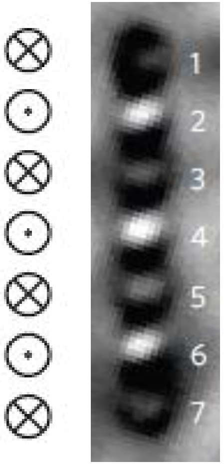
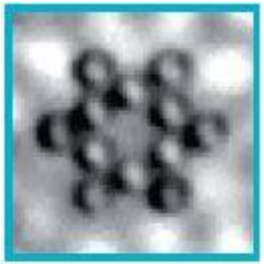
Atom-by-atom Engineering & Magnetometry of Tailored Nanomagnets





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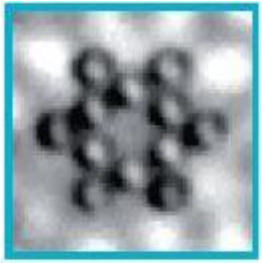
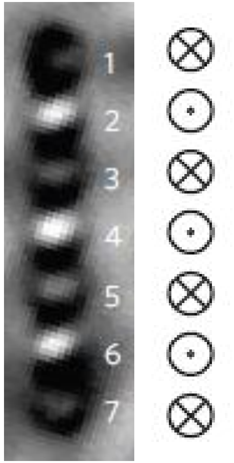




Phys 596
Dec. 4th, 2015

Published April 29th, 2012
A. Khajetoorians, *et al.*
Nature Physics DOI: 10.1038/NPHYS2299

Significant Advancement in Engineering Nanomagnetism

As magnetic devices are becoming smaller and approaching the limit of nanostructures built by separate atoms, knowledge of magnetic interactions on the atomic scale is essential.

- Authors provide best measurement of important long range magnetic interaction
- Authors use knowledge of this interaction to test theoretical model which describes the magnetic ground state of nanostructure
- Authors, based on the knowledge of this interaction, provided an experimental method to build nanomagnets with tailored properties

Outline for Our Presentation

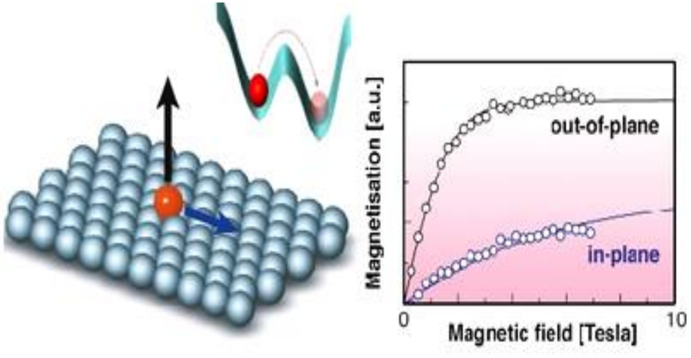
- Scientific Background
    - Magnetic Interactions, Scanning Tunneling Microscope (STM) & Spin-Polarized STM
- Summary of Results and Comparison to Previous work
    - Magnetic interactions & theoretical model versus experiment
- Critical Analysis of Articles Conclusions, Methods
    - How sound are the methods and importance of results
- Citation Analysis
    - Has the paper been important in the field and how the field has changed.

Relevant Magnetic Properties

The magnetic properties of thin films are due to the competition between several contributions such as Magnetic Anisotropy Energy and Exchange Interaction.

Magnetic Anisotropy

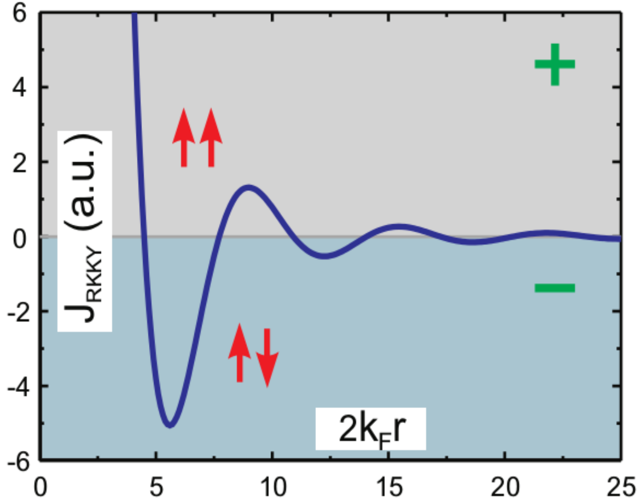
With magnetic anisotropy there is a preferred axis of magnetization.



- Oksana Gaier, PhD thesis (2009)

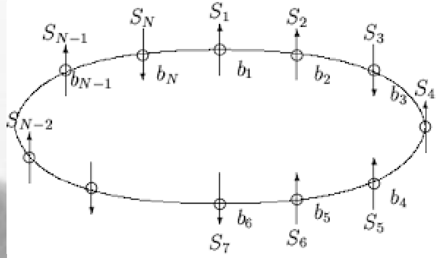
Indirect Exchange Interaction: RKKY interaction

A magnetic moment on a conducting surface polarizes the electron spin density which oscillates as a function of the distance from the atom. If a second magnetic moment is introduced, it couples to such oscillation.



The Ising Model(s) Describe Nanomagnet Coupling

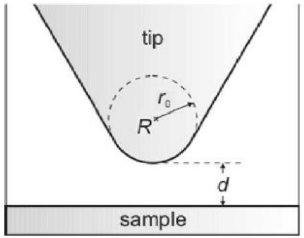
- The Ising model is a mathematical description of magnetic exchange interaction by considering ‘nearest neighbor’ interactions.
- The system studied by the authors can be described by the Ising model because of the strong magnetic anisotropy.
- Other Ising models exist, using more than ‘nearest neighbor’ calculations. The authors use one of these more sophisticated Ising models.



Ernst Ising (left) and his 1D spin ring (right) that is described in his 1925 paper

- Z. Phys 31,253–258; 1925

Spin-Polarized STM (SP-STM) to measure sample magnetic ground state



STM is a powerful tool to measure the topography of a conducting surface. STM can also be used to perform spectroscopy, since the tunnel current depends on the density of states of the sample:

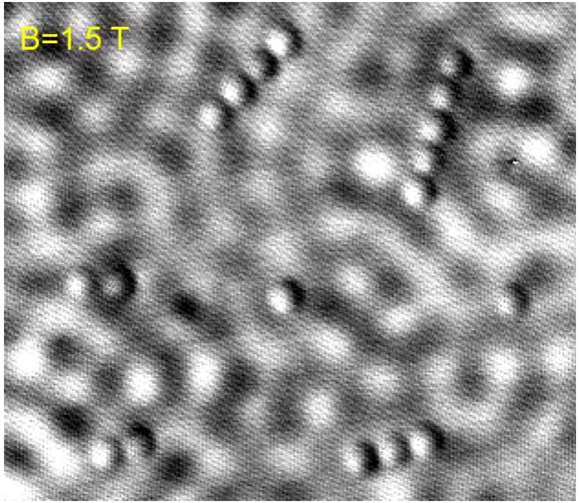
$$I(\mathbf{R}, U) \propto \rho_t(E_F{}^t, \mathbf{R}) \int_0^{eU} \rho_s(\mathbf{R}, E_F{}^s + E) dE$$

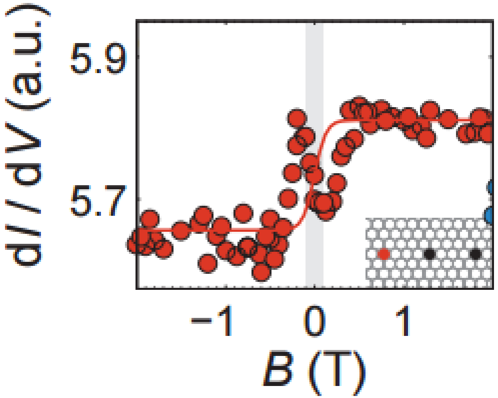
and

$$\frac{\partial I}{\partial U} \propto \rho_t \rho_s(\mathbf{R}, E_F{}^s + eU).$$

- Using a magnetic tip, the current depends on the angle between the tip and sample magnetization

$$\mathrm{d}I/\mathrm{d}U(U) = \mathrm{d}I/\mathrm{d}U(U)_0[1 + P_t P_s(E_F^s + eU) cos(\theta)]$$





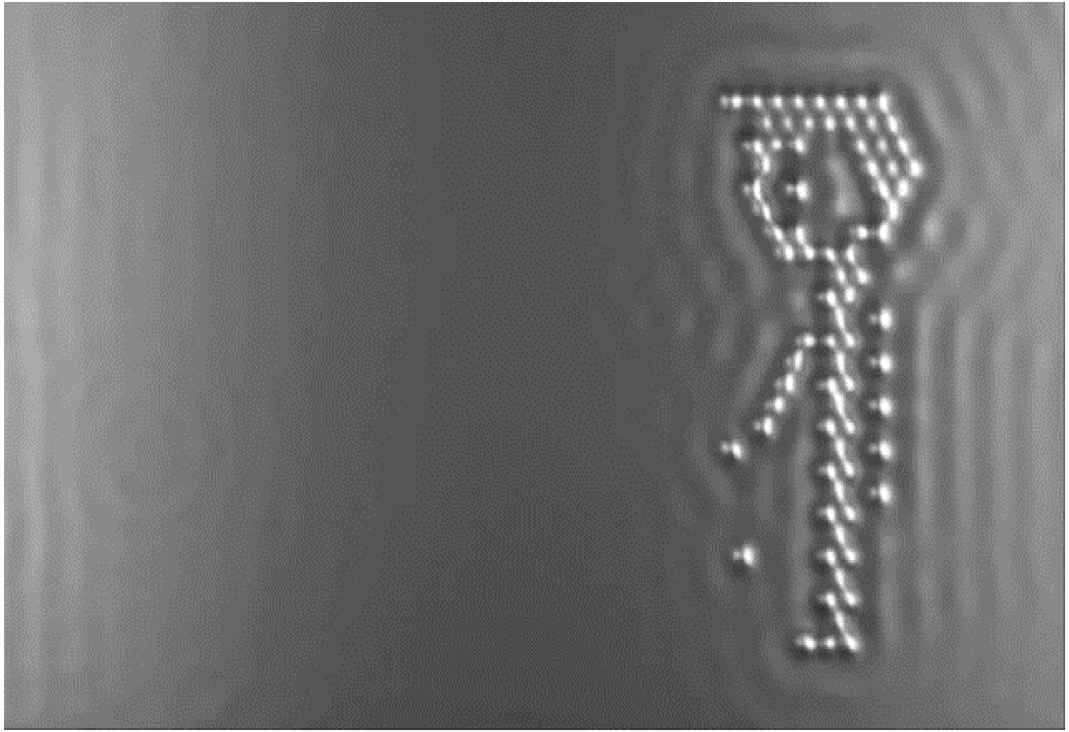
Single atom magnetization curve

- Jessica E. Bickel et al, *Phys. Rev B* 84, 054454 (2011)

STM as a tool to perform Atomic Manipulation

At a distance of few Å between the tip-apex and manipulated atom,the atomic orbitals are overlapping and a weak chemical bond is formed. It is possible to move the atom by moving the tip.

C atoms on Cu

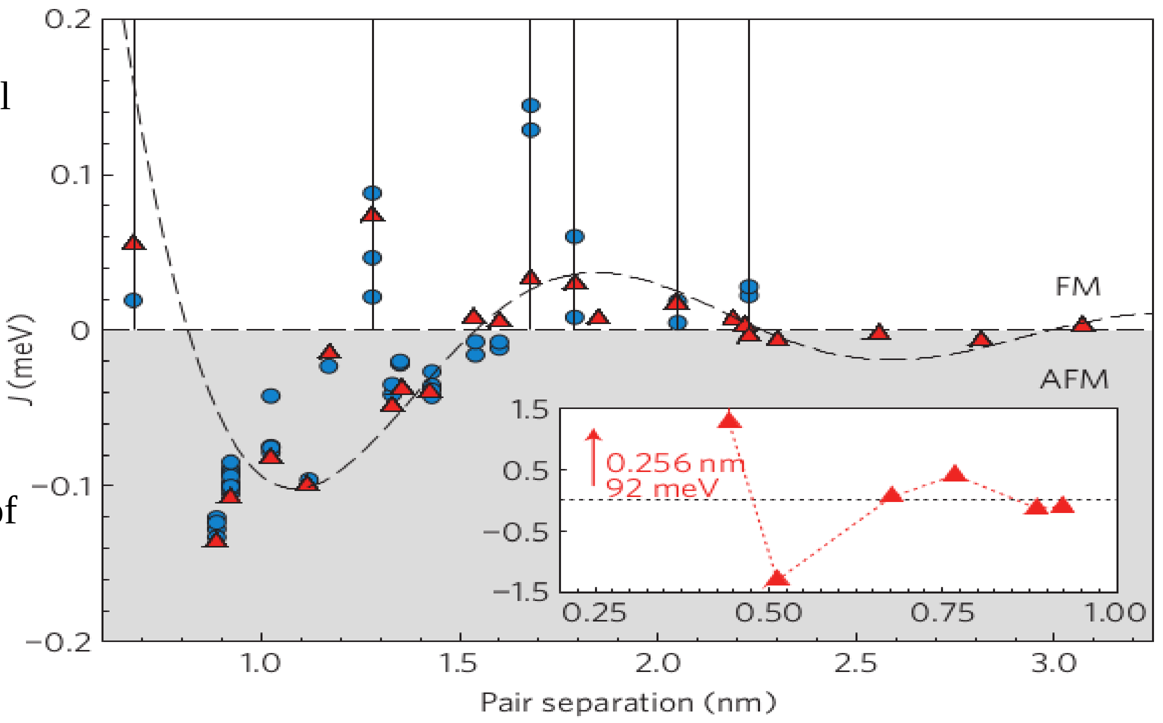


https://www.youtube.com/watch?v=oSCX78-8-q0

- IBM the smallest animation ever realized on a molecular scale

Experimental Measurement of RKKY Interaction

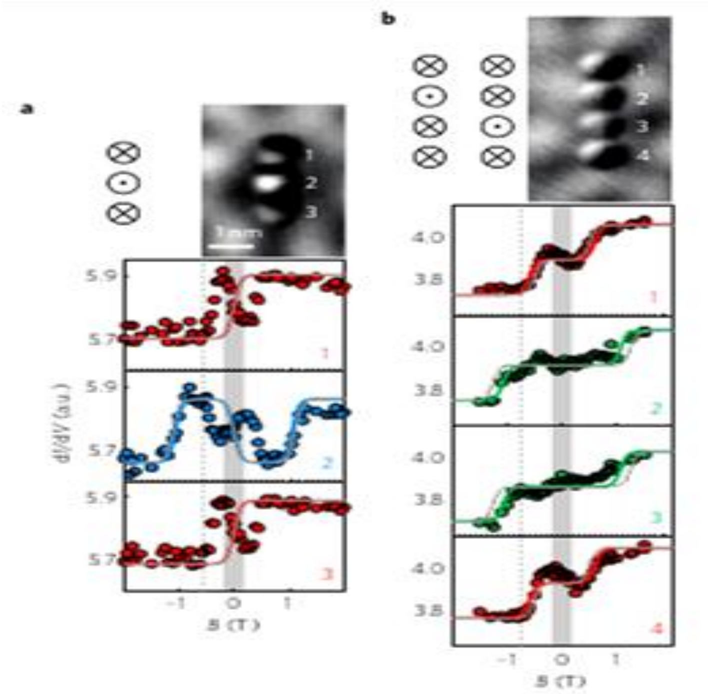
- Measured Jij extracted by fitting the magnetization curves to an Ising model (blue circles);
- Theoretical Jij determined by theoretical Ising model (red triangles).
- Fitting of J as a function of the pair distance d, using a sinusoidal RKKY function (dashed line):
- Improved on previous measurements of interaction from the same group



Measurement of the distance dependence of RKKY interaction (blue circles) compared to basic theory (dashed line) and Ising model (red triangles)

Ising Model Predicts Magnetization Curve for Nanomagnet Structures

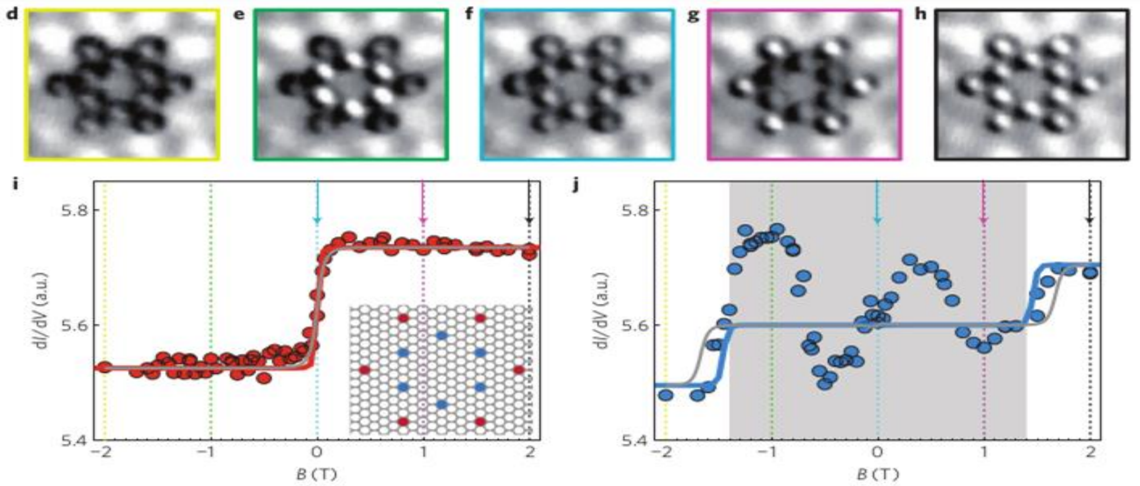
- With better knowledge of RKKY interaction, authors can test the Ising model for complicated nanomagnet configurations
- Can find the magnetization (↑ or ↓) of individual nanomagnets as a function of external B-field by measuring the differential conductance (colored circles)
- Comparison of Ising Model (solid lines) to experiment shows agreement for nanomagnet chains for almost all values of external magnetic field
- Additional verification of ground state can be done with SP-STM image (gray image taken at dashed line)



SP-STM image (top) and differential conductance (bottom three) for three nanomagnet chain

Ising Model Fails in Low B-Field Regime

- Previous experiments lacked sensitivity in low B-fields.
- With increased sensitivity, nanomagnet structures show deviation from Ising Model prediction (see j on the right)



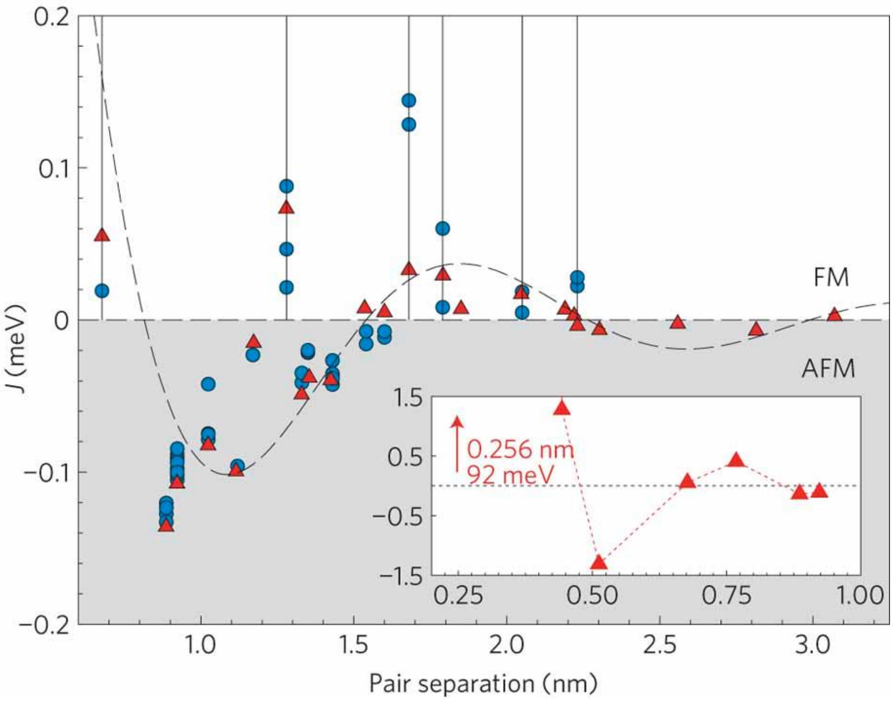
SP-STM images (d-h) and differential conductance curves (i-j) of a ‘kagome’ pattern, an important geometry with novel magnetic properties. The SP-STM was taken at the vertical dashed line with the corresponding color.

Authors' Conclusions

- Generally, Ising model explains magnetic ground states for nanomagnets
- Need to include contribution of the bulk states in calculation of RKKY to better predict nanomagnet properties
- For small B-fields, deviations from Ising model could be due to an additional magnetic field, the source of which is unknown
- The low B-field anomaly is an "interesting open issue" and a better theory is needed.

Our Critical Analysis

- Error “bars” are a bit ambiguous: “spread of data points is a measure for experimental error”
- A lot of references to supplementary material/methods
- Don’t provide a good explanation of the different types of theoretical models
- Quality/representation of data is exceptional
- Provides a method to build and study nanomagnets



Citation Analysis

60 Citations (on web of science), most of them mention our paper to show the capability of modern scanning tunneling spectroscopy technology

Field: Countries/Territories	Record Count	% of 60	Bar Chart
GERMANY	33	55.000 %	
FRANCE	8	13.333 %	
USA	7	11.667 %	
SPAIN	5	8.333 %	
ENGLAND	4	6.667 %	
NETHERLANDS	4	6.667 %	
SWITZERLAND	4	6.667 %	
BRAZIL	3	5.000 %	
PORTUGAL	3	5.000 %	
RUSSIA	3	5.000 %	
ARGENTINA	2	3.333 %	
ITALY	2	3.333 %	
POLAND	2	3.333 %	

Distribution of citations by countries

Field: Publication Years	Record Count	% of 60	Bar Chart
2014	22	36.667 %	
2013	19	31.667 %	
2015	15	25.000 %	
2012	4	6.667 %	

Distribution of citations by publication year

Impact on the field

- Its technique allows fine control of spin coupling, which could be used in nano-magnetic storage technology and provides tools to verify low-dimensional quantum system models.

- The approach could be used to answer fundamental questions of nanomagnetism such as real-space investigations of the phases of spin liquids or spin ices

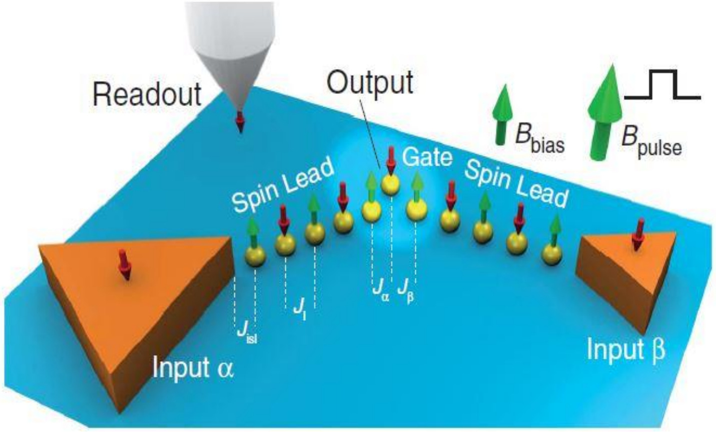


Diagram of an OR gate built by nanomagnets

Polyakov, Oleg P., and Valeri S. Stepanyuk. *J. Phys. Chem. Lett.* (2015)

A. A. Khajetoorians, et al. *Science* 332, 1062 (2011)

THANK YOU FOR LISTENING