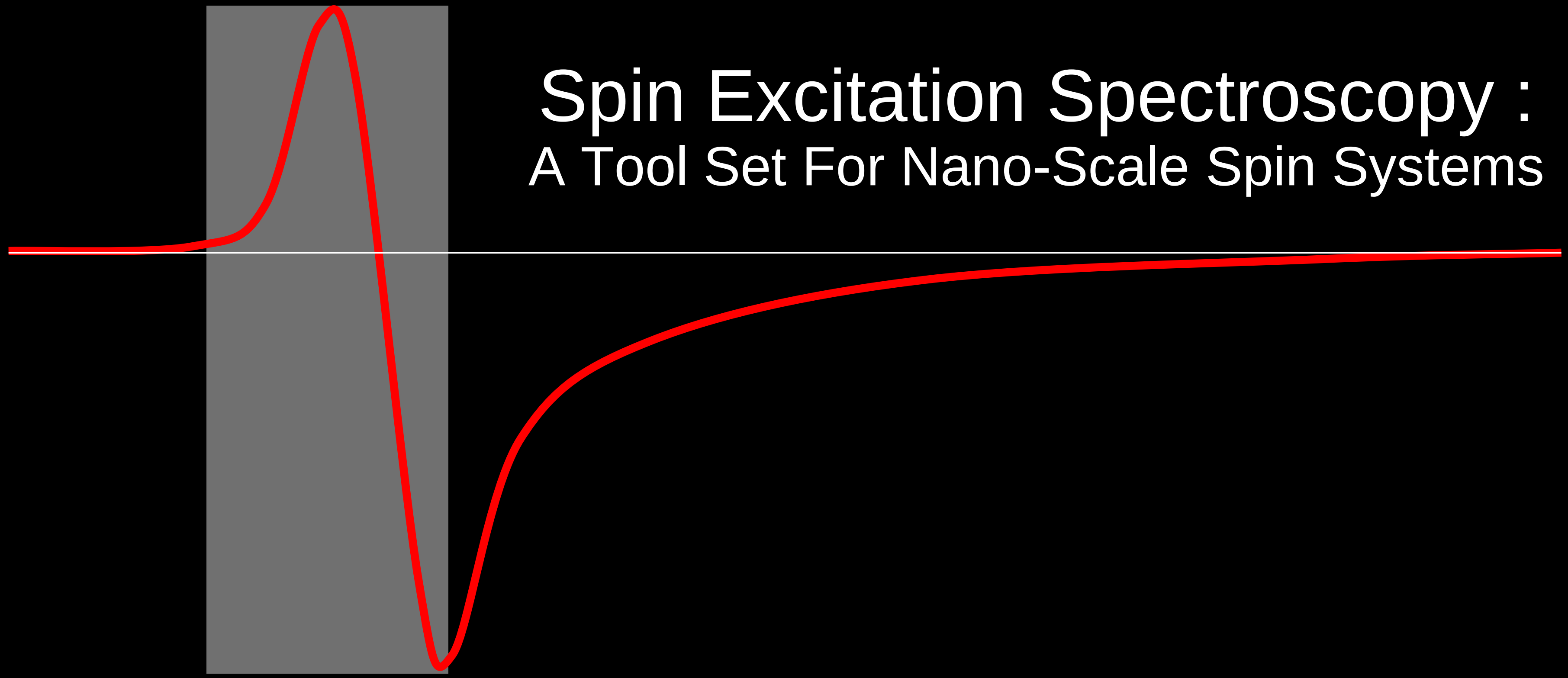
Don Eigler

IBM Fellow

IBM



Spin Excitation Spectroscopy :

A Tool Set For Nano-Scale Spin Systems

NSF Grantees Conference, Arlington, VA.

December 6, 2010

A Challenge

Build a "Spin-Only" Nano-Scale Digital Computer

Question:

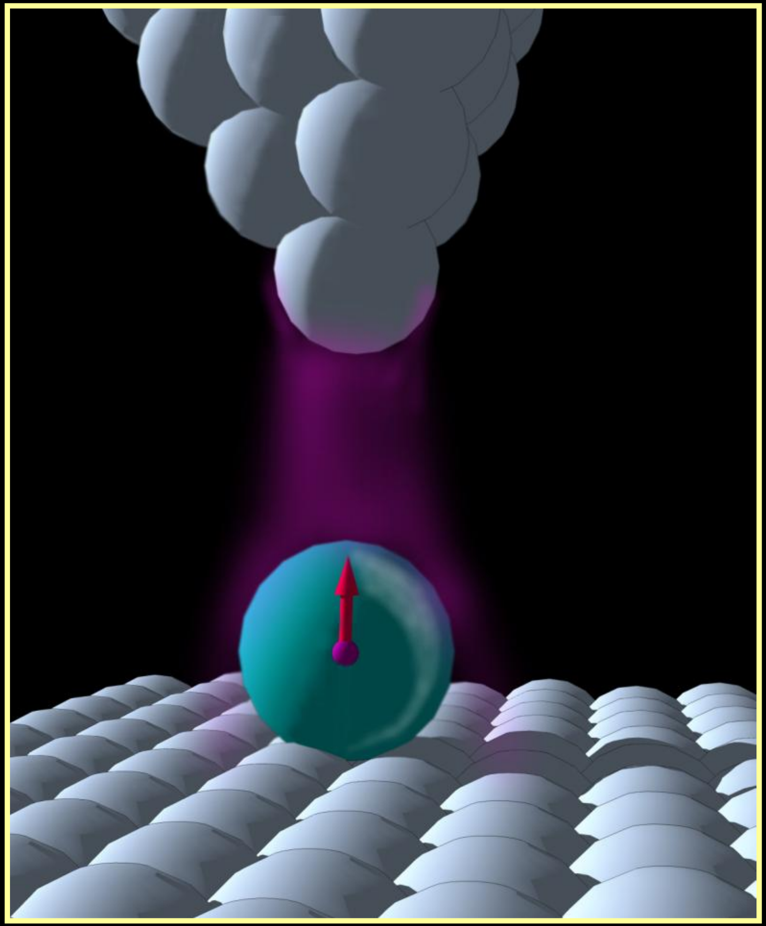
How can one can engineer computational functionality into a nanometer-scale system of spins?

Prerequisite:

A tool for measuring spin properties at the atomic scale.


An STM is a powerful tool, but …
conventional STM topographs tell nothing about spin

Spin Excitation Spectroscopy

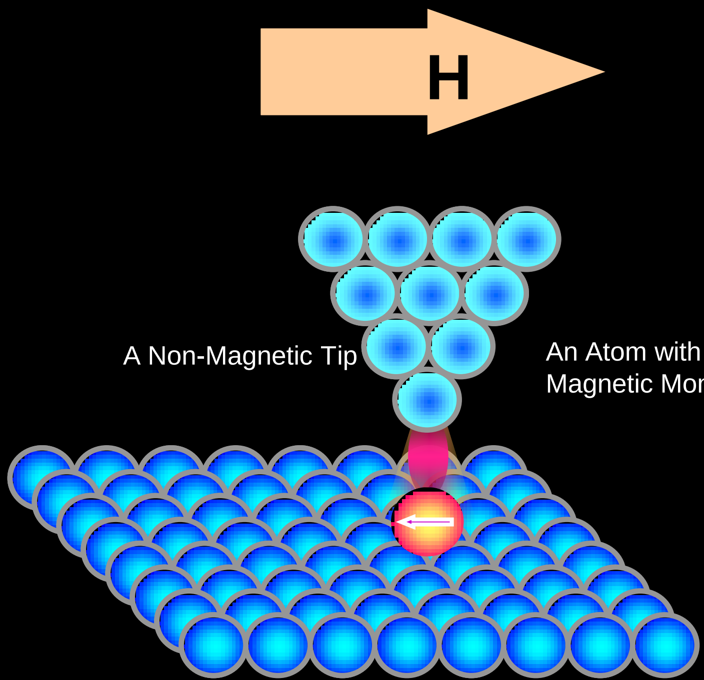


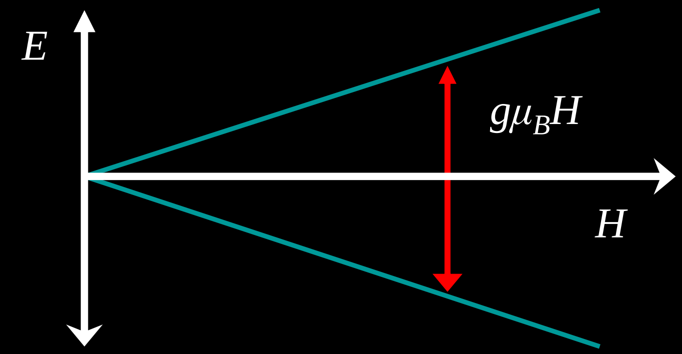
Part I : Energetics

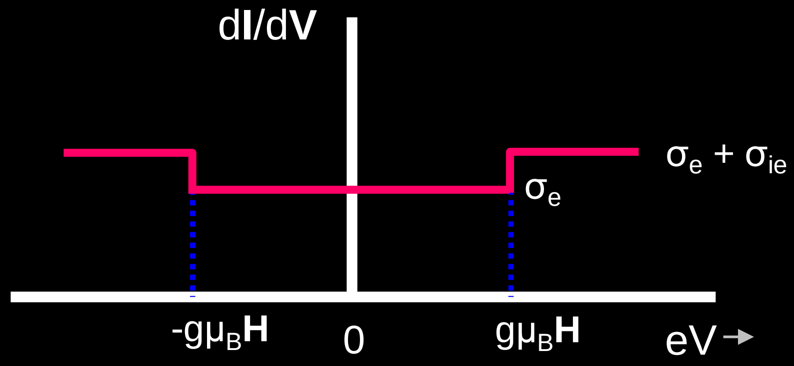
Spin Excitation Spectroscopy

A variant of inelastic electron tunneling spectroscopy

R. C. Jaklevic, J. J. Lambe, *Phys. Rev. Lett.* **17**, 1179 (1966)



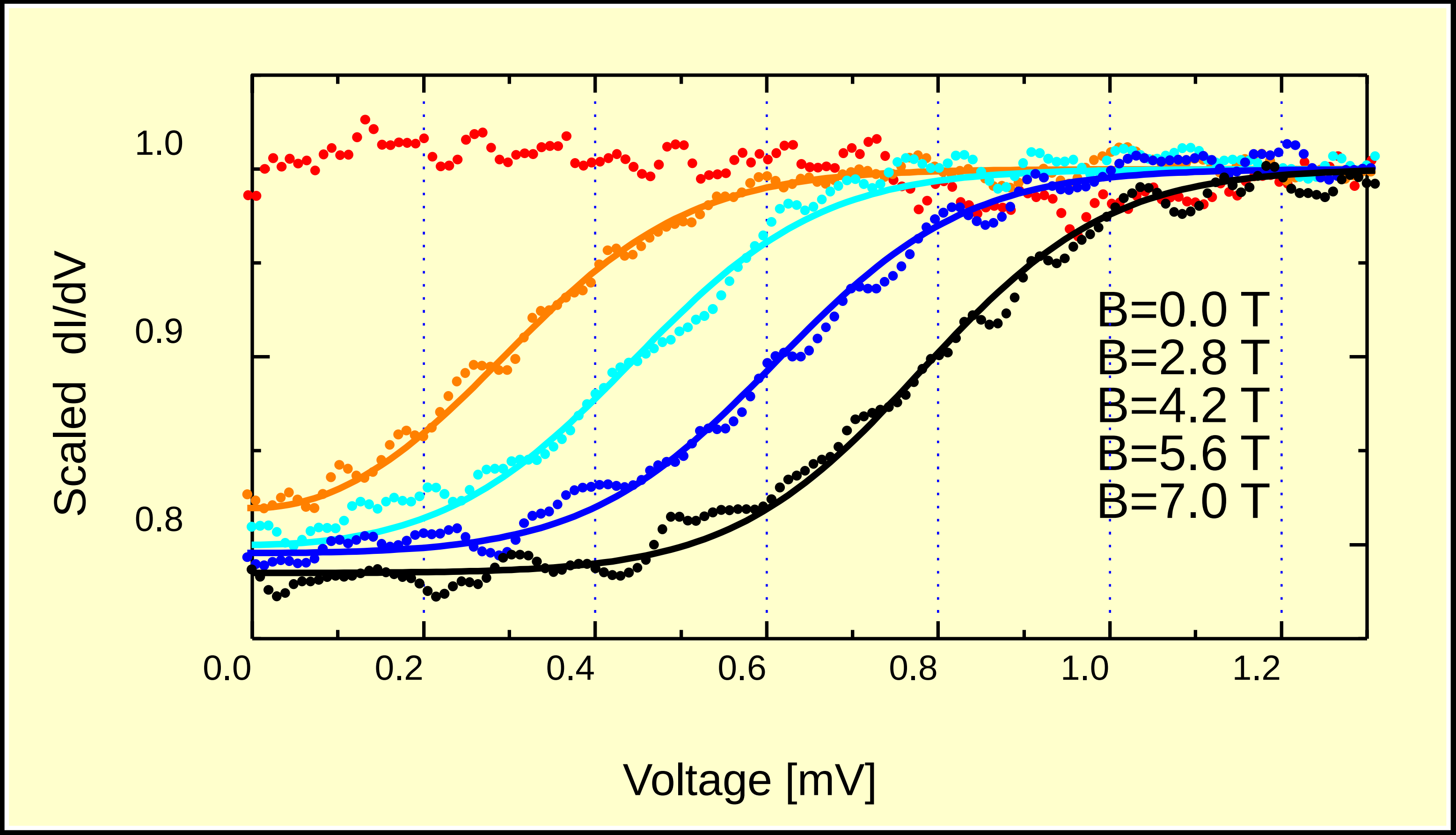




$$K_B T \ll g\mu_B H$$

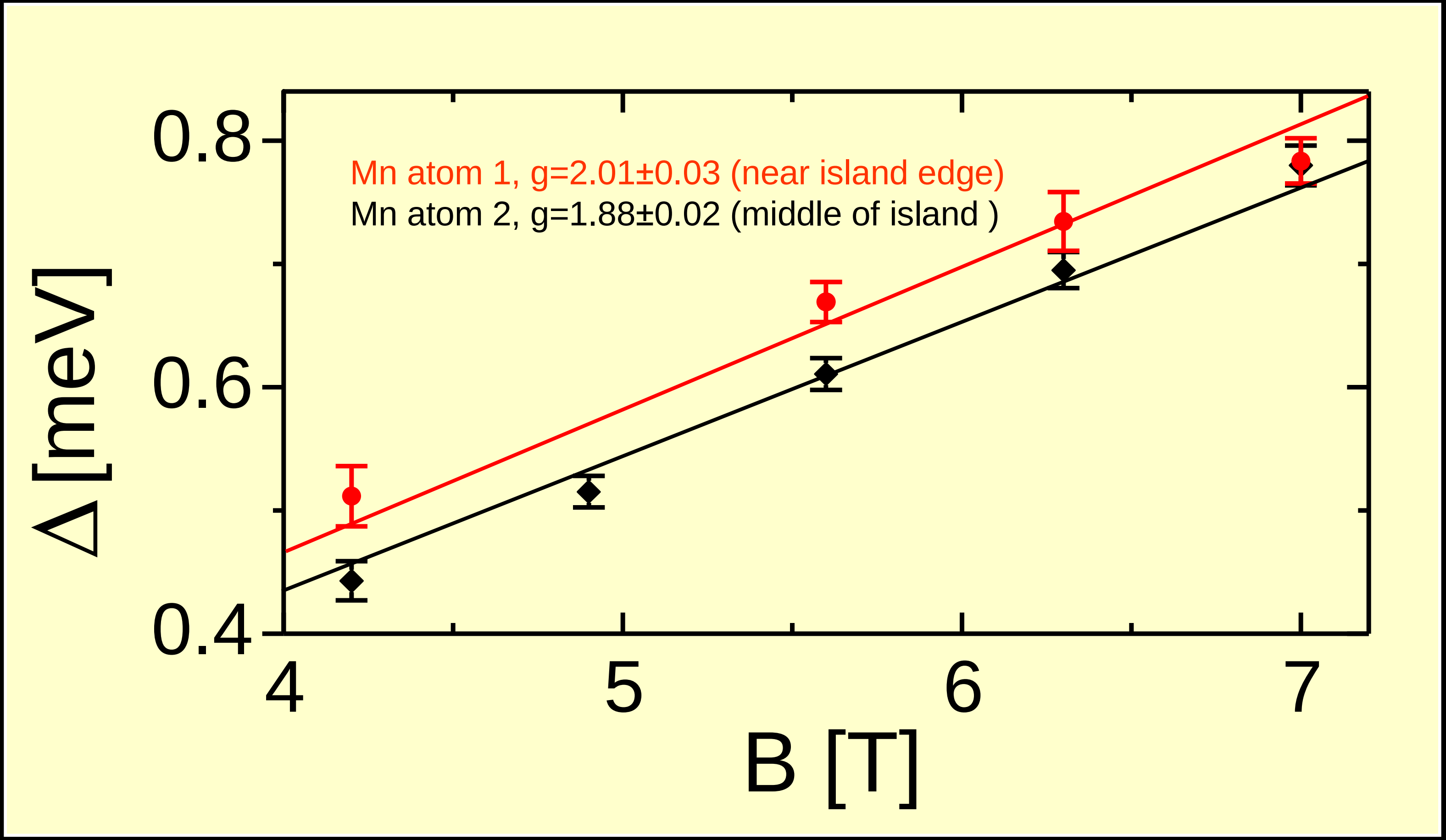
A.J. Heinrich, J.A. Gupta, C.P. Lutz and D.M. Eigler, *Science* **306**, 466 (2004)

The Spin Excitation Signal From a Single Manganese Atom



A.J. Heinrich, J.A. Gupta, C.P. Lutz and D.M. Eigler, *Science* **306**, 466 (2004)

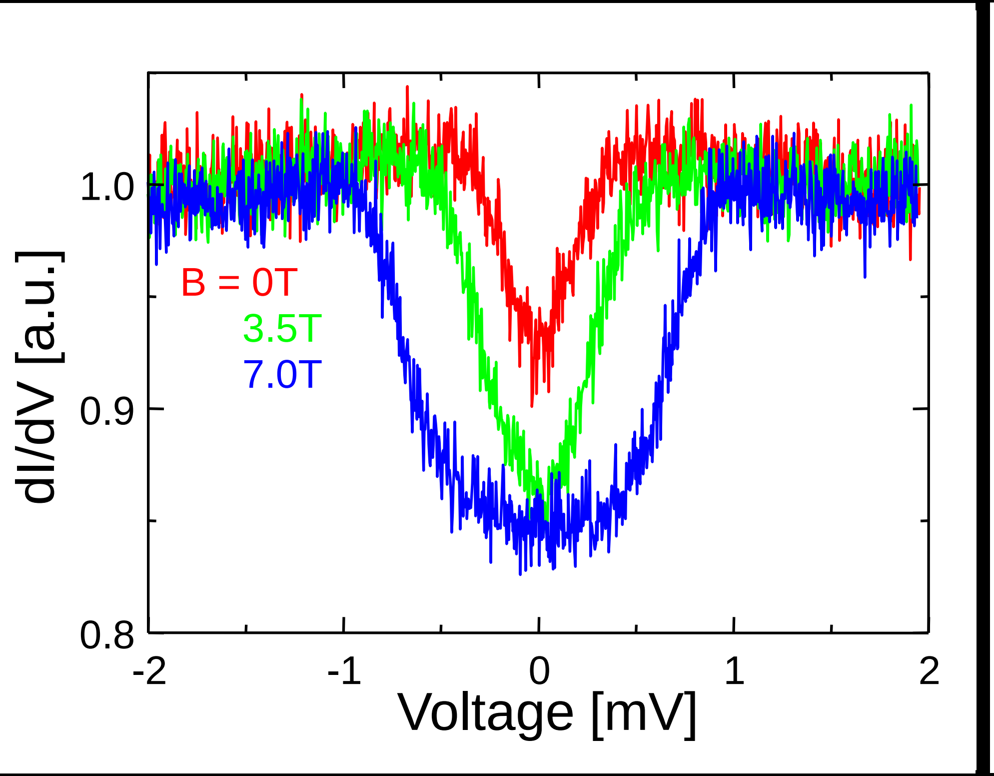
Site-Specific Measurement of Single-Atom g-Value

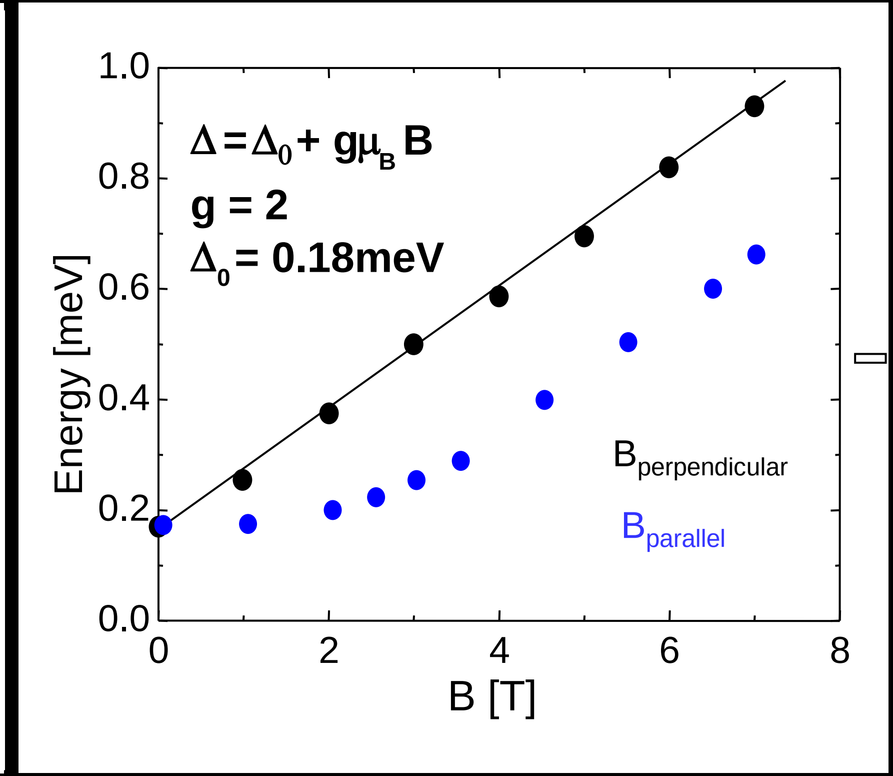


Mn on Al_2O_3 island on NiAl

A.J. Heinrich, J.A. Gupta, C.P. Lutz and D.M. Eigler, *Science* **306**, 466 (2004)

Measurement of Single-Atom Anisotropy Energy





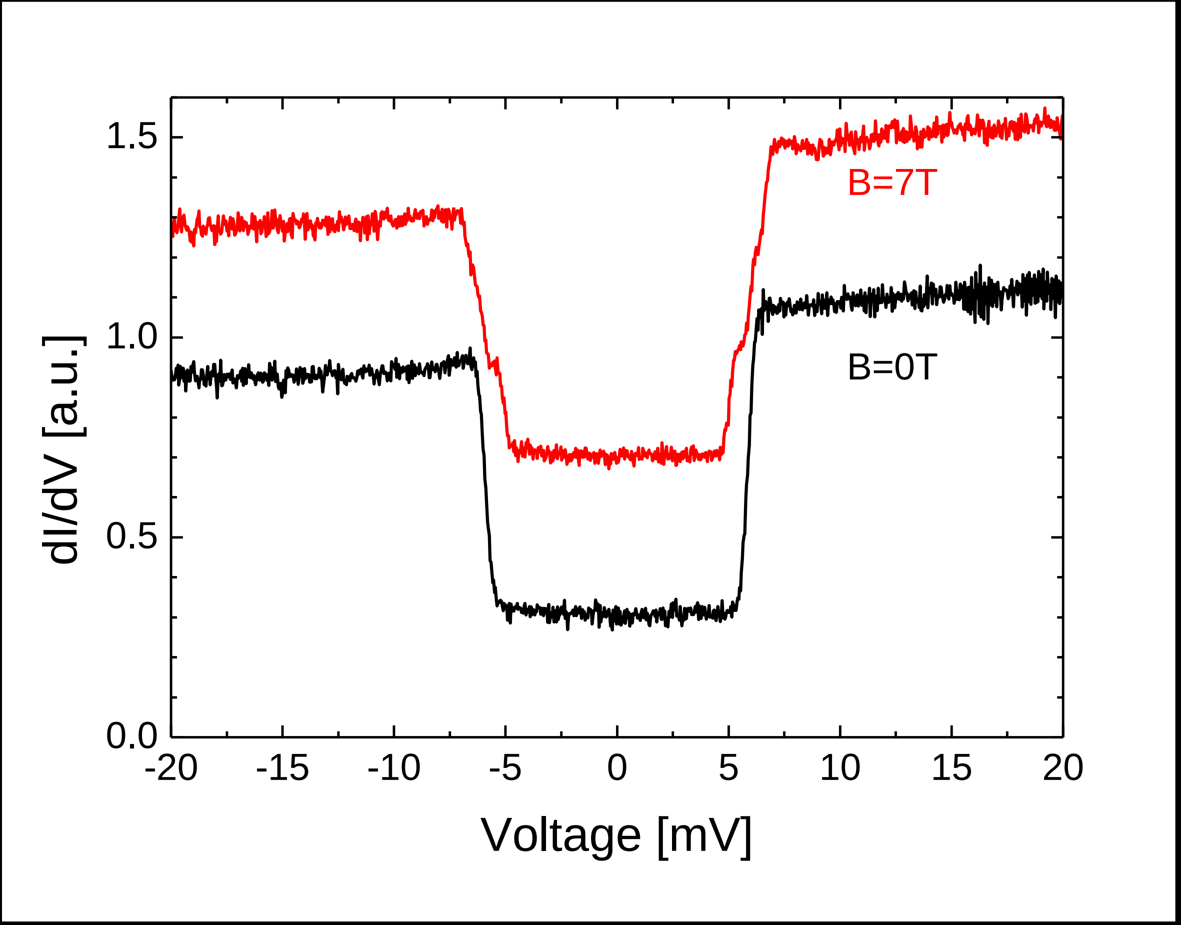
- Magneto-crystalline anisotropy: $H = g\mu_B S \cdot B + DS_z^2$
- Easy axis perpendicular to surface

Mn Monomer Anisotropy Energy = 0.18 meV

C. Hirjibehedin, C-Y Lin, A.F. Otte, M. Ternes, C.P. Lutz, B.A. Jones and A.J. Heinrich, *Science* **317**, 1199(2007)

Measurement of Exchange Coupling Between Atoms

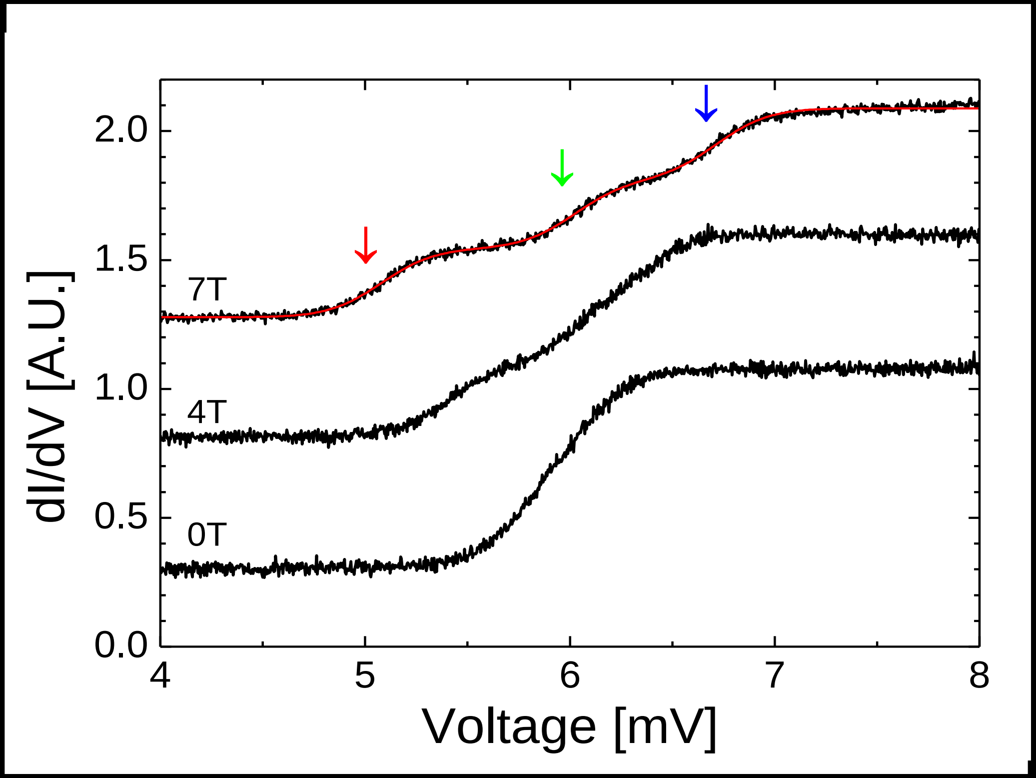
Mn Dimer on CuN on Cu (100)

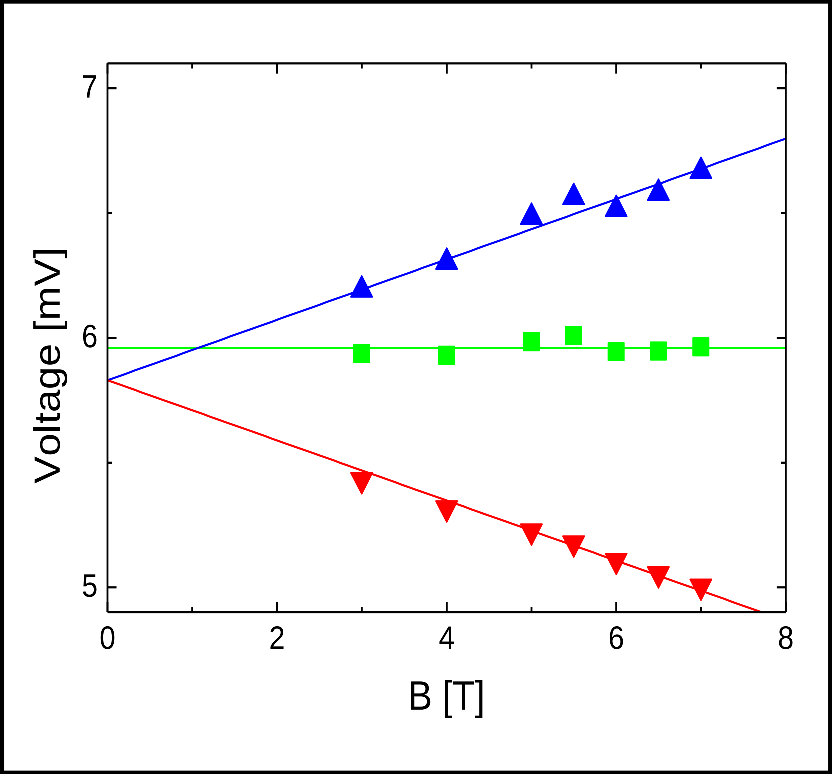


|J| = 6mV

C. Hirjibehedin, C.P. Lutz and A.J. Heinrich, *Science* **312**, 1021(2006)

Field Dependence of Mn Dimer Spectrum

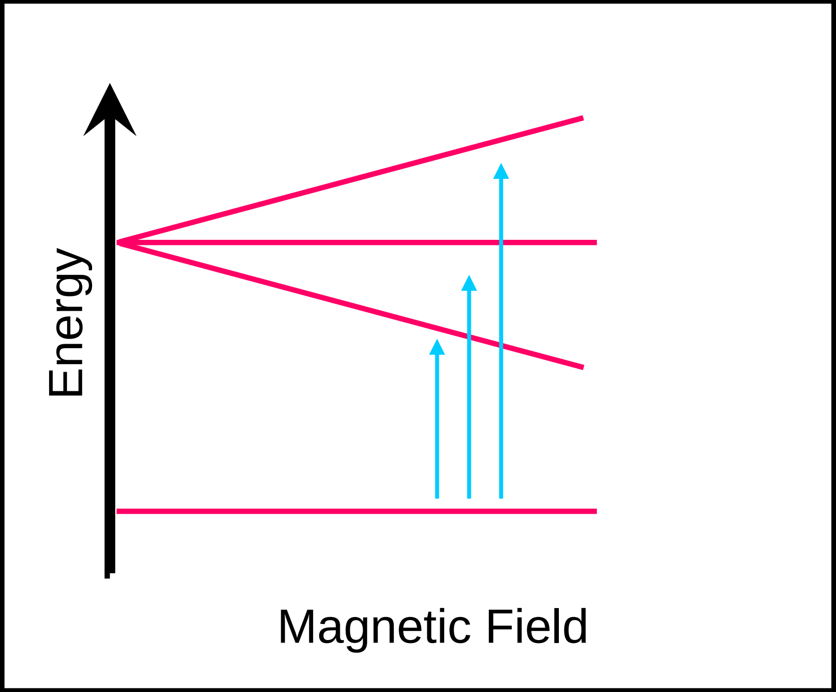




- Dimer step at ~6mV splits into three distinct steps

Determination of Ground State Spin Configuration

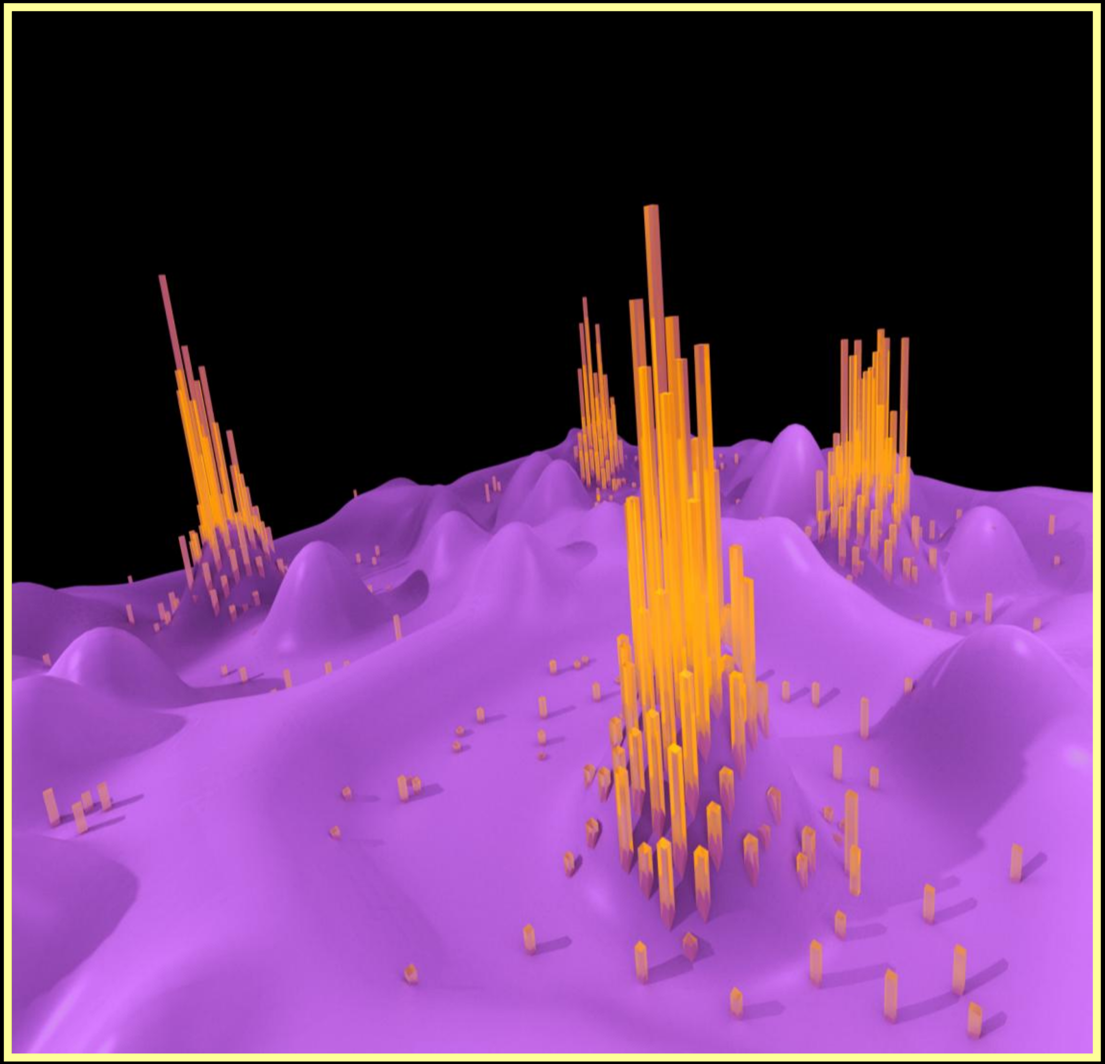
- For S=0 (singlet) the first excited state is S=1 (triplet)
- Singlet has no low-lying excitations



- The Ground State of the Mn Dimer is a Spin Singlet.
- The Mn Atoms are Antiferromagnetically Coupled

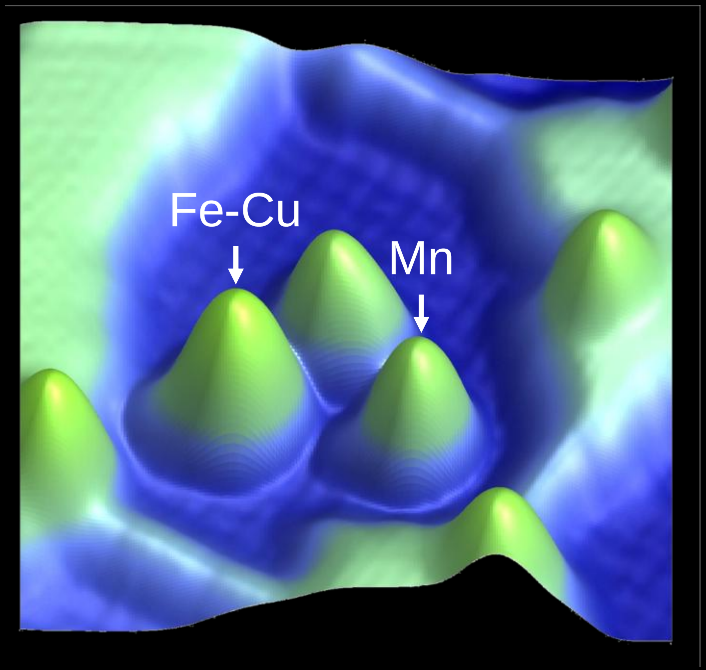
C. Hirjibehedin, C.P. Lutz and A.J. Heinrich, *Science* **312**, 1021(2006)

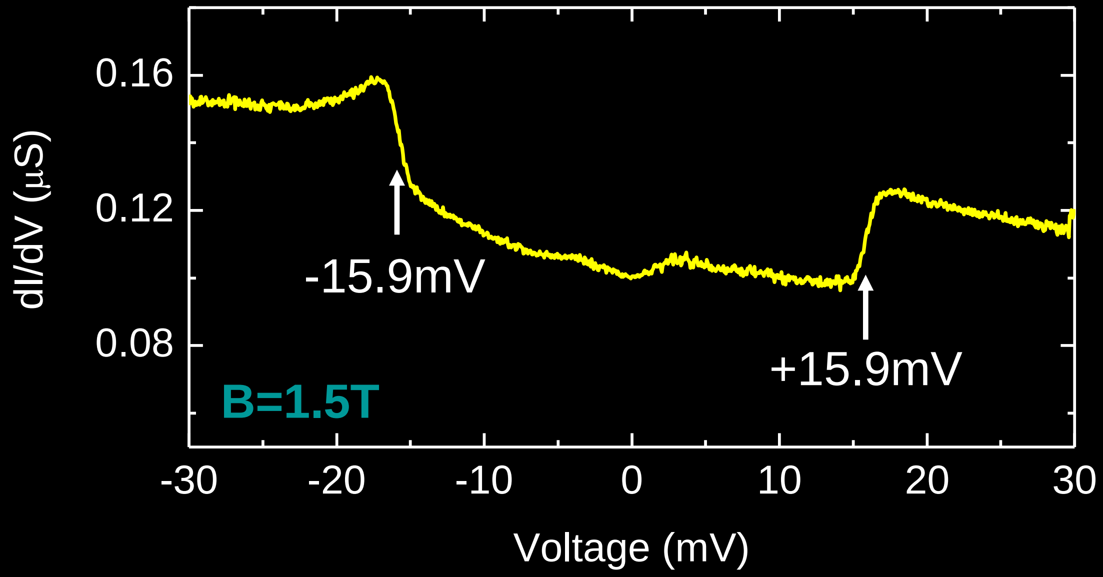
Spin Excitation Spectroscopy



Part II : Dynamics

High Magneto-Crystalline Anisotropy Fe-Cu Complex





- **Very large easy-axis magneto-crystalline anisotropy**
- **Spectra show saturation behavior when tunnel current is large**

Question: Could it have a long spin relaxation time, T_1 ?

Pump-Probe Technique to Measure Spin Relaxation Time, T_1

1) Pump:

Use a super-threshold voltage pulse to create a spin excitation

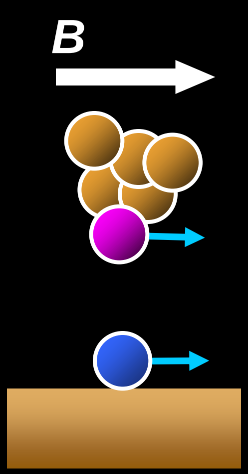
2) Probe:

Use a sub-threshold voltage pulse to sense the spin orientation at a variably delayed time following the pump pulse

Single Atom Spin Dynamics

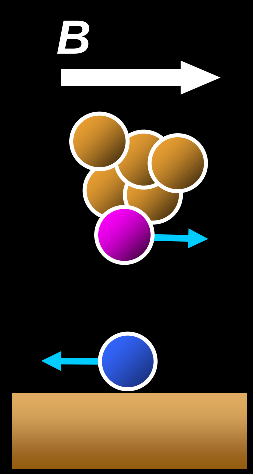
Pump-Probe Measurement of Electron Spin Relaxation Time, T_1

Magneto-Resistive Tunneling Conductance



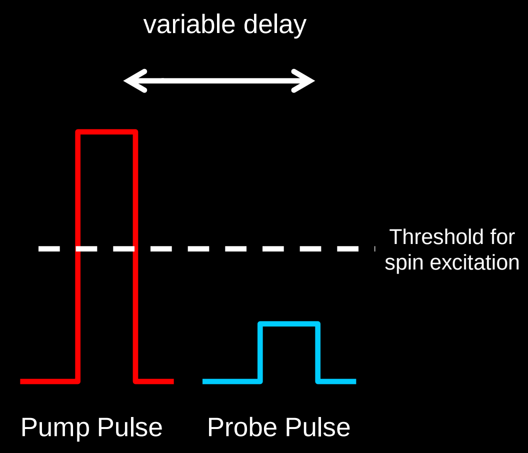
Ground State Spin Configuration

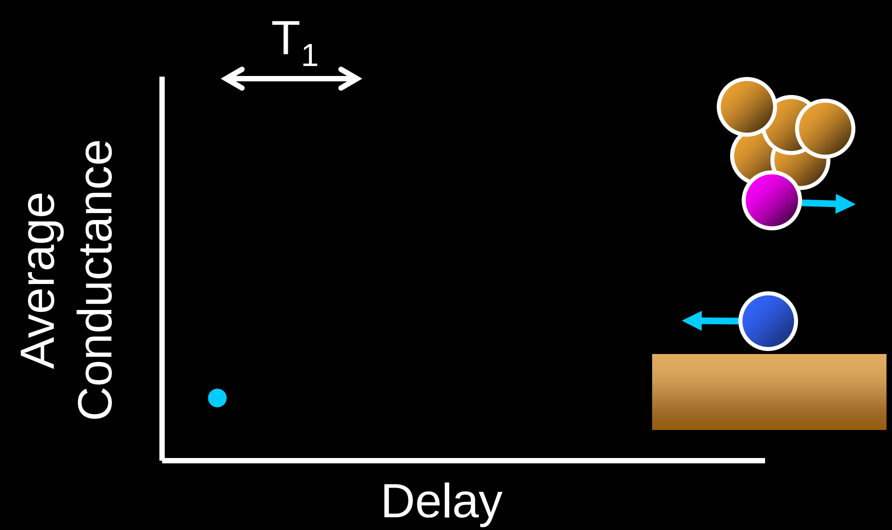
High elastic conductance



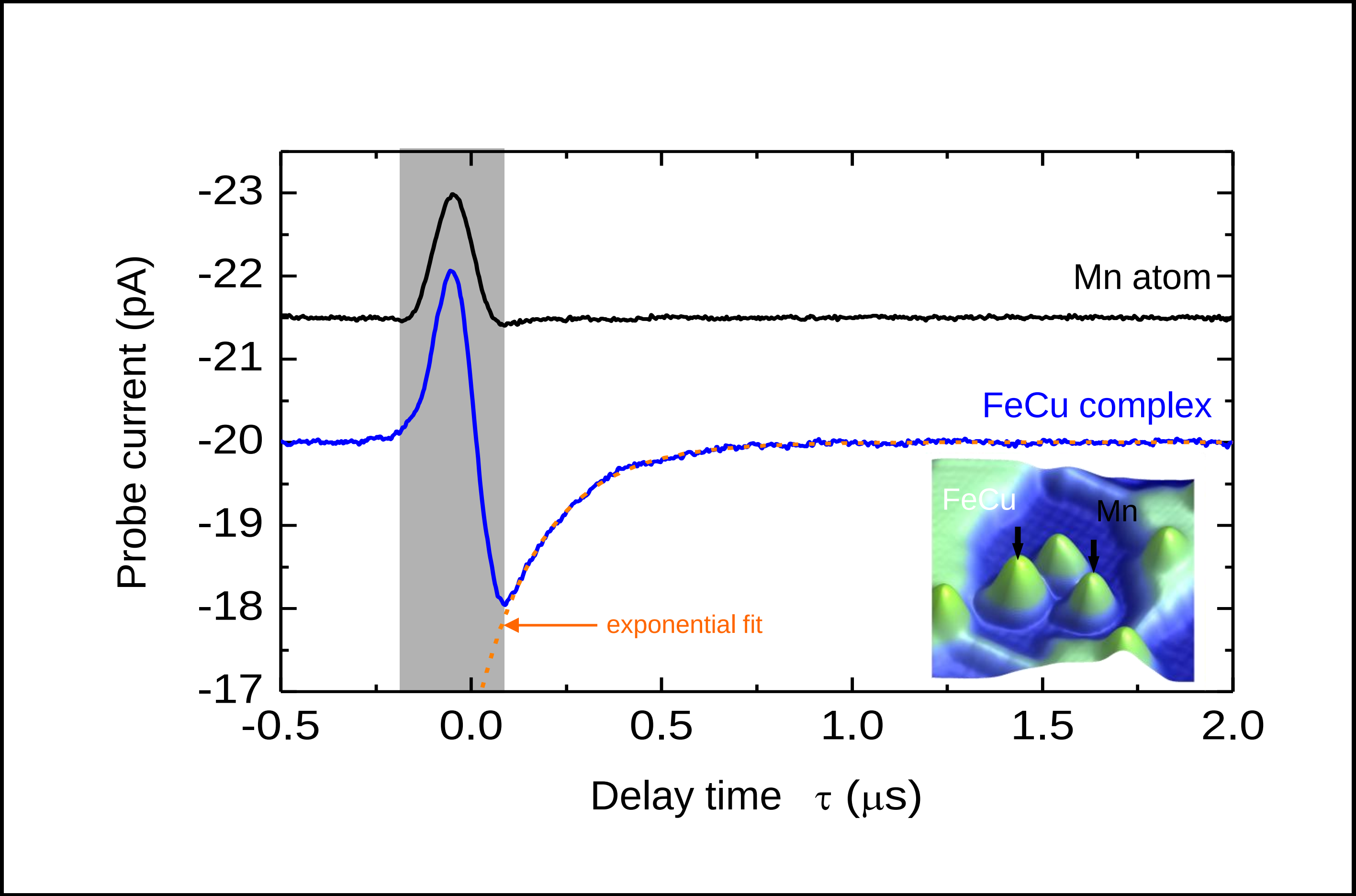
Excited State Spin Configuration

Low elastic conductance





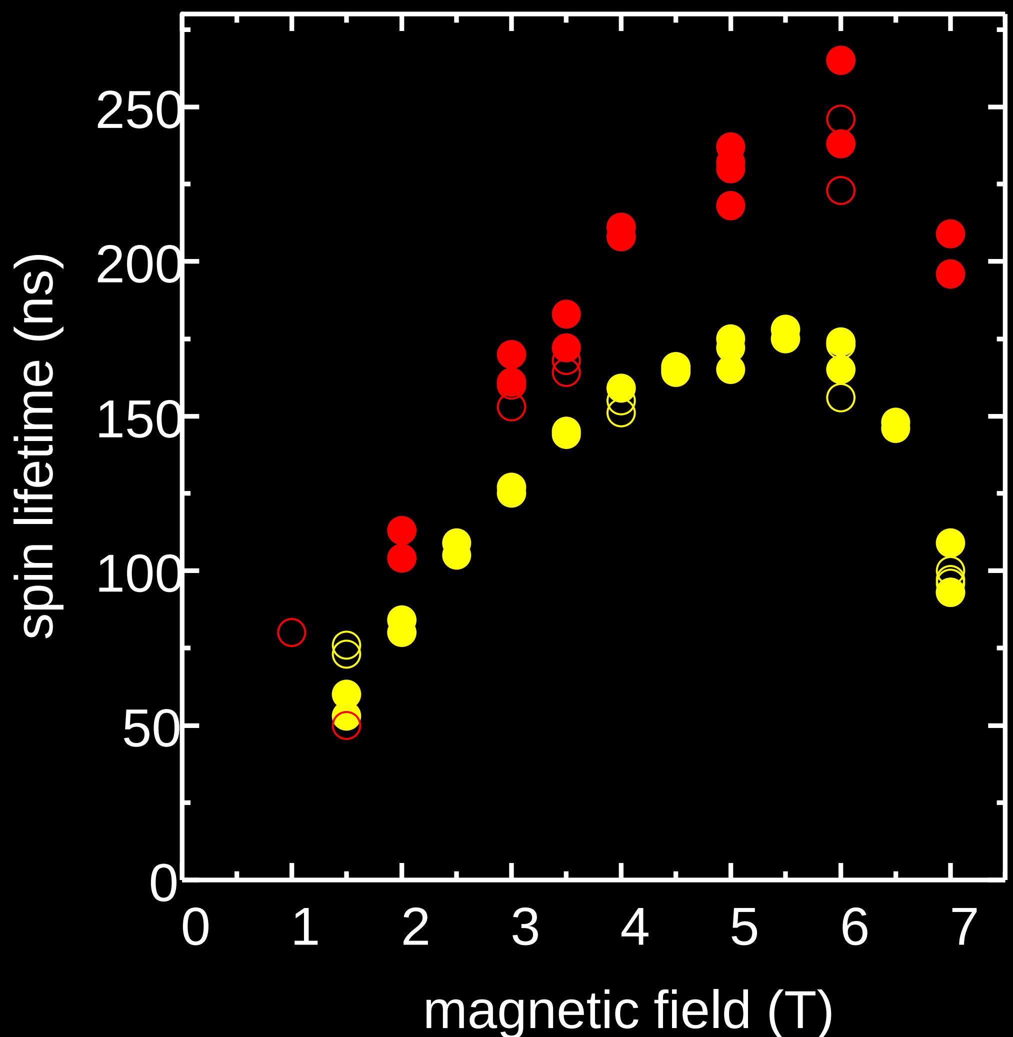
Single-Atom Pump-Probe Measurement of T_1

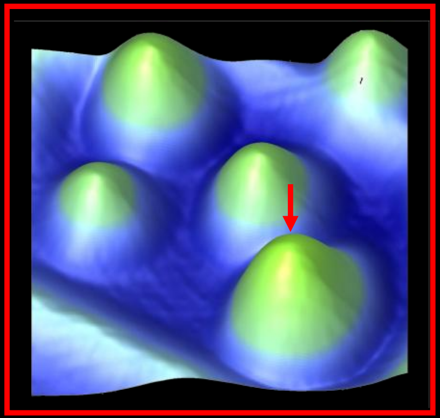


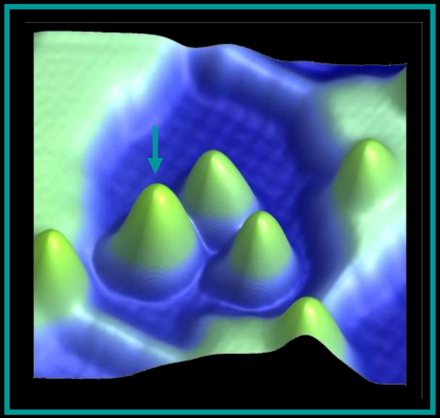
$T_1 = 180 \pm 12$ ns

S. Loth, M. Etzkorn, C.P. Lutz, D.M. Eigler and A.J. Heinrich, *Science*, **329**, 1628 (2010)

Magnetic Field and Site Dependence of T_1

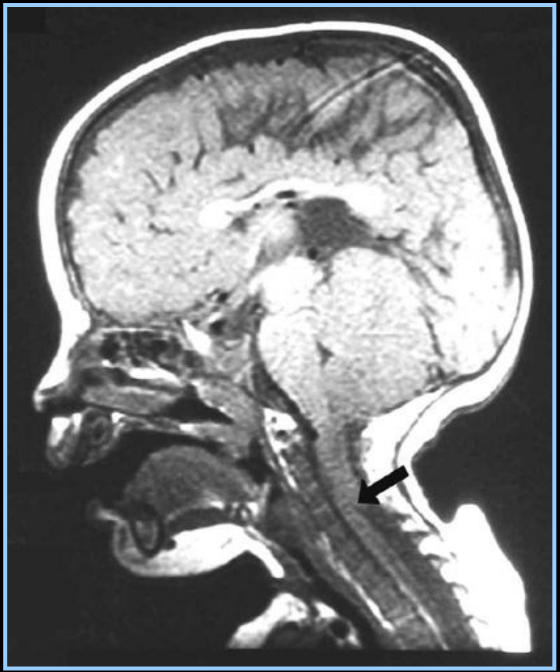






Ability to Measure Site Dependent Variations in T_1

Spin Contrast Imaging

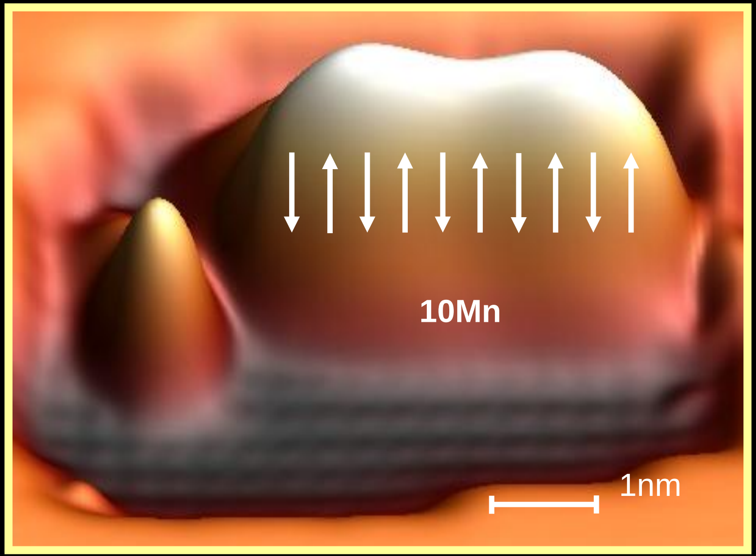


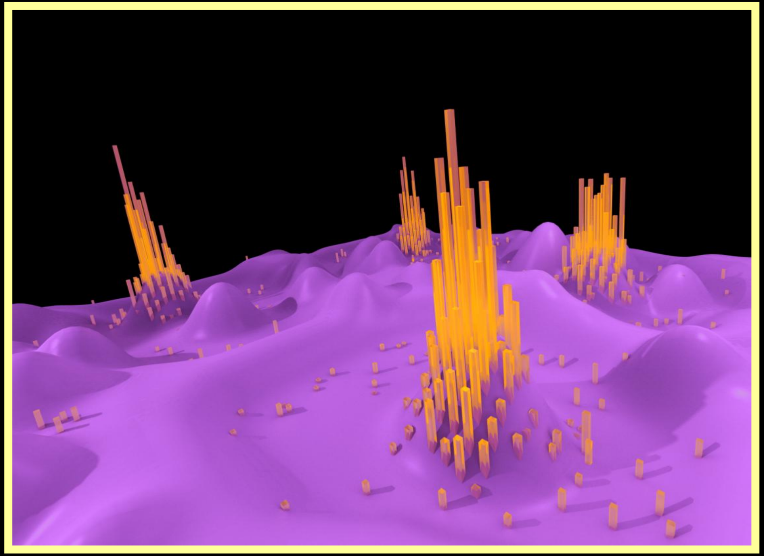
Contrast From Spatial Variations in Nuclear T1

A Comparison Between
Magnetic Resonance & Spin Excitation Spectroscopy :

	NMR & ESR	Spin Excitation Spectroscopy
g-value	✓	✓
T_2	✓	Not yet
T_1	✓	✓
Spectral Resolution	Excellent	Poor
Spatial Resolution	Poor	Excellent
Field Homogeneity	Issue	No Problem
Sample Heterogeneity	Issue	No Problem

What We Can Learn From Spin Excitation Spectroscopy





Energetics

- Atom Specific g-Value
- Magnitude Anisotropy Energy
- Symmetry of Anisotropy Field
- Orientation of Anisotropy Field
- Magnitude and Sign of Exchange Energy
- Ground State Spin Configuration
- Excited State Spin Configuration

Dynamics

- Atom Specific Relaxation Time, T_1
- Magnetic Field Dependence of T_1
-
-
-

Correlation of Spin Properties with Local Structural, Electronic, Chemical & Mechanical Properties

Cast of Characters

Andreas Heinrich	IBM	Team Leader
Chris Lutz	IBM	Resident Genius
Bruce Melior	IBM	Technical Support
Jay Gupta	Ohio State	Postdoc
Cyrus Hirjibehedin	UCL	Postdoc
Markus Ternes	MPI Stuttgart	Postdocs
Sebastian Loth	TBD	Postdoc
Sander Otte	TU Delft	Grad Student
Markus Etzkorn	EPFL	Visitor
Barbara Jones	IBM	Theory
C-Y Lin	Taiwan	Theory Postdoc

Work partially funded by the Office of Naval Research