Bellaterra:
January
2011

Architecture & Design of Molecule Logic Gates and Atom Circuits

AtMol Conf. Series

Molecular prototypes for spin-based CNOT and SWAP quantum logic gates

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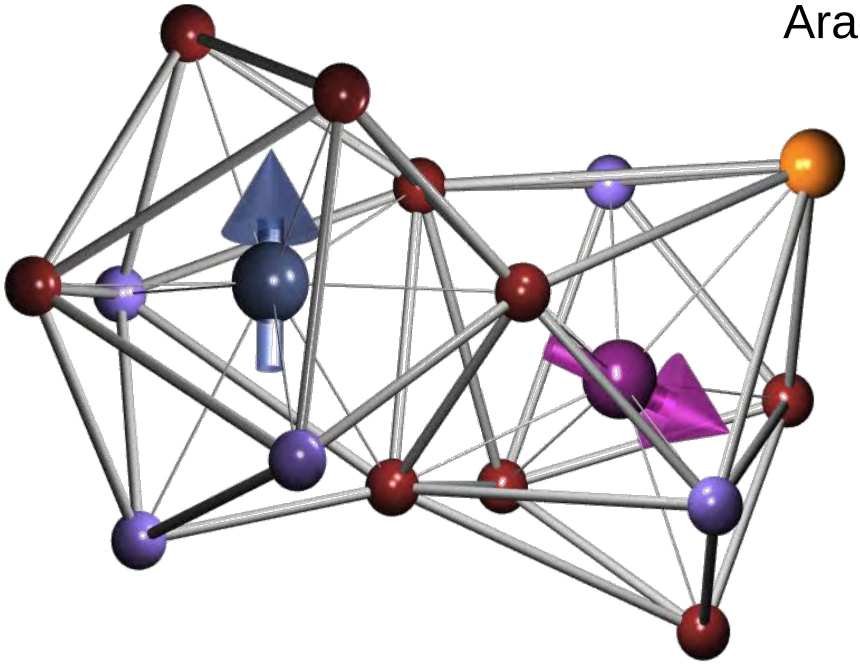
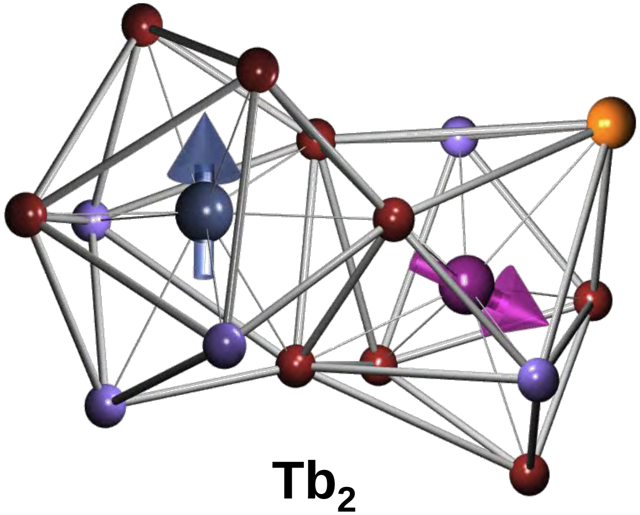
Instituto de Ciencia de Materiales de Aragón (Zaragoza, Spain)

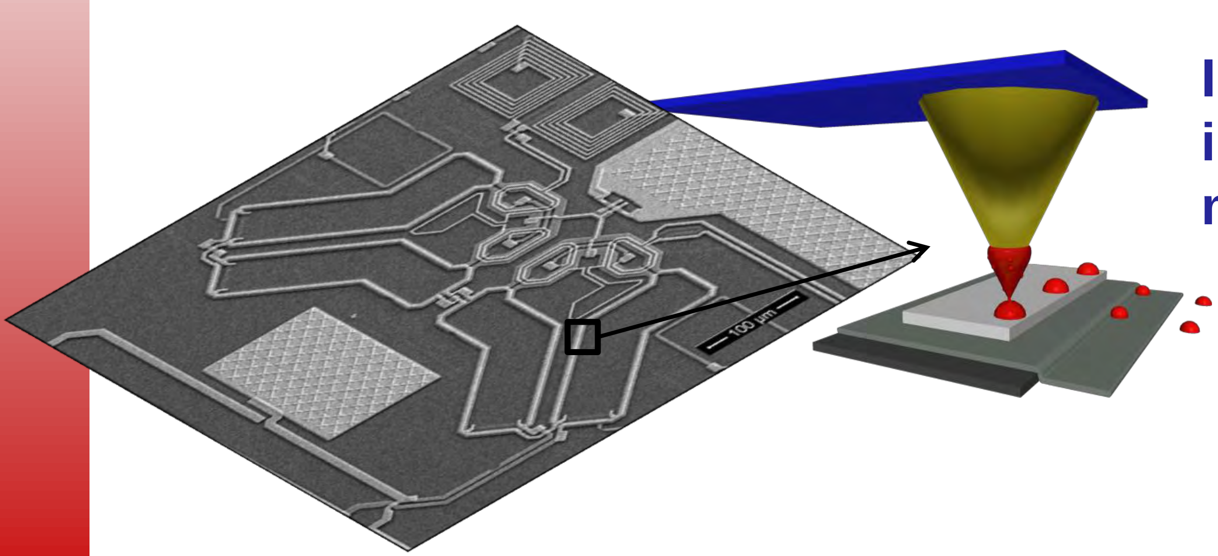


25 años 1985-2010 icma INSTITUTO DE CIENCIA DE MATERIALES DE ARAGÓN

Outline

Molecular design of CNOT and SWAP quantum gates

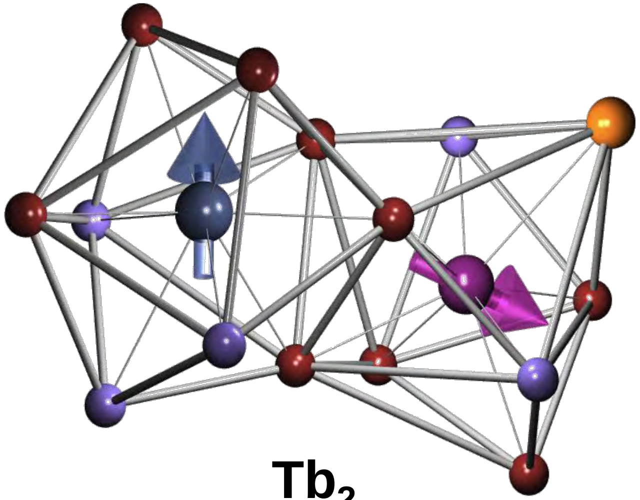




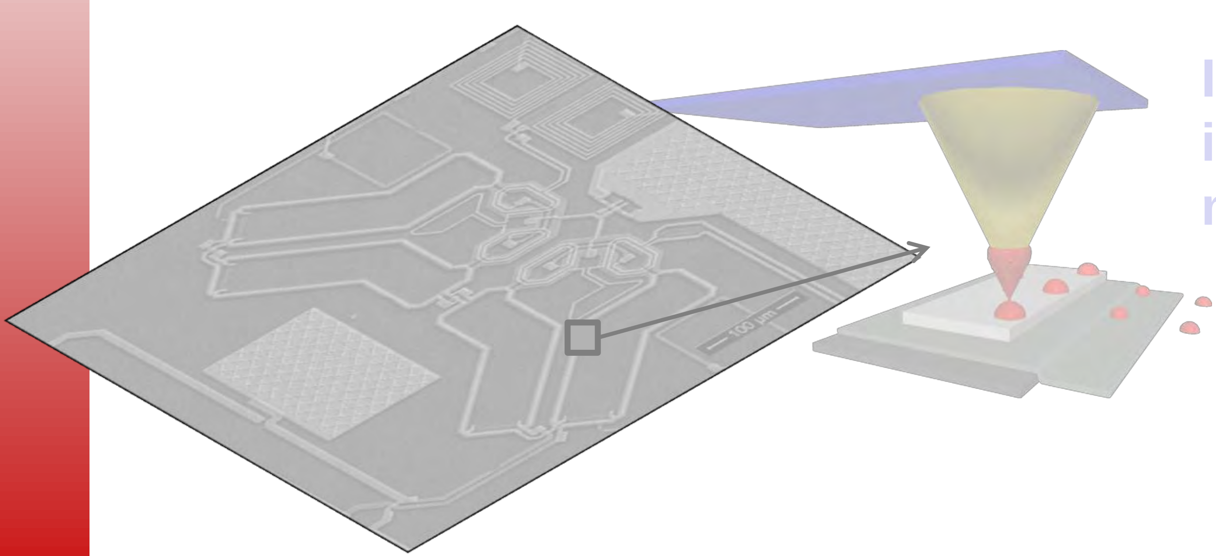
Integration of SMM into superconducting microdevices

Outline

Molecular design of CNOT and SWAP quantum gates



Tb_2



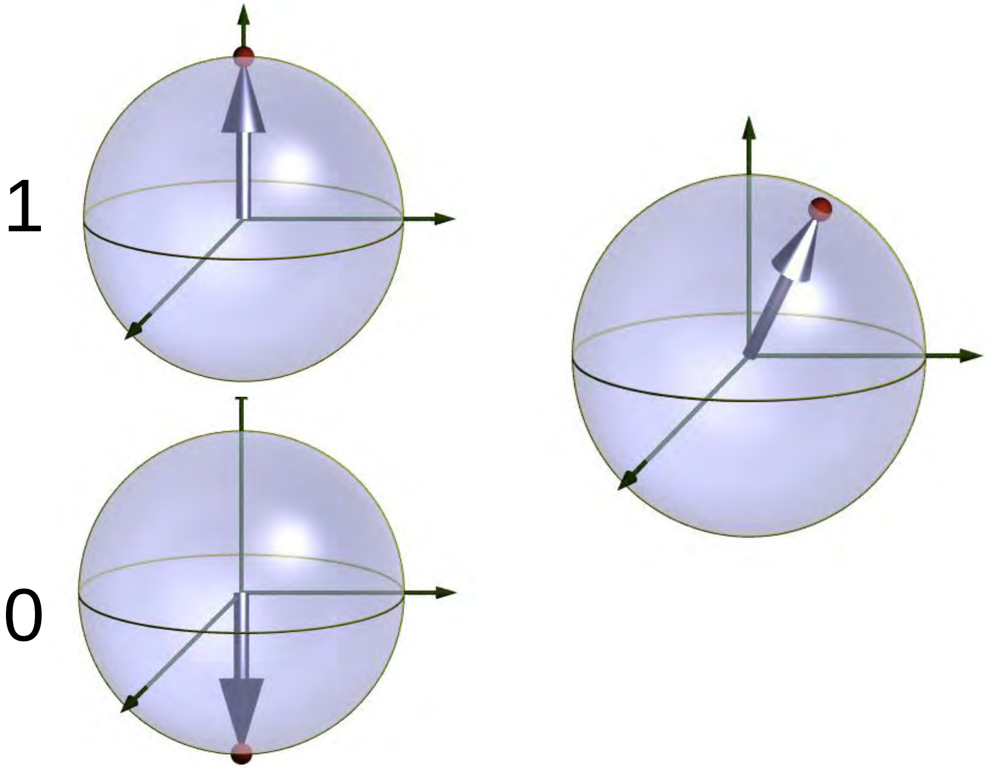
Integration of SMM into superconducting microdevices

Quantum computers

Richard Feynman, 1982

Quantum processing of information

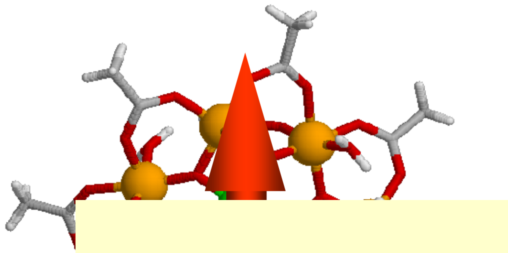
Bit → Qubit



Molecular qubits

Unitary operations

Single qubits



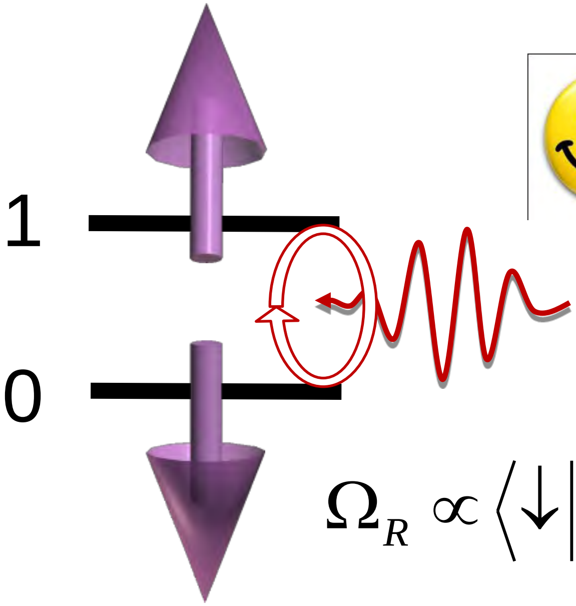
- **Chemically synthesized**
- **Carry magnetic moment**

Scalability

Identical entities

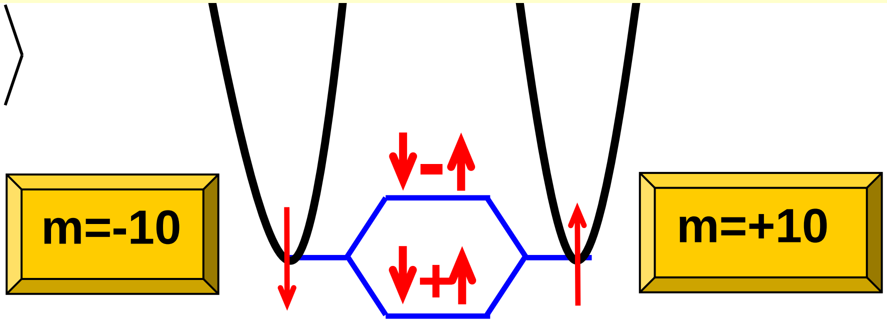
Read-out

Initialization



$$\Omega_R \propto \langle \downarrow | \vec{b}_{rf} \vec{S} | \uparrow \rangle$$

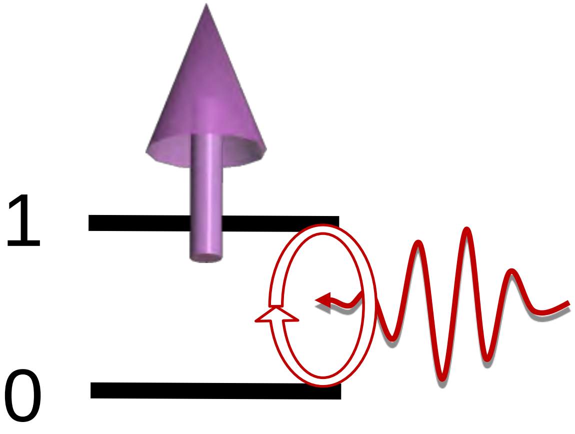
$$|\uparrow\rangle \rightarrow \alpha|\uparrow\rangle + \beta|\downarrow\rangle$$



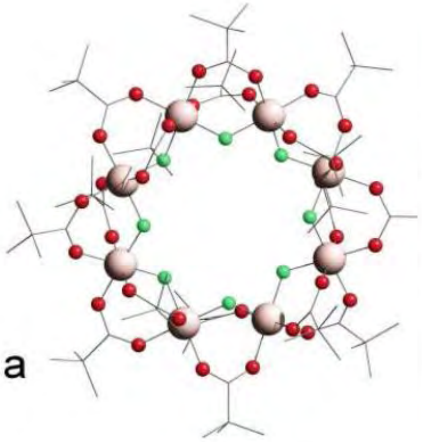
Molecular qubits

Unitary operations

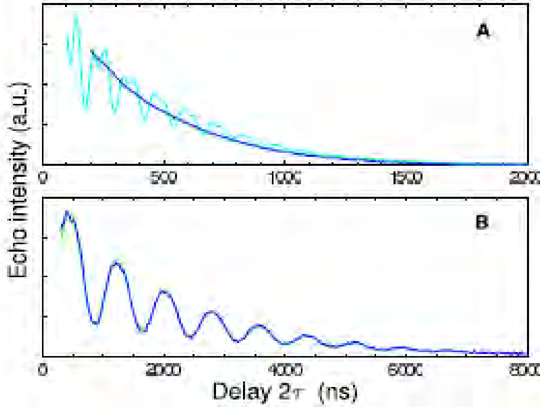
Single qubits



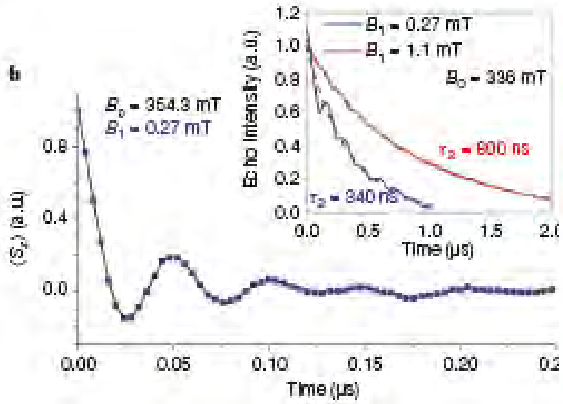
$$|\uparrow\rangle \rightarrow \alpha|\uparrow\rangle + \beta|\downarrow\rangle$$



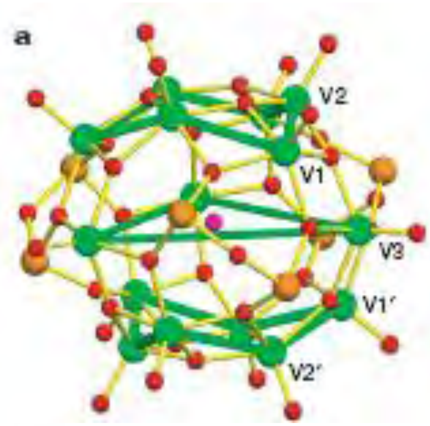
Cr$_7$Ni, S = 1/2



A. Ardavan et al. Phys. Rev. Lett. **98**, 057201 (2007)



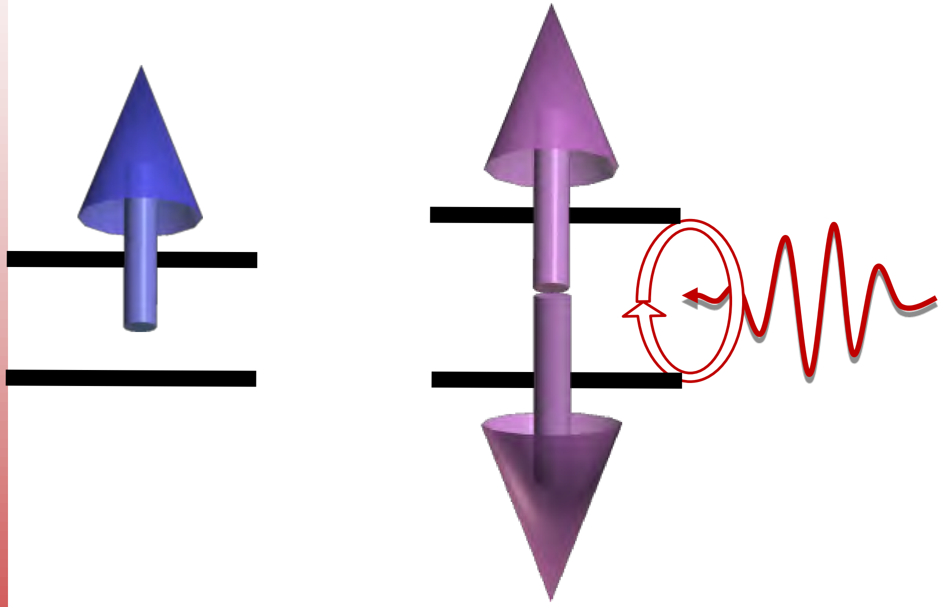
S. Bertaina et al. Nature **453** (2008)



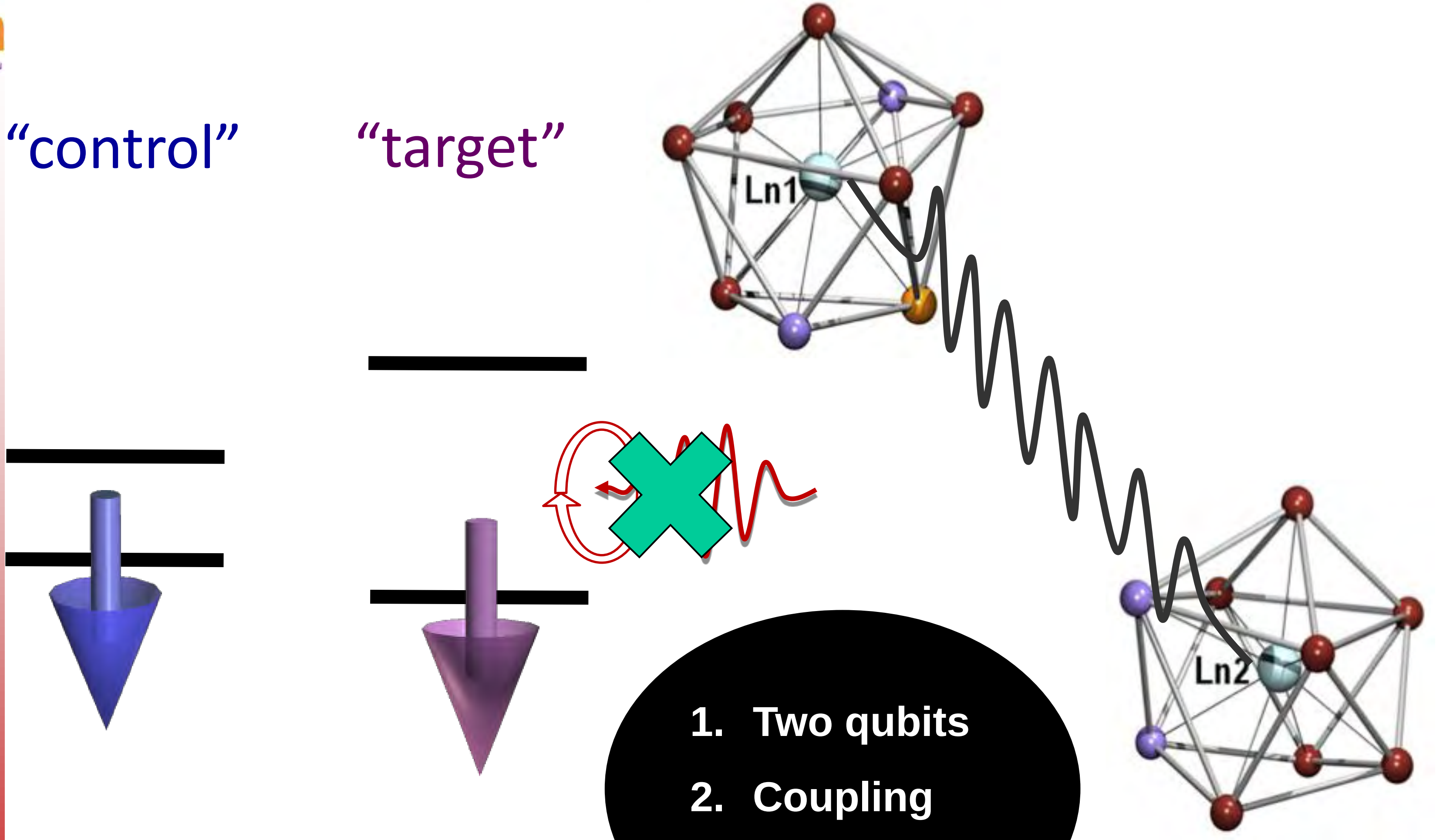
V$_{15}$, S = 1/2

CNOT (universal) quantum logic gate

“control” “target”



CNOT quantum logic gate



1. Two qubits
2. Coupling
3. Asymmetry

Molecular design

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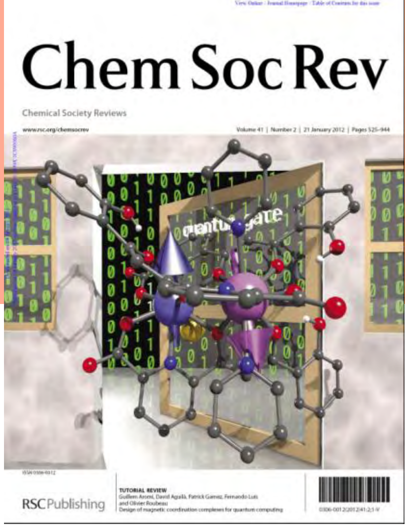
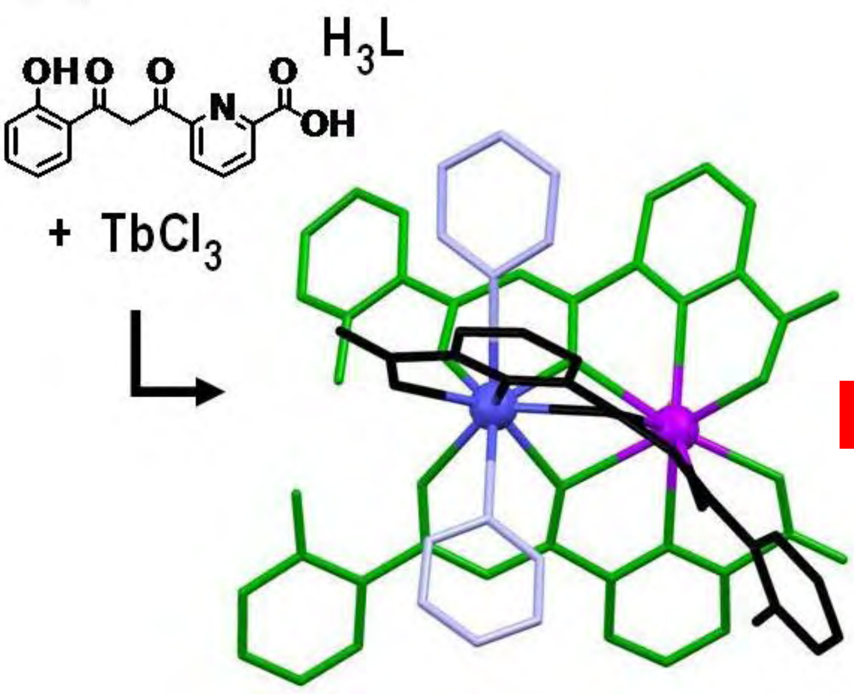
DE MATERIALES DE ARAGÓN

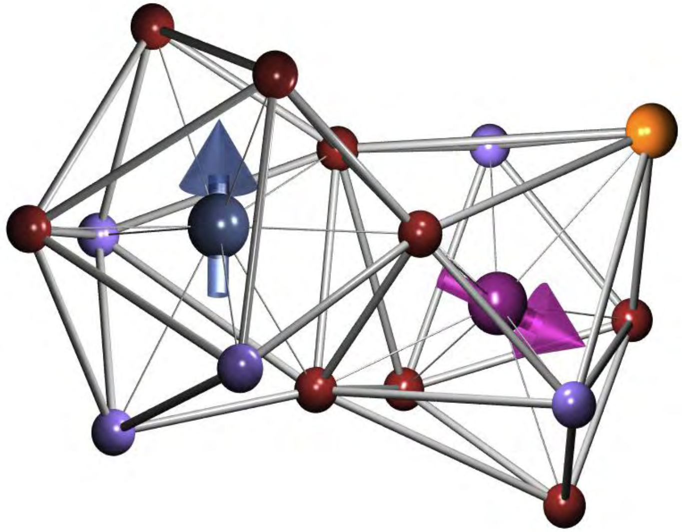
D. Aguilà *et al*, Inorg. Chem. **49** (2010) 6784
G. Aromí, D. Aguilà, P. Gámez, F. Luis, and O. Roubeau,
Chem. Soc. Rev., (2012), DOI: 10.1039/C1CS15115K





Dinuclear $[Tb]_2$ complex

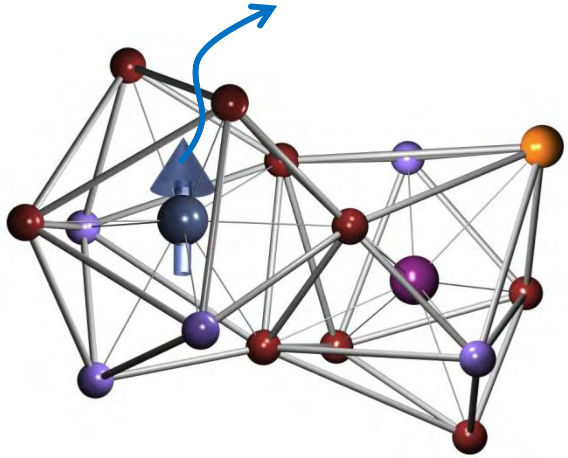
Linked to three asymmetric H_3L ligands



Two anisotropic spins in different coordinations

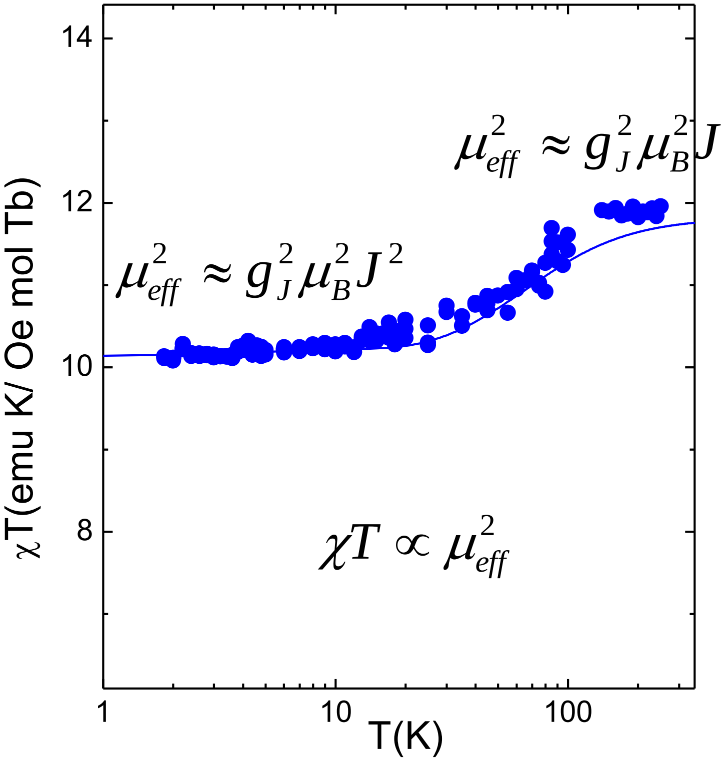
Definition of qubit states

[LaTb] $J = 6$, $g_J = 3/2$



Definition of qubit states

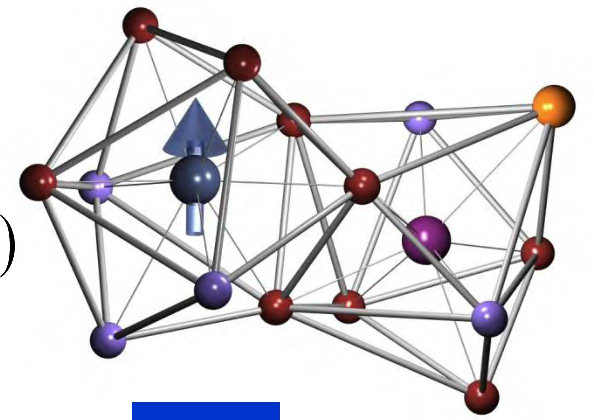
[LaTb] $J = 6,\ g_J = 3/2$

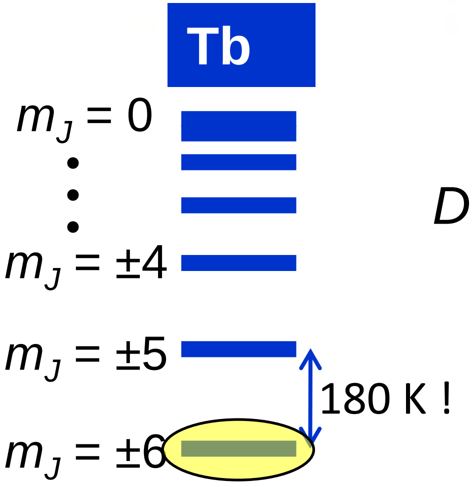


$$\mu_{eff}^2 \approx g_J^2 \mu_B^2 J(J+1)$$

$$\mu_{eff}^2 \approx g_J^2 \mu_B^2 J^2$$

$$\chi T \propto \mu_{eff}^2$$





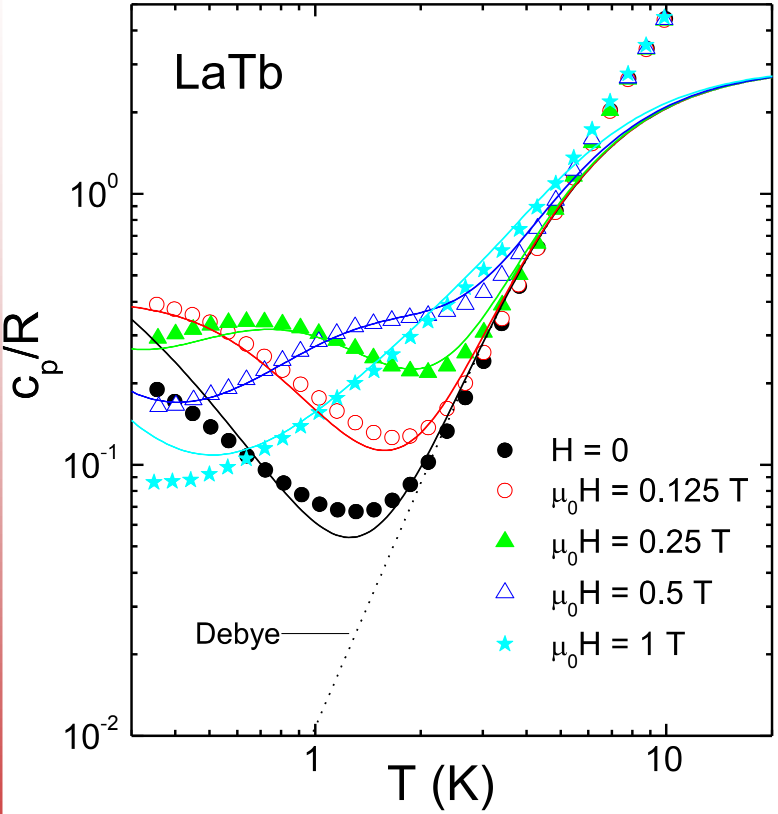
$D = 19$ K

$$\mathcal{H}_{anis} = -DS_z^2 - g_J \mu_B \left(H_x J_x + H_y J_y + H_z J_z \right)$$

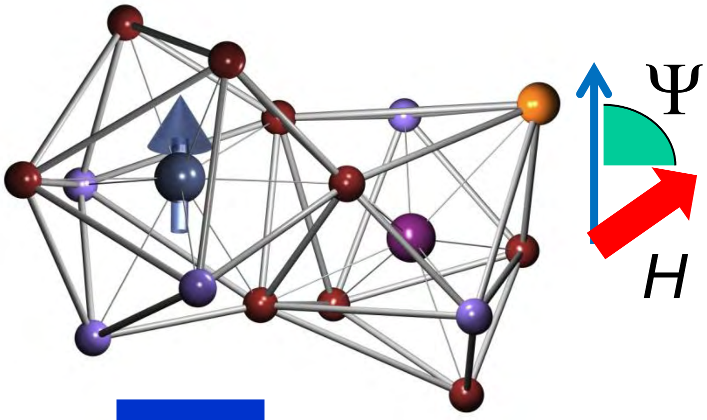
Two states

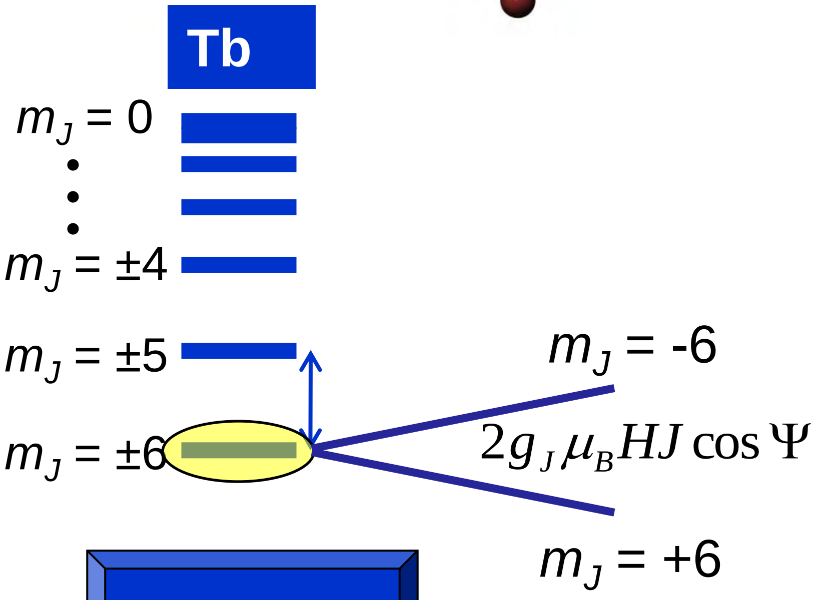
Definition of qubit states

[LaTb] $J = 6$, $g_J = 3/2$



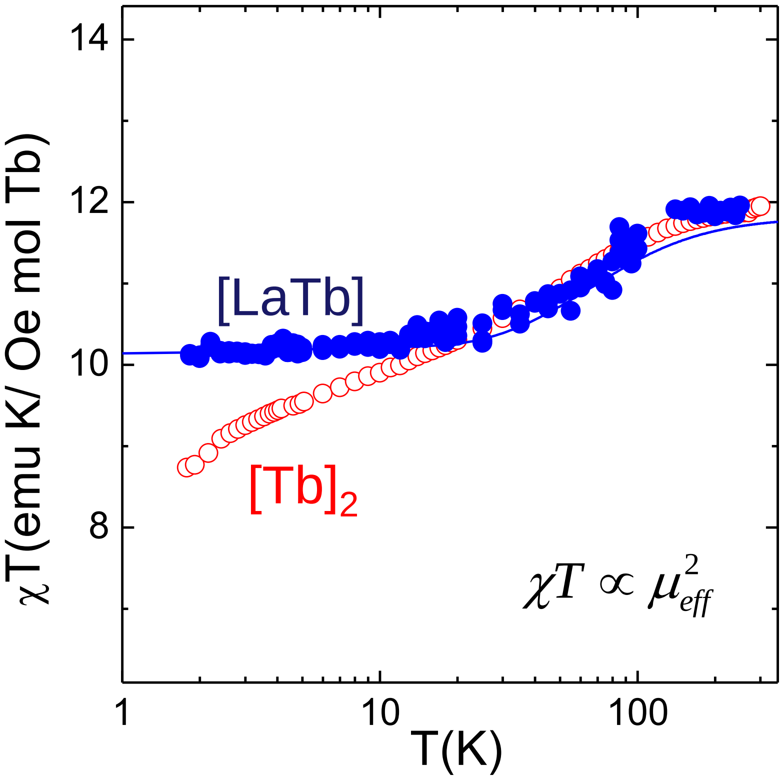
$$\mathcal{H}_{m=\pm 6} = -g_J \mu_B H_z J_z$$



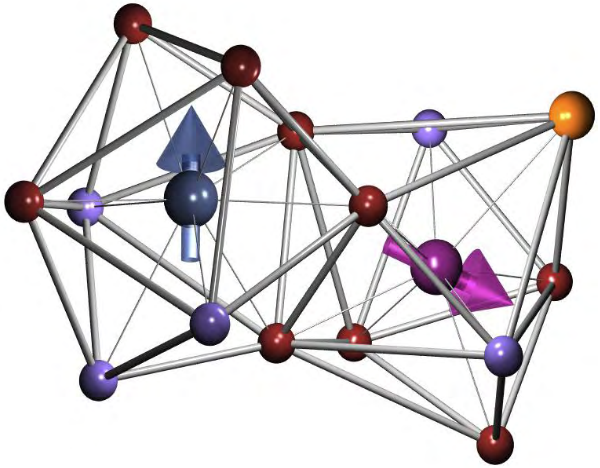


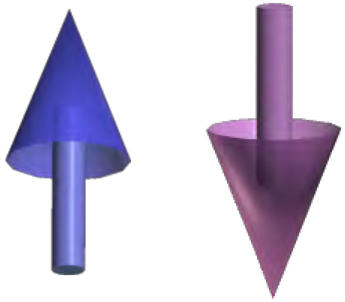
Two states

Coupling between the Tb^{3+} qubits



$[Tb]_2$

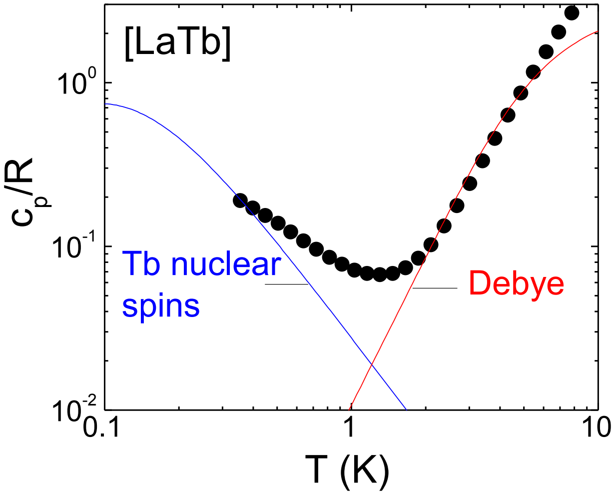


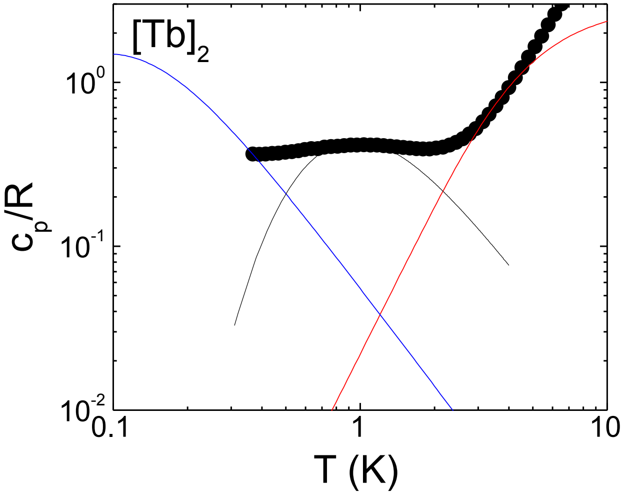


AF coupling

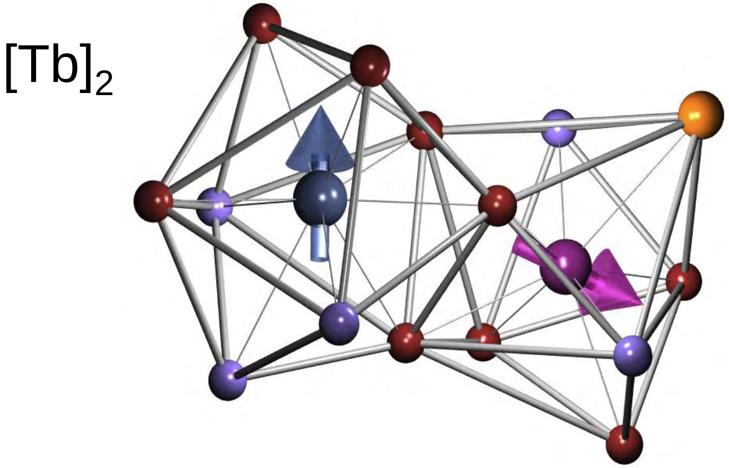
$$\mathcal{H}_{exch} = -J_{ex} J_{z1} J_{z2}$$

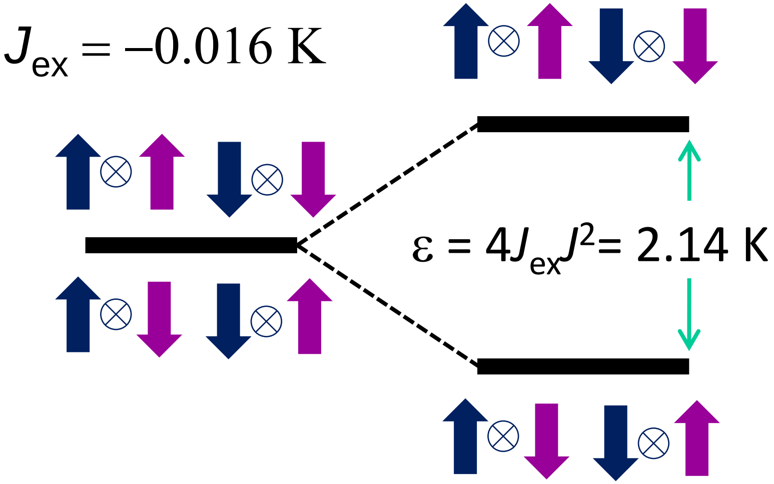
Coupling between the Tb^{3+} qubits





$$\mathcal{H}_{exch} = -J_{ex} J_{z1} J_{z2}$$

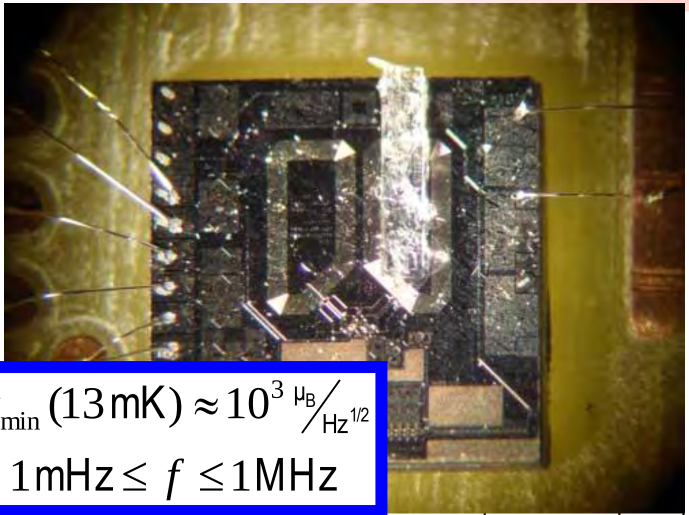




$J_{ex} = -0.016$ K

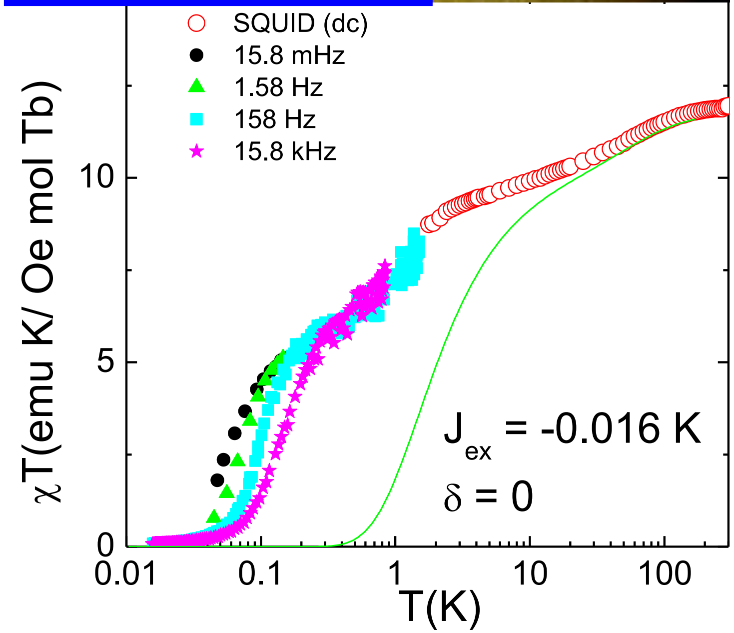
$\varepsilon = 4J_{ex}J^2 = 2.14$ K

Magnetic asymmetry

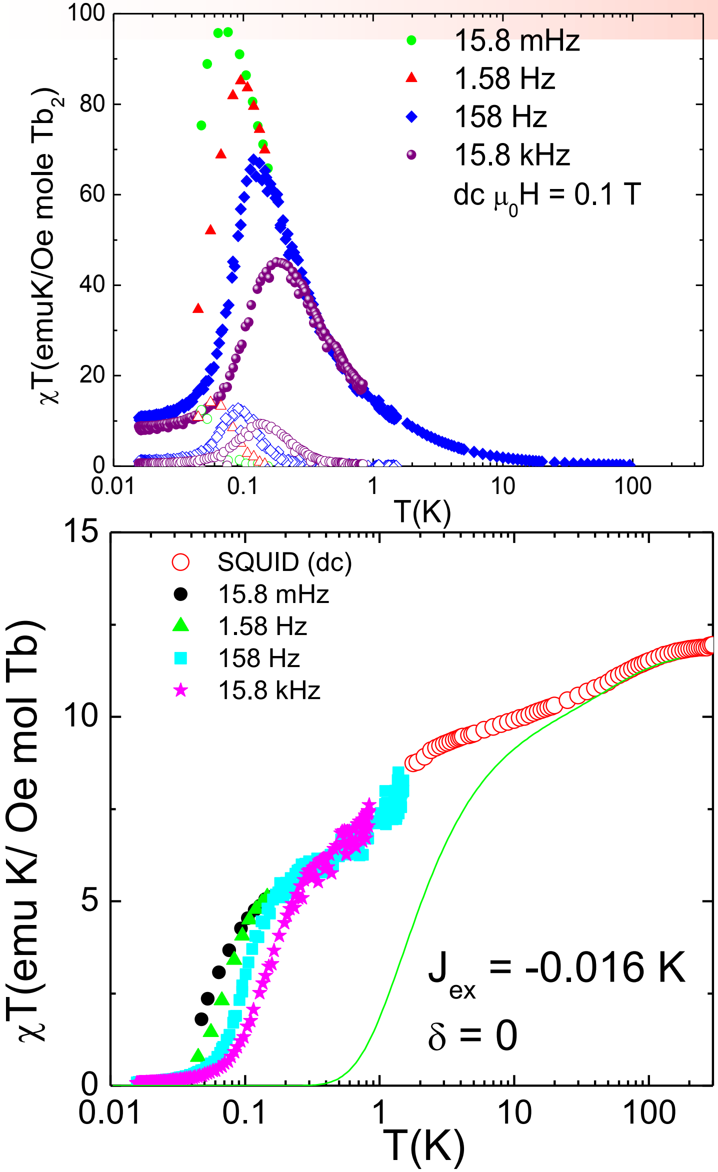


$$\mu_{\min}(13\,\mathrm{mK}) \approx 10^{3}\ {}^{\mu_B}\!/_{\mathrm{Hz}^{1/2}}$$

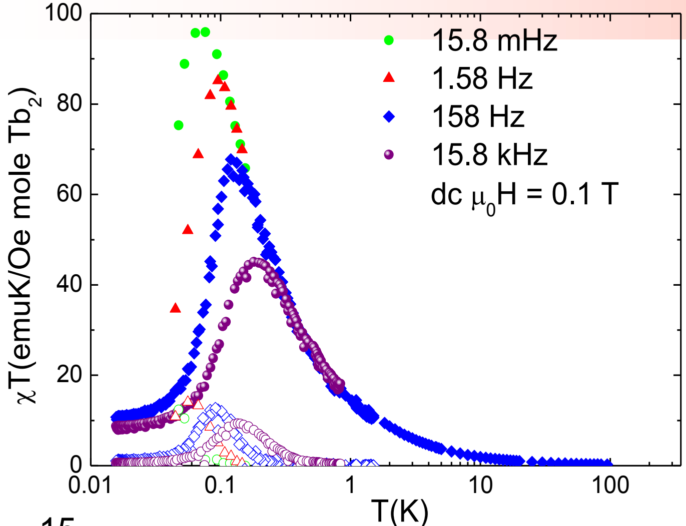
$$1\,\mathrm{mHz} \le f \le 1\,\mathrm{MHz}$$

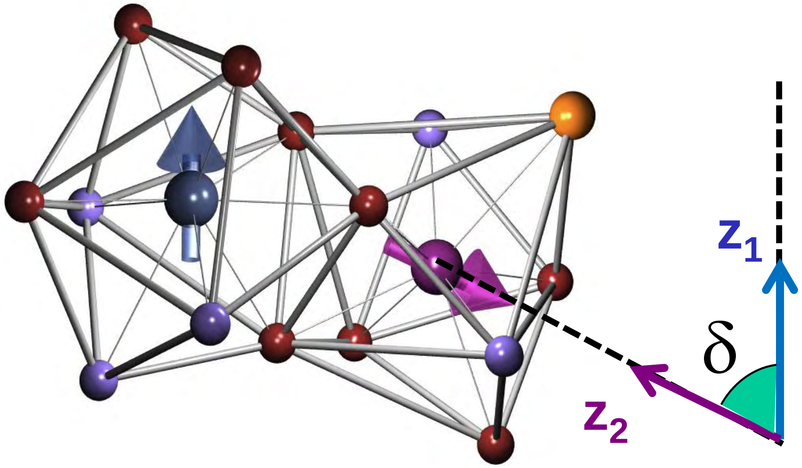


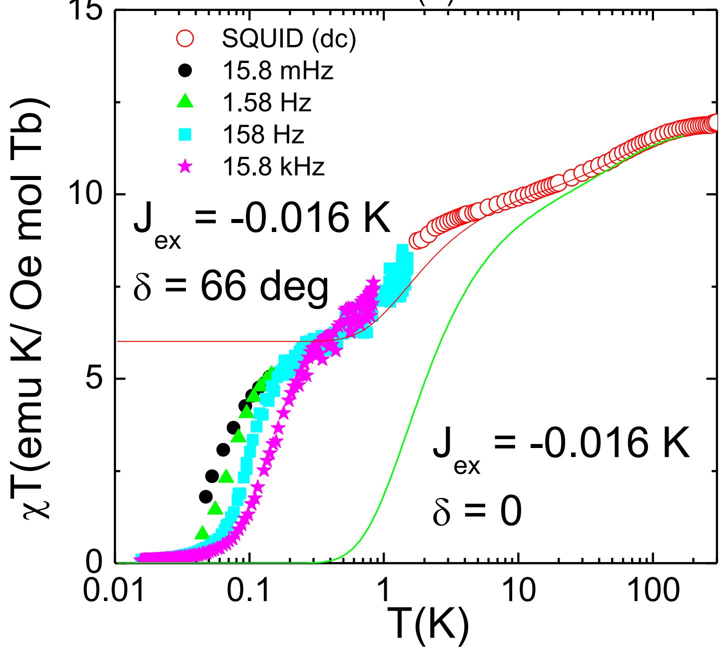
Magnetic asymmetry



Magnetic asymmetry



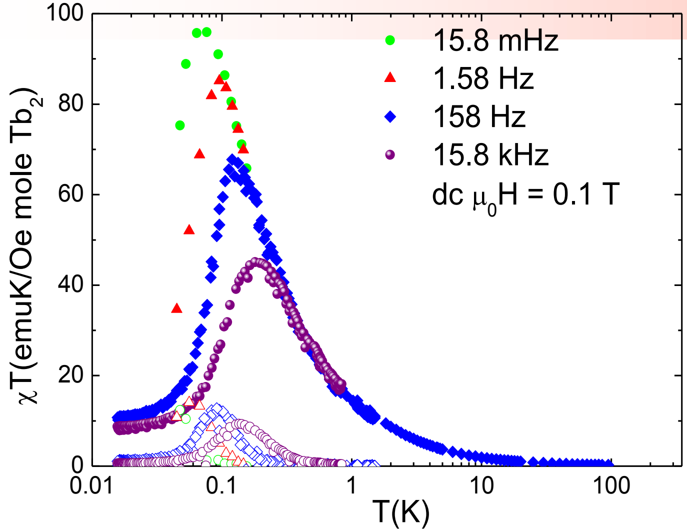


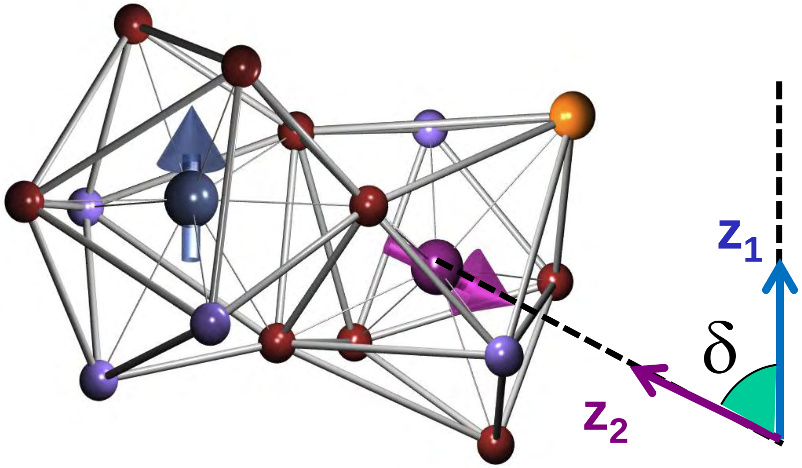


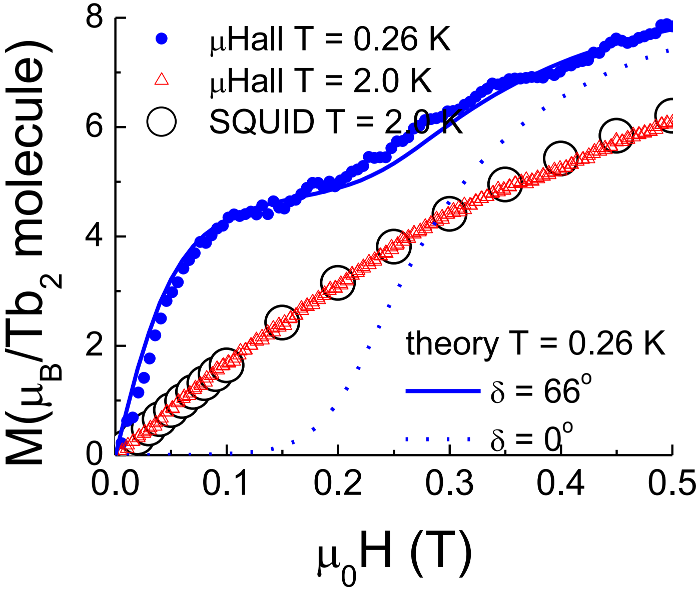
δ = 66 degrees

Noncollinear anisotropy axes

Magnetic asymmetry



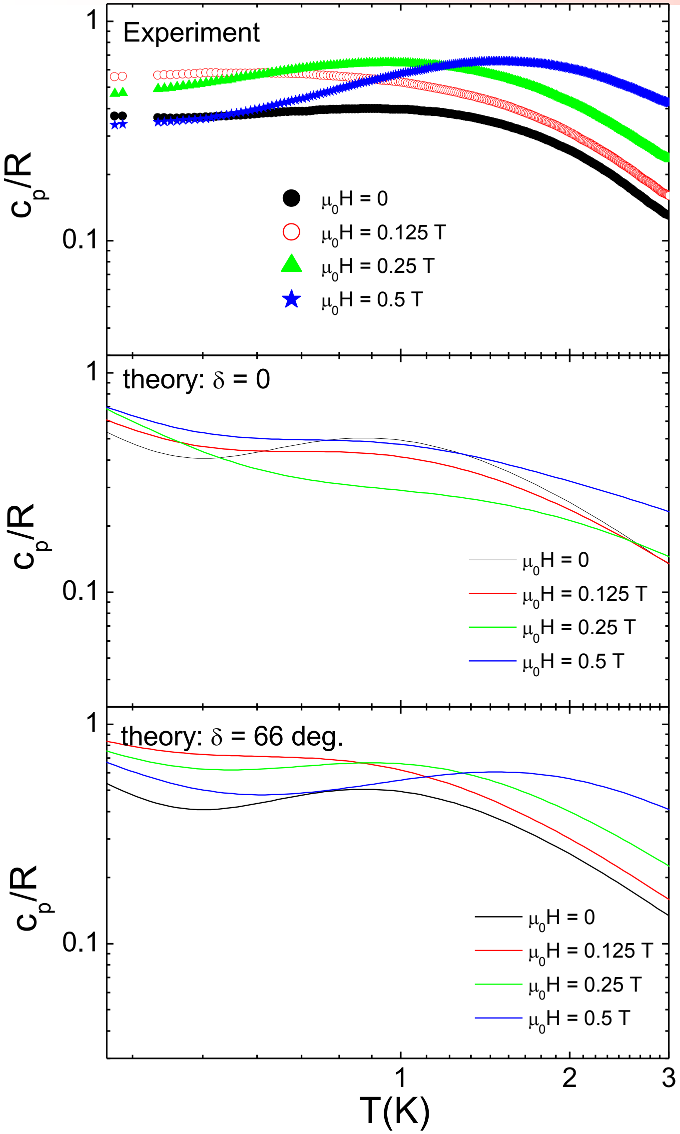


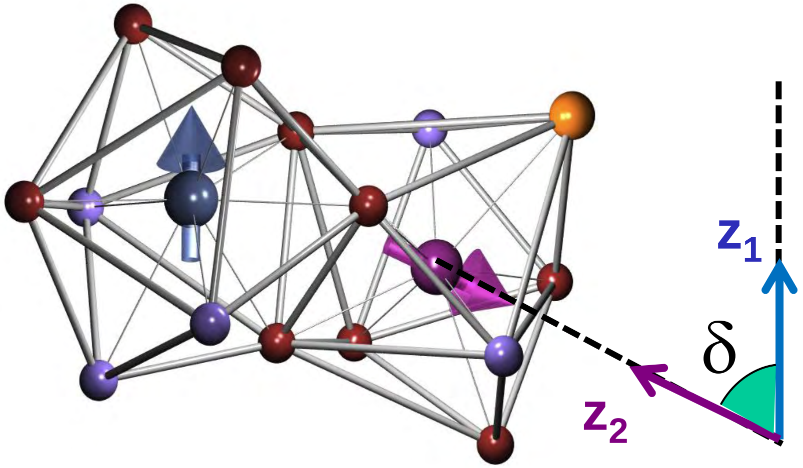


δ = 66 degrees

Noncollinear anisotropy axes

Magnetic asymmetry





δ = 66 degrees

Noncollinear anisotropy axes

Heterometallic clusters

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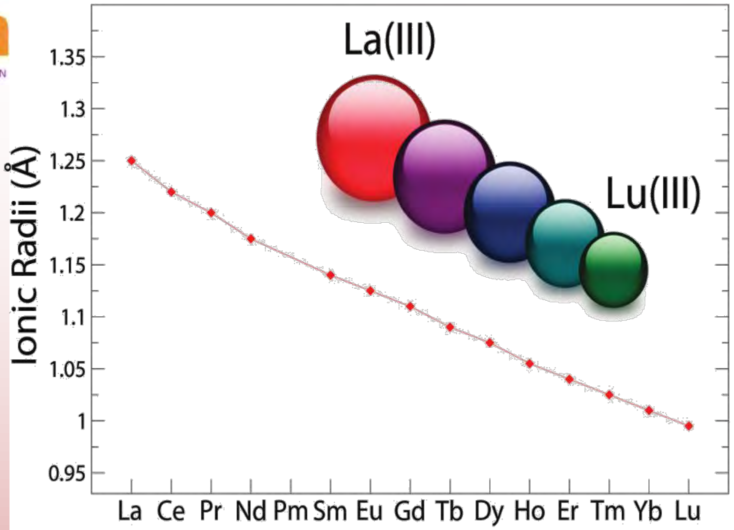
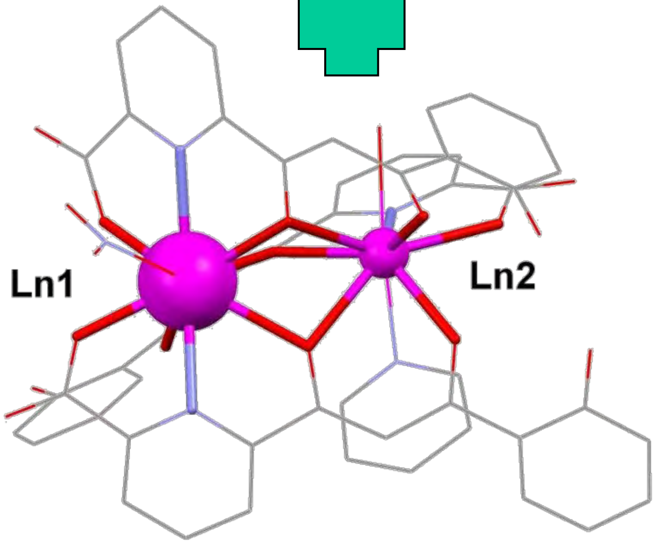
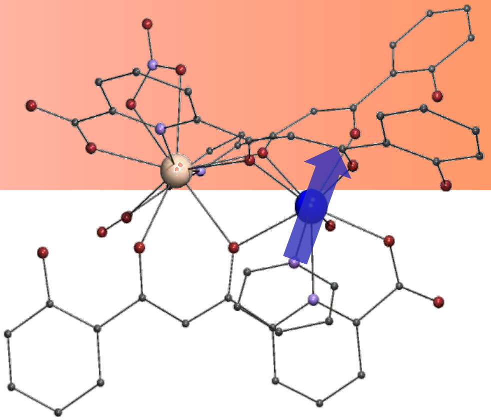


✚

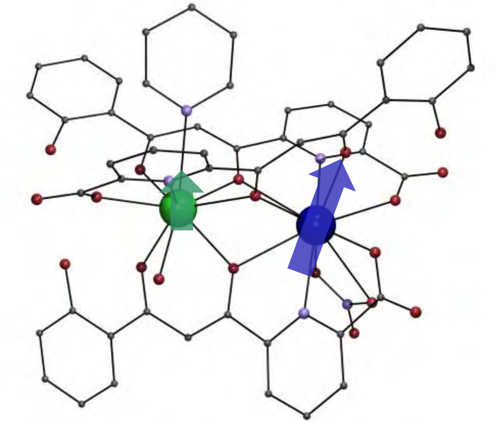


[LaEr]



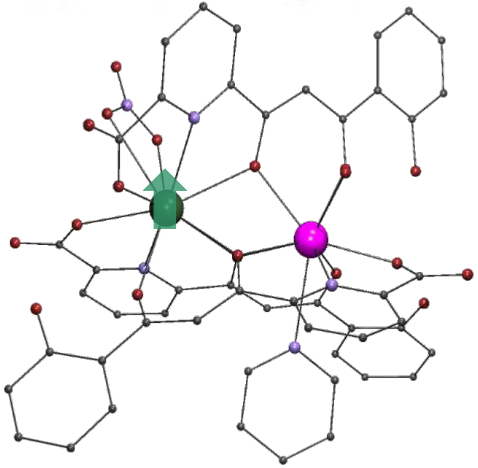
Er^{3+}
$J = 15/2$,
$g_J = 6/5$

[CeEr]

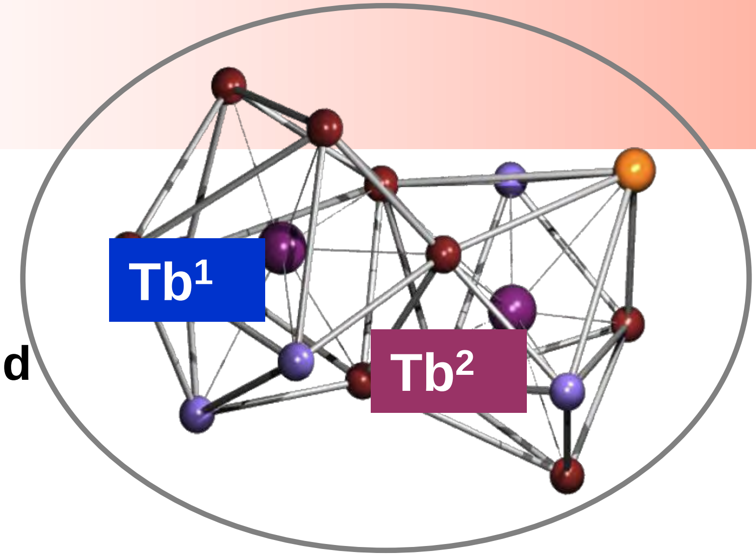


Ce^{3+}
$J = 5/2$,
$g_J = 6/7$

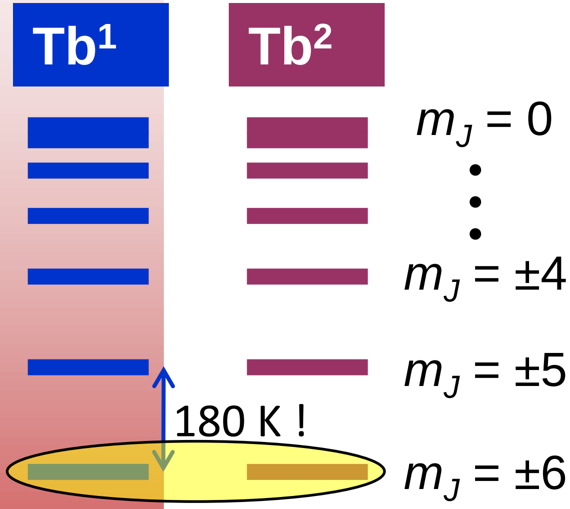
[CeY]



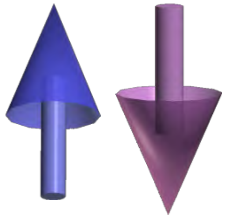
All ingredients are met!



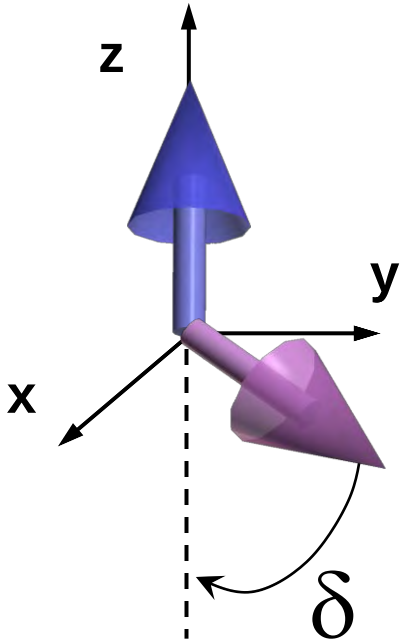
99.99% lie in the ground state below 20 K



Antiferromagnetic exchange below 3 K



Non-collinear easy axes or different ions



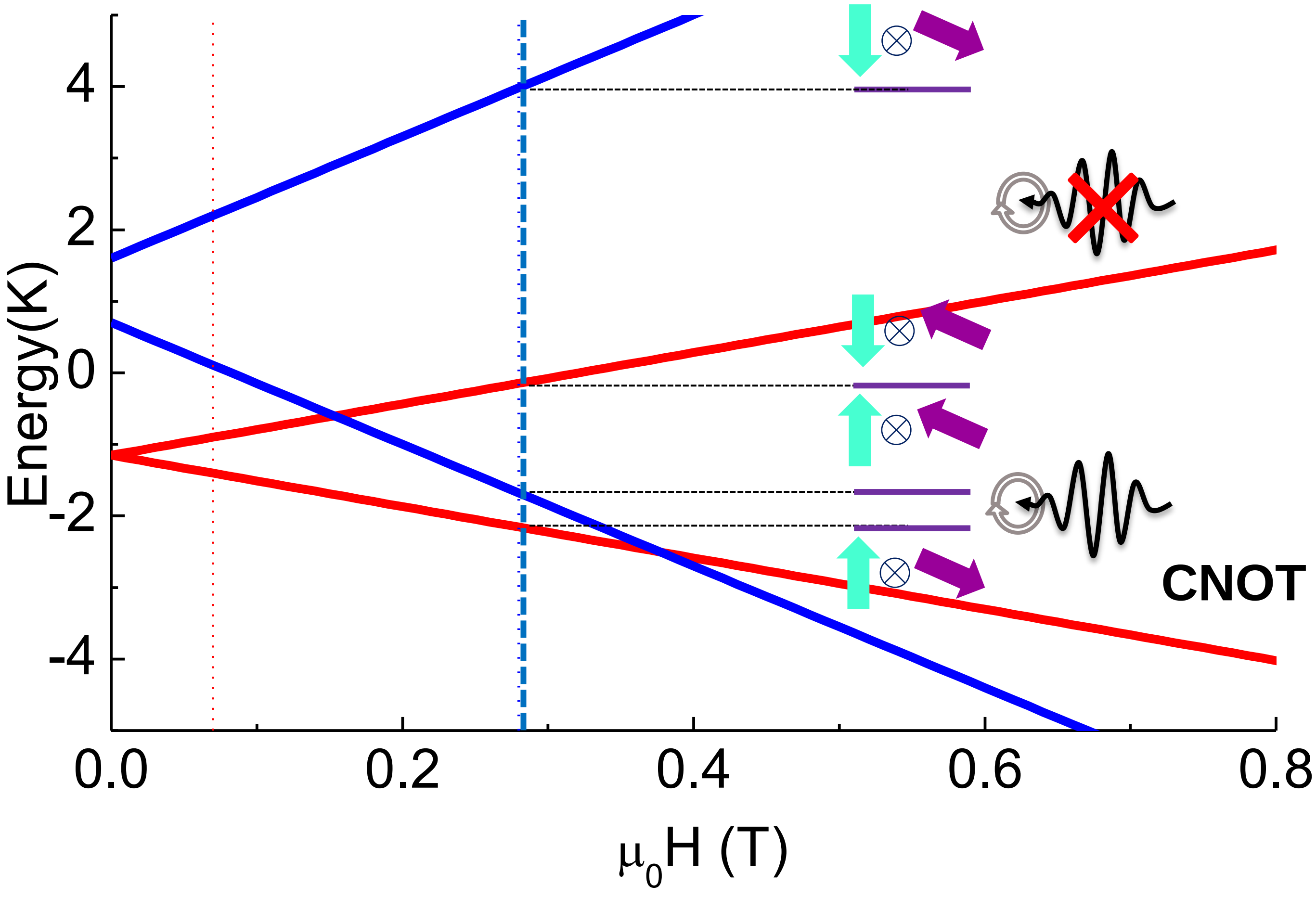
two qubits √

interaction √

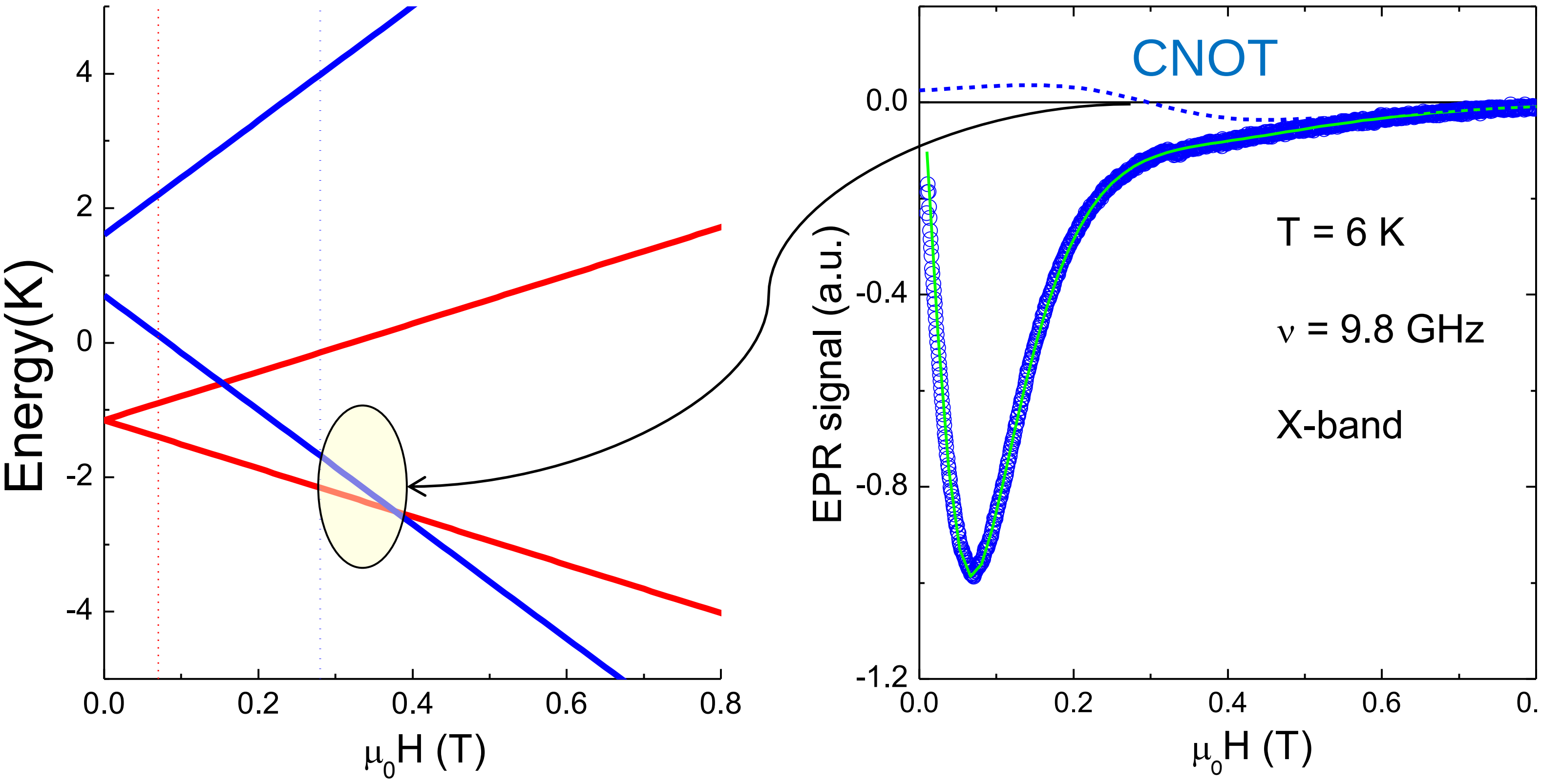
$\delta = 66$ deg √

[Tb]$_2$ as a CNOT logic gate

$$\mathcal{H}_{m=\pm 6} = -2J_{ex}J_{z1}J_{z2} - g_J\mu_B\left(H_{z1}J_{z1} + H_{z2}J_{z2}\right) + A_{hf}\left(J_{z1}I_{z1} + J_{z2}I_{z2}\right)$$

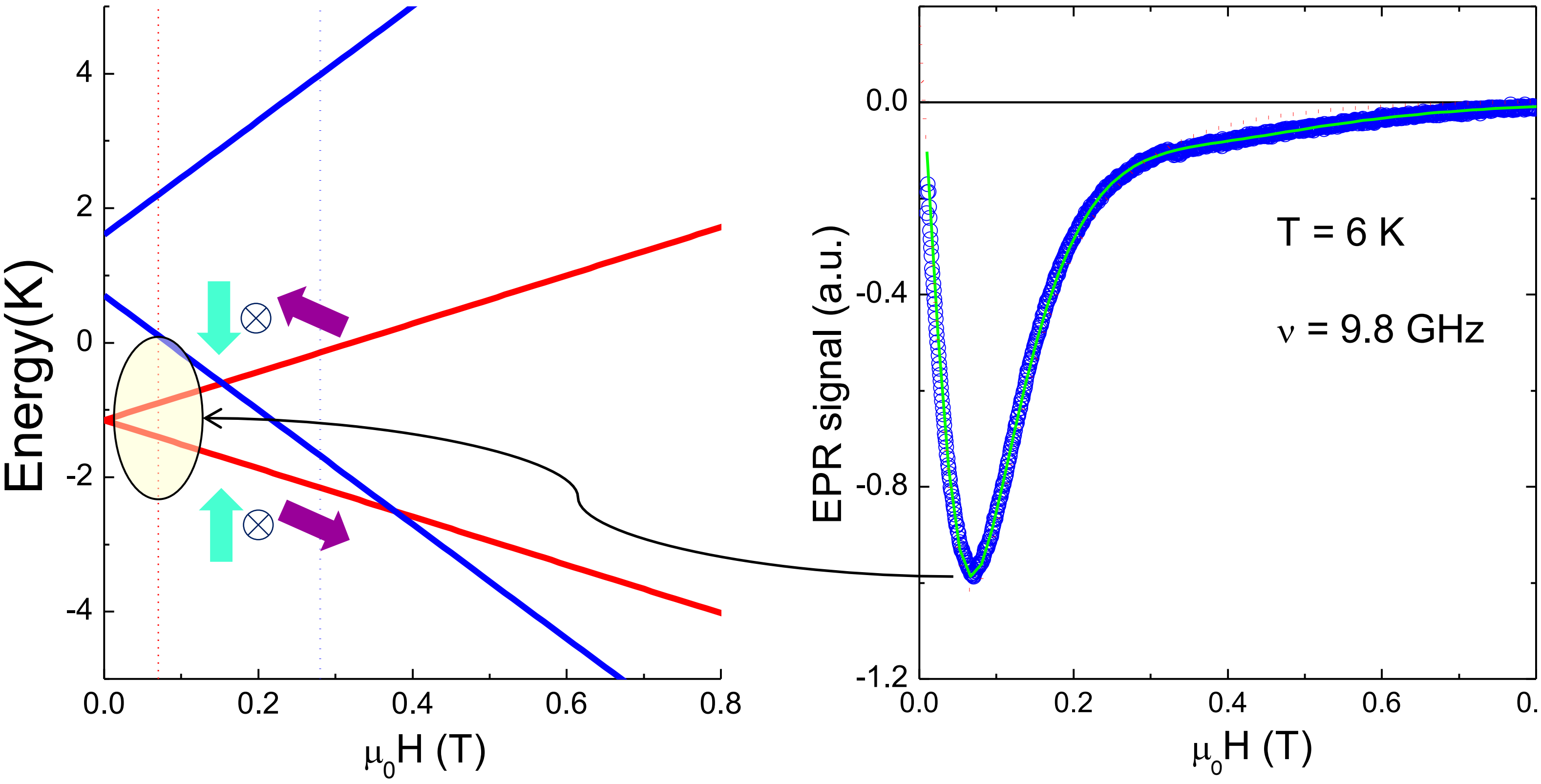


Implementation by EPR



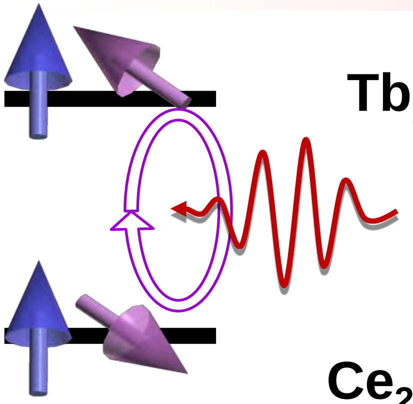
CNOT transitions are not forbidden

F. Luis *et al*, Phys. Rev. Lett. **107**, 117203 (2011).



SWAP gate operations are also possible!

Quantum coherence? (X-band pulsed EPR)

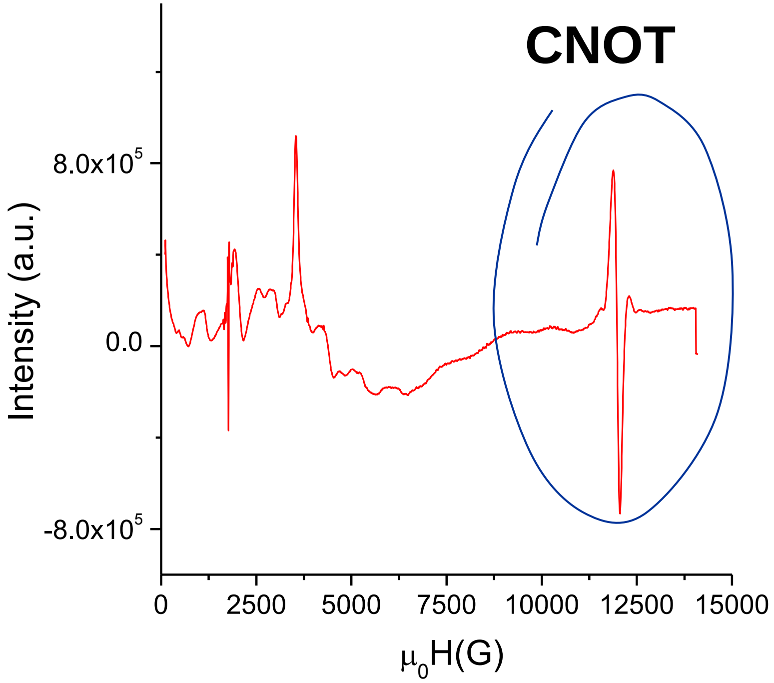


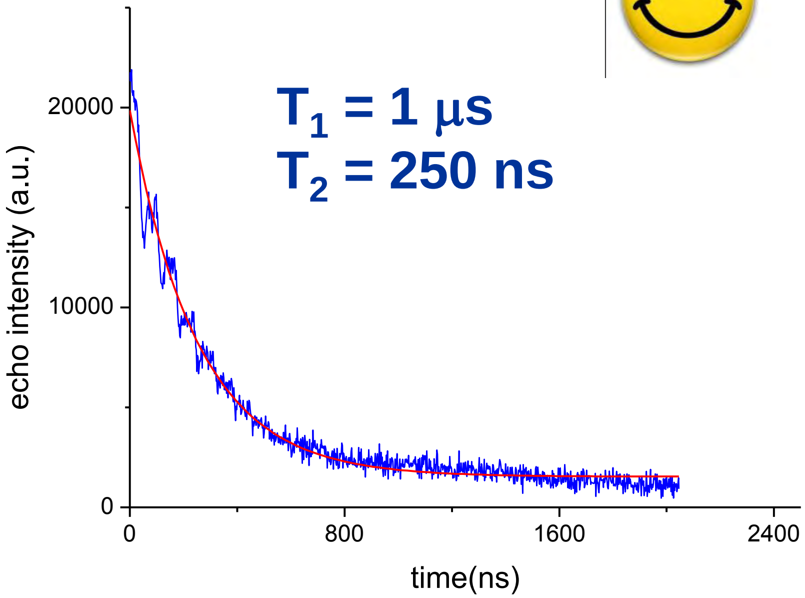
Tb_2: $m = -6$ → $m = +6$ **ECHO?**

NOT OBSERVED

Ce_2: $m = -1/2$ → $m = +1/2$

OBSERVED!!

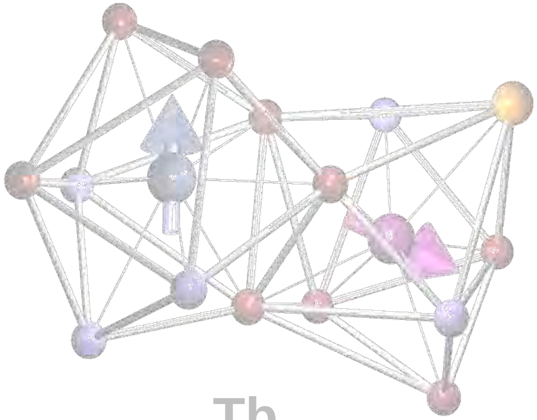


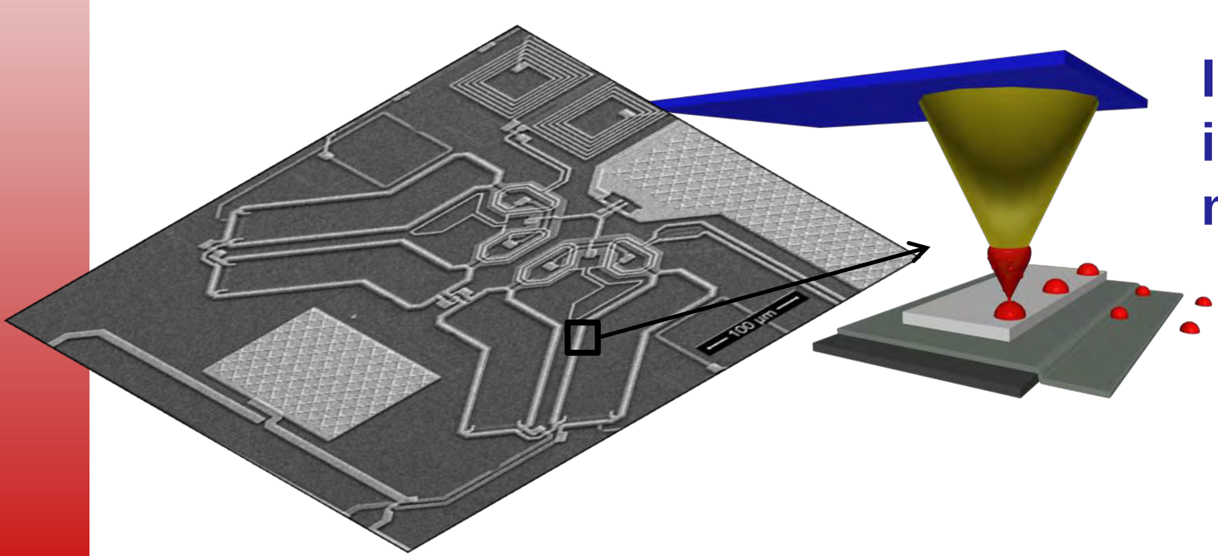


$T_1 = 1\ \mu s$
$T_2 = 250\ ns$

Outline

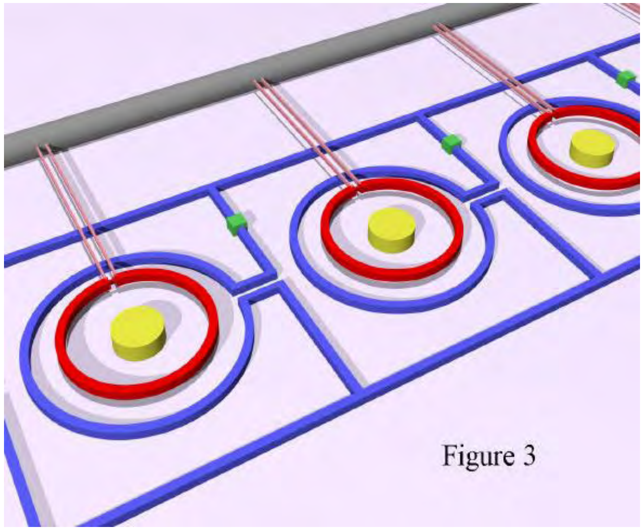
Molecular design of CNOT and SWAP quantum gates



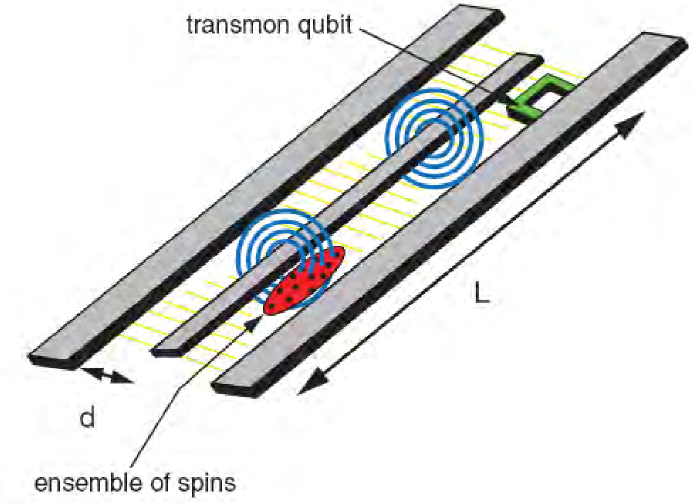


Integration of SMM into superconducting microdevices

Hybrid quantum computation architectures



Magnetic qubits as hardware for quantum computers.
J. Tejada, E. M. Chudnovsky, E. del Barco, J. M. Hernandez and T. P. Spiller, Nanotechnology **12** (2001) 181–186



Cavity QED Based on Collective Magnetic Dipole Coupling:
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Atac Imamoglu, PRL **102**, 083602 (2009)

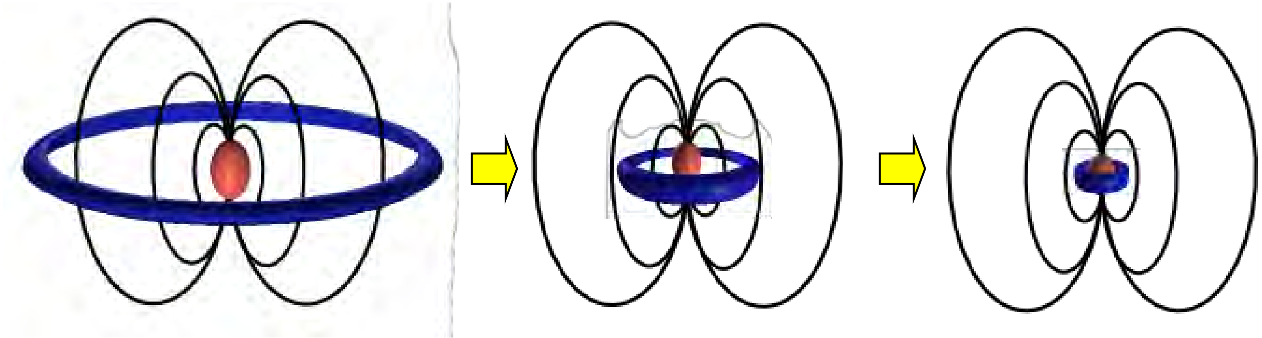
Molecule-based qubits and qugates

+

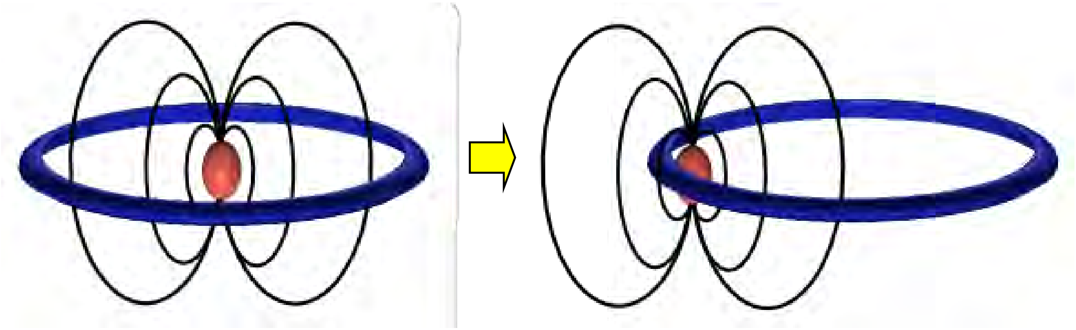
Superconducting μcircuits

The goal: maximizing the flux coupling

1. Scaling down the dimensions of the loop



2. Playing with the sample position !!!

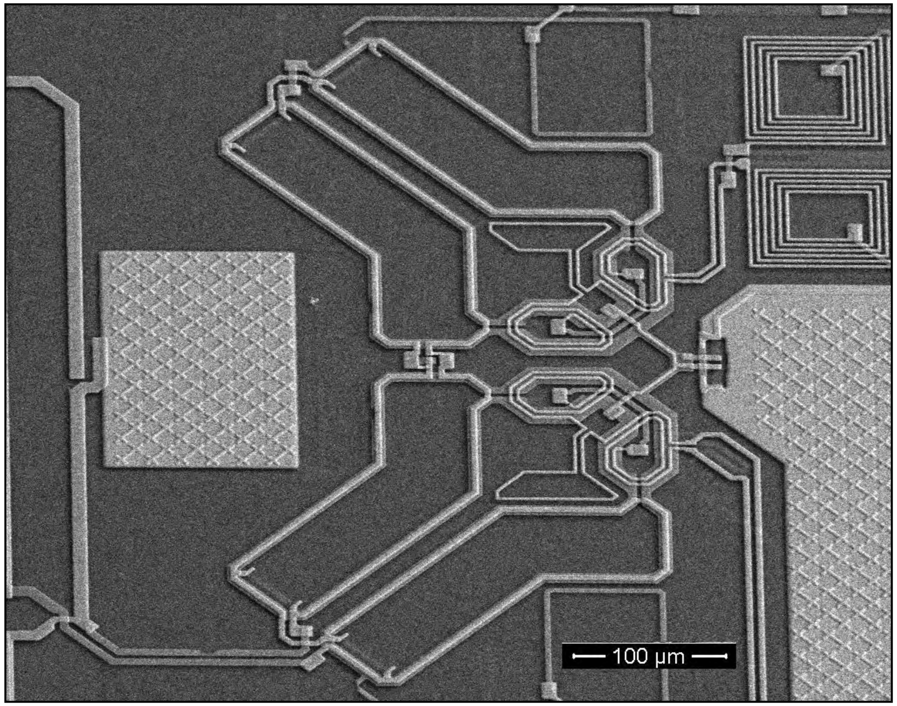


“The first challenge is the placement of a single nanoparticle close to the nanoSQUID while achieving sufficient magnetic coupling between the particle and the device”

C. P. Foley and H. Hilgenkamp. Supercond. Sci. Technol. **22**, 064001 (2009).

The device: microSQUID ac susceptometer

MJ Martínez-Pérez, J. Sesé, F. Luis, D. Drung and T. Schurig Rev. Sci. Instrum. **81**, 016108 (2010)



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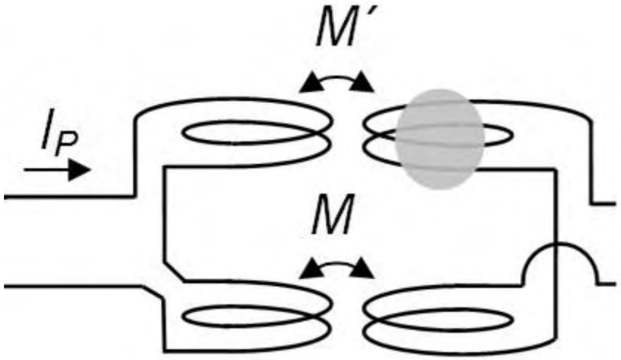

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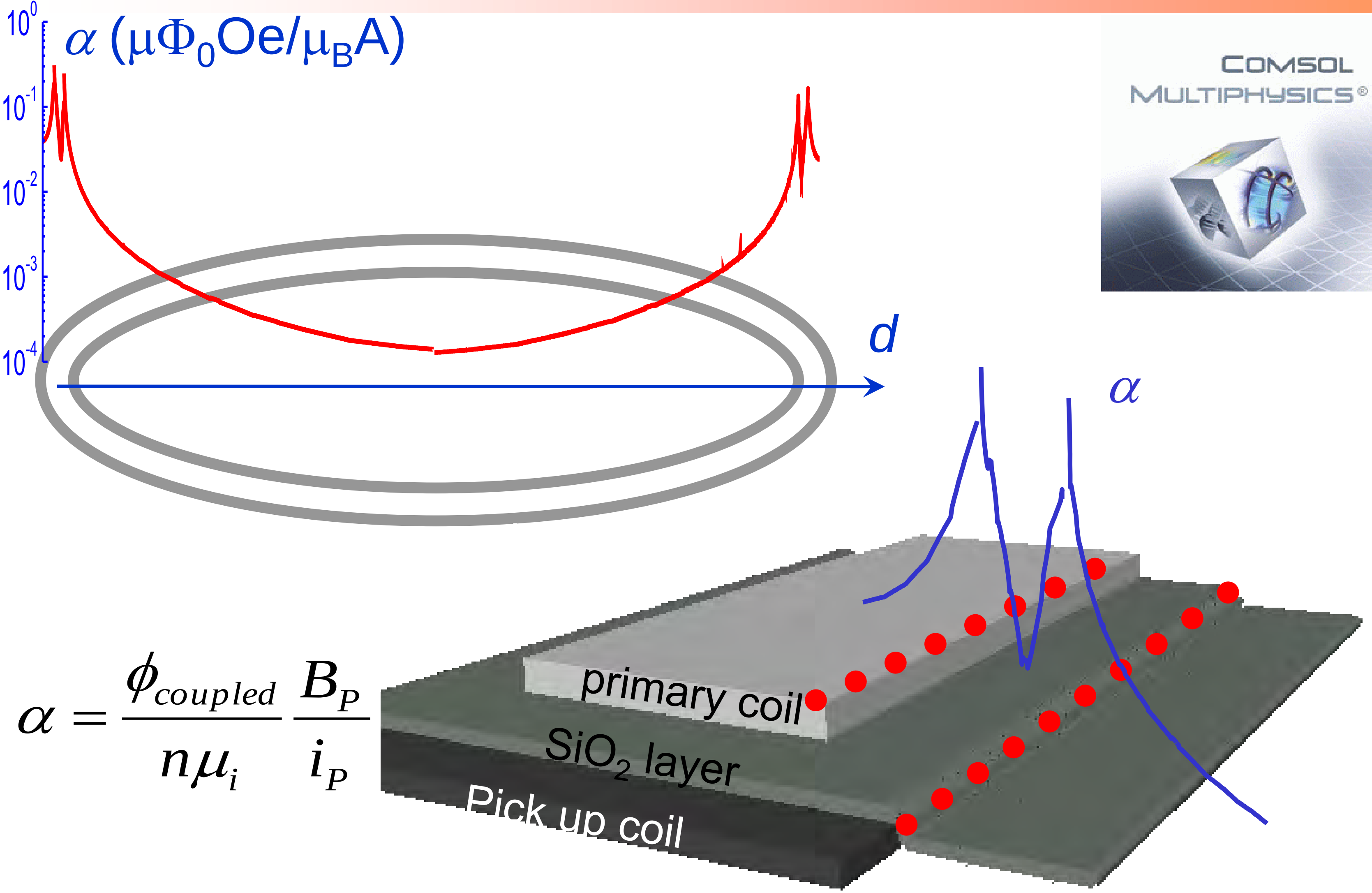
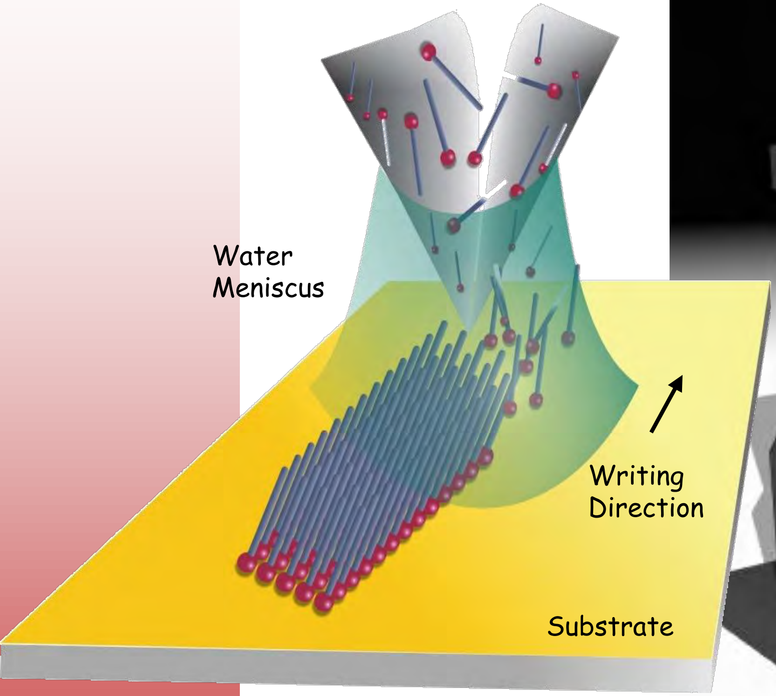
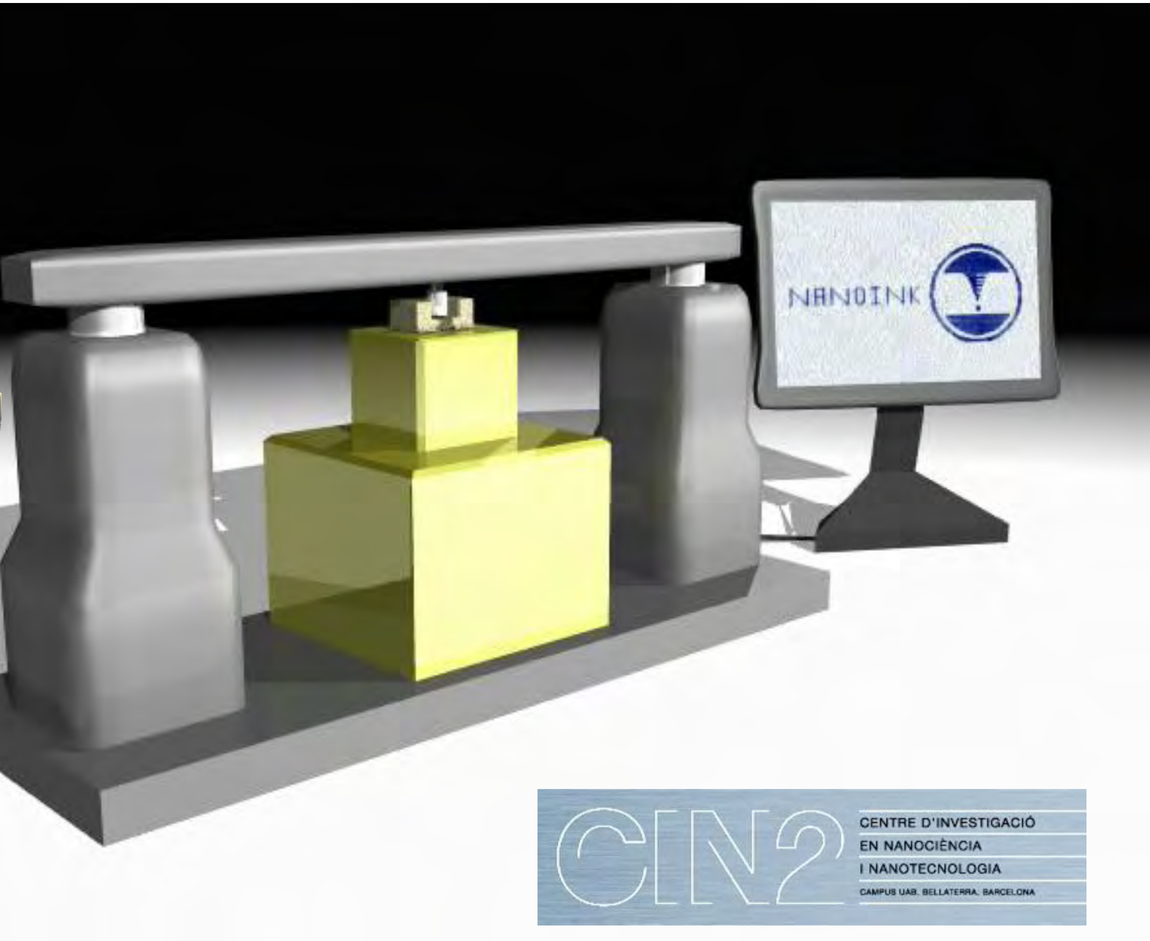


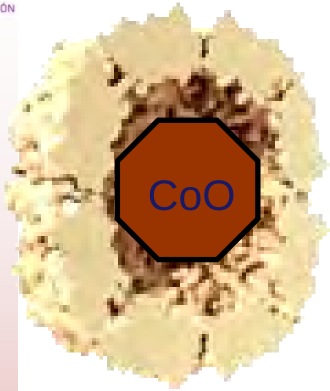
$$\alpha = \frac{\phi_{coupled}}{n\mu_i}\frac{B_P}{i_P}$$

The tool: Dip pen nanolithography

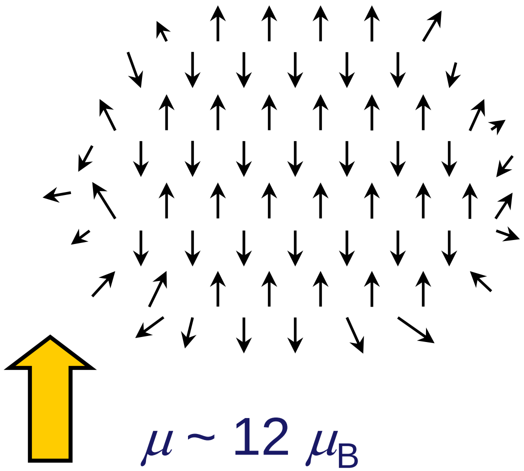




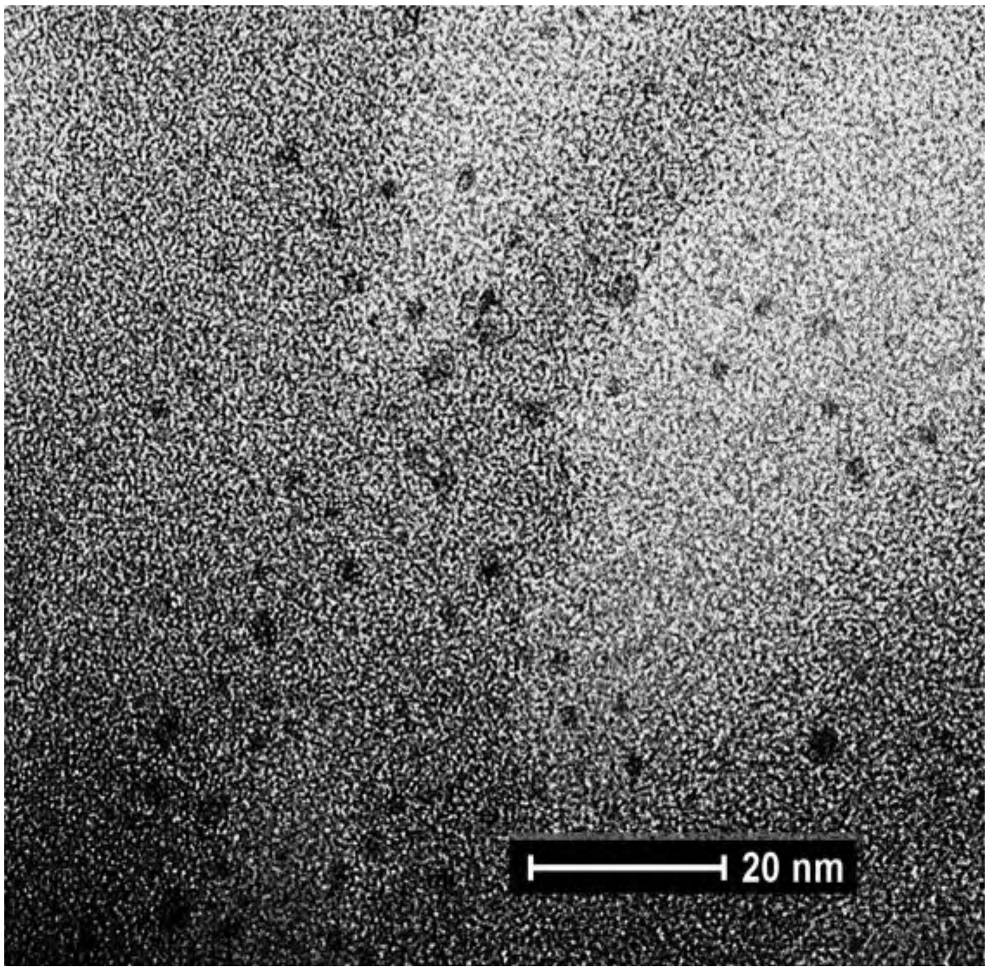
The sample: ferritin-based nanomagnets (CoO)

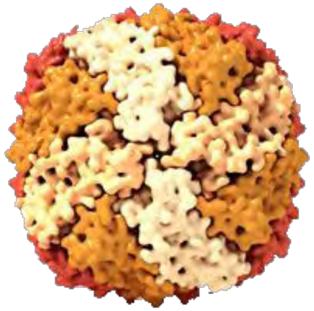


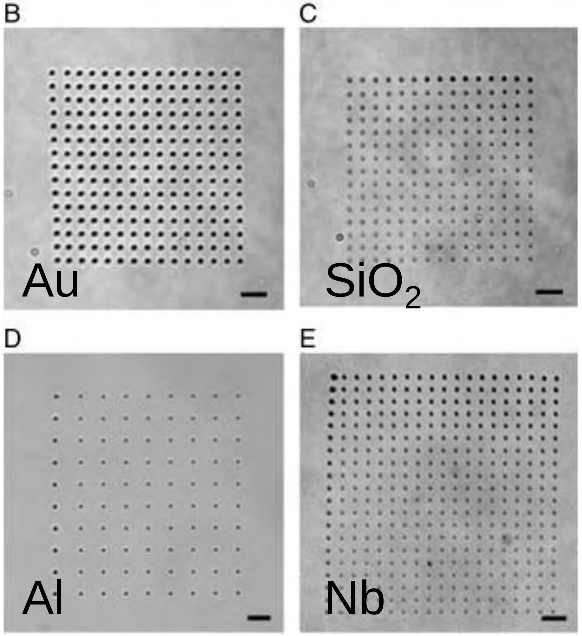
2 nm sized
Antiferromagnetic particle

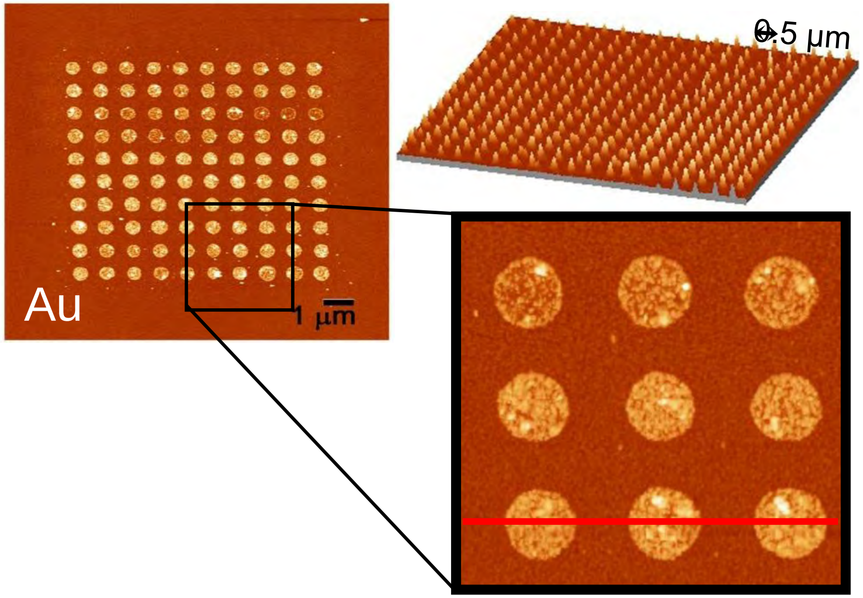


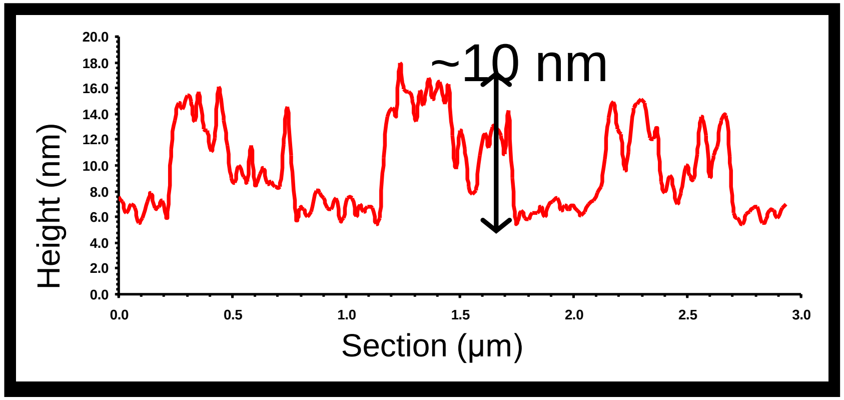
$\mu \sim 12\ \mu_B$



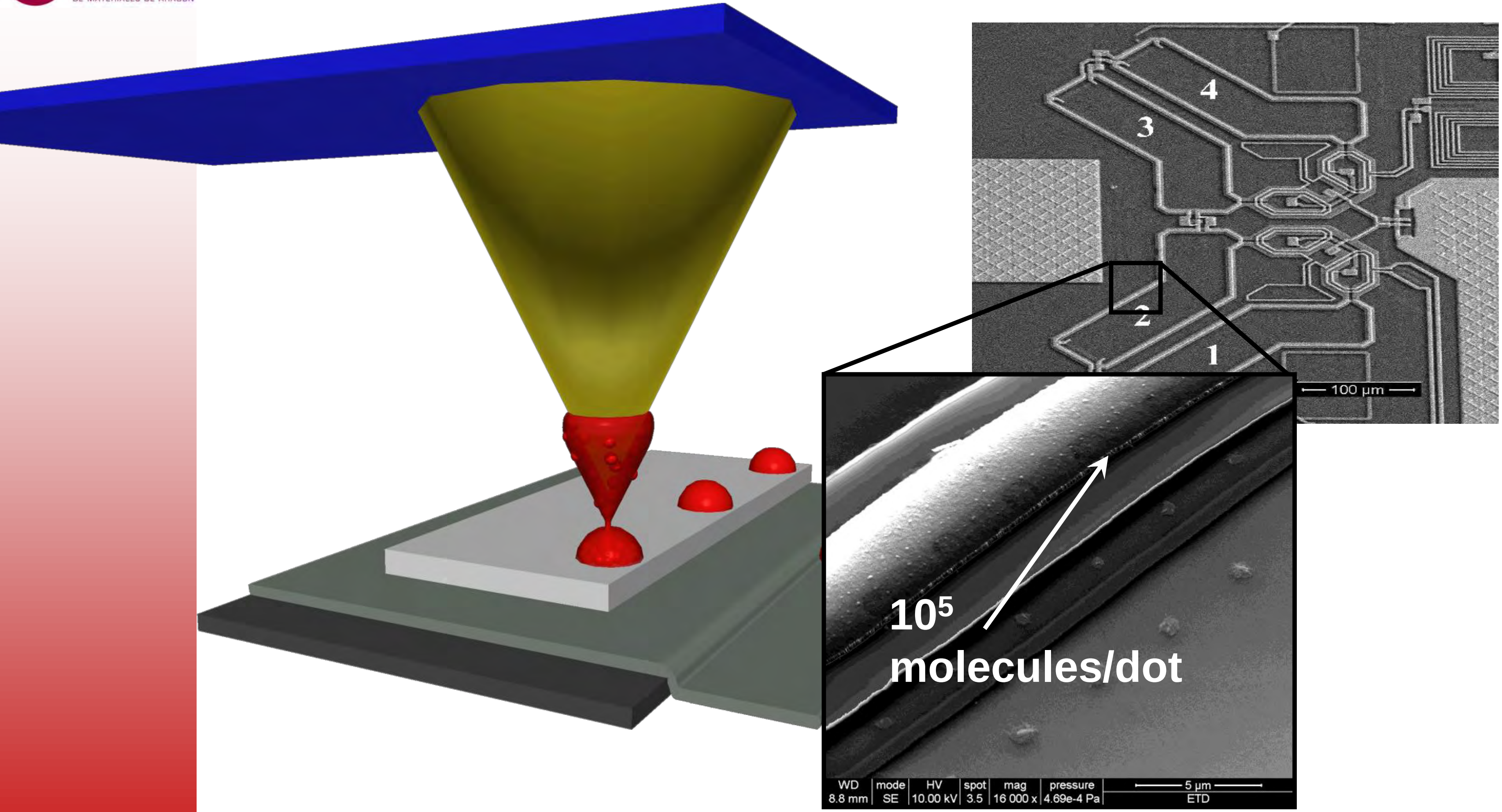



B
Au
C
SiO_2
D
Al
E
Nb


0.5 µm
Au
1 µm


~10 nm
Height (nm)
20.0
18.0
16.0
14.0
12.0
10.0
8.0
6.0
4.0
2.0
0.0
0.0
0.5
1.0
1.5
2.0
2.5
3.0
Section (µm)

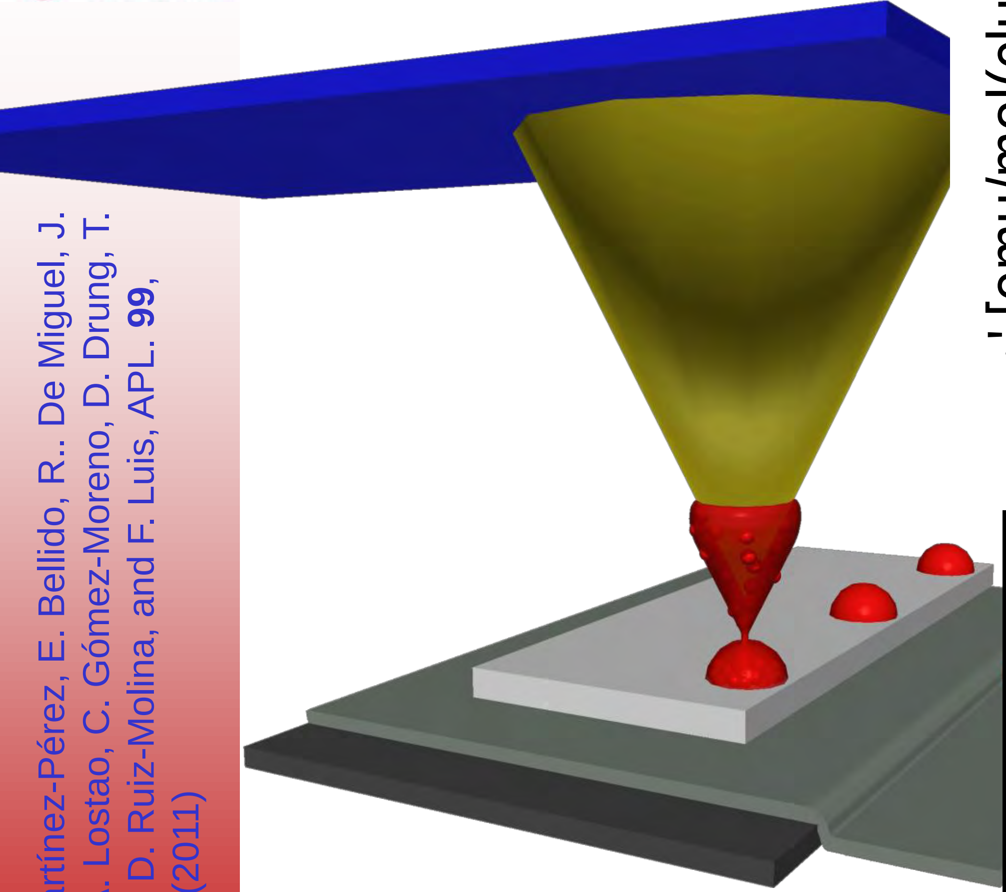
Direct deposition on the most sensitive areas

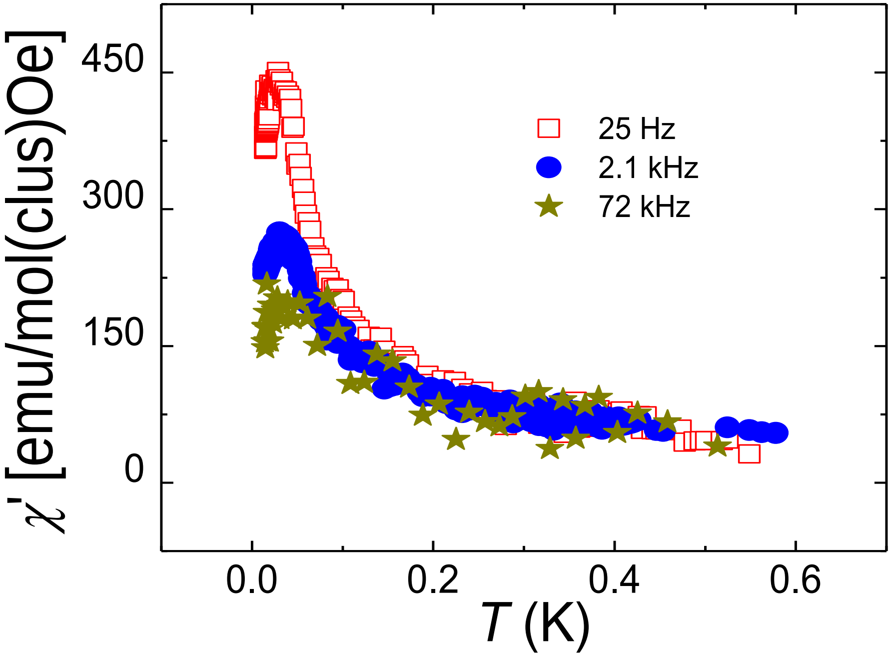


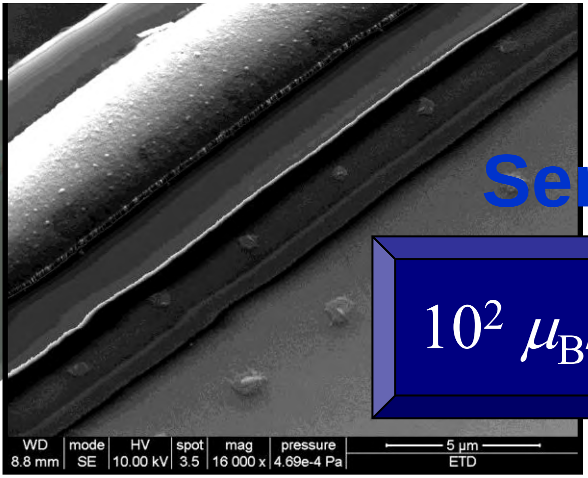
10^5 molecules/dot

Detection of the linear response of a SMM monolayer

M. J. Martínez-Pérez, E. Bellido, R.. De Miguel, J. Sese´, A. Lostao, C. Gómez-Moreno, D. Drung, T. Schurig, D. Ruiz-Molina, and F. Luis, APL. **99**, 032504 (2011)

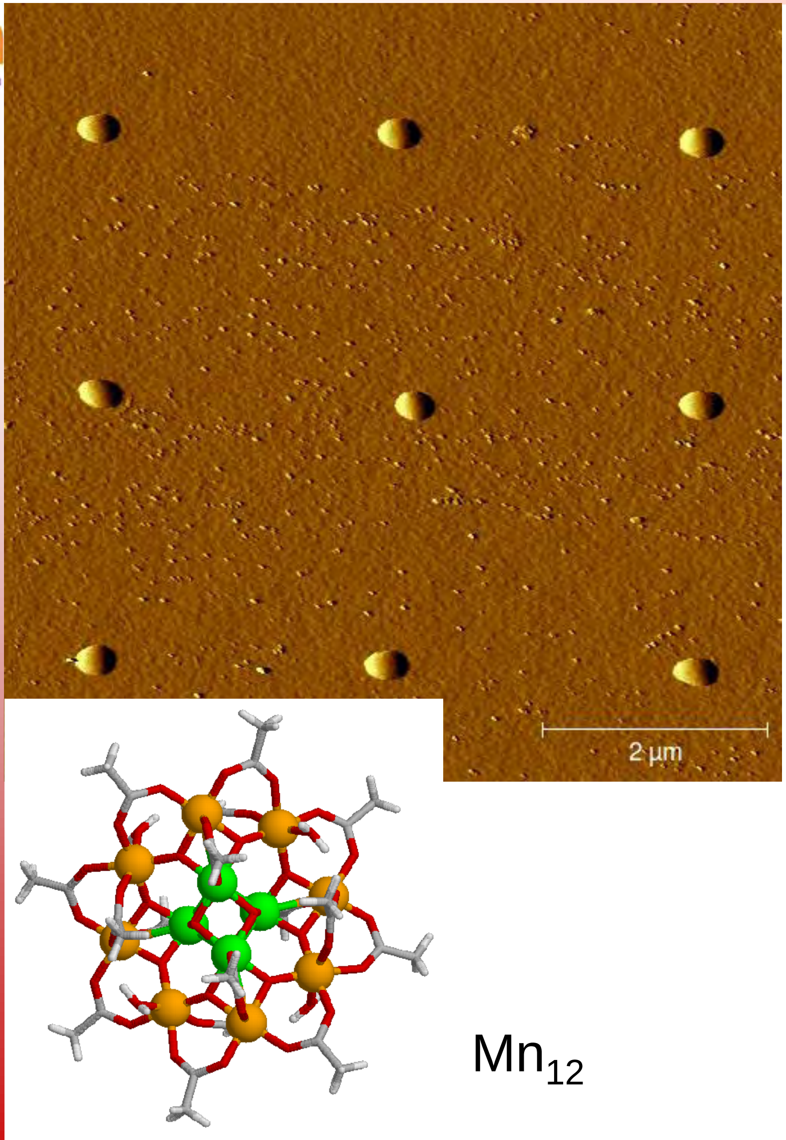




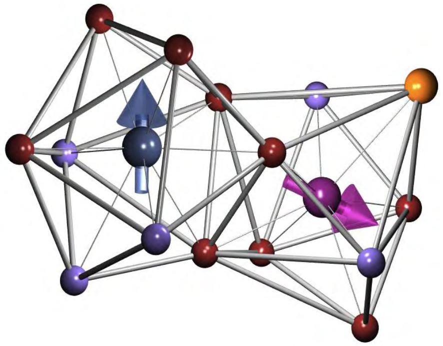


Sensitivity

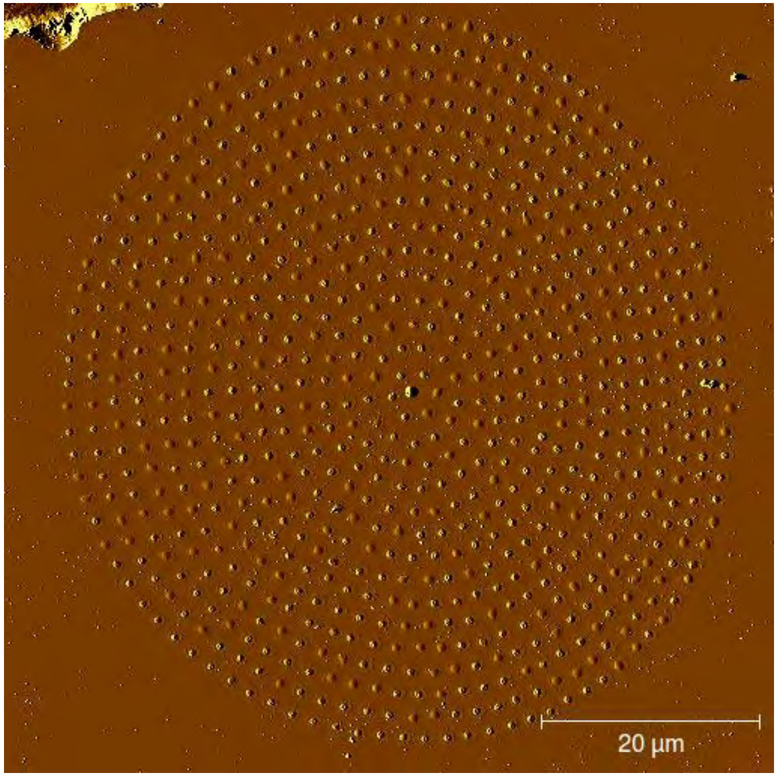
$10^2\ \mu_B/\mathrm{Hz}^{1/2}$



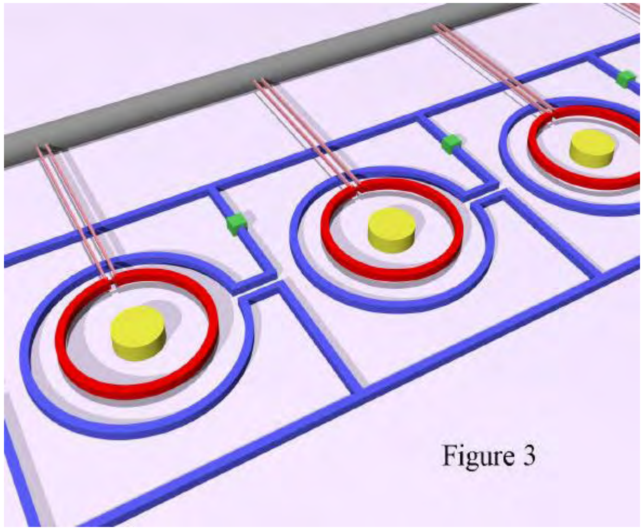
Mn$_{12}$



Gd$_2$



Towards the implementation of quantum computation architectures



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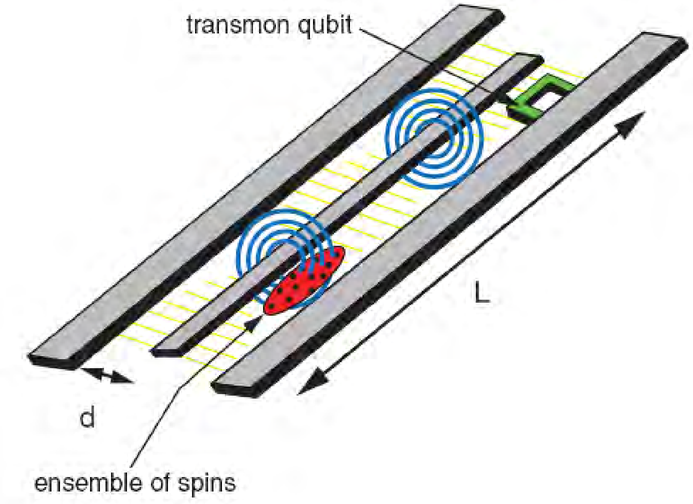

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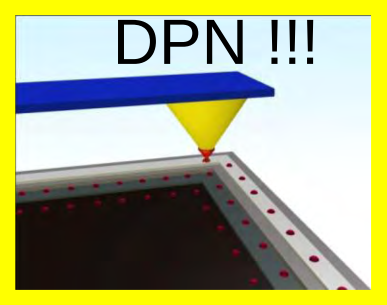
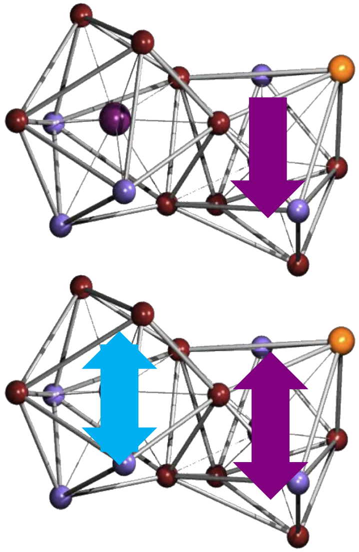


Superconducting μcircuits

CONCLUSIONS

- [LnLn'] clusters, designed and synthesized via coordination chemistry, meet the following ingredients
  - proper definition of qubit states
  - weak AF coupling between qubits
  - magnetic asymmetry

molecular prototypes for CNOT quantum gates



  - SWAP gate operations can be performed in the same molecule

- Dip pen nanolithography offers a very attractive tool to integrate molecular qubits into superconducting microdevices: towards the implementation of quantum architectures

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