Revealing Properties and Interactions of Individual Magnetic Adatoms and Nanostructures by SP-STM

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Outline

I) Revealing Fundamental Magnetic Interactions between Individual Adatoms by Single-Atom Magnetometry

- Indirect magnetic exchange (RKKY) interactions on the atomic scale
- Tailored nanomagnets and all-spin atomic-scale logic devices
- Dzyaloshinskii-Moriya (DM) interactions between individual adatoms
- Novel class of bottom-up designed magnets with tunable chirality!

II) Chiral Magnets revealed by 3D-Vectorial Spin Mapping based on SP-STM

- Chiral spin spirals in atomic spin chains
- Discovery of nanoskyrmion lattices in ultrathin transition metal films
- Single skyrmion creation and annihilation by SP-STM

→ Towards novel concepts of information technology based on bottom-up designed topological magnets
Spin-Polarized STM for Revealing & Manipulating Magnetic Structures on the Atomic Scale

Correlation between
- atomic structure
- electronic structure
- spin structure

at ultimate spatial, time
and energy resolution!

\[ I_{sp} = I_0 [1 + P_S P_T \cos(\vec{M}_S, \vec{M}_T)] \]

- R. Wiesendanger et al., Science 255, 583 (1992)
- R. Wiesendanger, Rev. Mod. Phys. 81, 1495 (2009)
Principle of Single-Atom Magnetometry based on SPSTM

Single-Atom Magnetization Curve: Fe Atom on Cu(111)

Fit to Langevin Function:

\[ E = -mB \cos \theta - K_{\perp} \cos^2 \theta \]

\[ \langle M_z \rangle \propto \frac{\int d\theta \sin \theta \cos \theta e^{-E/k_BT}}{\int d\theta \sin \theta e^{-E/k_BT}} \]

Magnetic moment:
\[ m = 3.5 \mu_B \]

Magnetic anisotropy:
\[ K = 1 \text{ meV} \quad \text{(out-of-plane)} \]

From Single-Atom Magnetization Curves to RKKY-Coupling

\[ B_{\text{crit}} \sim |J| \]

\[ \frac{dI}{dV} \text{ (a.u.)} \]

\[ B \text{ (T)} \]

Isolated atom

\[ d = 1.024 \text{ nm} \]
Oscillatory Indirect Magnetic Exchange in Fe Pairs on Cu(111)

A. A. Khajetoorians et al., Nature Physics 8, 497 (2012)
Antiferromagnetic Fe Chain on Cu(111) created by Single-Atom Manipulation

$B = -0.625 \, \text{T}$

$B = -1.25 \, \text{T}$

Spin-resolved $\frac{dI}{dV}$

$1 \, \text{nm}$

$0.5 \, \text{Å}$
Anti-Ferromagnetically Coupled Quantum Corral

B = -1.25 T (saturated)
B = -0.75 T (anti-phasing)

-10 mV; 600 pA

2 nm
SAMCs of AFM Coupled Chains

<table>
<thead>
<tr>
<th>Chain Length</th>
<th>3</th>
<th>4</th>
<th>5</th>
</tr>
</thead>
<tbody>
<tr>
<td>$J$ (μeV)</td>
<td>-86</td>
<td>-32</td>
<td>-76</td>
</tr>
<tr>
<td>$a$ (μM)</td>
<td>0</td>
<td>0.25</td>
<td>0.5</td>
</tr>
<tr>
<td>$b$ (1/1)</td>
<td>5</td>
<td>5</td>
<td>7</td>
</tr>
</tbody>
</table>
Kagomé Lattice

A. A. Khajetoorians et al., Nature Physics 8, 497 (2012)
NOVEL APPROACH TOWARDS FUNDAMENTAL STUDIES IN CONDENSED MATTER RESEARCH

Single Adatom Properties

Individual Atoms

Adsorption on Substrate

Distance-dependent Interactions

Atomistic Spin Dynamics

Correlation Effects

Artificial Nanostructures

Use of Single-Atom Manipulation

Single-Atom Spectroscopy

Single-Atom Magnetometry

On-line monitoring of resulting structures

→ NOVEL MATERIALS BY DESIGN
(magnets, superconductors,...)
From Model-Type Magnetic Nanostructures To Atomic-Scale Spintronic Devices
Utilize RKKY-coupling to tailor magnetic state of output!

A. A. Khajetoorians et al., Science 332, 1062 (2011)
Logical Input Negation and Lead Construction

- Tune magnetic coupling ↔ Manipulate inter-atomic distance
- First atom’s spin state stabilized by nanoscale island
- Antiferromagnetic coupling regime

A. A. Khajetoorians et al., Science 332, 1062 (2011)
Spin “Cascading”

Applied B-field → Switch island state
Input inversion → Spin-propagation
OR - Gate (spin-inverted tip = NOR)

3 nm

-10 mV; 600pA; B = 50mT
Characteristics of Single Atom Spin Logic

No atom movement involved  →  Fast switching processes
No charge transport involved  →  Negligible energy dissipation;
                                electrical contact properties are irrelevant!
Future Perspectives for Atomic Spin Chains coupled to Small Magnetic Clusters

- RKKY-coupled nanostructures:
  - detailed studies of expected retardation effects in spin signal propagation

Interface-Driven Non-collinear Spin States

Dzyaloshinskii-Moriya interaction due to spin-orbit coupling

\[ E_{\text{DM}} = \sum_{i,j} D_{ij} \cdot (S_i \times S_j) \]

T. Moriya, Phys. Rev. 120, 91 (1960).

when inversion symmetry is broken

SPSTM: Cycloidal spin spirals with unique rotational sense


M. Bode et al., Nature 447, 190 (2007)
P. Ferriani et al., PRL 101, 27201 (2008)
S. Meckler et al., PRL 103, 157201 (2009)
M. Menzel et al., PRL 108, 197204 (2012)
Chiral Spin Spirals in Bi-Atomic Fe Chains on Ir(001)

DM-interaction is responsible for chiral spin spiral formation!

M. Menzel et al., PRL 108, 197204 (2012)
Discovery of Interface-Driven Skyrmionic Lattices in a Monolayer of Fe on Ir(111)
3D Vectorial Spin Map of 1 ML Fe on Ir(111)

in-plane magnetization

out-of-plane magnetization

S. Heinze et al., Nature Physics 7, 713 (2011)
Microscopic Origin of the Skyrmion Lattice

\[ H = - \sum_{i,j} J_{ij} \mathbf{S}_i \cdot \mathbf{S}_j + \sum_{i,j} D_{ij} (\mathbf{S}_i \times \mathbf{S}_j) + \sum_i A_i (S^z_i)^2 \]

- **exchange**
- **Dzyaloshinskii-Moriya**
- **anisotropy**

\[ - \sum_{ij} B_{ij} (\mathbf{S}_i \cdot \mathbf{S}_j)^2 - \sum_{ijkl} K_{ijkl} \left[ (\mathbf{S}_i \mathbf{S}_j)(\mathbf{S}_k \mathbf{S}_l) + (\mathbf{S}_j \mathbf{S}_k)(\mathbf{S}_l \mathbf{S}_i) - (\mathbf{S}_i \mathbf{S}_k)(\mathbf{S}_j \mathbf{S}_l) \right] \]

- Dzyaloshinskii-Moriya interaction chooses skyrmion lattice out of several possible 2D spin textures for Fe on Ir(111)
- due to 4-spin interaction 2D spin textures are favored over ferromagnetic and 1D spin spiral states

⇒ Nanoskyrmion lattice is energetically most favorable among the possible 2D magnetic states even in zero field!
First report on isolated chiral magnetic skyrmions in a Pd-Fe bilayer on Ir(111)!

$U = +200$ mV
$I = 1.0$ nA
$T = 2.2$ K
$B = -1.5$ T

→ skyrmion looks axisymmetric with out-of-plane-tip
From Imaging of Individual Skyrmions to Local Manipulation by Spin-Polarized Current Injection
Writing and Deleting Single Skyrmions in a Bilayer of Pd-Fe on Ir(111) by a SP-STM tip

Writing and deleting of single skyrmions by localized spin current injection
Imaging of individual skyrmions by in-plane sensitive SP-STM probe tip

N. Romming et al., Science 341, 6146 (2013)
Switching Mechanism

(i) thermal noise
(ii) Joule heating
(iii) non-thermal excitations from injected electrons
(iv) spin transfer torque

→ analyze switching behavior as function of current $I$, voltage $U$, and applied $B$-field!

Switching Mechanism

low bias: non-perturbing imaging
higher bias: increased switching frequency due to non-thermal excitations by injected electrons

→ switching rate increases linearly with current

At low $U$, $I$: no switching
→ thermally activated switching does not play a role!
At constant power: switching rate still depends critically on $U$
→ local (Joule-)heating does not play a decisive role!
Switching Mechanism

(i) thermal noise

(ii) Joule heating

(iii) non-thermal excitations from injected electrons

(iv) spin transfer torque

spin transfer torque leads to a shift of ~100 mT → induces directionality to the switching!

- Single-atom magnetometry has been established

- Model-type nanomagnets with predetermined sign and strength of pairwise (RKKY and DM) interactions have been built

- All-spin atomic-scale logic devices have been demonstrated

- Chiral nanoscale spin spirals and skyrmions resulting from interfacial DM interactions were discovered by 3D vector-resolved SP-STM
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