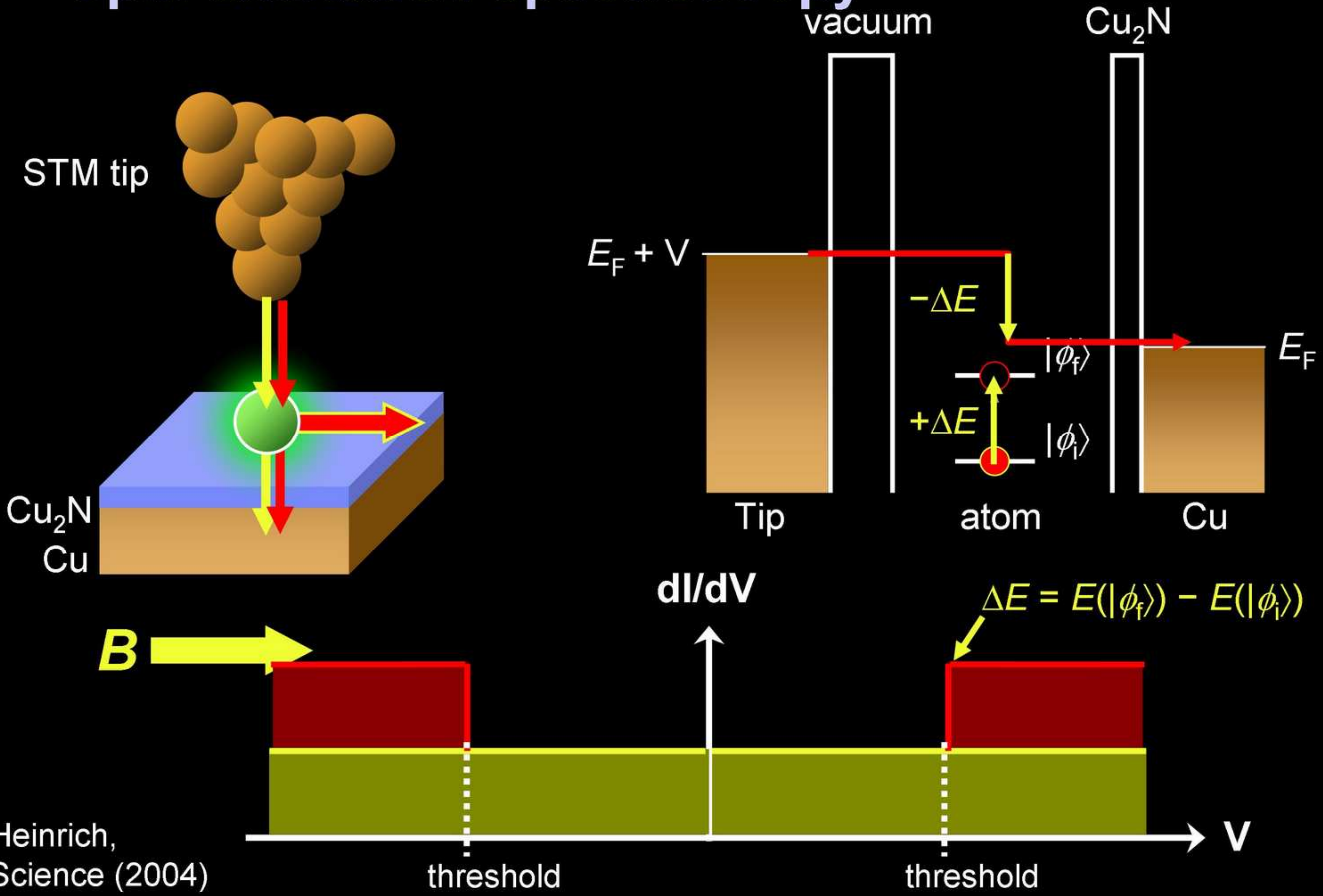


Inelastic co-tunneling
Interaction Hamiltonian:

$$\vec{s} \cdot \vec{S} + u$$

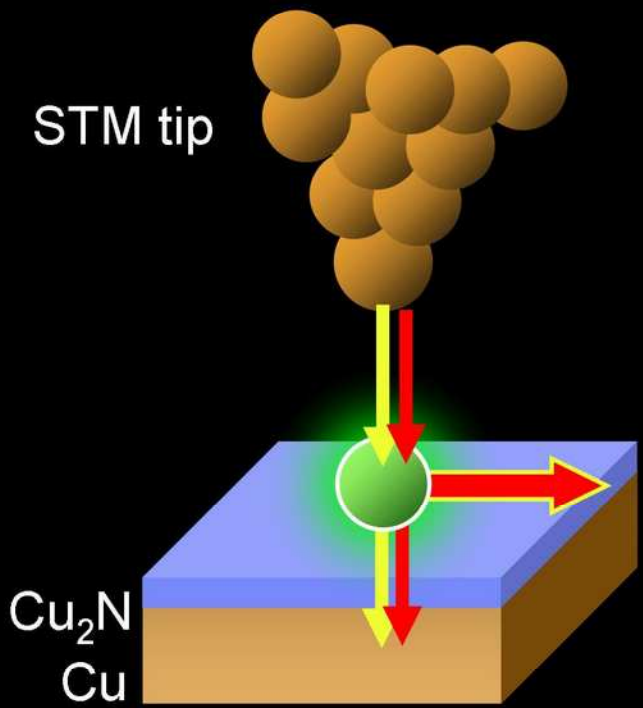
e.g. Schrieffer, Wolff Phys. Rev. **149** 491 (1966)

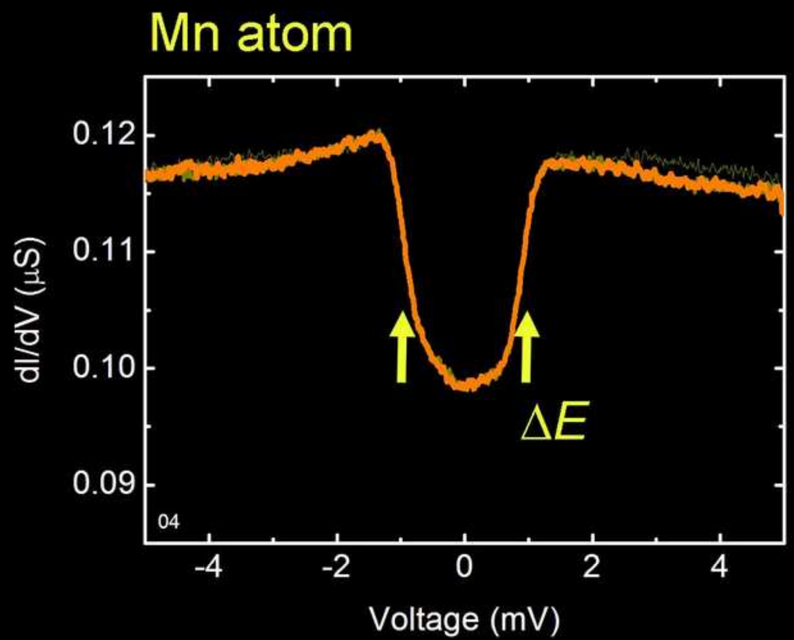
Spin excitation spectroscopy

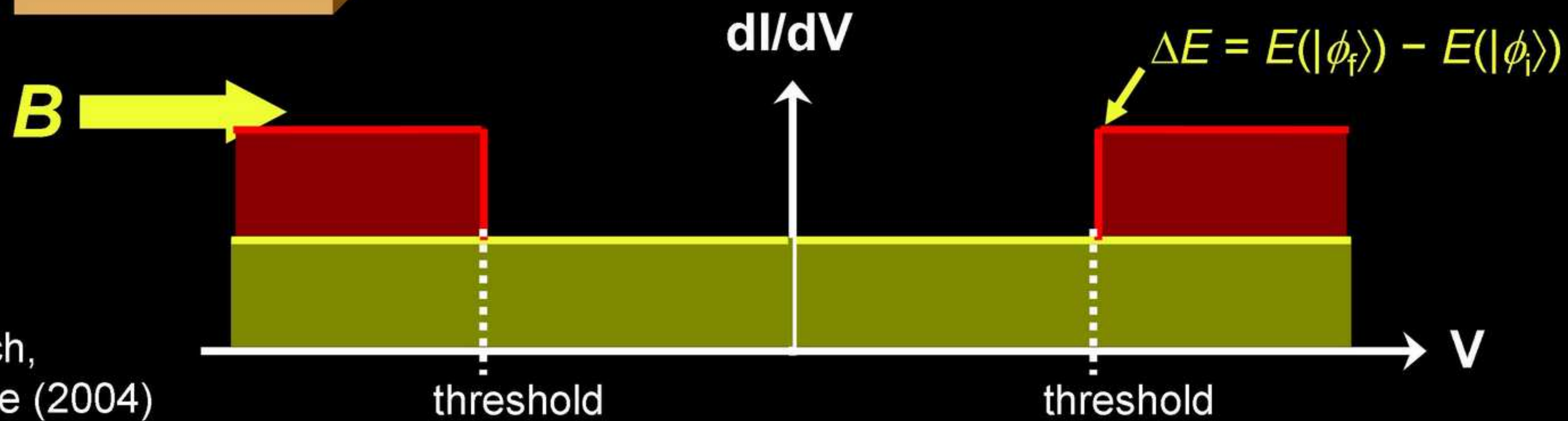


Heinrich,
Science (2004)

Spin excitation spectroscopy

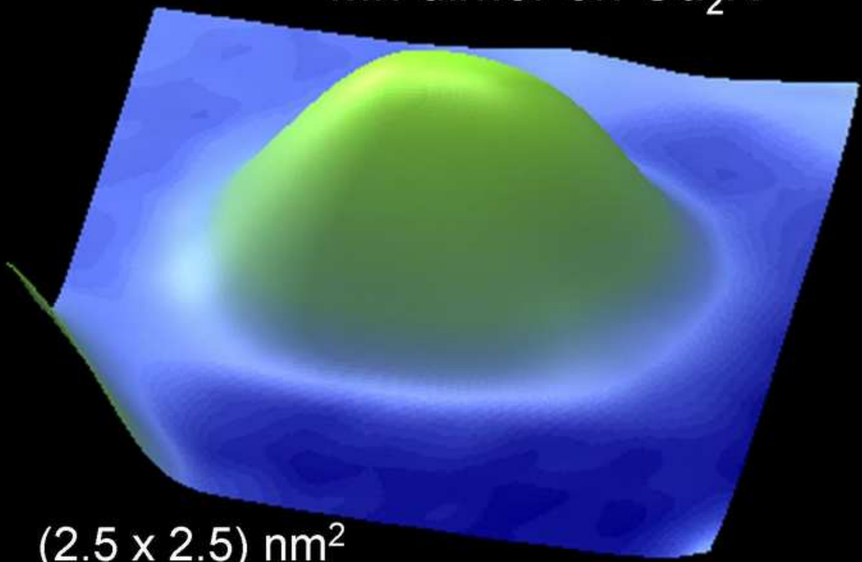


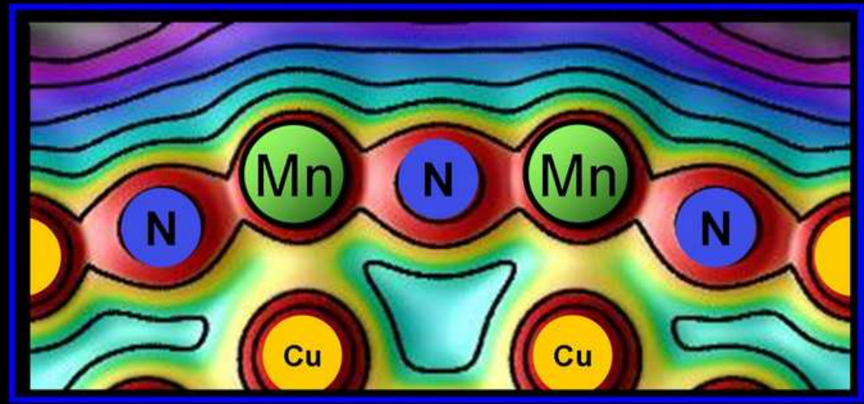




Heinrich, Science (2004)

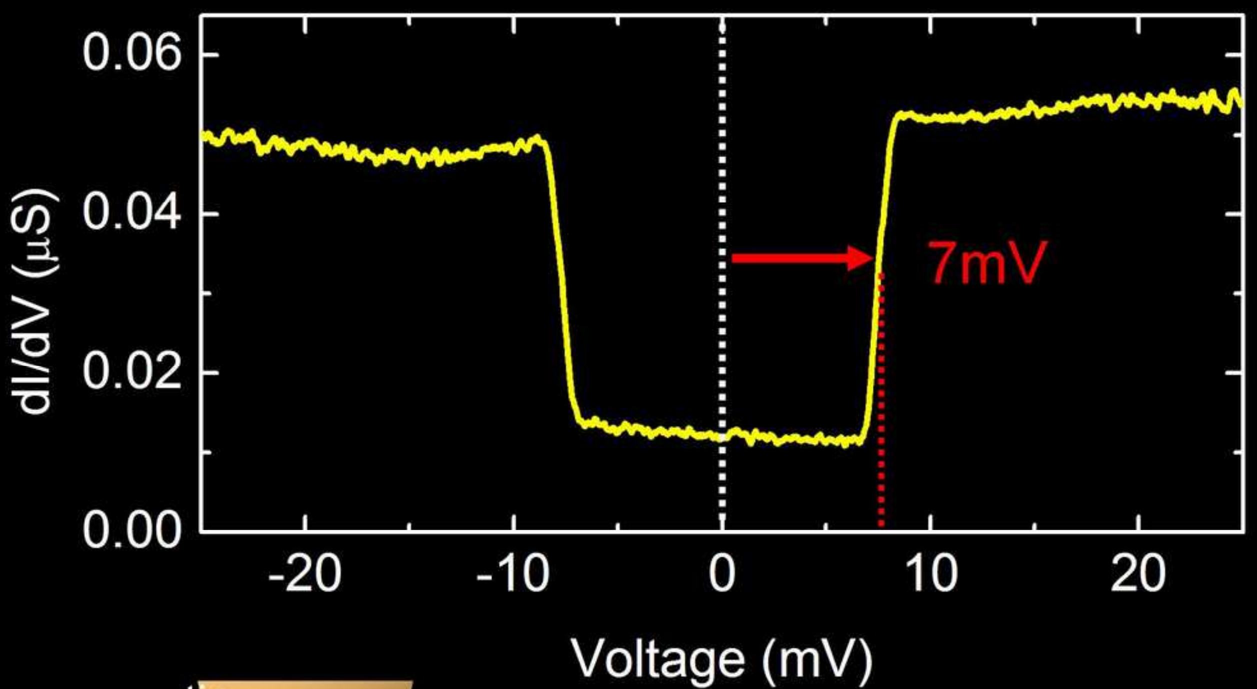
Spin excitations in Mn-N-Mn dimer

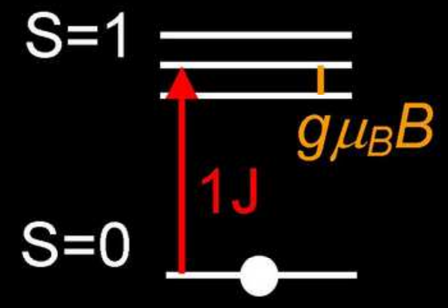


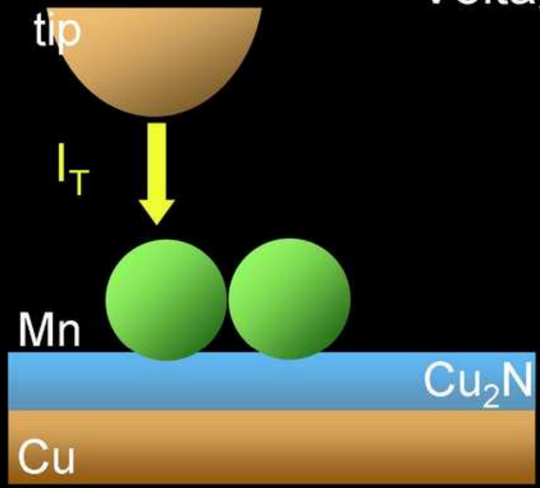


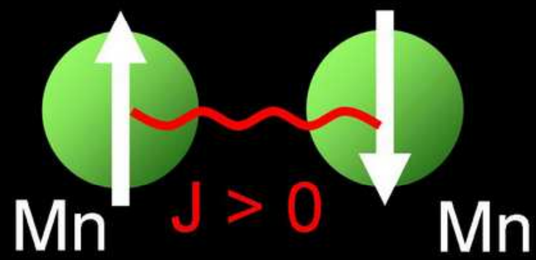
- **Polar covalent bonds between Mn and N on Cu_2N**
- **surface-embedded molecular magnet (?)**

Spin excitations in Mn-Mn dimer



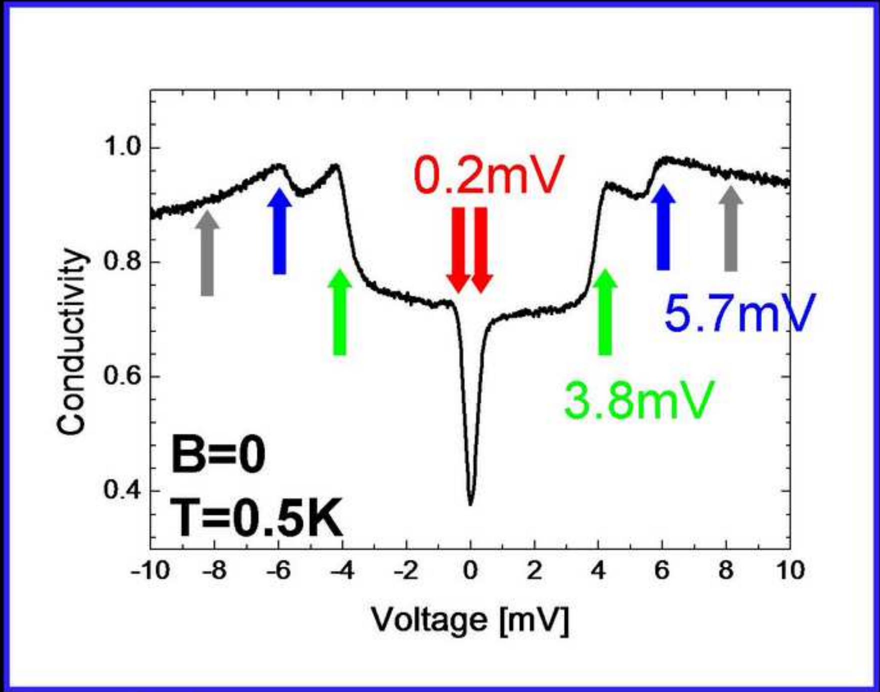




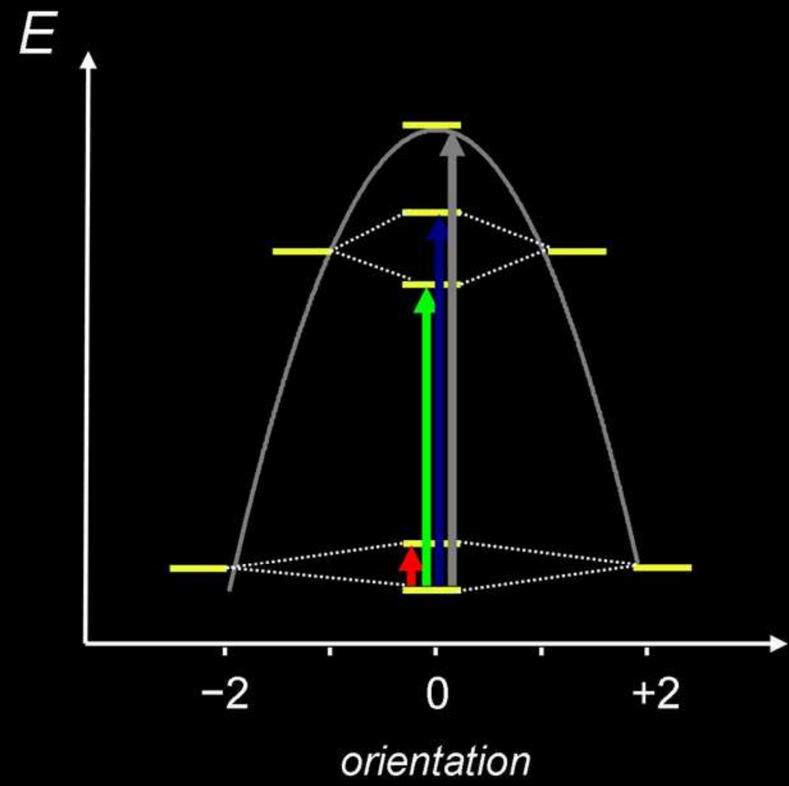


Hirjibehedin et al., Science (2006)

Fe on Cu-site on Cu_2N



Fe − Cu_2N
1 magnetic atom
***S* ≈ 2**



$$H = -g\mu_B B_z S_z + DS_z^2 + E(S_x^2 - S_y^2)$$

$S = 2$, $g = 2.11$, D = -1.5 meV, E = 0.3meV

- Same binding site as Mn
- Large uni-axial magnetic anisotropy
- Large transverse anisotropy that causes spin state mixing

Hirjibehedin, *et al.* Science (2007)

Exploring individual spins

Energetics:

Spin magnitude, magnetic anisotropy, Spin Hamiltonian

Science 306, 466 (2004)
Science 317, 1199 (2007)

Dynamics:

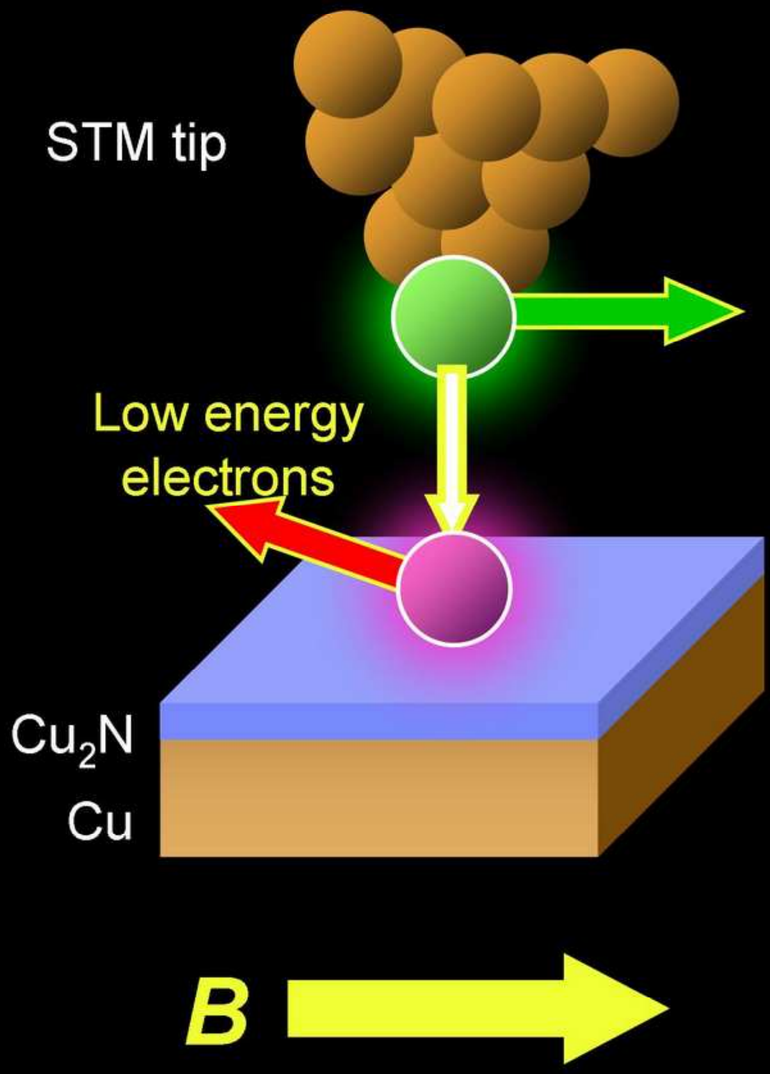
Spin lifetime, scattering mechanisms, *coherent evolution*

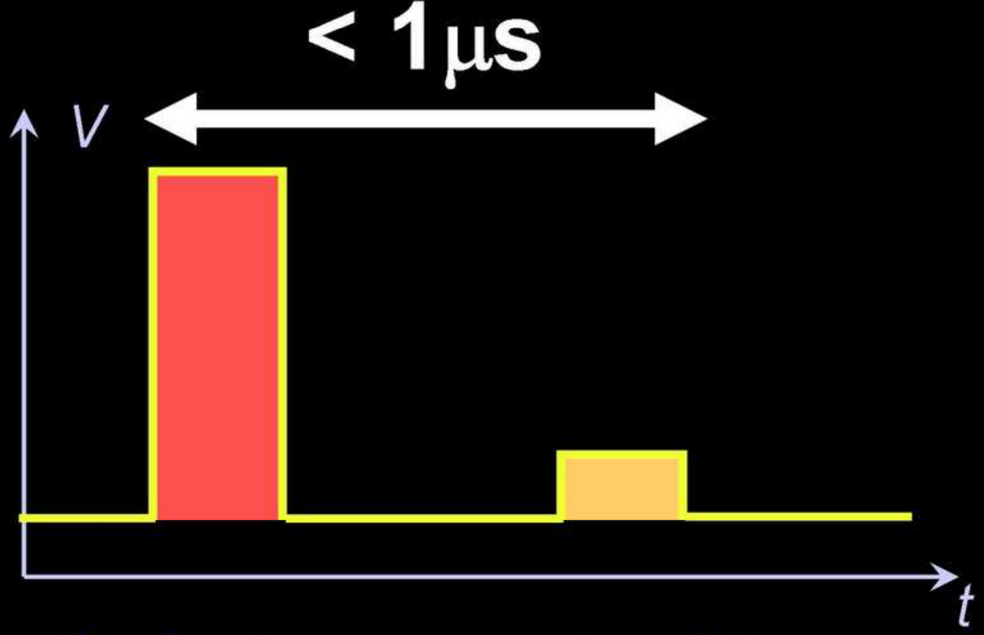
Nature Physics, **6** 340 (2010)
Science, **329** 1628 (2010)

Structure:

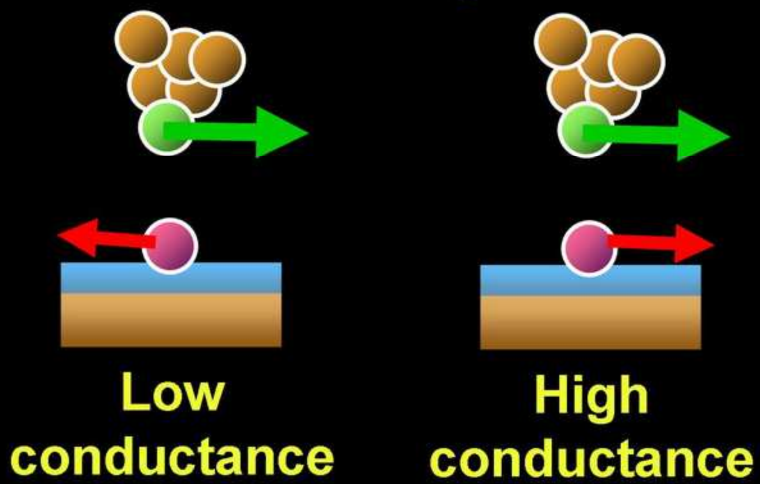
Binding site, nearby atoms, free carrier density, local environment

Measuring the dynamics of a single spin

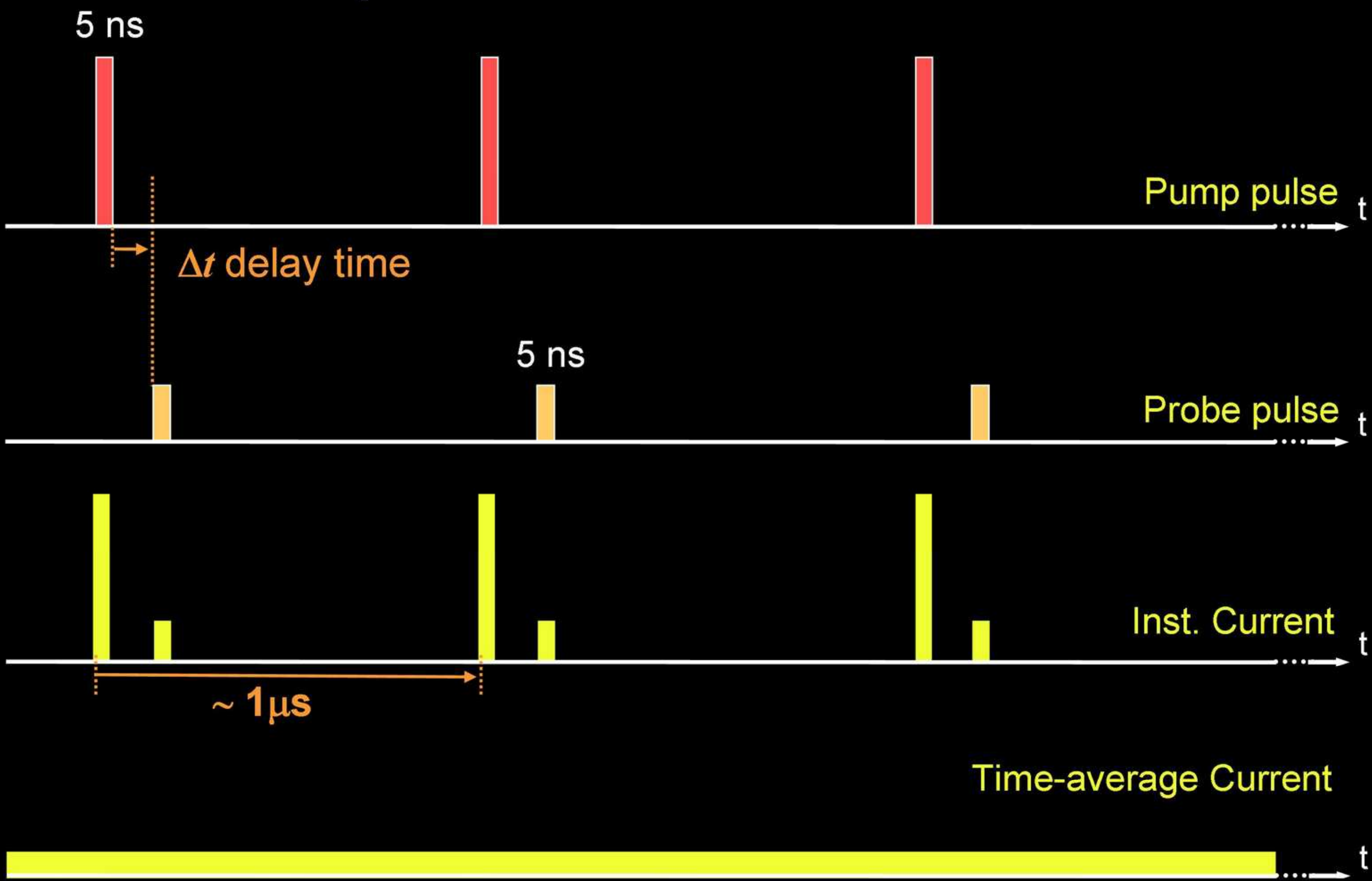




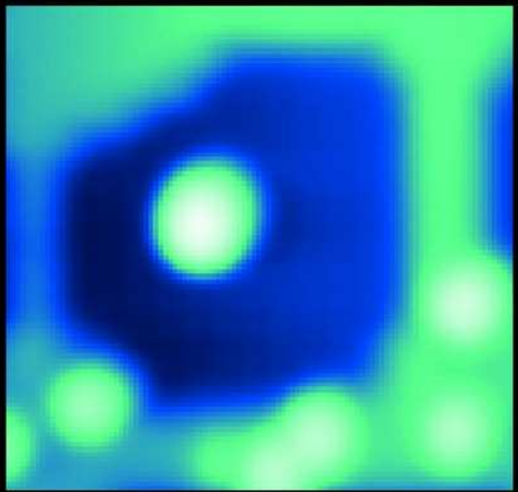
Read-out uses magnetoresistance:



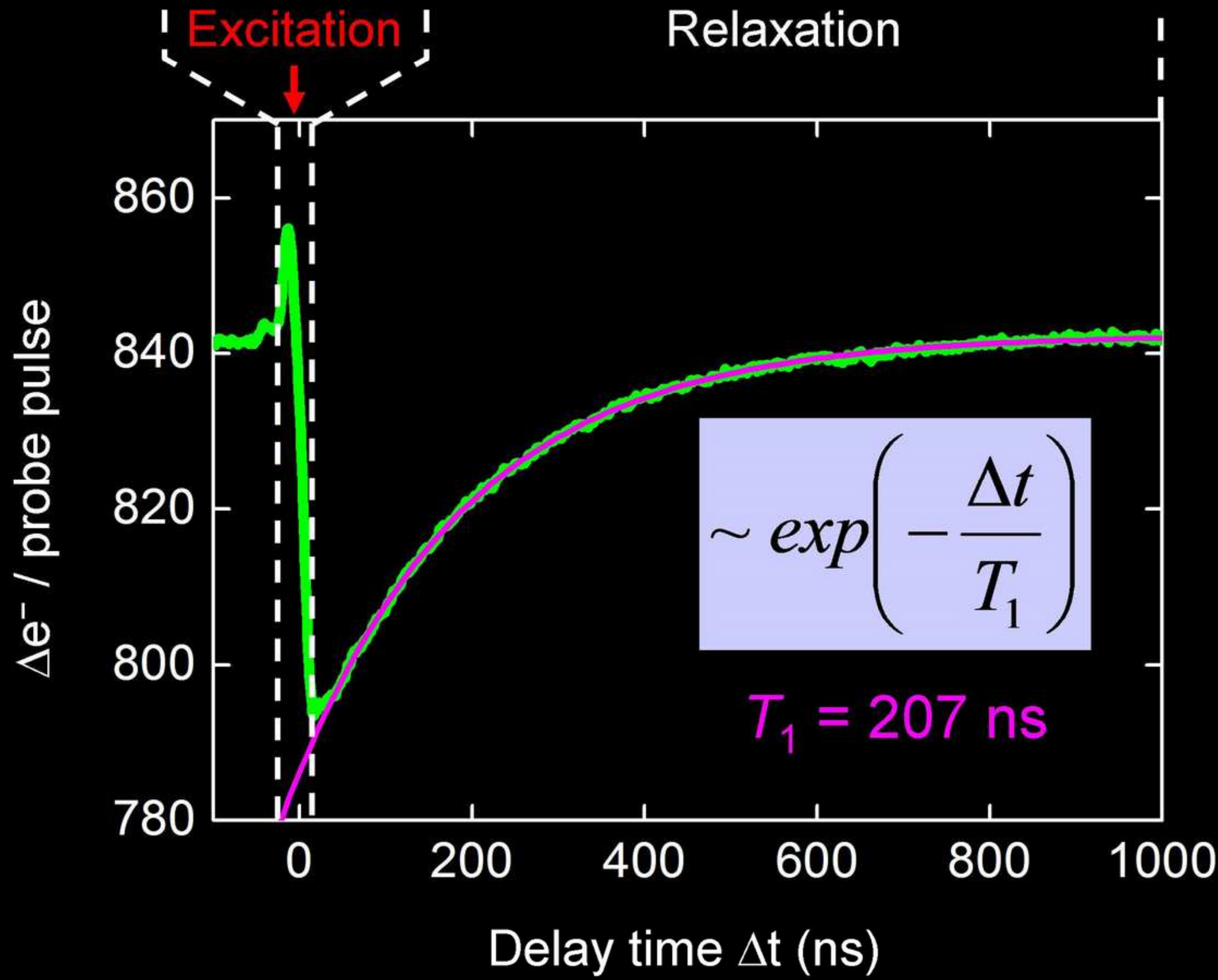
Electrical Pump – Probe scheme



Pump – Probe Measurement of a single spin

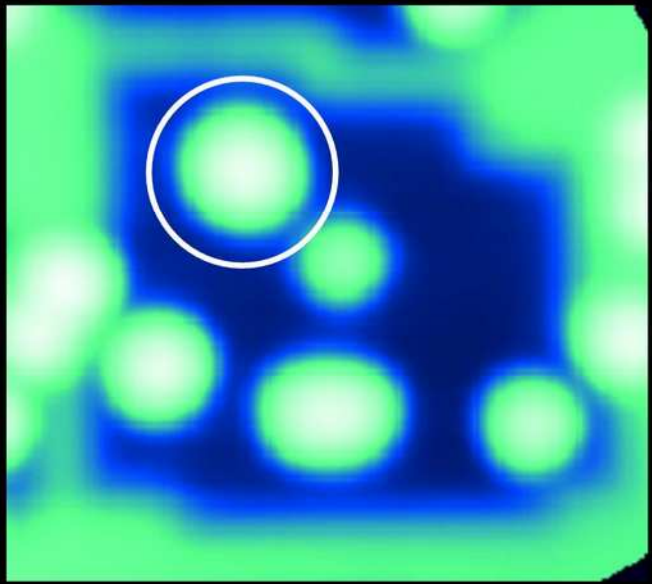


Close spaced
Fe-Cu dimer
B = 6.5T

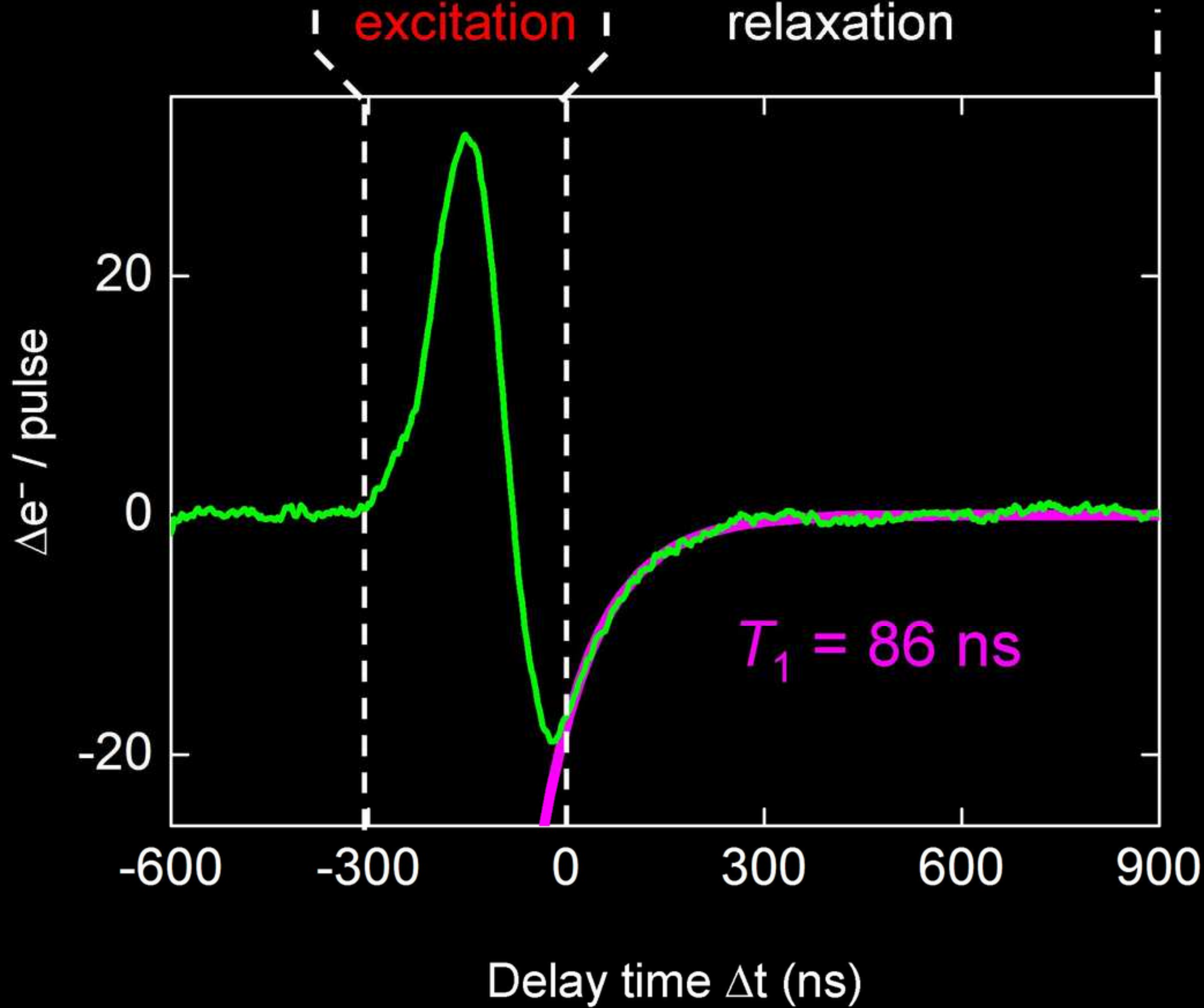


Science (2010)

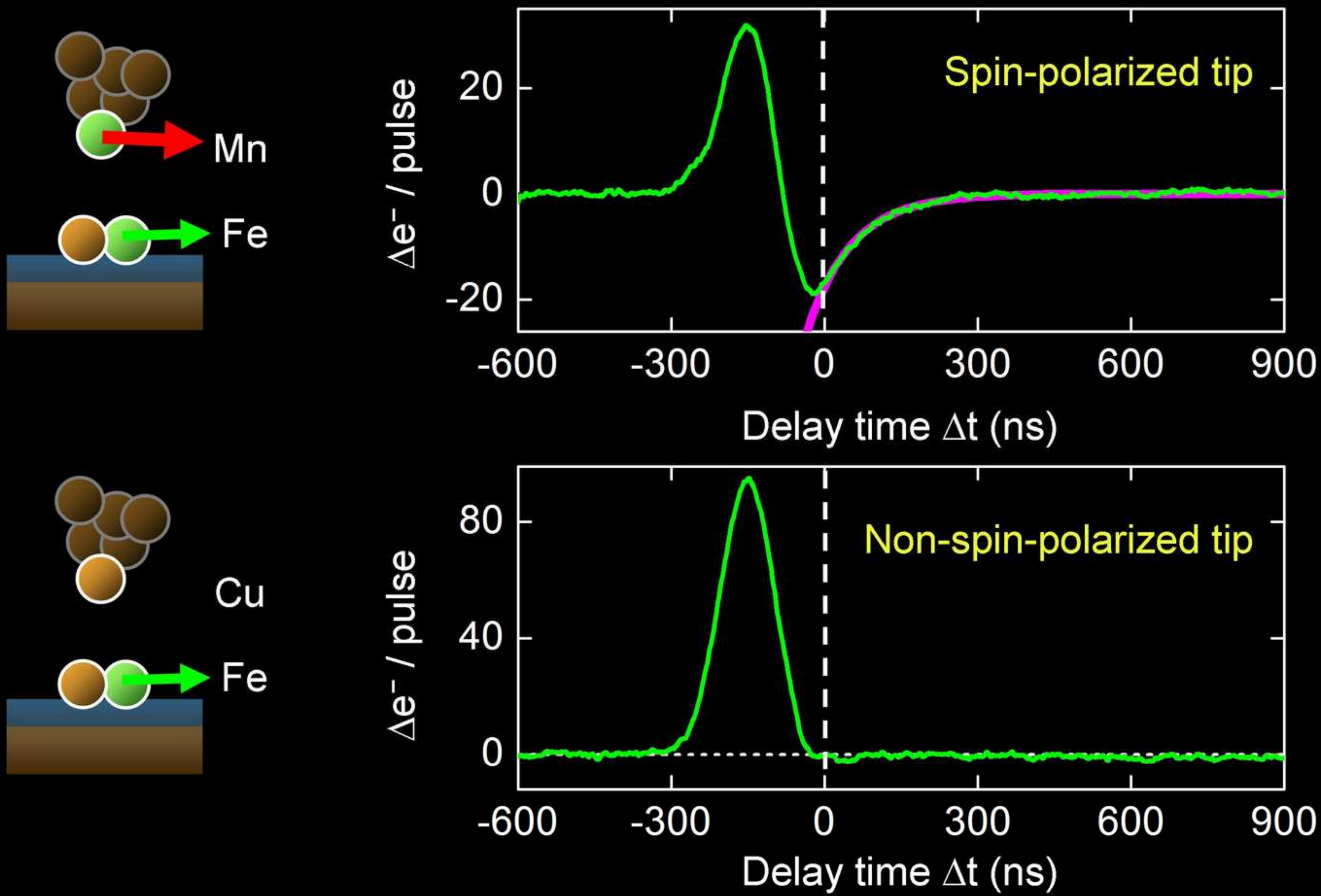
Pump – Probe Measurement of a single spin



Different Fe-Cu dimer
B = 7T



It is time dependent, but is it spin?



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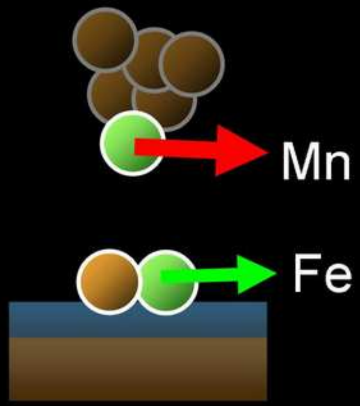
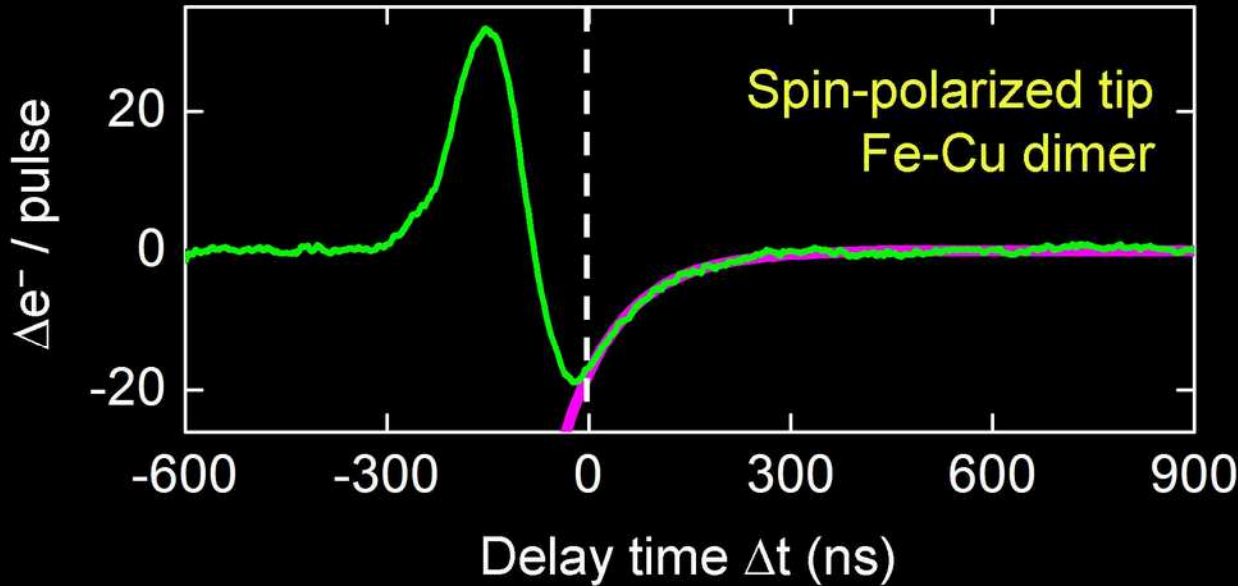
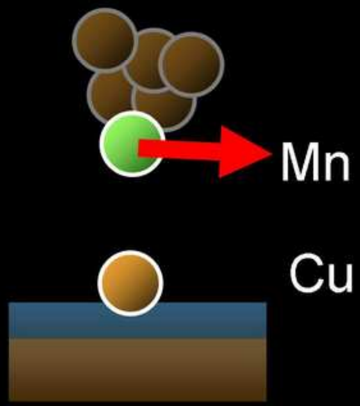
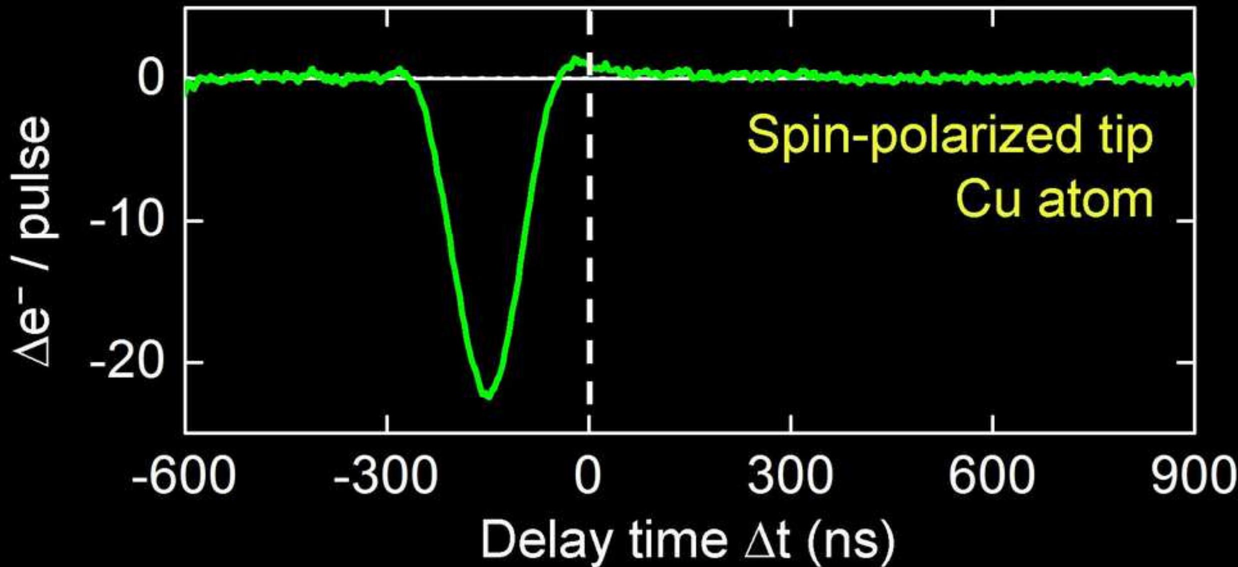


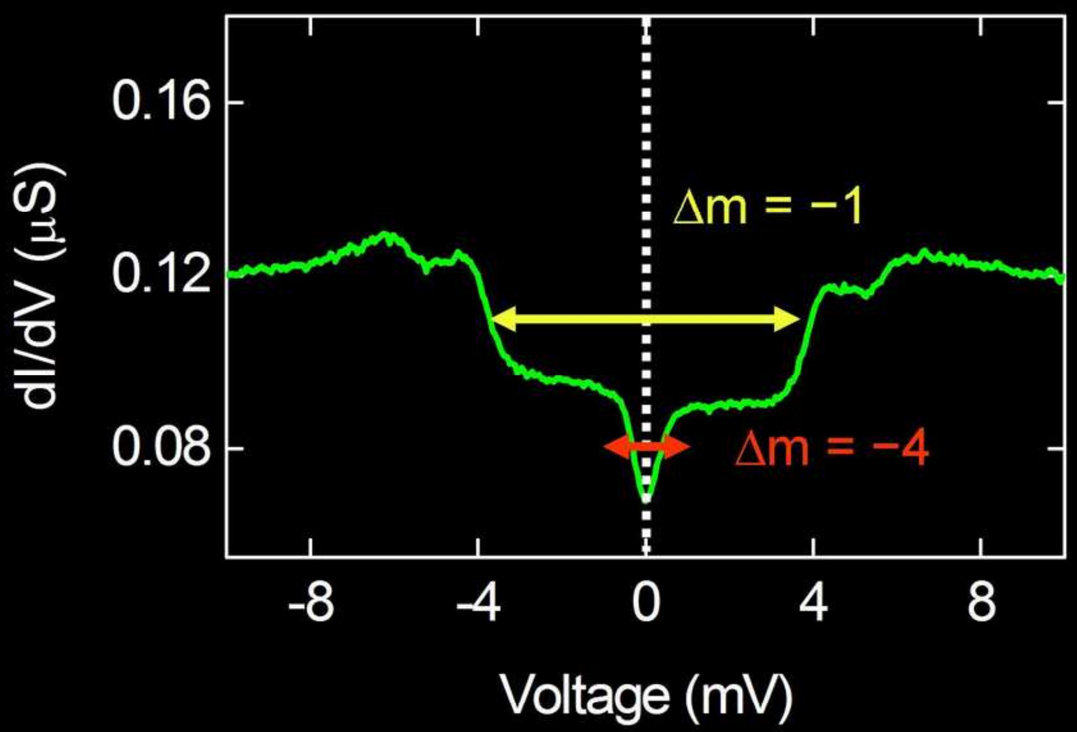


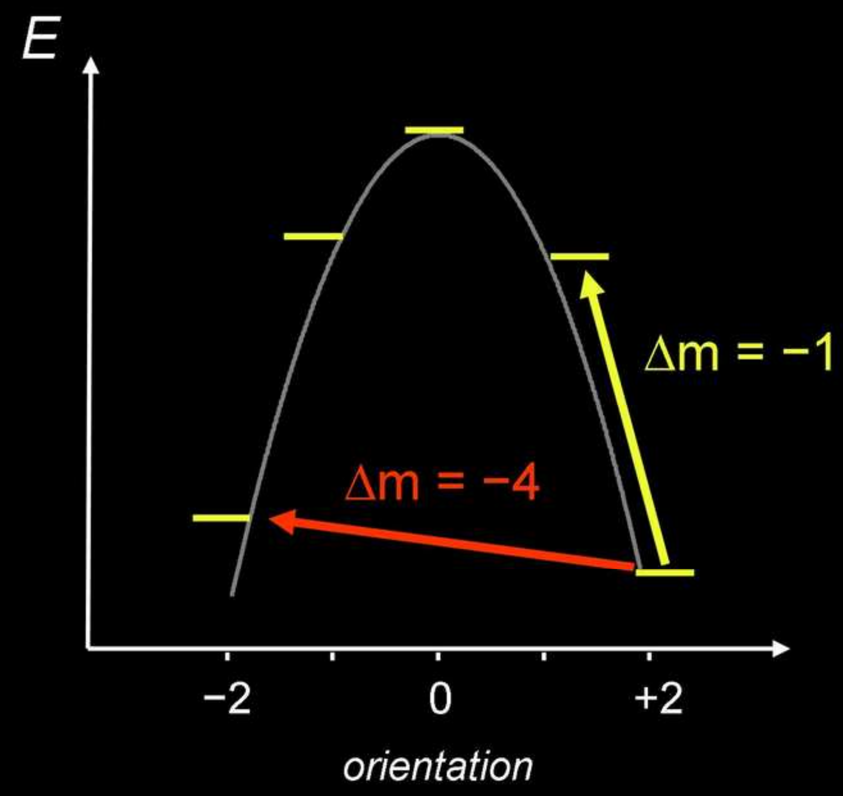


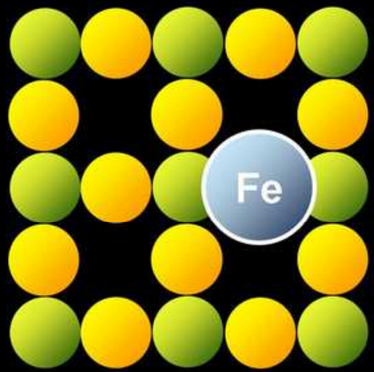


Yes, it's spin.

Anisotropy engineering

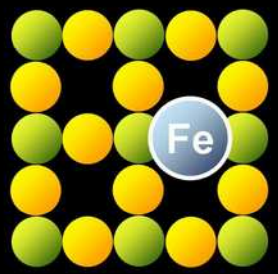




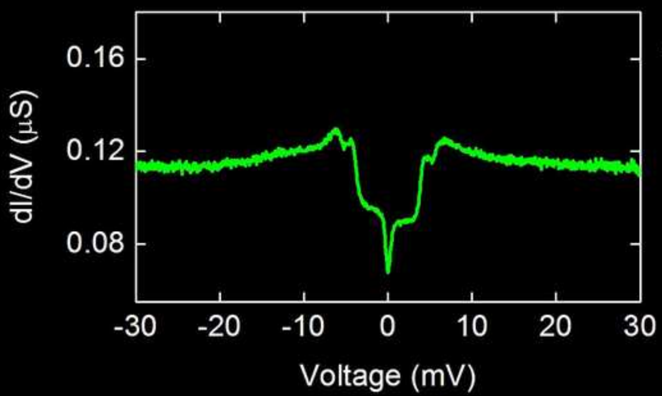


- 4 meV step: allowed transition −> measure for D
- 1 meV step: forbidden transition −> measure for E
- **Goal: maximize D and minimize E.**

Anisotropy engineering

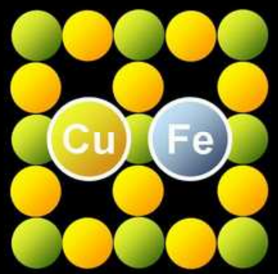


Fe

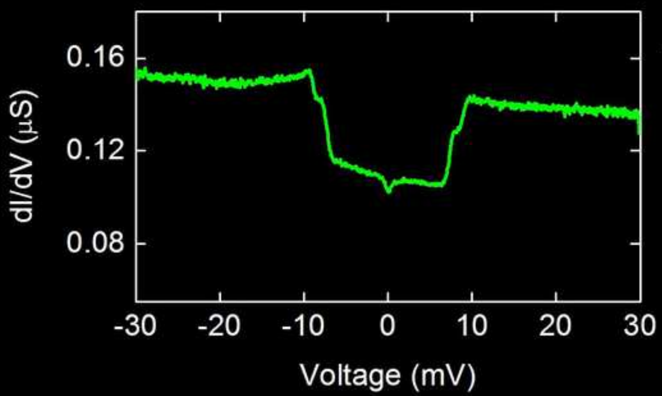


Anisotropy barrier: 5 meV
Strong mixing

Unstable. $T_1 \approx 1$ns

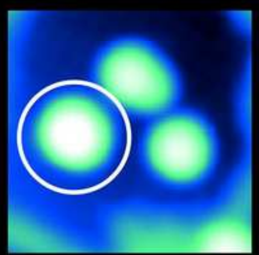


Cu−N−Fe

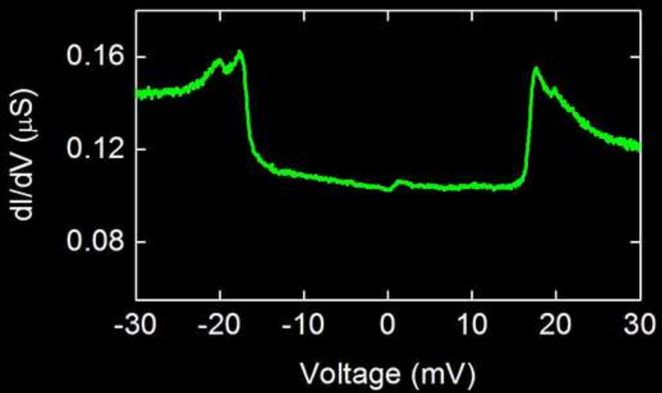


Anisotropy barrier: 10 meV
Reduced mixing

Increased stability. $T_1 \approx 8$ ns



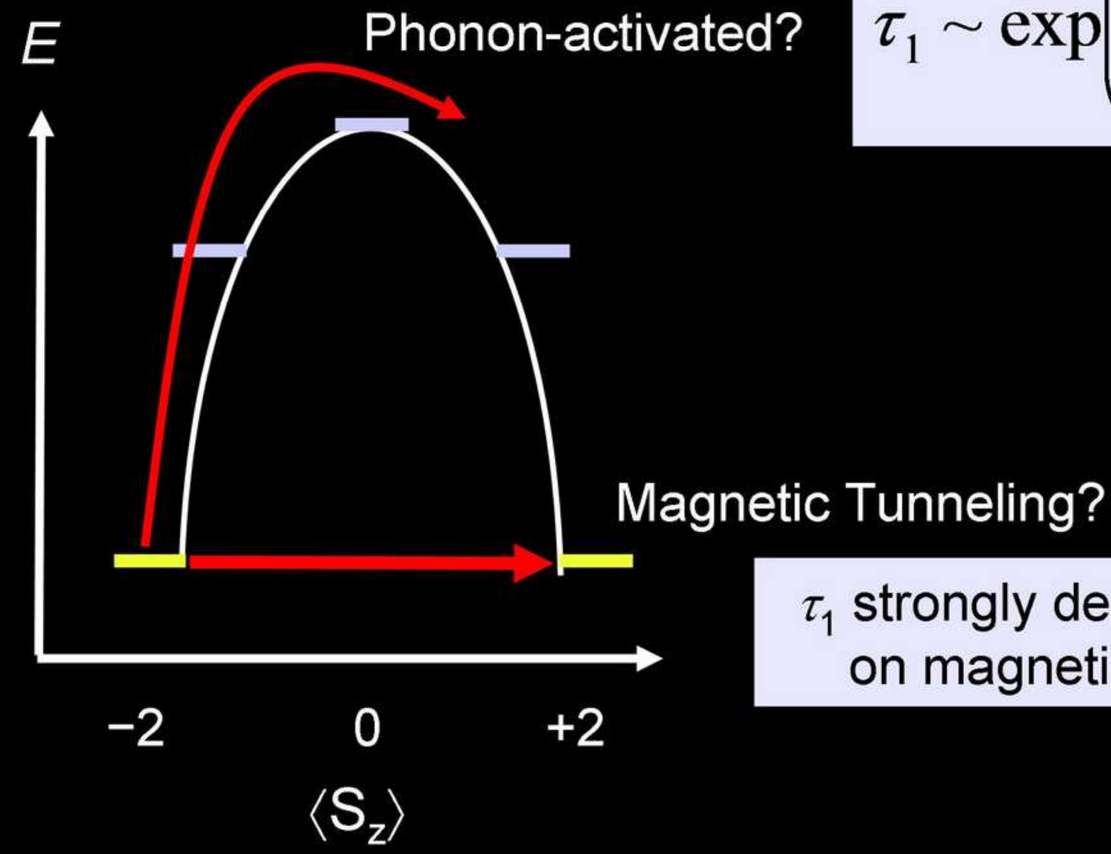
Close-spaced
Cu−Fe dimer



Anisotropy barrier: 22 meV
Minimal mixing

Long lived. $T_1 >$ 200ns

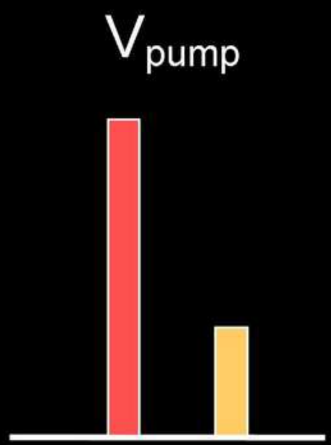
What is the spin relaxation channel?

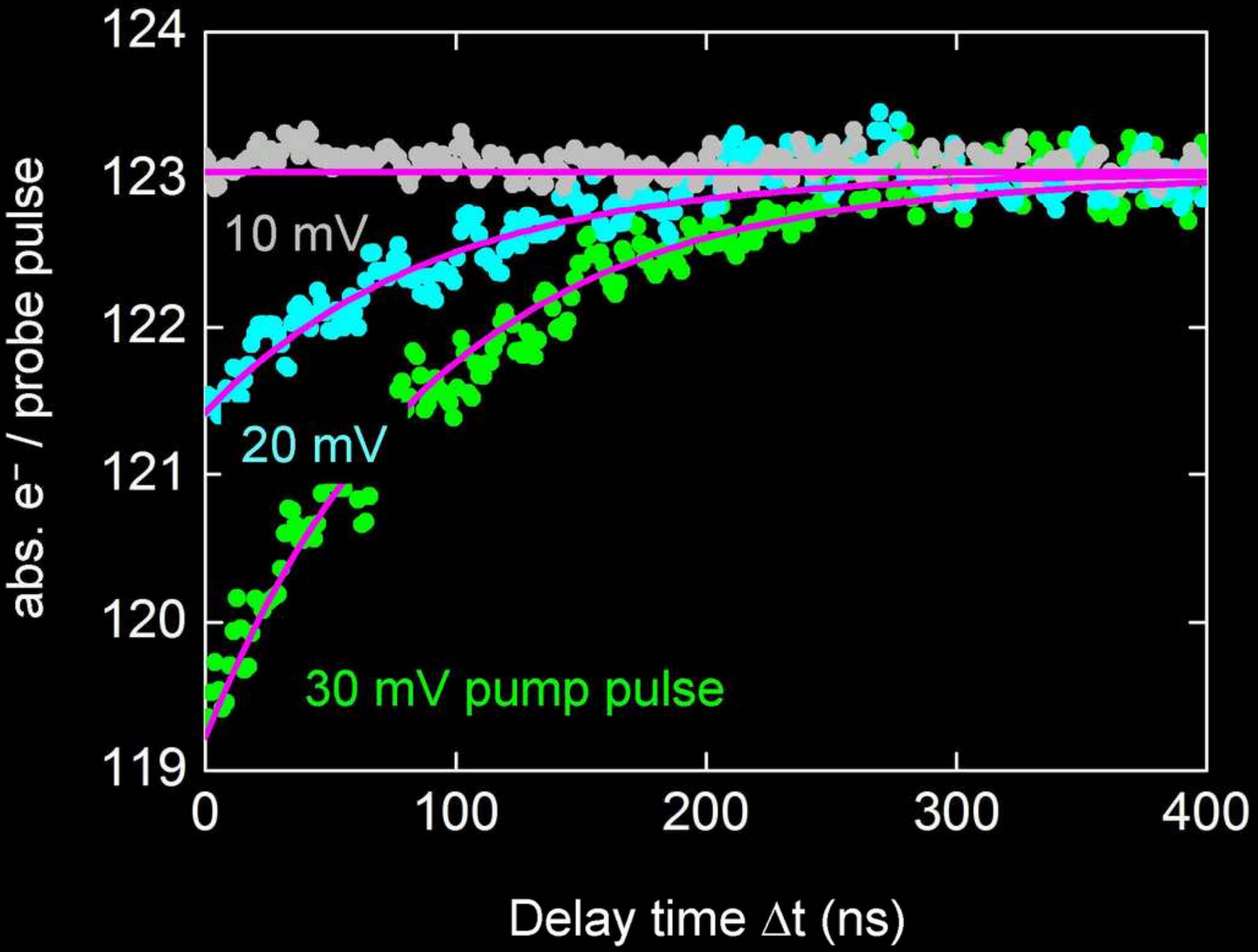


$$\tau_1 \sim \exp\left(\frac{E_a}{k_B T}\right)$$

τ_1 strongly dependent on magnetic field

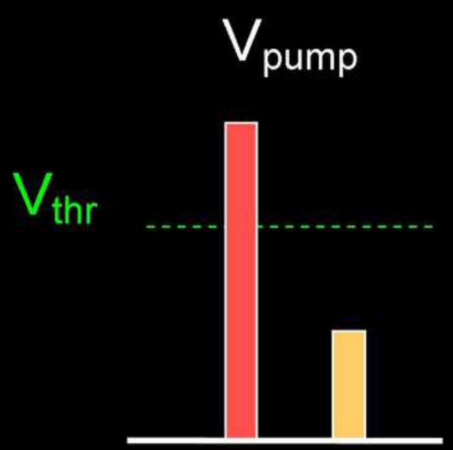
Energy dependence of the excitation

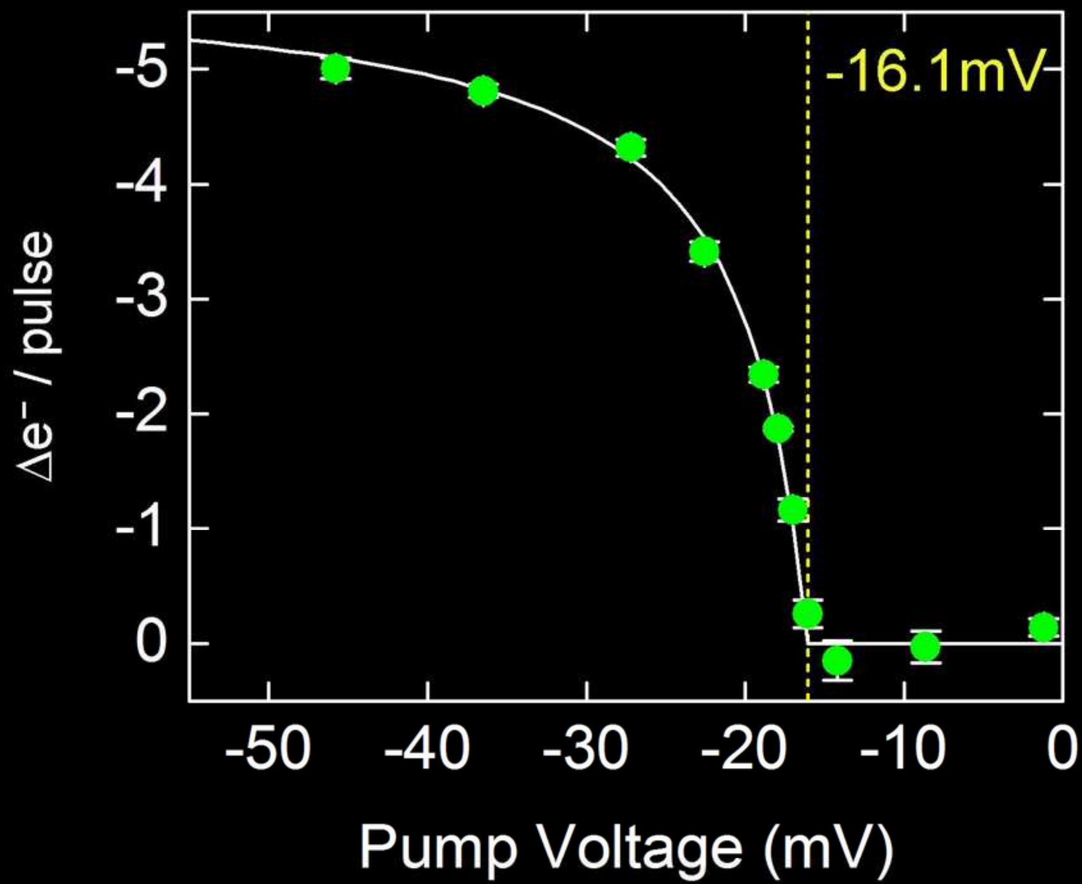




- Signal magnitude changes with the energy of the pump pulse
- Characteristic relaxation time stays constant.

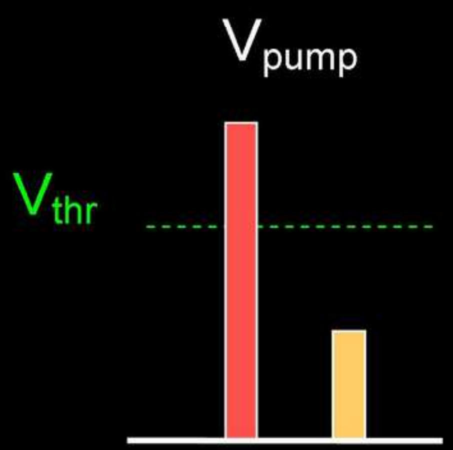
Energy dependence of pump-probe signal

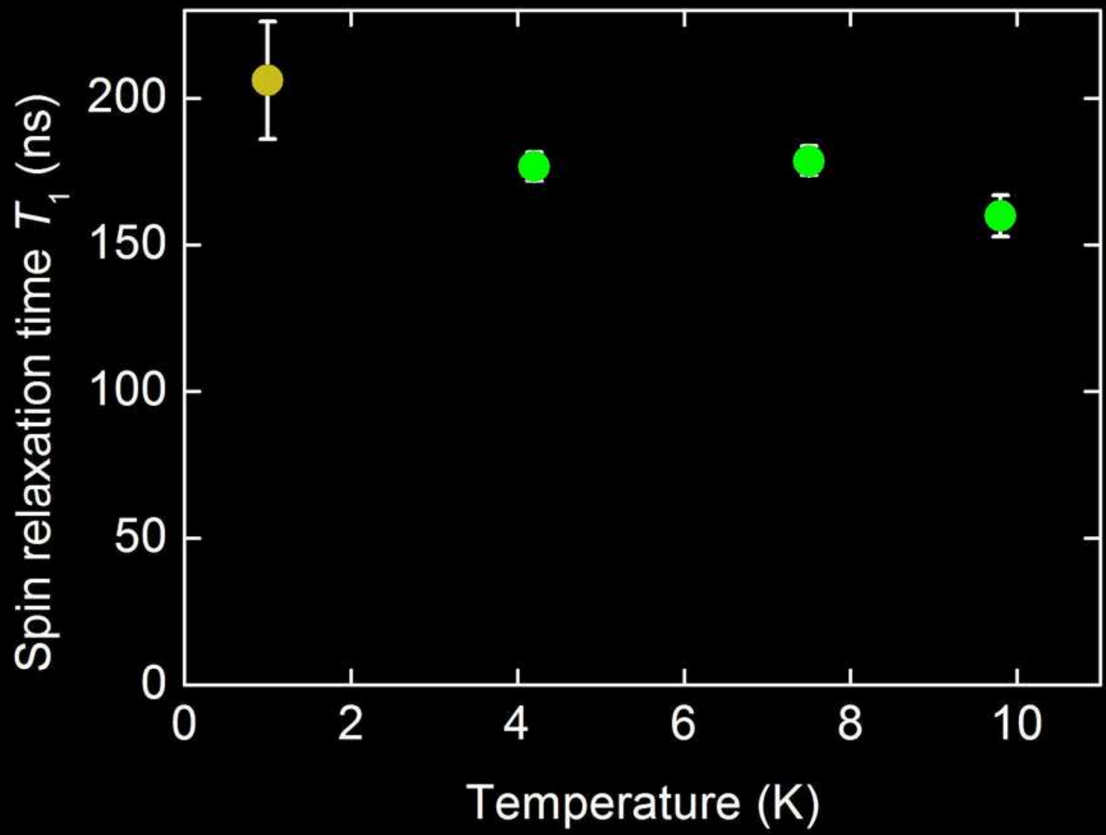




- **One clearly defined threshold energy of 16 meV**
  - **Thermal energy at 0.5 K is 40 μeV**

Energy dependence of pump-probe signal





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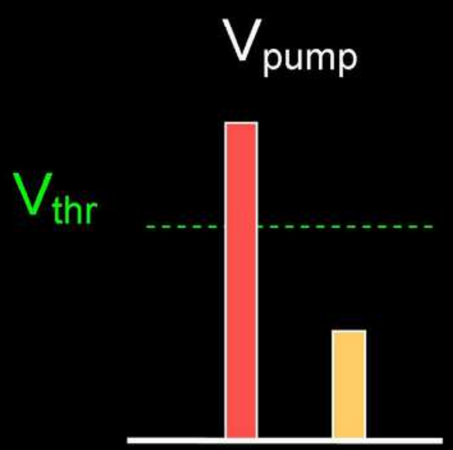

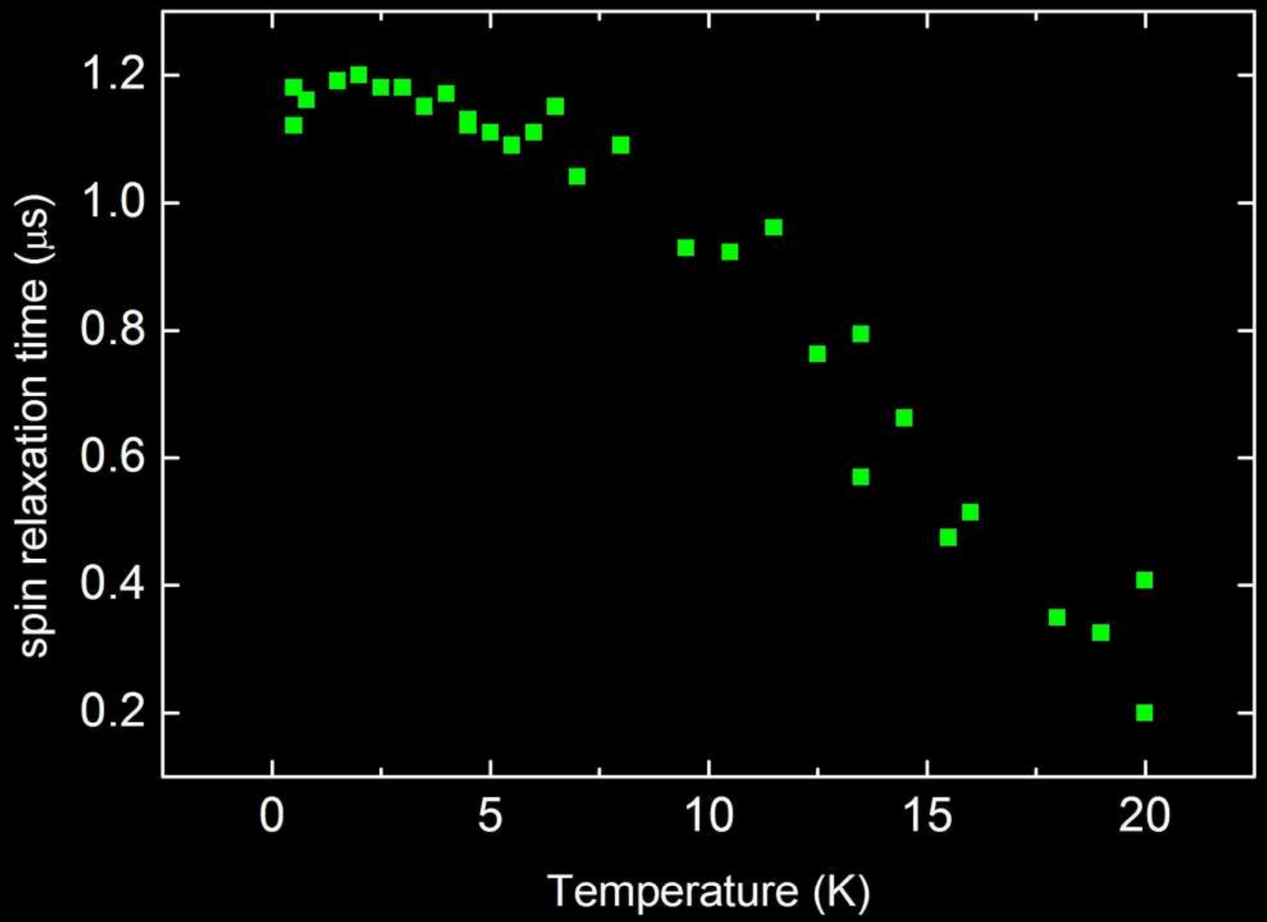

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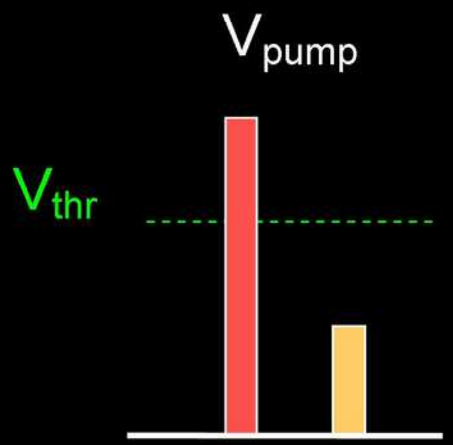
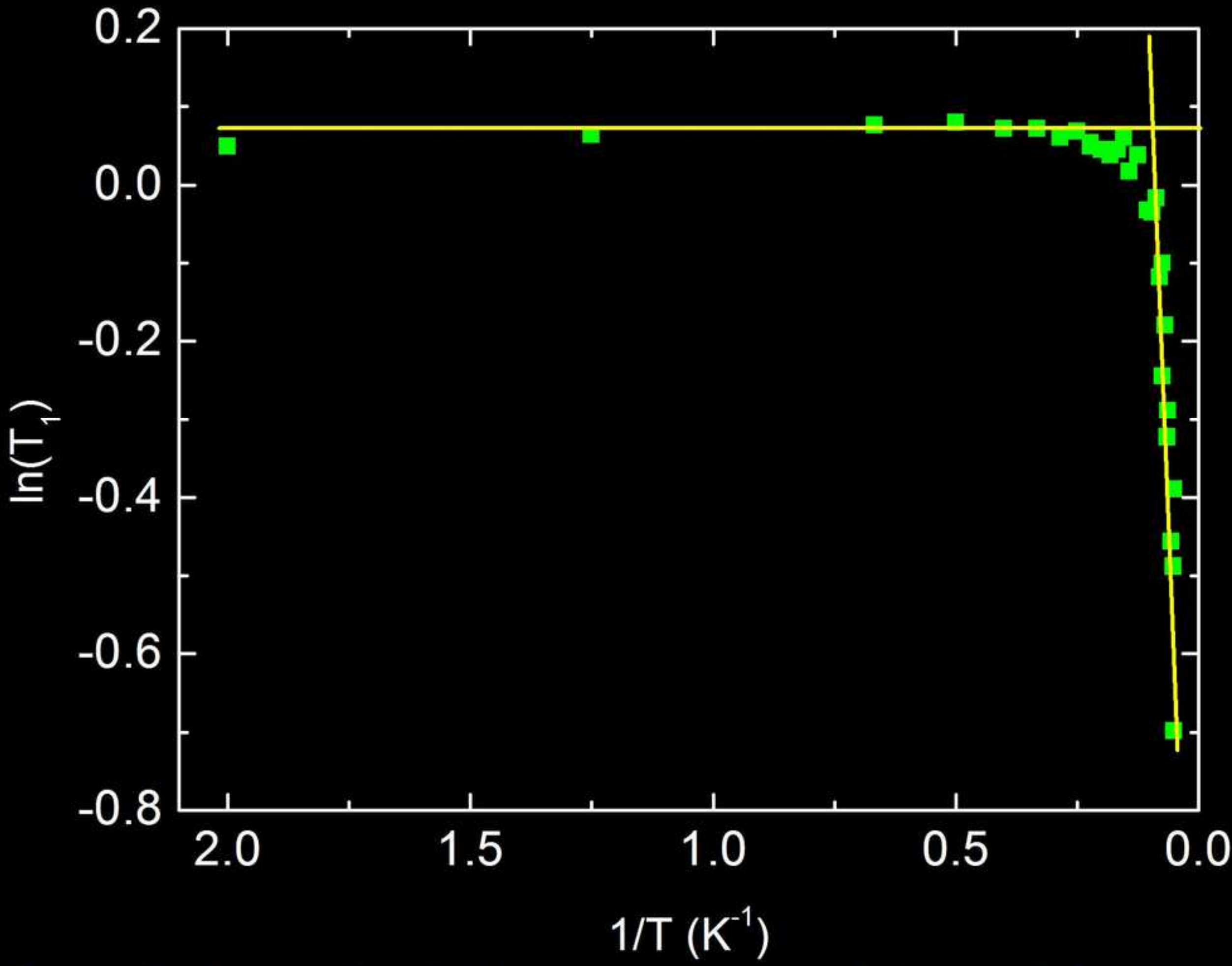
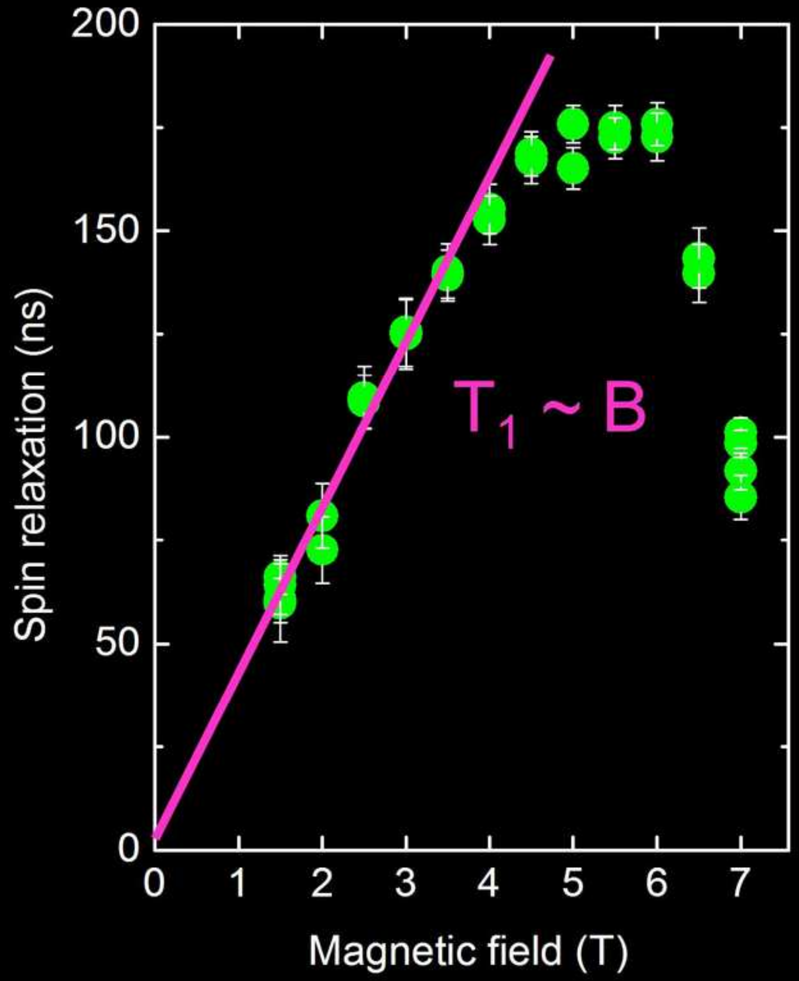


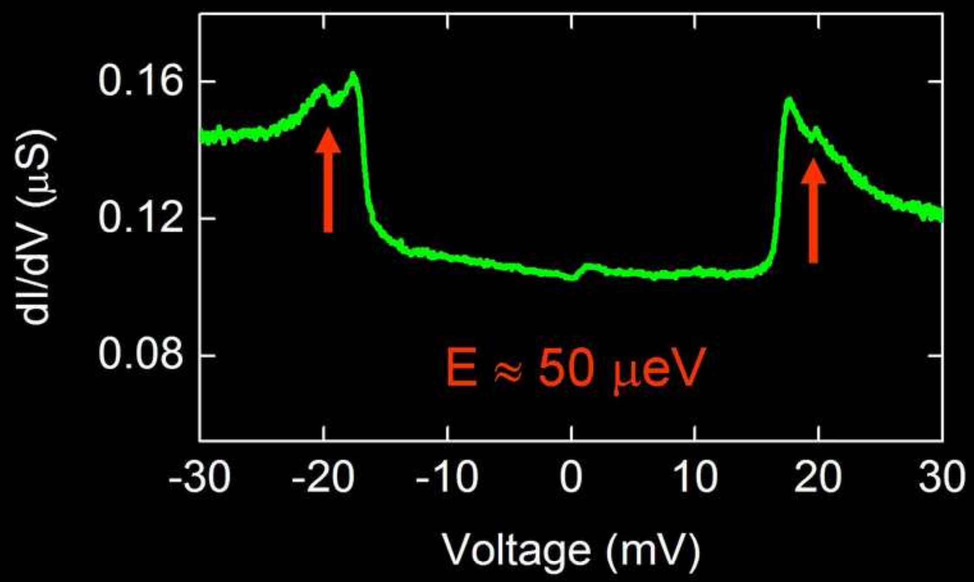


- One clearly defined threshold energy of 16 meV
  - Thermal energy at 0.5 K is 40 μeV
- Thermal relaxation negligible

Magnetic field dependence of spin relaxation time

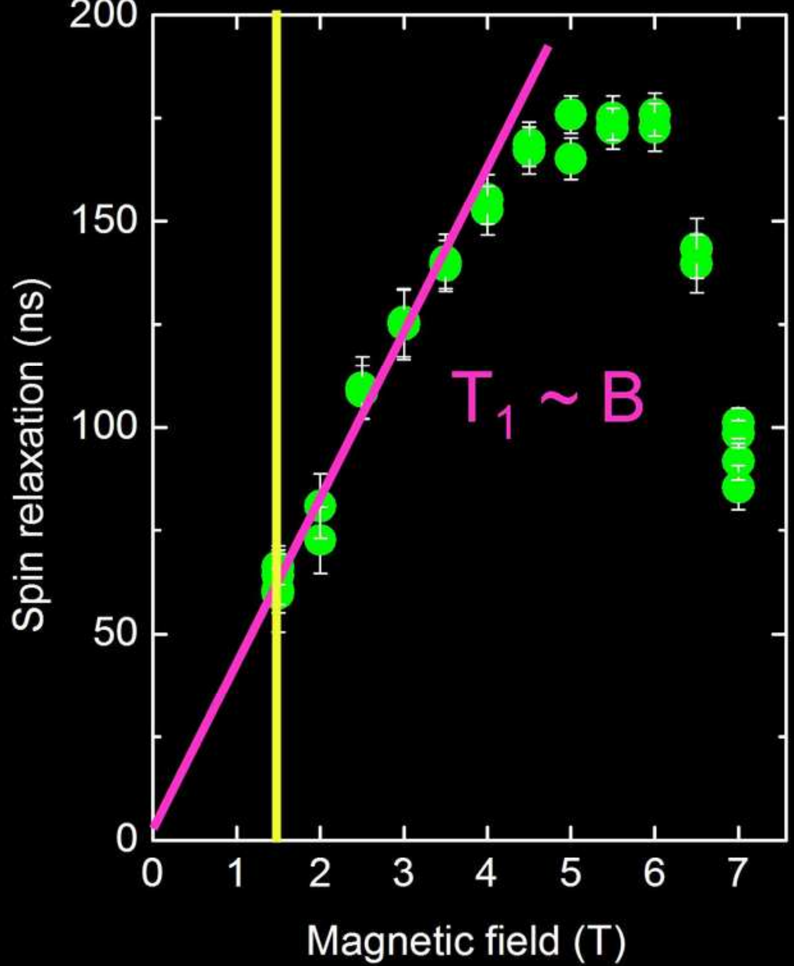


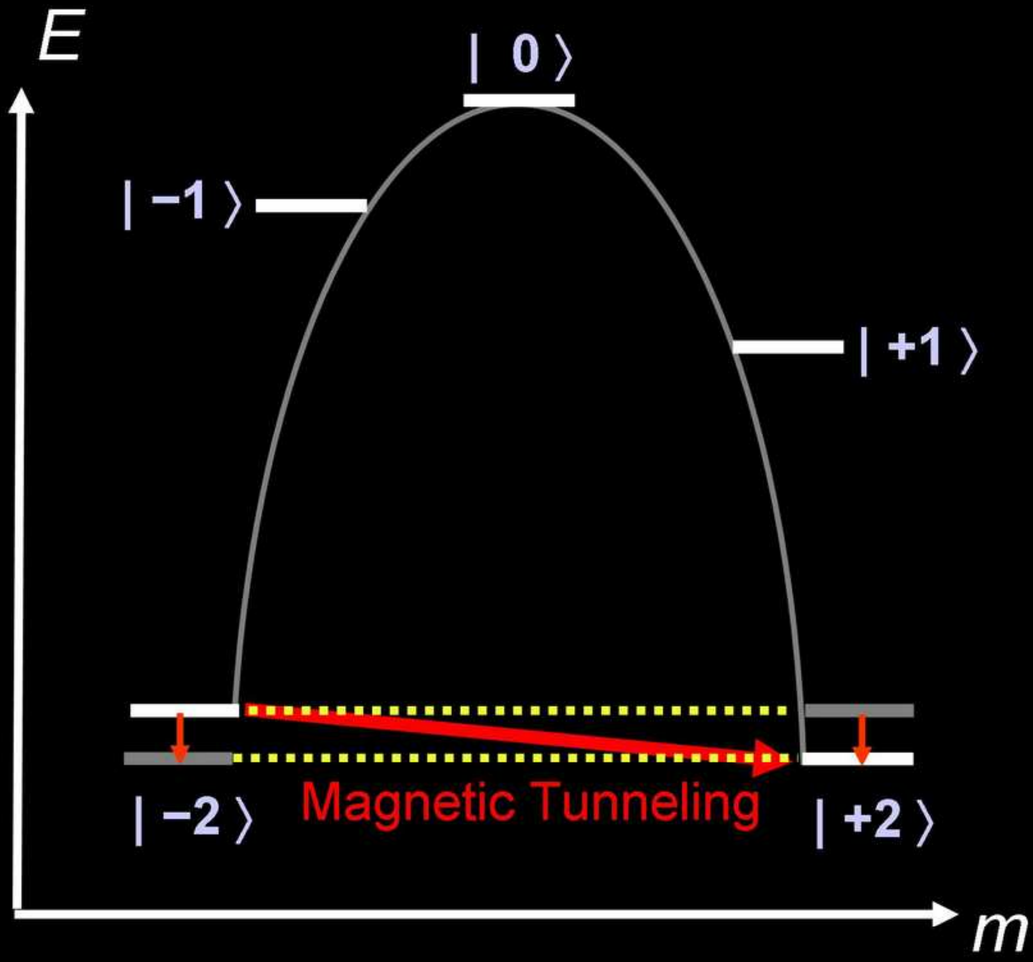
- Dynamical information: consistent with magnetic tunneling limiting the spin lifetime.



- Energetic information: magnetic tunneling caused by finite transverse anisotropy

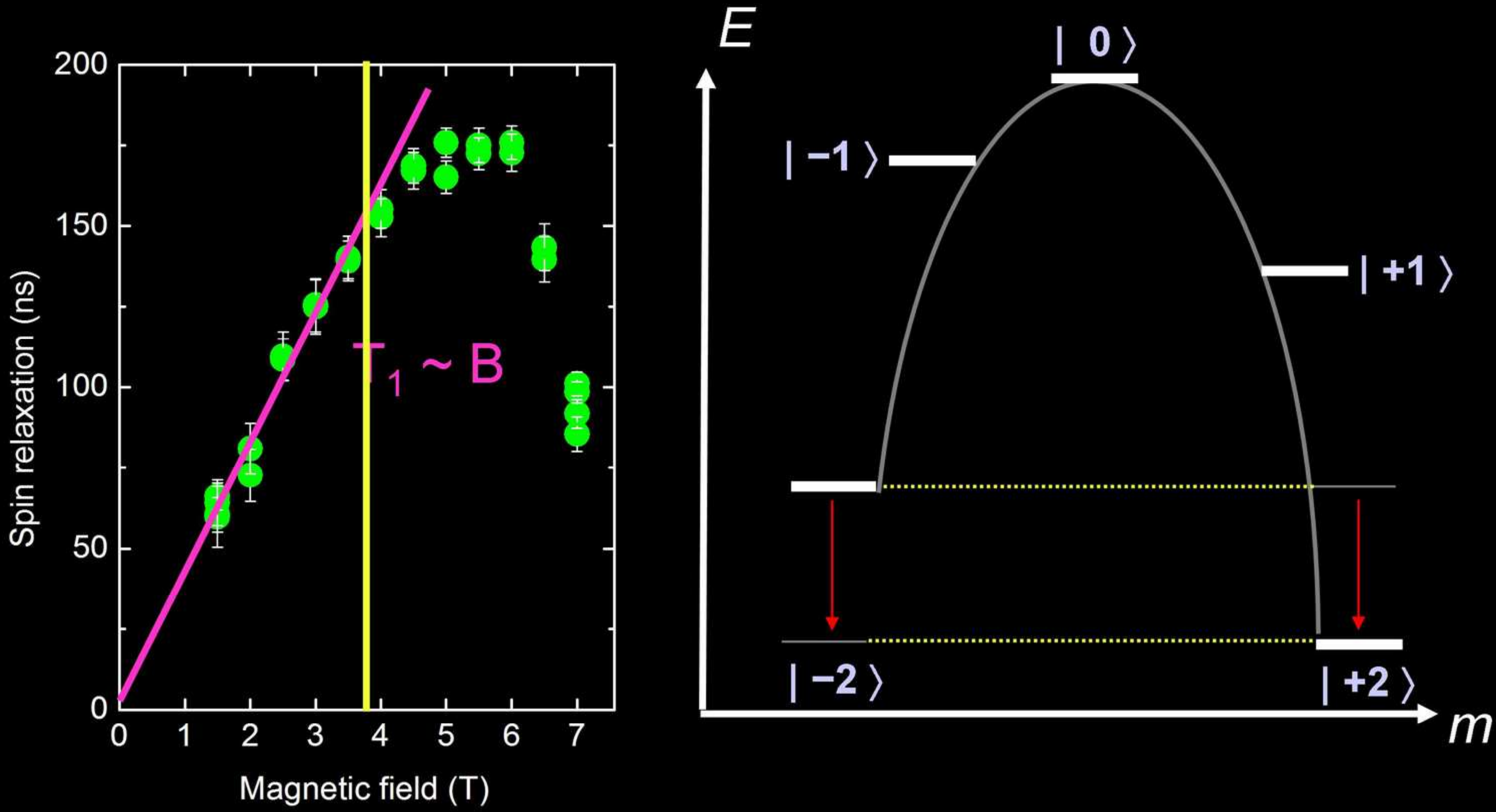
Magnetic field dependence of spin relaxation time





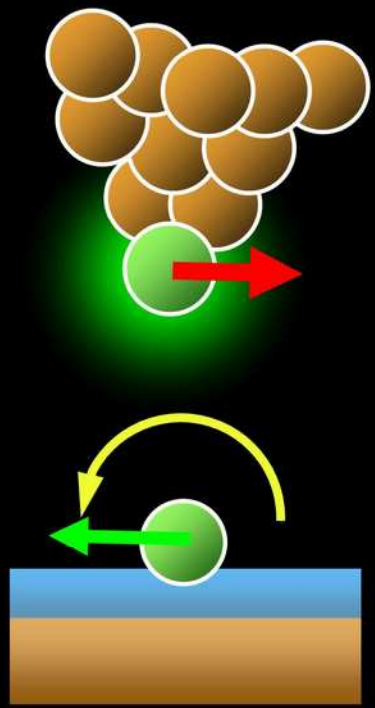
- Relaxation arises from mixing of the | −2 〉 and the | +2 〉 states

Magnetic field dependence of spin relaxation time



- Relaxation arises from mixing of the | −2 〉 and the | +2 〉 states
- The mixing decreases with increasing magnetic field

Summary



STM-based exploration of quantum spins:

- Energetic structure
- Dynamic behavior
- Spin lifetime engineering

(ns × nm)