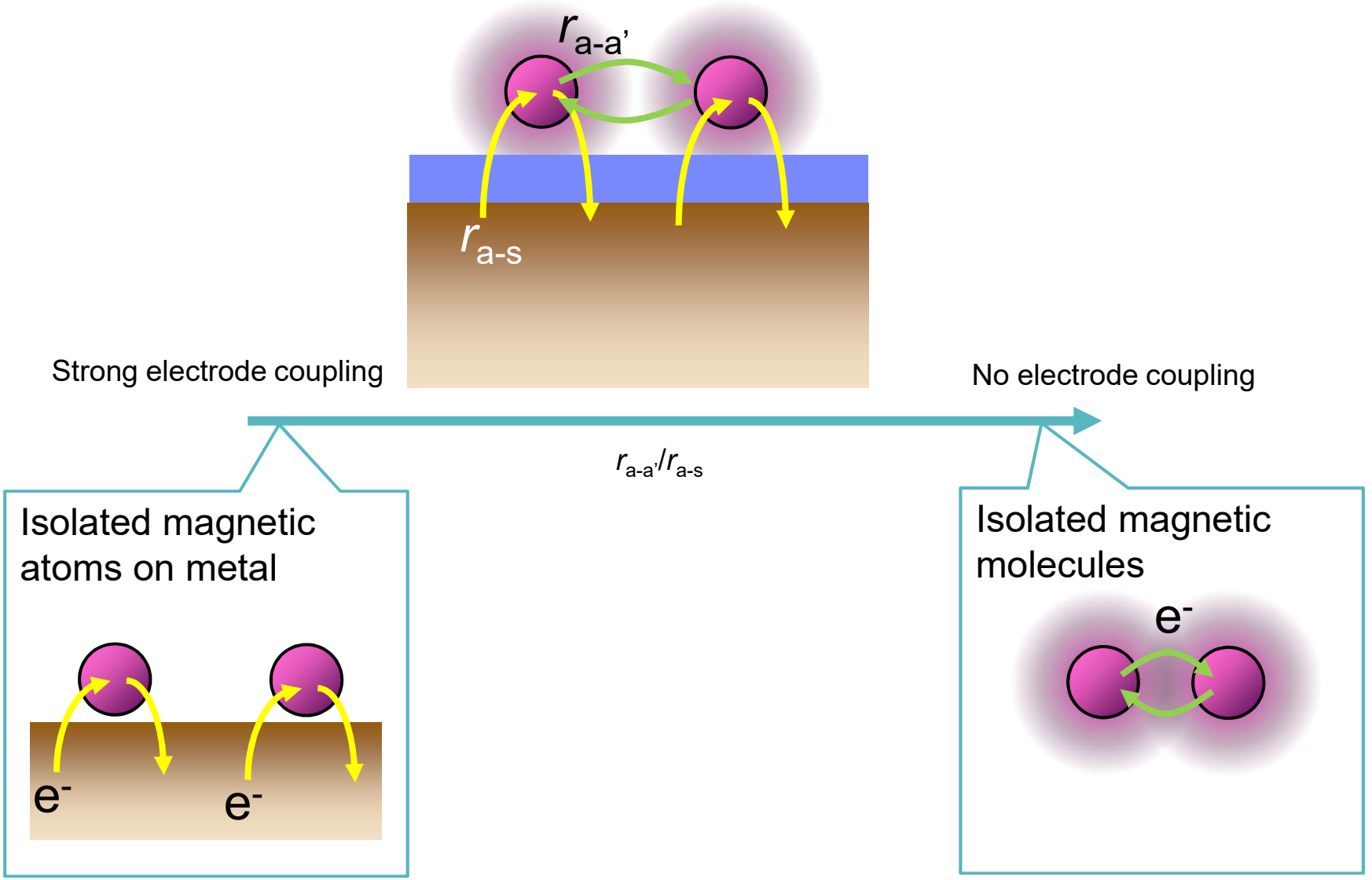
Universität Stuttgart
Institute for Functional Matter and Quantum Technologies

Image: Peter Garten, CUI Hamburg

Electon scattering vs. spin entanglement



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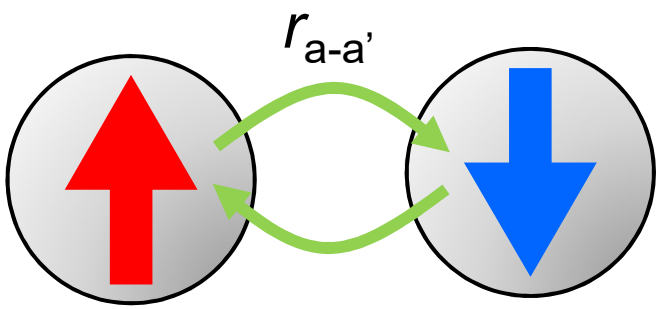
Coupled Atoms: Closed Quantum System

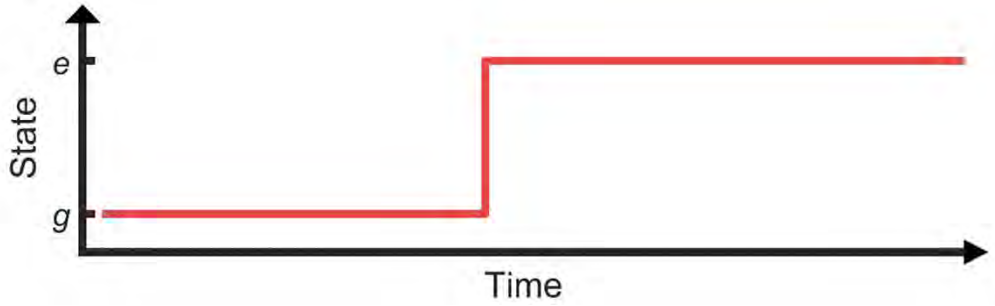


Ground state

$$|\varphi_-\rangle = |\uparrow\downarrow\rangle - |\downarrow\uparrow\rangle$$

Excited state

$$|\varphi_+\rangle = |\uparrow\downarrow\rangle + |\downarrow\uparrow\rangle$$



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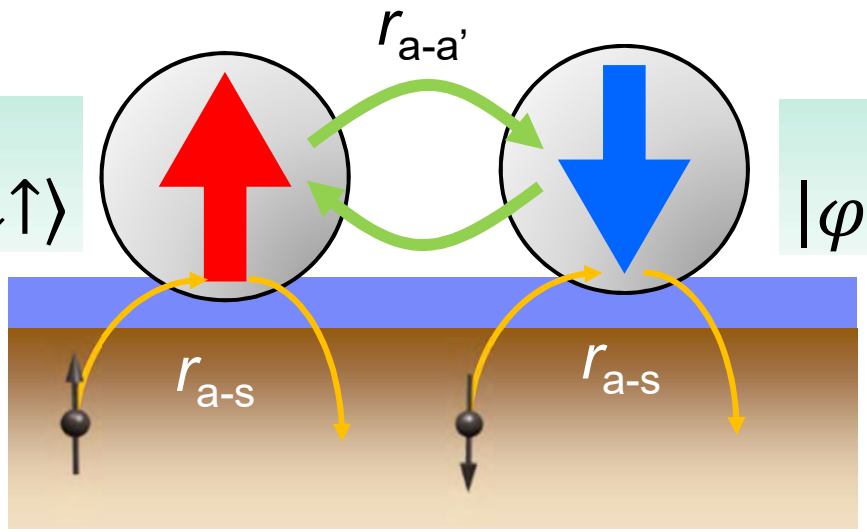
Coupled Atoms on Surface: Open Quantum System

Ground state

$|\varphi_-\rangle = |\uparrow\downarrow\rangle - |\downarrow\uparrow\rangle$



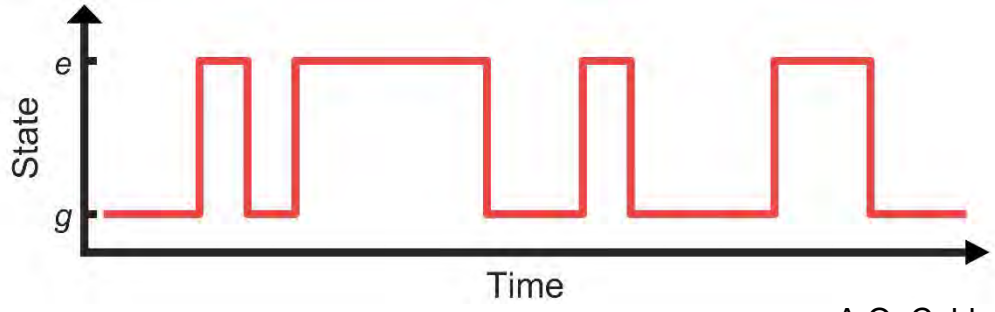
Excited state

$|\varphi_+\rangle = |\uparrow\downarrow\rangle + |\downarrow\uparrow\rangle$

Scattered states

$|\uparrow\downarrow\rangle,$

$|\downarrow\uparrow\rangle$



A.O. Caldeira, A.J. Leggett PRL 46 211 (1981)

F. Delgado, S. Loth, M. Zielinski, J.Fernandez-Rossier EPL 109 57001 (2015)

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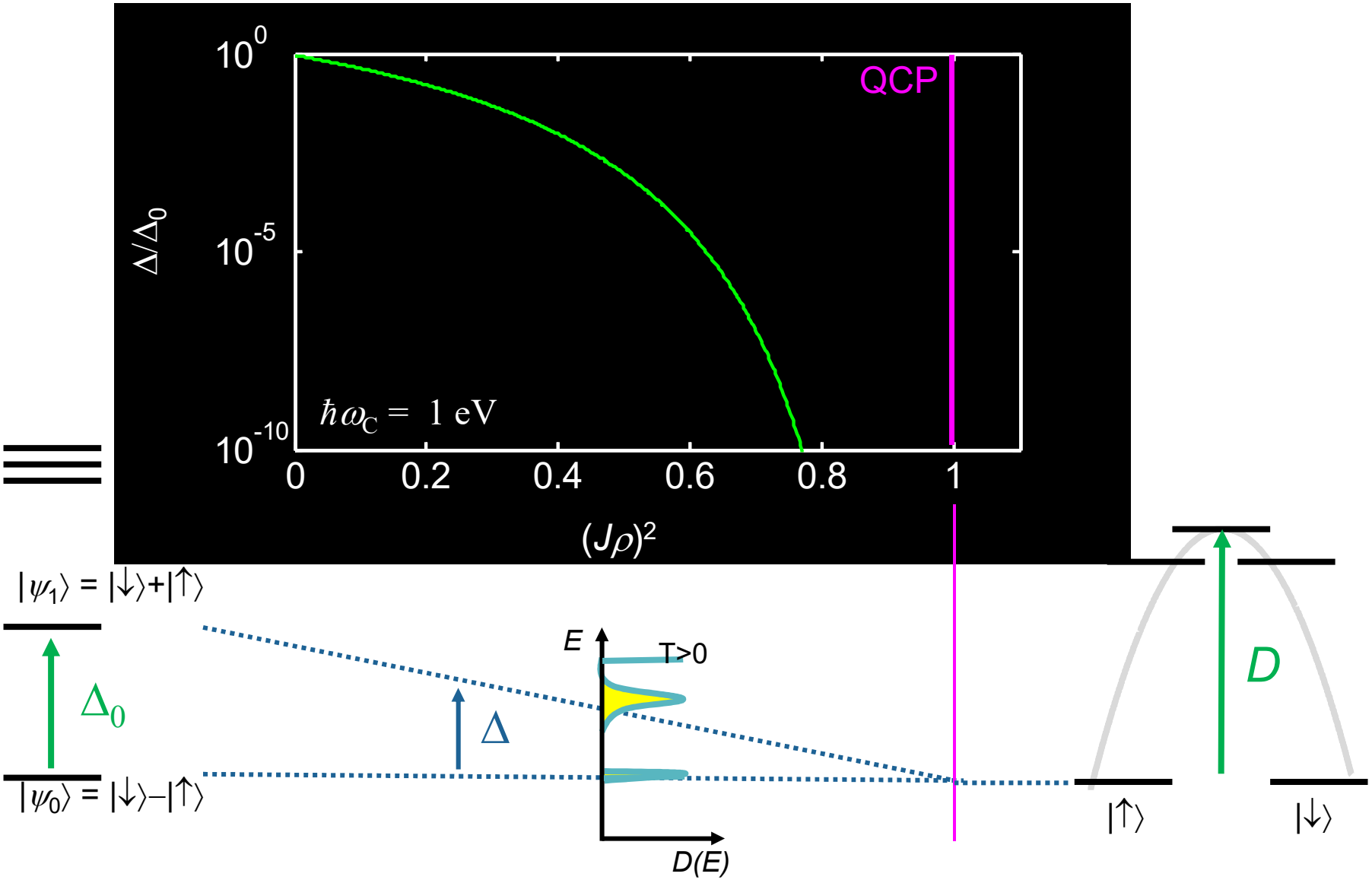
Renormalized level splitting – Spin Boson model



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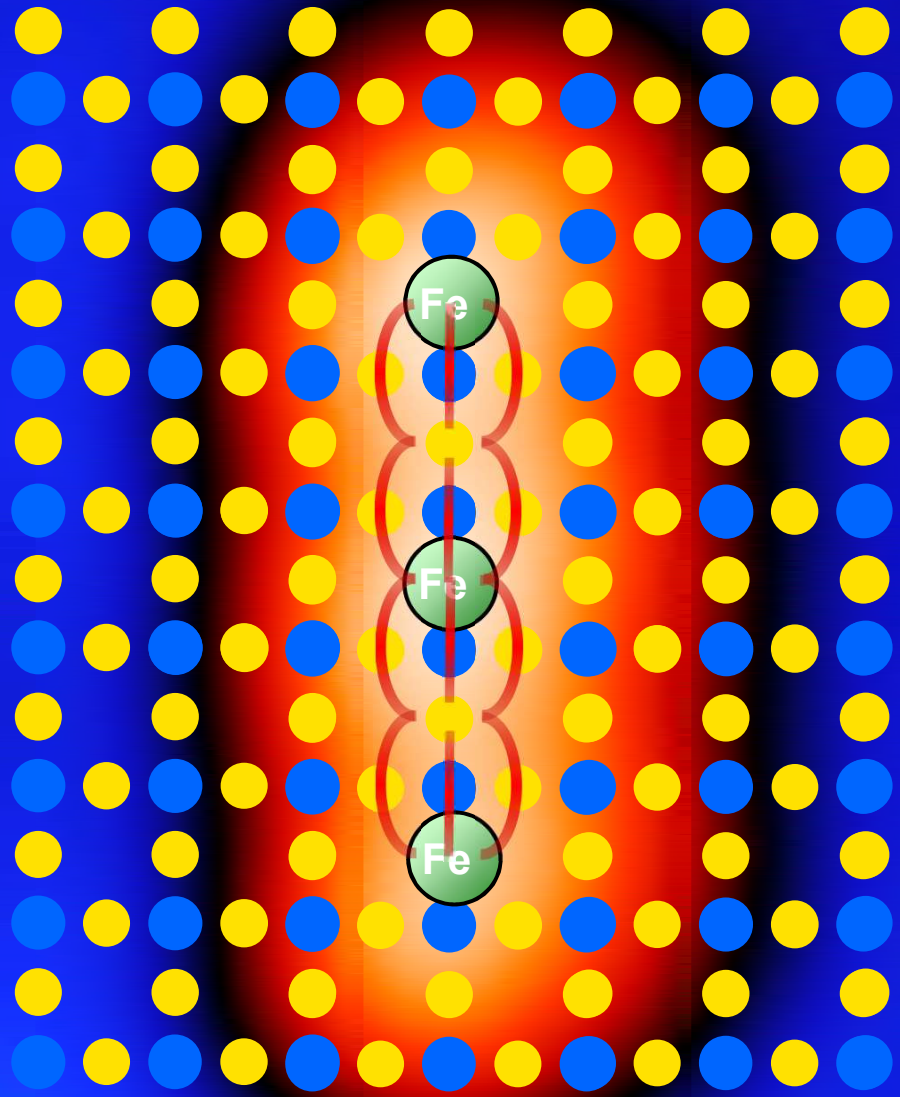
F. Delgado, SL, M. Zielinski, J. Fernandez-Rossier EPL 2015

Fe_3 spins sensor



1 nm

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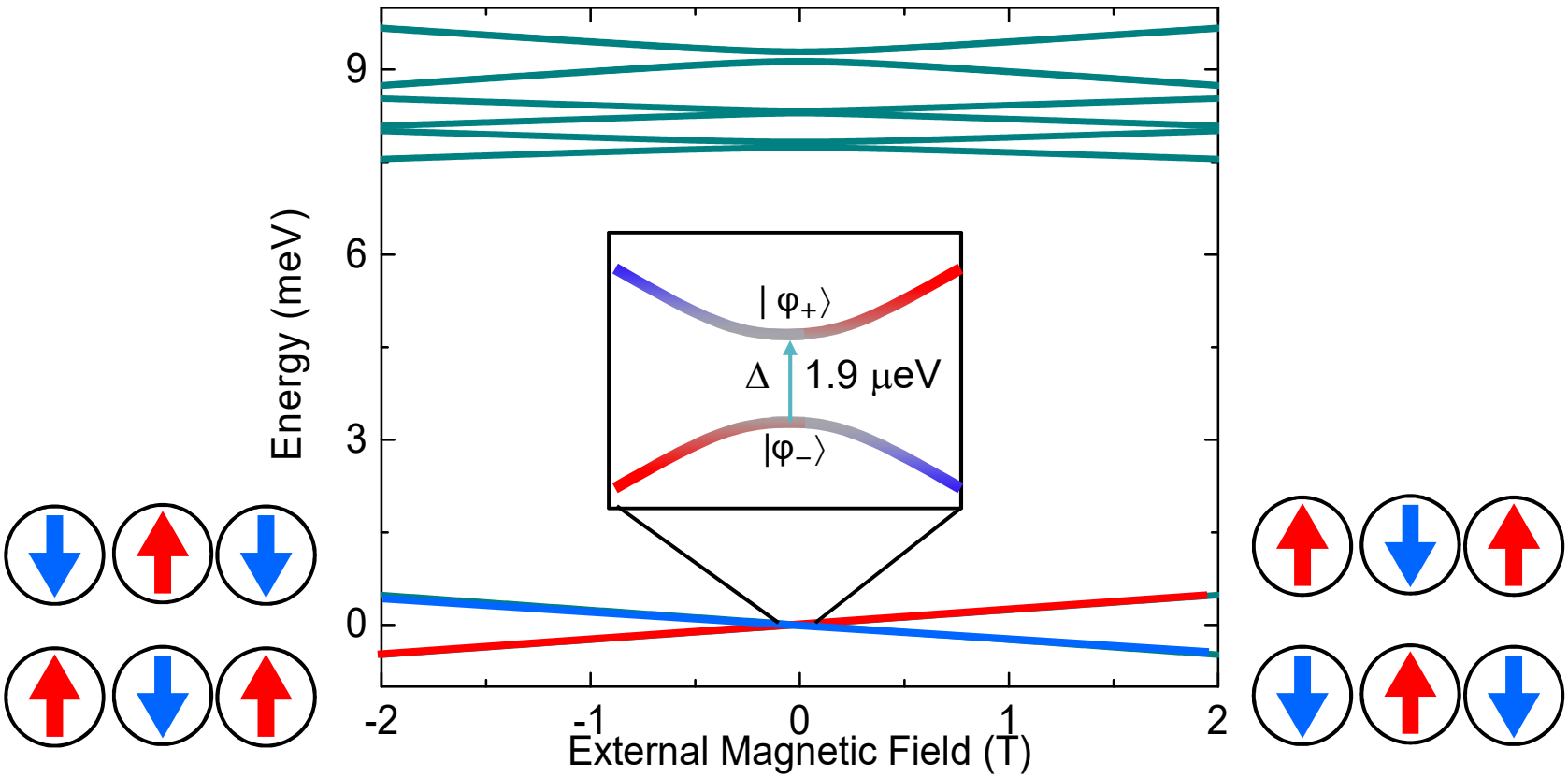
Spin state spectrum of Fe trimer



Entangled ground state and avoided level crossing at $B = 0$

$$|\varphi_+\rangle = |+2-2+2\rangle + |-2+2-2\rangle$$
$$|\varphi_-\rangle = |+2-2+2\rangle - |-2+2-2\rangle$$

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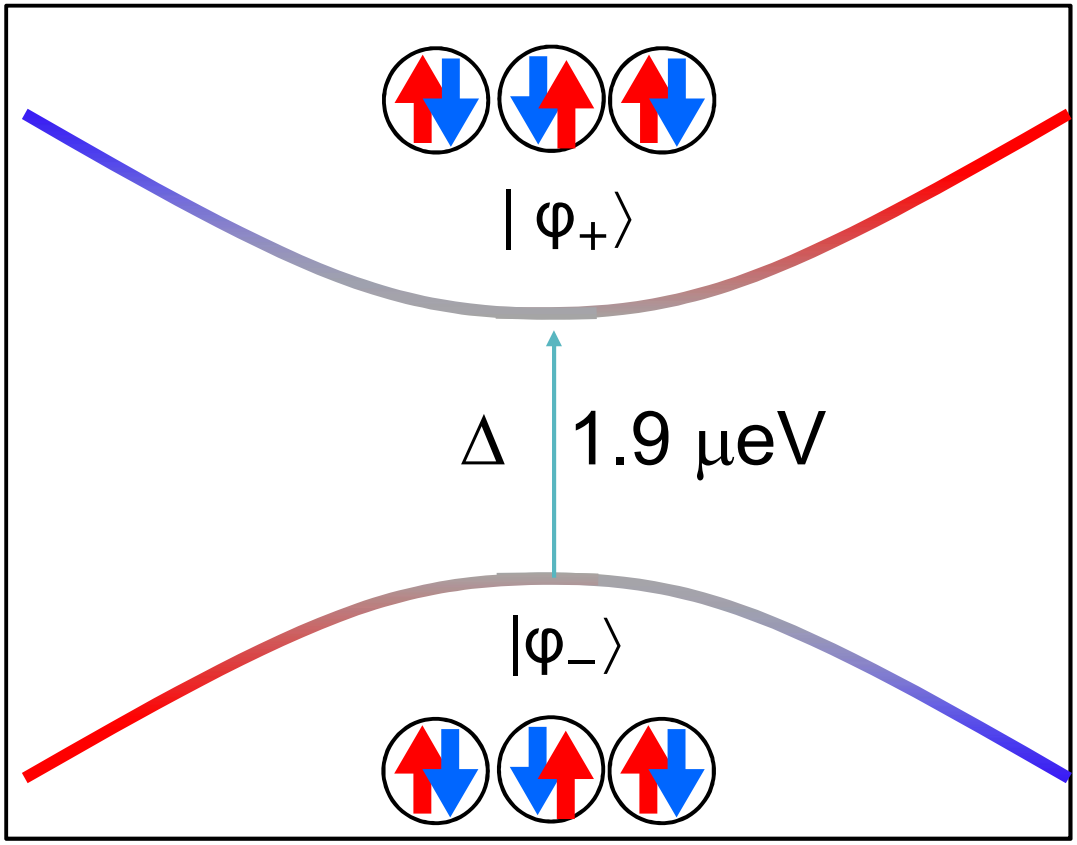
Entangled ground state and avoided level crossing at $B = 0$



$$|\varphi_+\rangle = |+2-2+2\rangle + |-2+2-2\rangle$$

$$|\varphi_-\rangle = |+2-2+2\rangle - |-2+2-2\rangle$$

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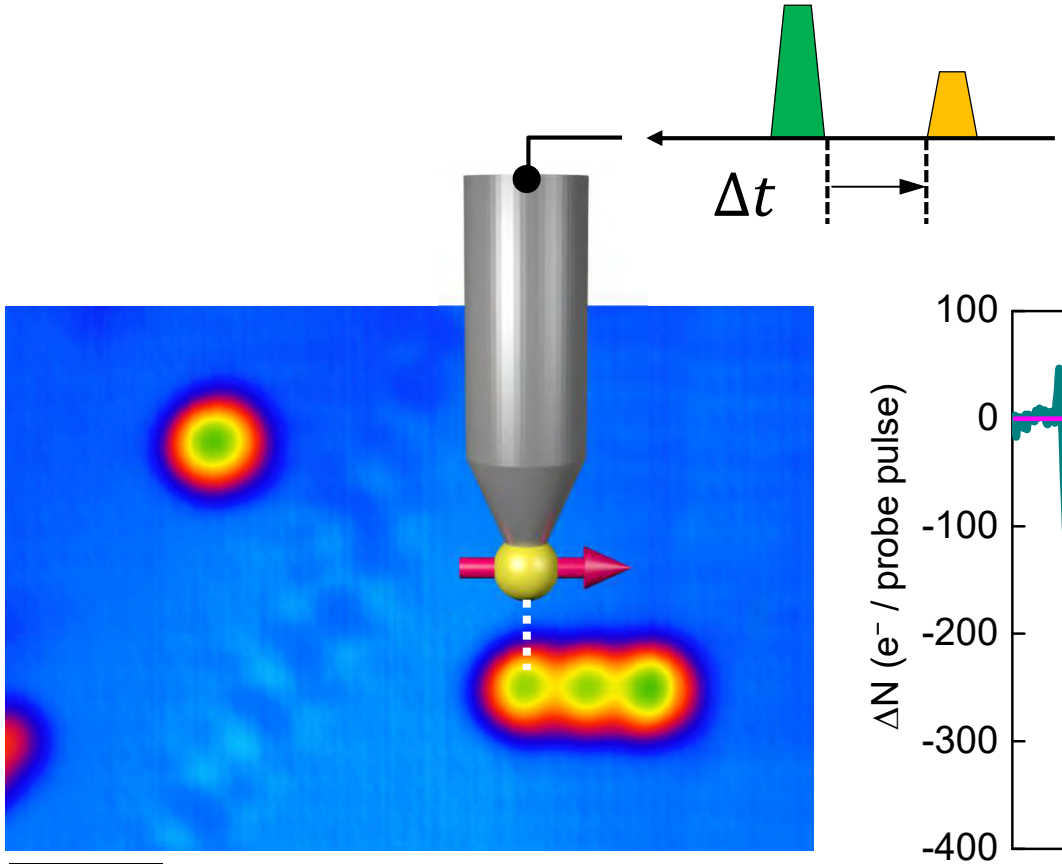
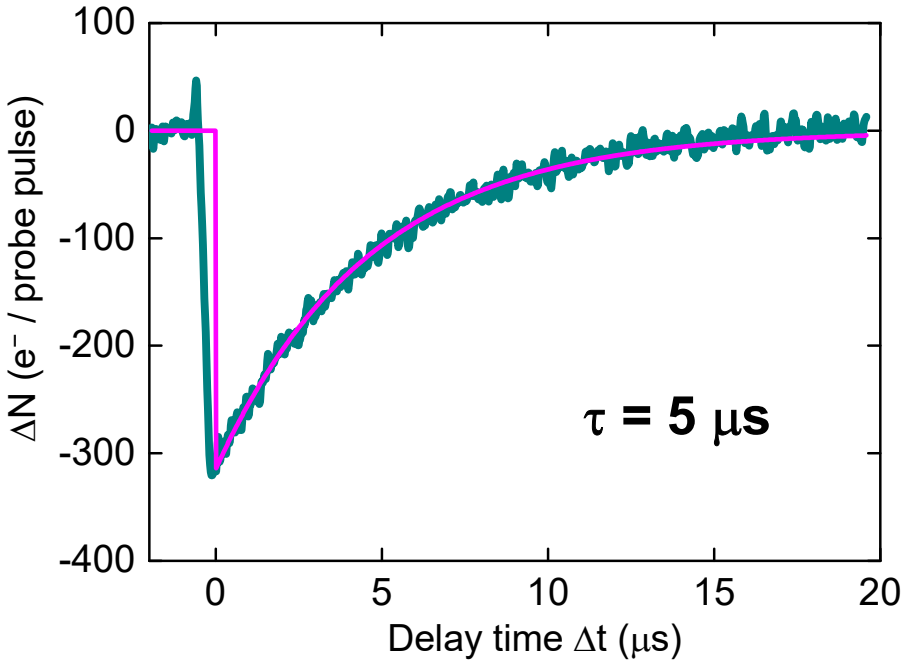
Spin lifetime of few-atom spin systems $(Fe_3)_{Cu2N}$





technique see: Science 329 1628 (2010).

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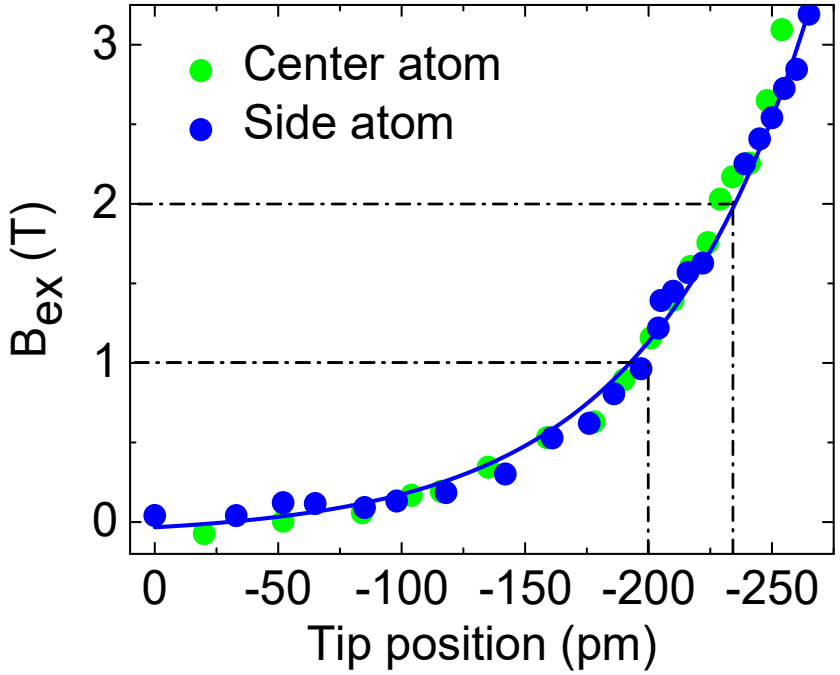
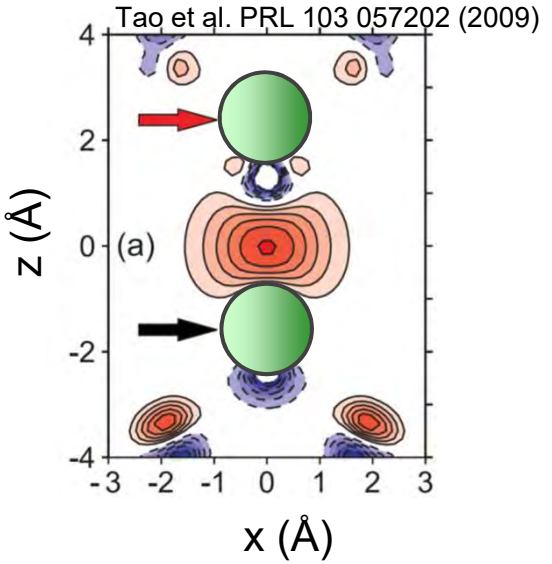
Interatomic exchange bias field





S. Yan, D.J. Choi, J.A.J Burgess, S. Rolf-Pissarczyk, S. Loth
Nature Nano 10 40 (2015)

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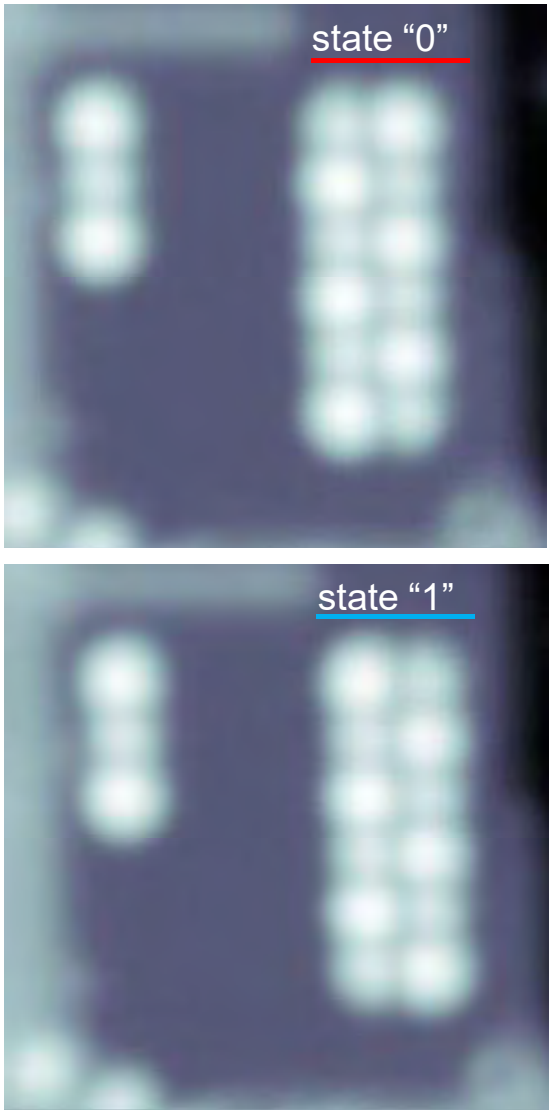
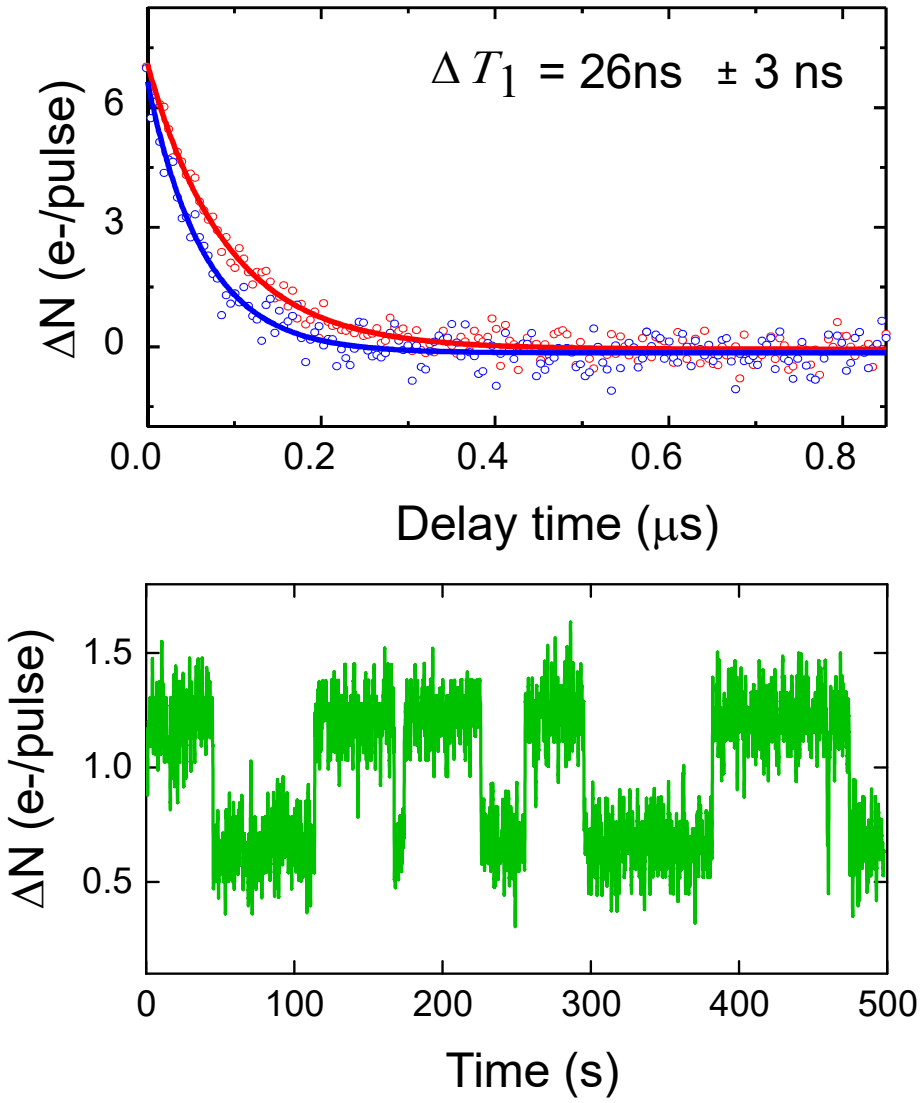
Remote Spin sensing at the atomic scale





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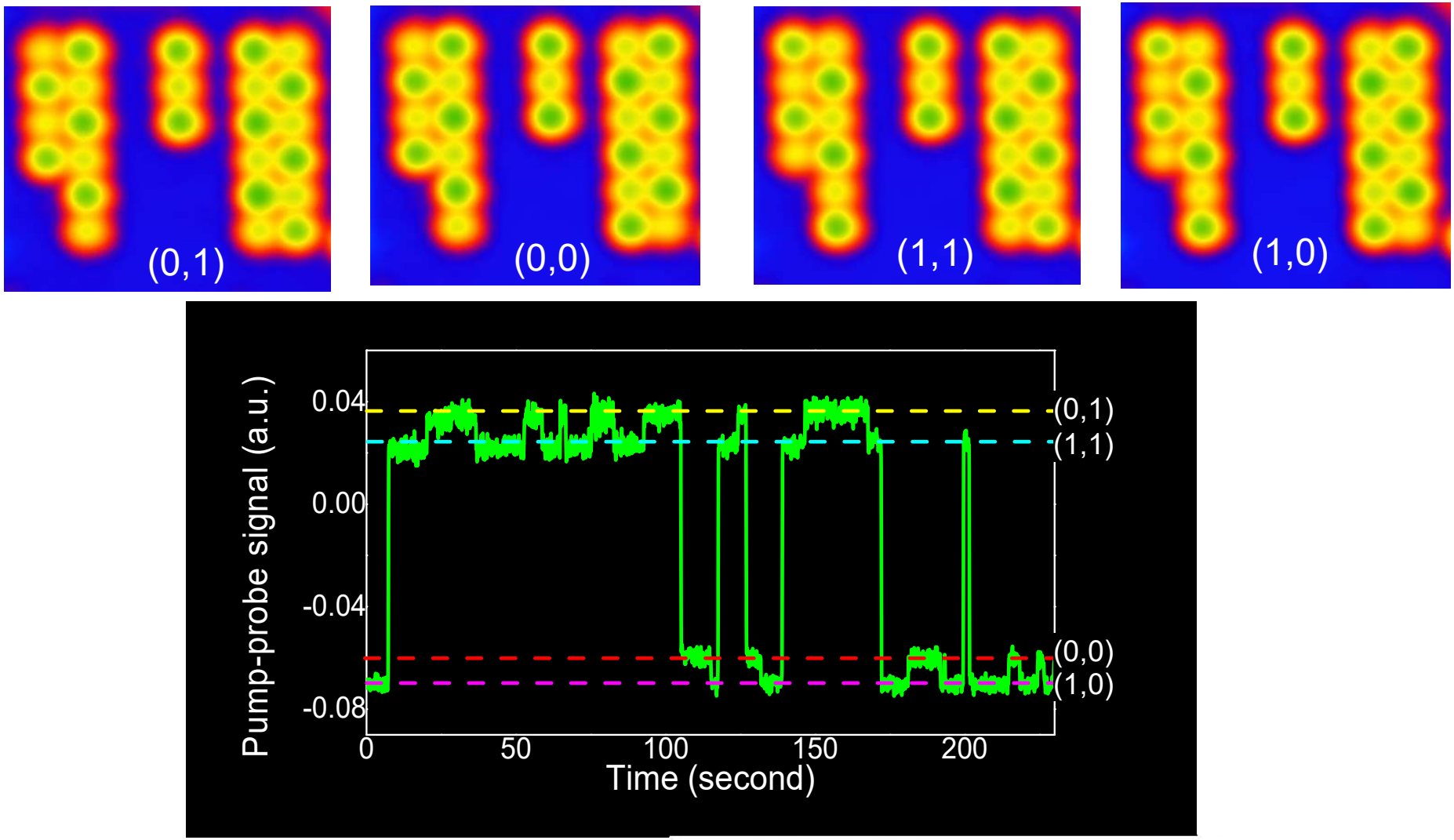
Science Advances 3 e1603137 (2017)

Remote sensing of correlated spin states



Antiferromagnetic correlation: $\frac{P_{(0,1)} + P_{(1,0)}}{P_{(0,0)} + P_{(1,1)}} = 1.12 \pm 0.09$

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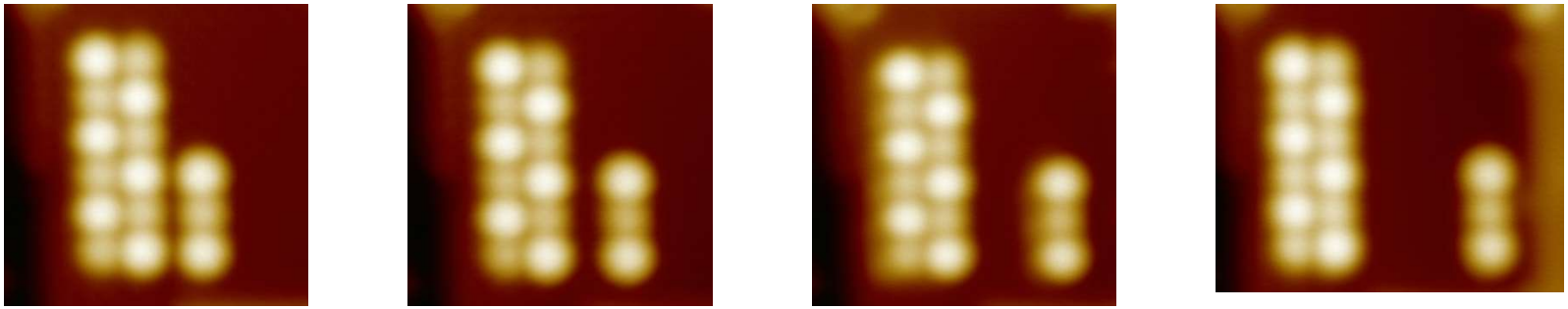
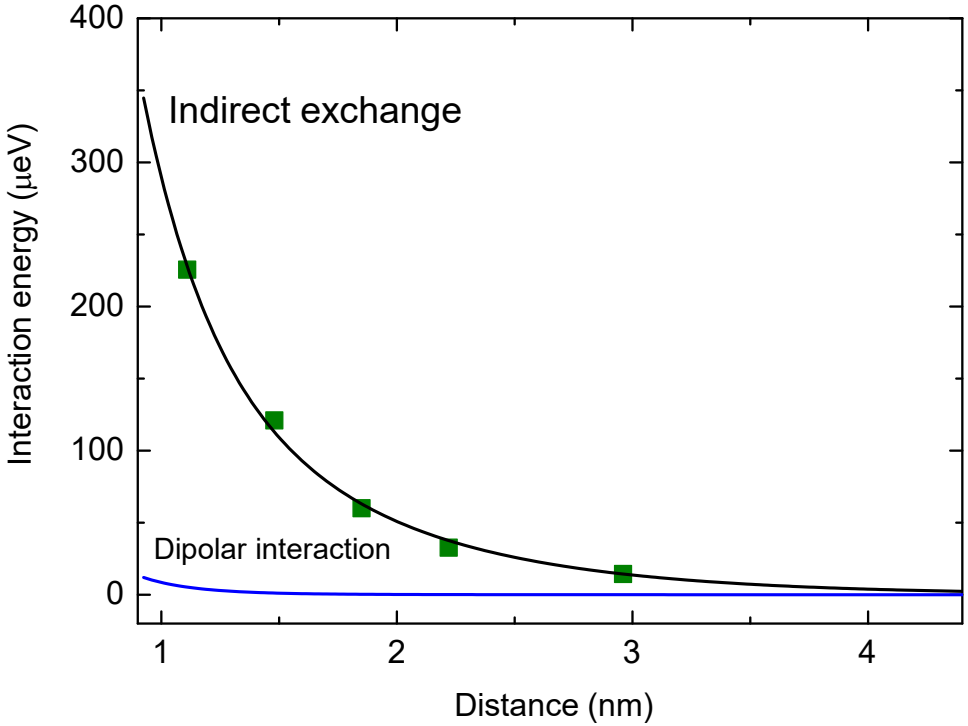
Long-range p-d exchange interaction





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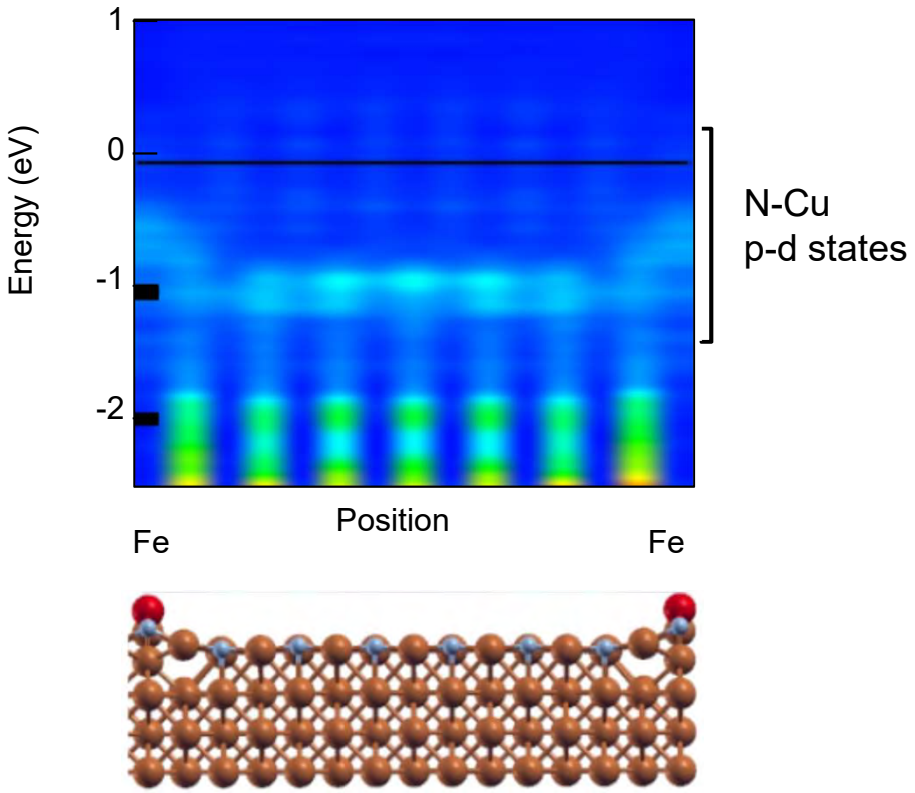
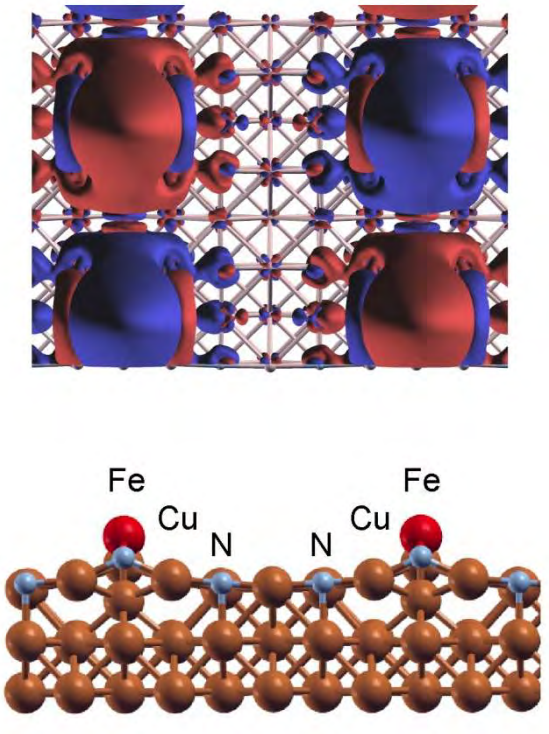
Long-range p-d exchange through Cu_2N network





S. Yan, L. Malavolti, J. Burgess, A. Droghetti, A. Rubio, S. Loth, *Science Advances* 3 e1603137 (2017)

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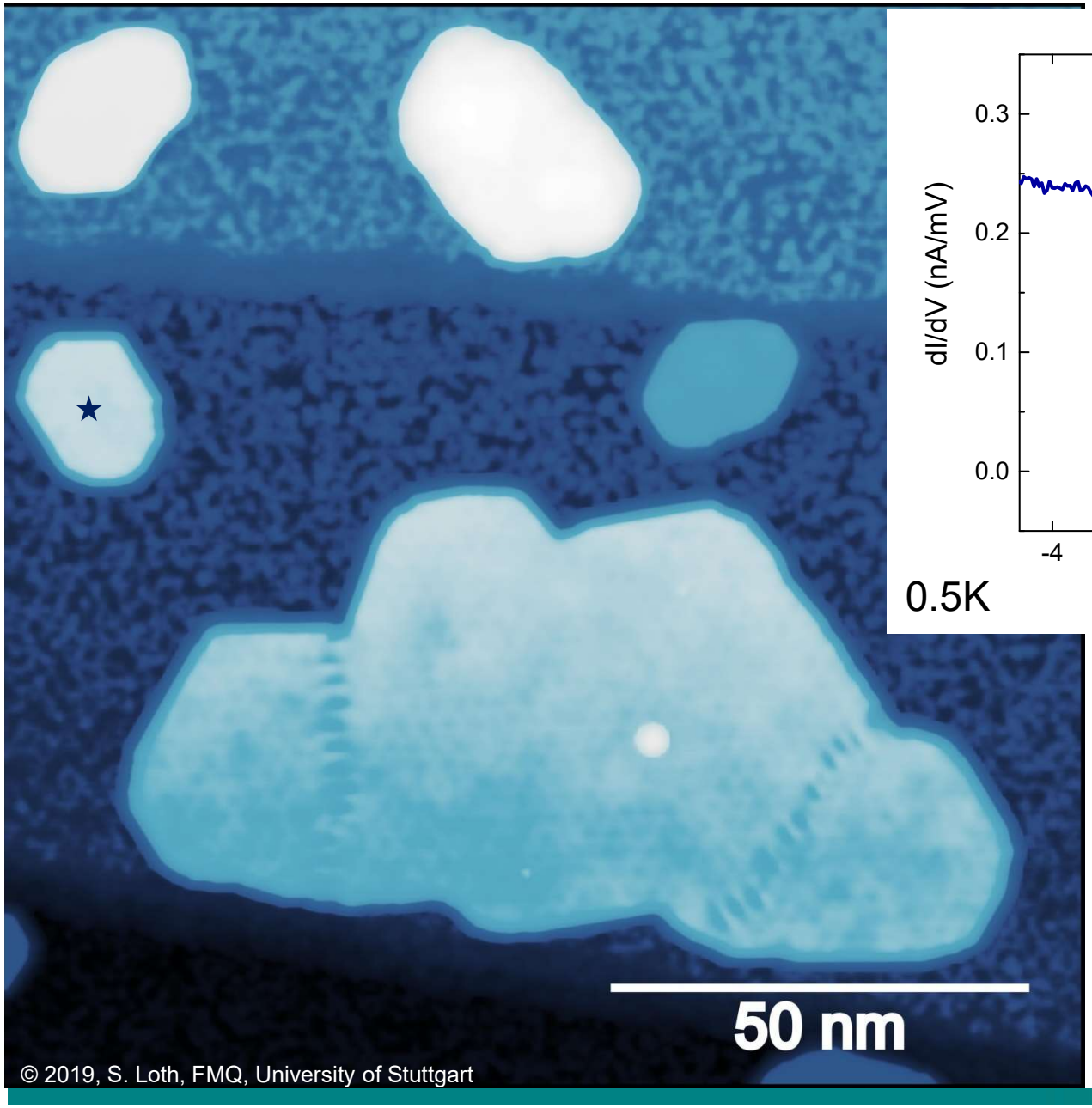
‘2D’ superconducting substrate: Pb on Si(111) 7x7



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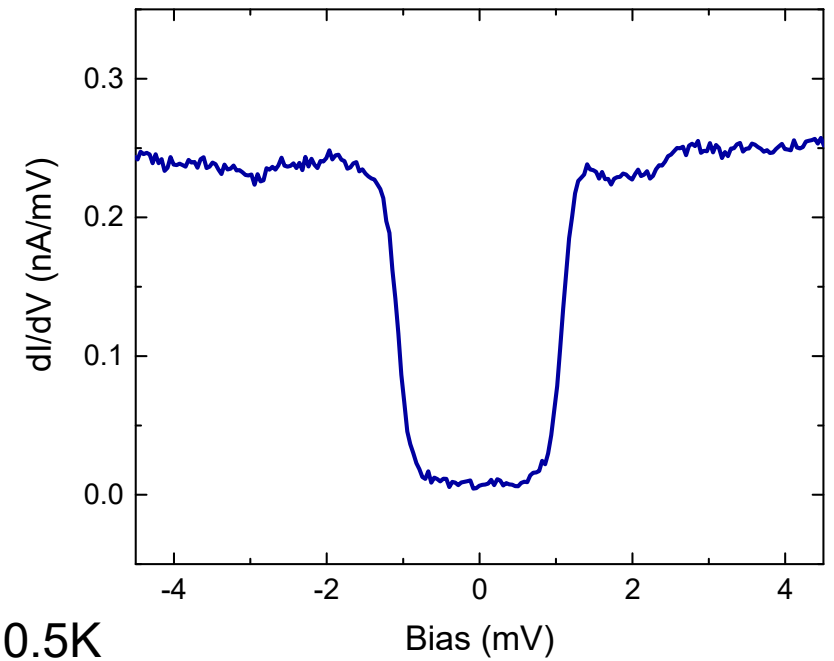


0.5K

5mV; 1nA

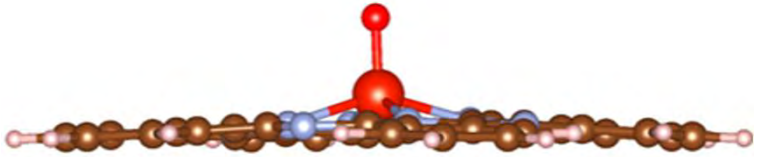
H_c up to 5 T

PRB 94 224504 (2016)

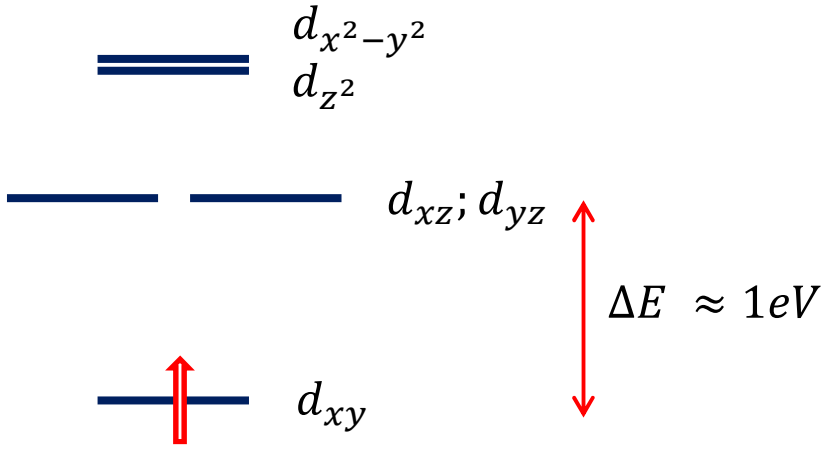
Molecular qubit: Vanadyl phthalocyanine (VOPc)

Collaboration with: M. Mannini, R. Sessoli, U Florence

Vandayl ion: $[V{=}O]^{2+}$



$$S = \frac{1}{2}\,, \qquad g = 2\,, \qquad I = \frac{7}{2}$$



$$T_1 = 14\,ms \qquad T_2^* = 3.4\,\mu s$$

(at 4 K), Atzori M. et *al.*; *JACS* **2016**, 138, 2154

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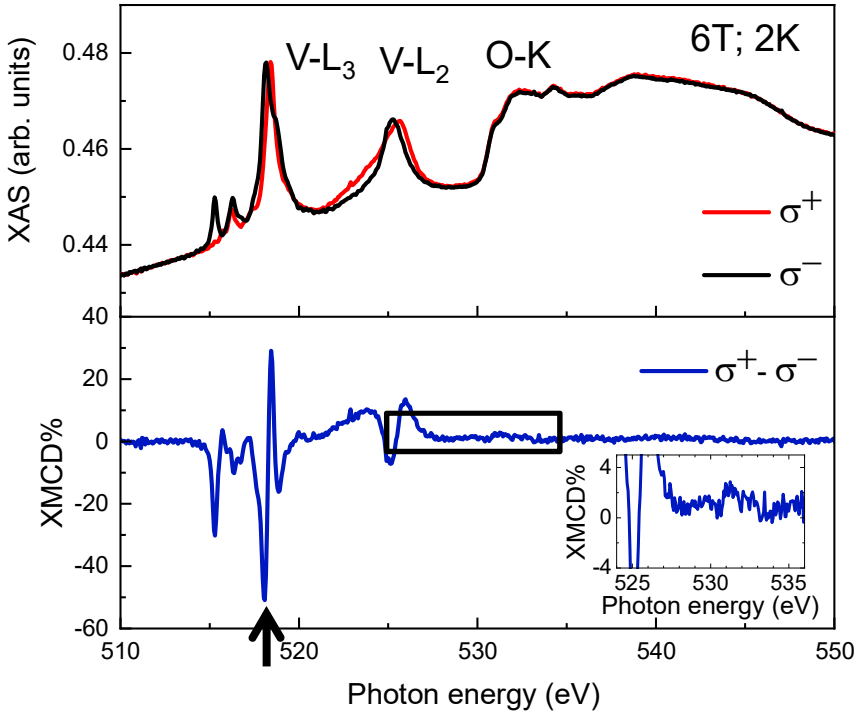
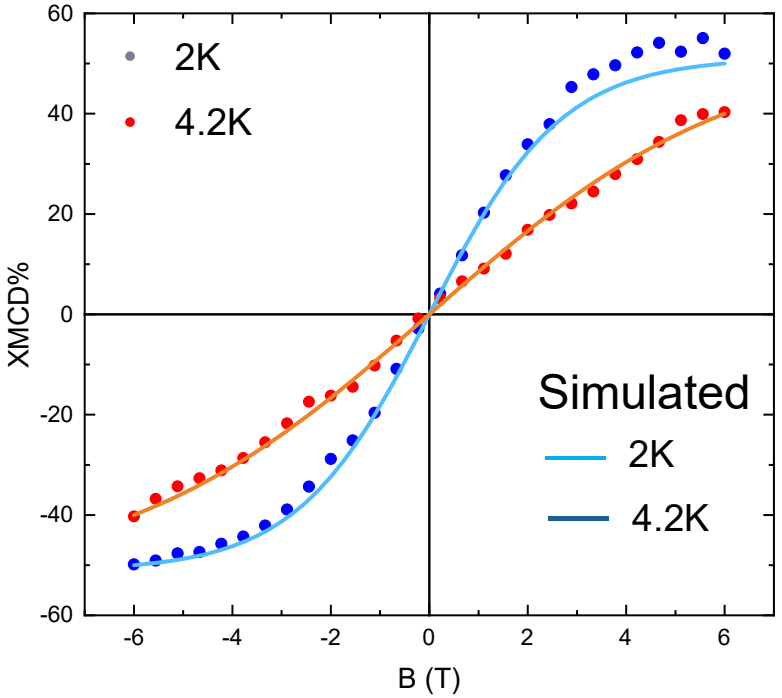
XMCD characterization – Pb(111) single crystal

Vanadium $L_{3,2}$ edges + Oxygen K edge





Spectra comparable with VOPc on Ag, Si:

Eguchi. , et *al.*; J. Phys. Chem. C **2013**, 117,22843

Eguchi. , et *al.*; J. Phys. Chem. C **2014**, 118,17633

$$S = \frac{1}{2};\ g = 2$$

$$XMCD\% = \mathrm{A} \cdot \frac{\sum_S g \cdot \mu_B \cdot S \cdot \exp\left(\frac{g \cdot \mu_B \cdot H \cdot S}{KT}\right)}{\sum_S \exp\left(\frac{g \cdot \mu_B \cdot H \cdot S}{KT}\right)}$$

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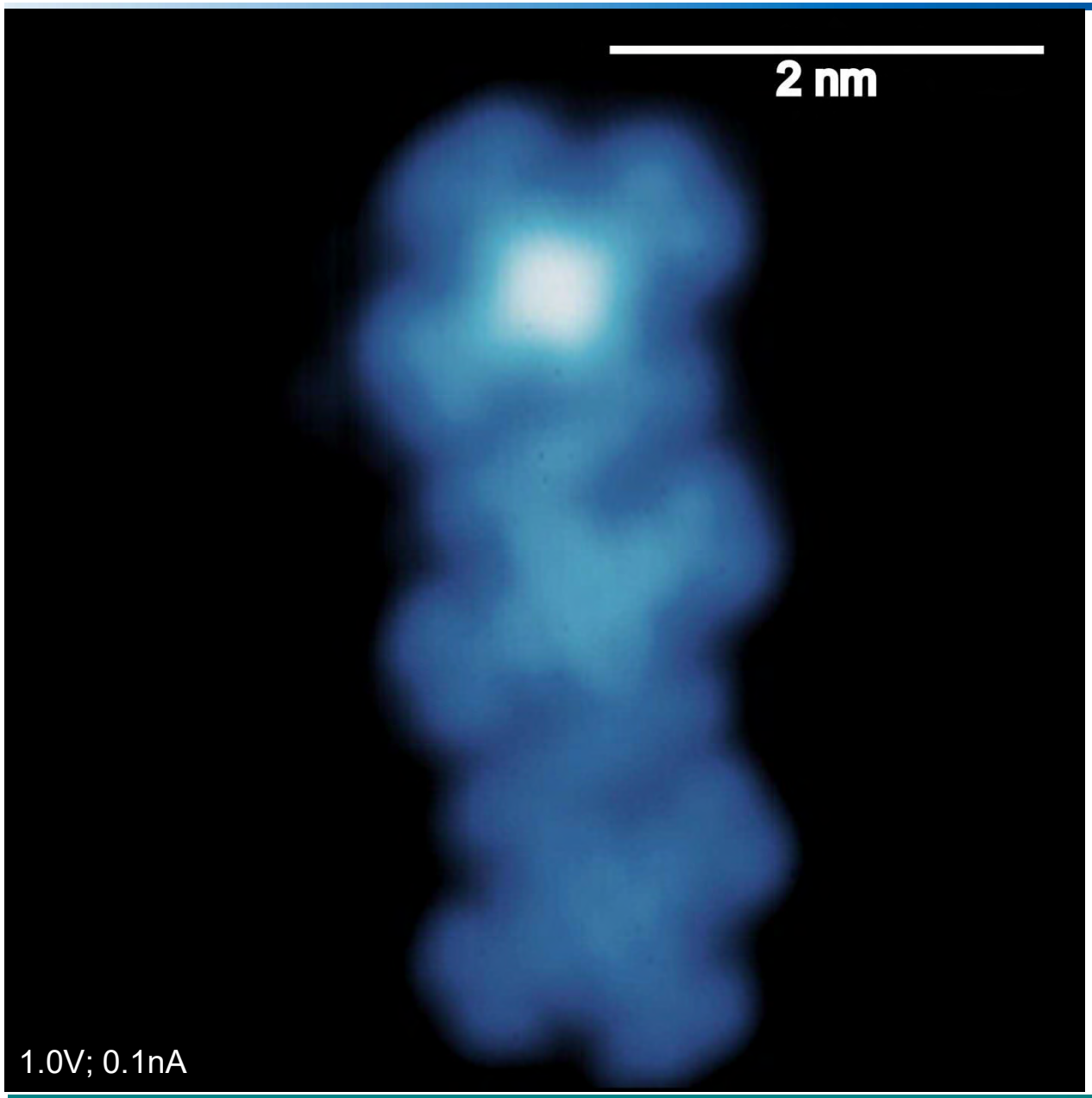
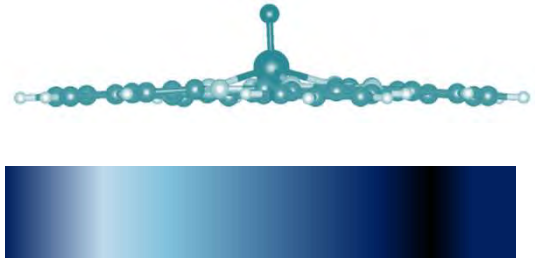
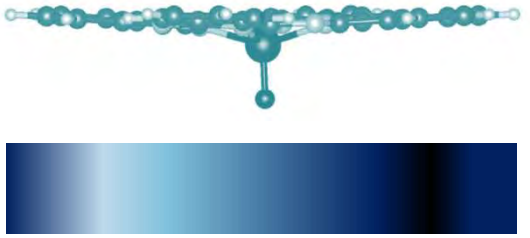
VOPc molecules on Pb island



Oxygen-Up



Oxygen-Down



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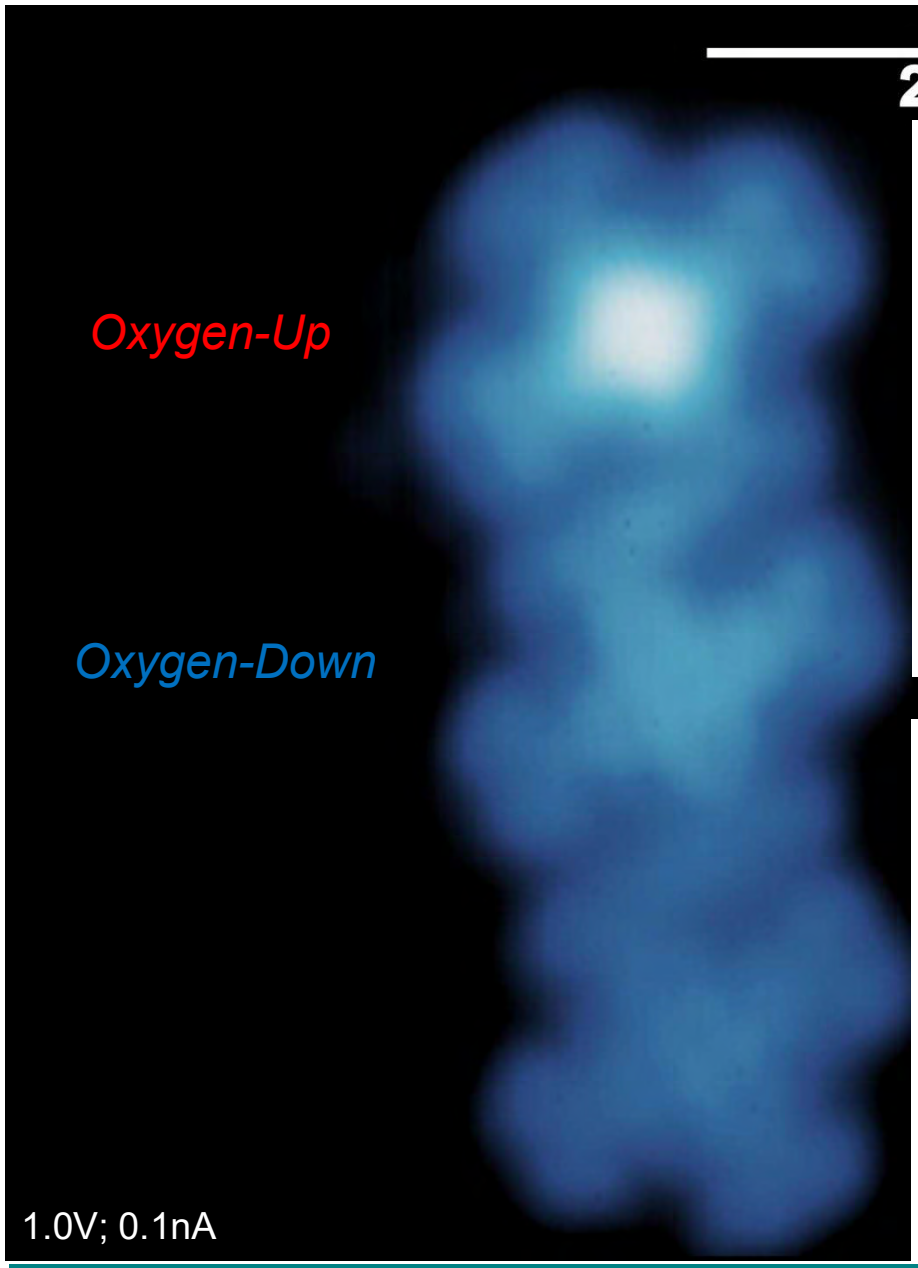
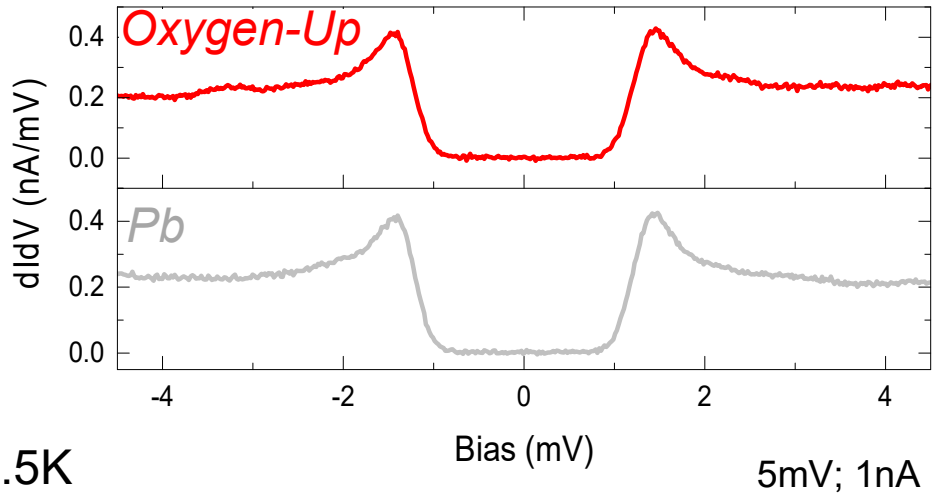
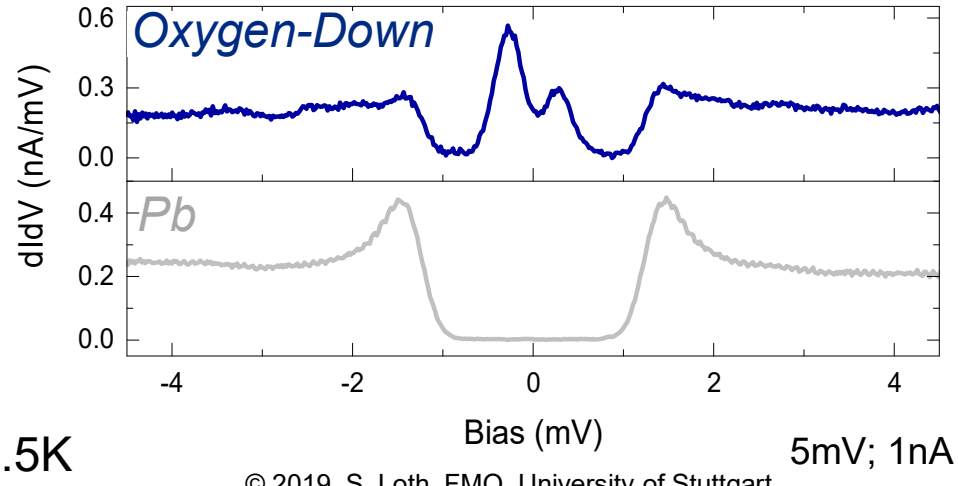
VOPc molecules on Pb island







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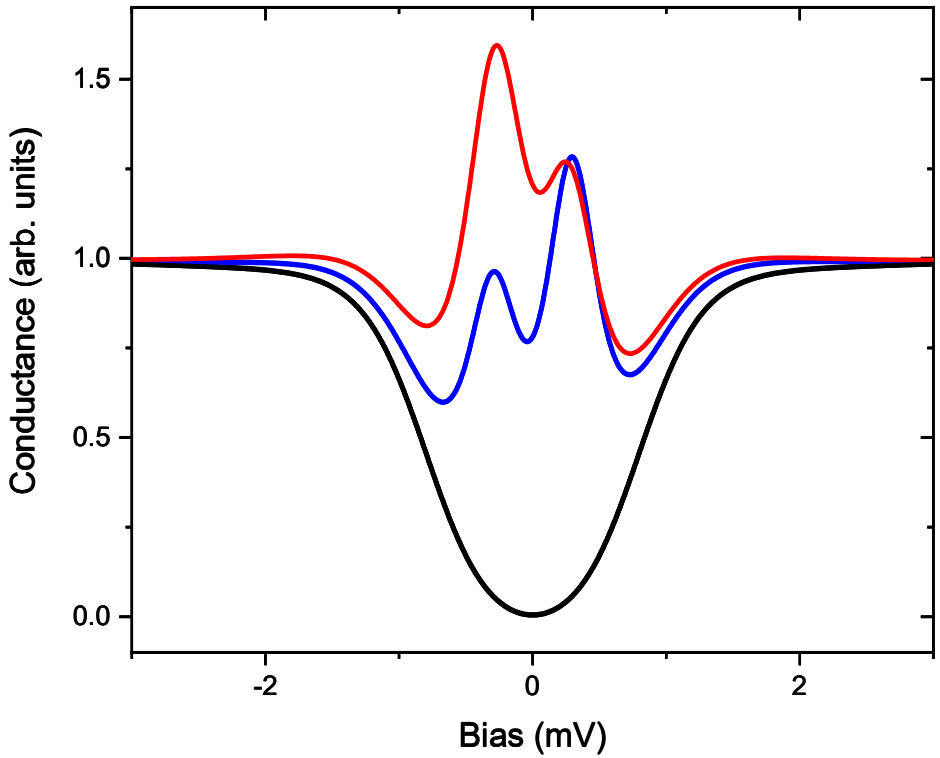
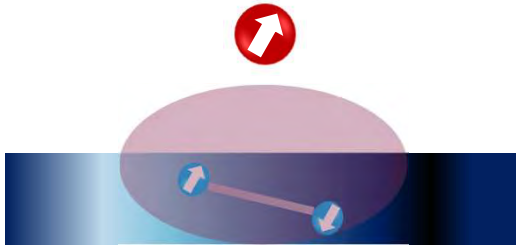
Magnetic centers on superconductors





$$\mathcal{H} = \mathcal{H}_0 + \mathcal{H}_{sd}$$

$$\mathcal{H}_0 = \sum_{k\sigma} \varepsilon_k a^{\dagger}_{k\sigma} a_{k\sigma} - \Delta_0 \sum_k (a^{\dagger}_{k\uparrow} a^{\dagger}_{-k\downarrow} + a_{-k\downarrow} a_{k\uparrow})$$

$$\mathcal{H}_{sd} = -\frac{J}{2N} \sum_{kk'} a_k^{\dagger} \boldsymbol{\sigma} a_{k'} \cdot \boldsymbol{S}$$

Shiba H. Prog. Theor. Phys. **1968**, 40, 435

Yu-Shiba-Rusinov states
- weak vs. strong spin-superconductor interaction
- Quasiparticle excitation localized in the superconductor

Heinrich B. W. , et *al.*; Progress in Surface Science **2018**, 93,1
Farinacci L. , et *al.*; arXiv:1807.01344

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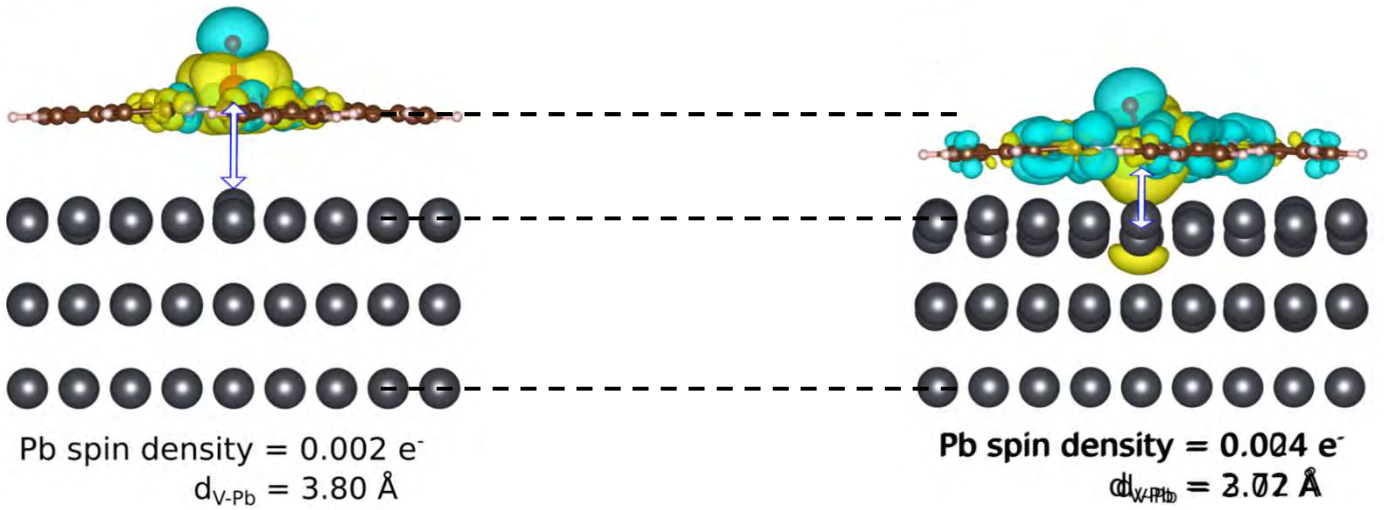
Orbital symmetry determines spin-surface interaction



Orbital: d_{xy} symmetry
No interaction

Orbital: symmetry-broken
Strong interaction

L. Malavolti et al. Nano Lett. 18 7955 (2018)

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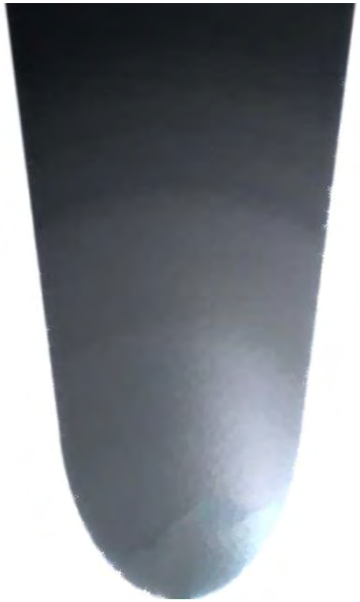
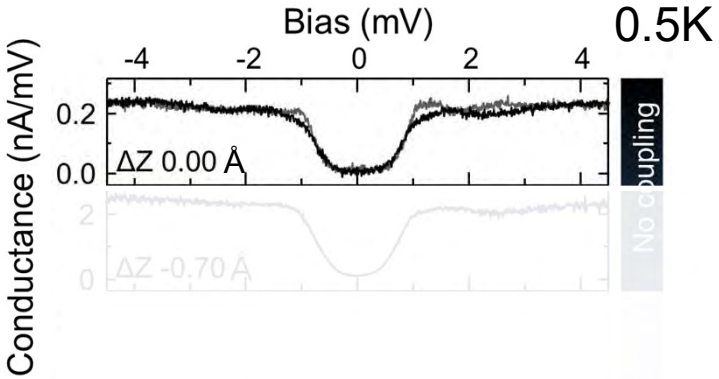
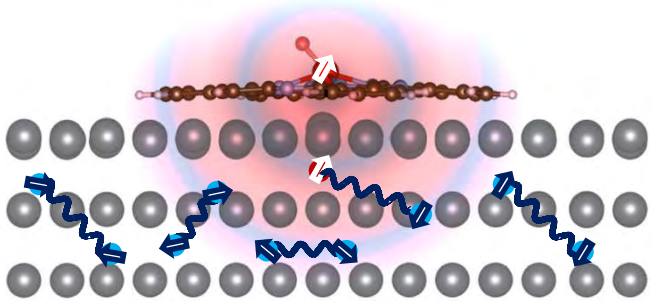
Oxygen-Up – Tuning the YSR bound states energy







L. Malavolti et al. Nano Lett. 18 7955 (2018)

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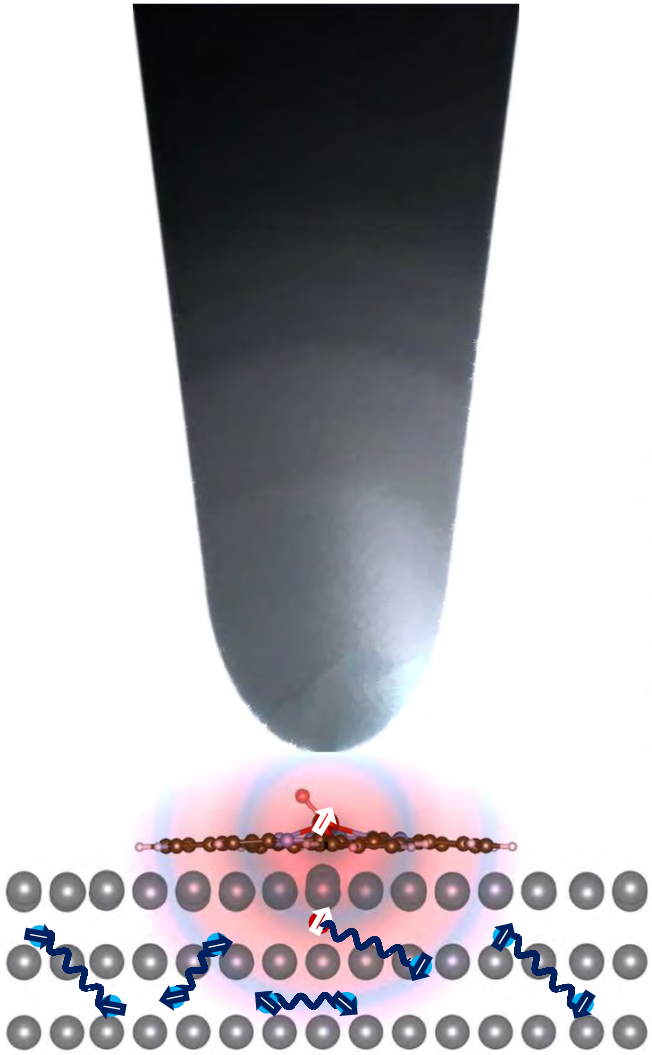
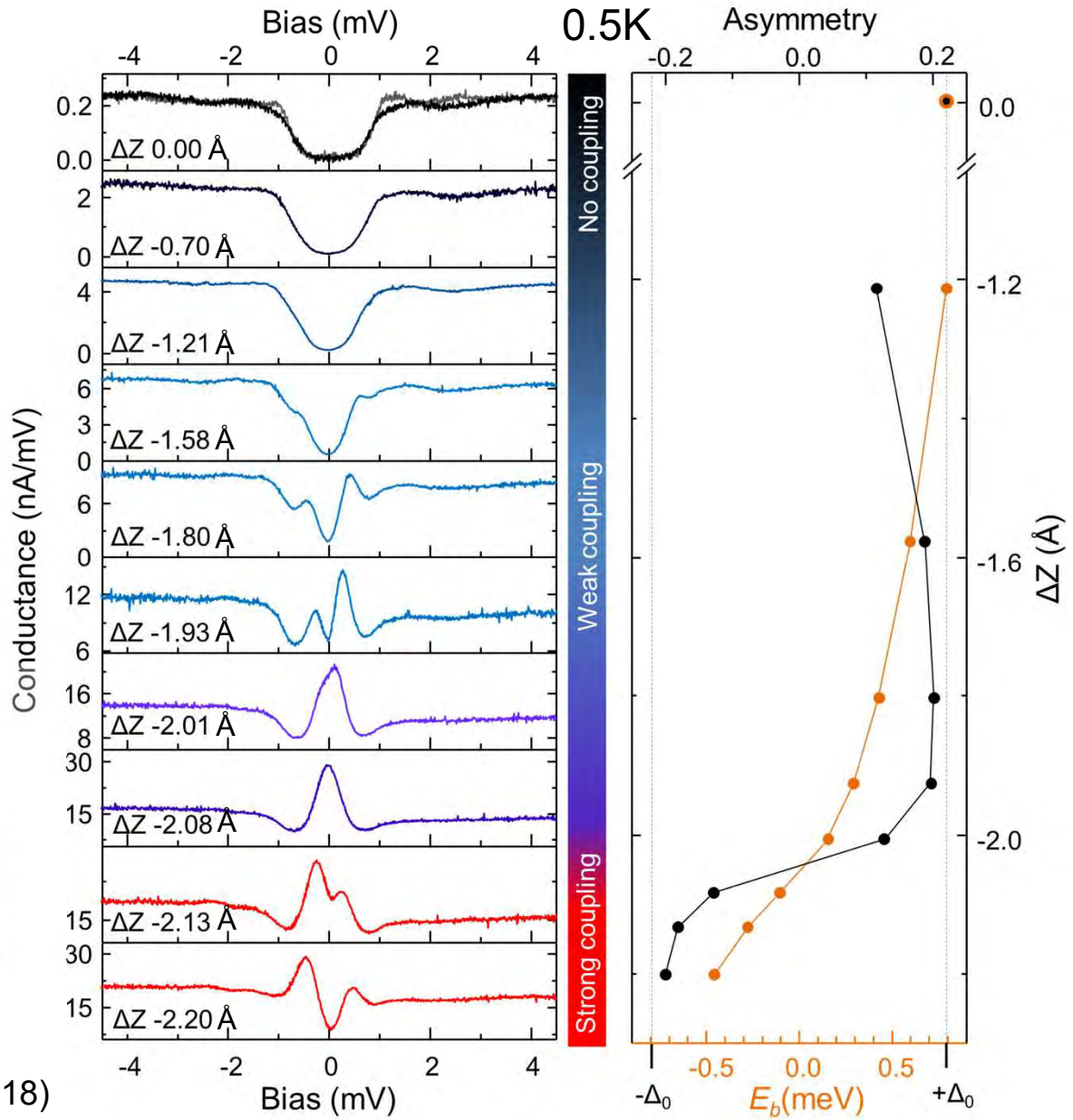
Oxygen-Up – Tuning the YSR bound states energy





L. Malavolti et al. Nano Lett. 18 7955 (2018)

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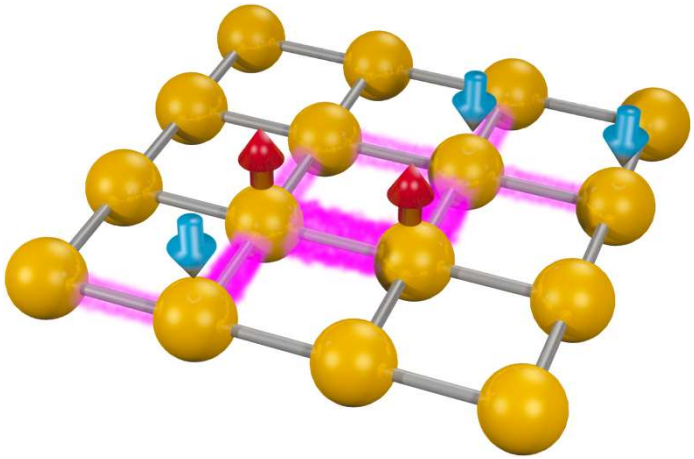
- Nanometer-range spin sensing by p-d hybridization in Cu_2N
- VOPc on superconductor isolated spin by orbital symmetry



dasQ
ERC starting grant

www.fastatoms.de

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