Enhancing the magnetic anisotropy of atomic structures:
The ultimate magnetic bit

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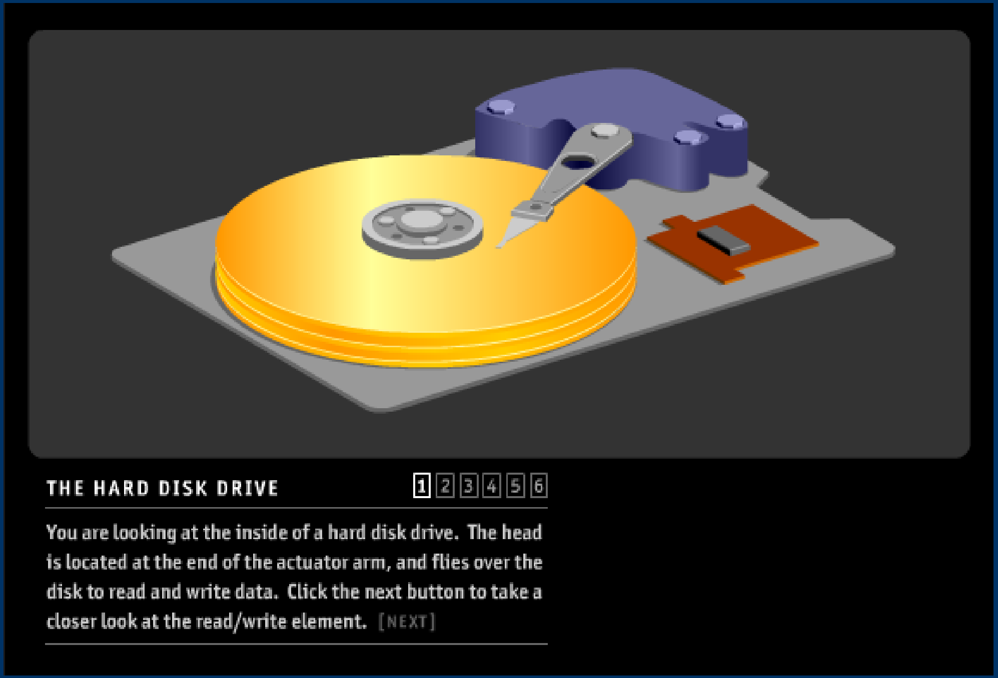
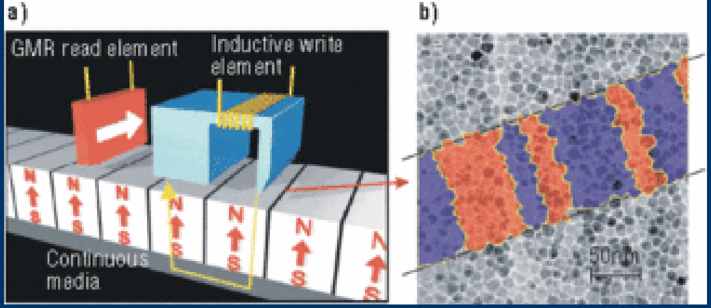
MOTIVATION: the hard disk drive



THE HARD DISK DRIVE

You are looking at the inside of a hard disk drive. The head is located at the end of the actuator arm, and flies over the disk to read and write data. Click the next button to take a closer look at the read/write element. [NEXT]

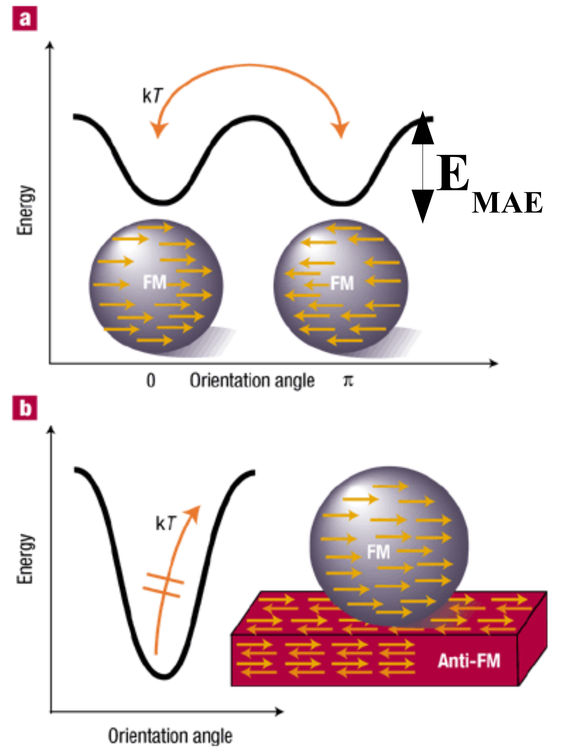


The grains eventually become unstable

Source: http://www.research.ibm.com/research/gmr.html

The super-paramagnetic limit I

Magnetic anisotropy barrier versus thermal fluctuations



Eisenmenger and Schuller, Nature Materials (2003)

$$M = M_0 \ e^{-t/\tau}$$

$$\tau = 10^{-9} \ e^{E_{MAE}/KT} \ s = 10^{-9} \ e^{V \ \epsilon_{SHAPE}/KT} \ s$$

Critical time → $\tau = 10^2 \, seconds$

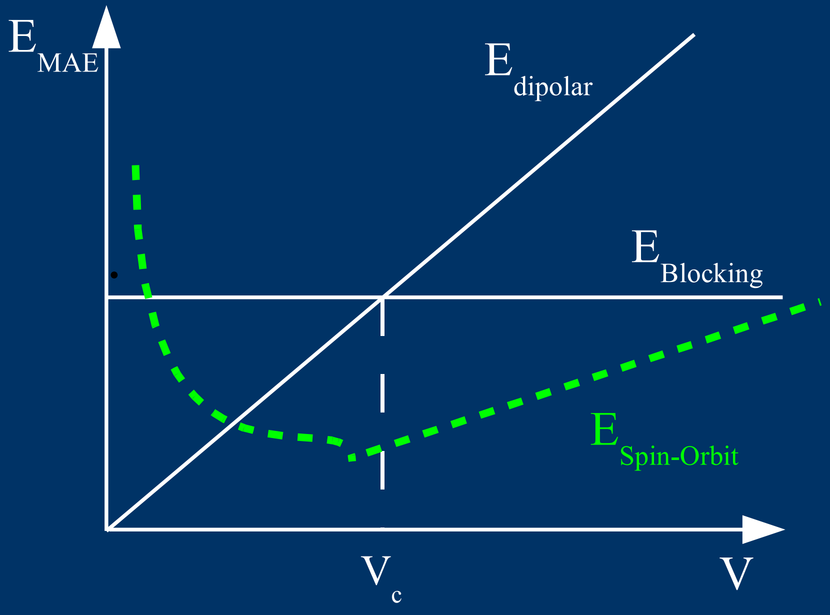
$$E_{MAE,Critical} = V_C \ \epsilon_{SHAPE} = 25 \, K \, T_B = E_{Blocking}$$

↓ Critical Volume

↓ Blocking Temperature

The super-paramagnetic limit II

$Set \quad T_B = 300\ K$ → $E_{Blocking} = 600\ meV$



$E_{MAE} = E_{dipolar} + E_{Spin\text{-}Orbit}$

$V_c \sim$ 25 nm for Fe particles
10 nm for Co particles

Enhancing the MAE via the SO interaction

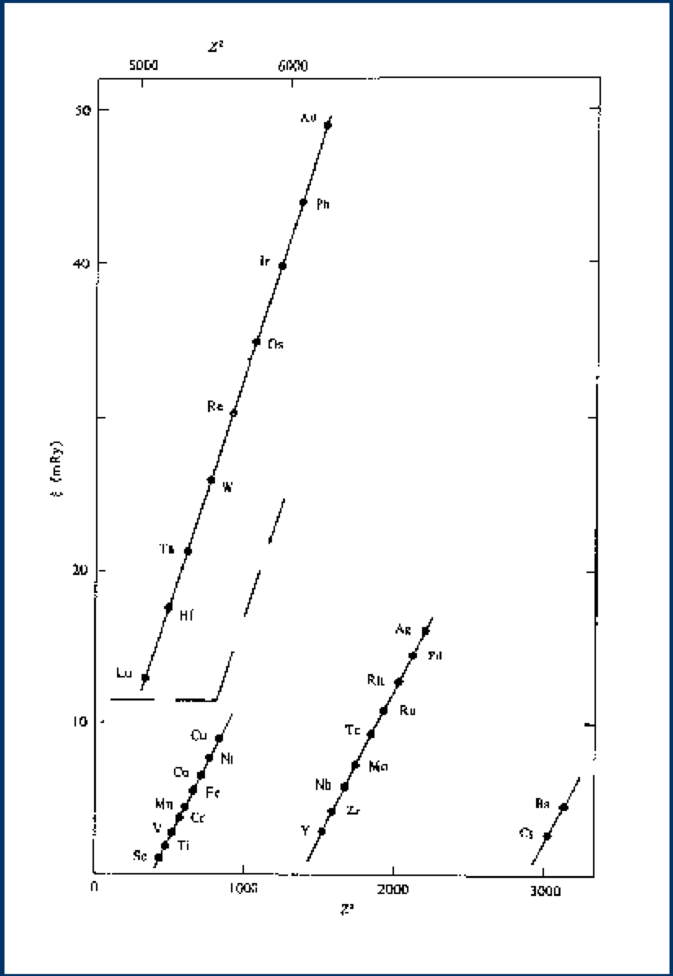
A. R. Mackintosh and O. K. Andersen, Electrons at the FS

P. Bruno, Physical origins and theoretical models of magnetic anisotropy

Bulk samples $E_{SO} \sim \dfrac{\xi^4}{E_F^3}$

Thin films $E_{SO} \sim \dfrac{\xi^2}{E_F} \sim 1\,meV$

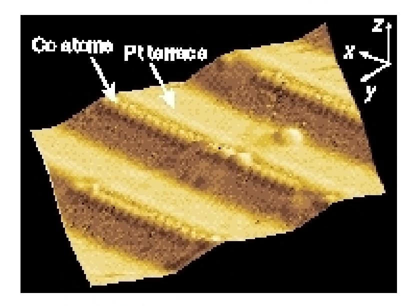
Atomic structures $E_{SO} \sim \xi$



Beating the super-paramagnetic limit

Giant Magnetic Anisotropy of Single Cobalt Atoms and Nanoparticles, Gambardella et al., Science (2003).

$E_{SO} \sim 5$ meV



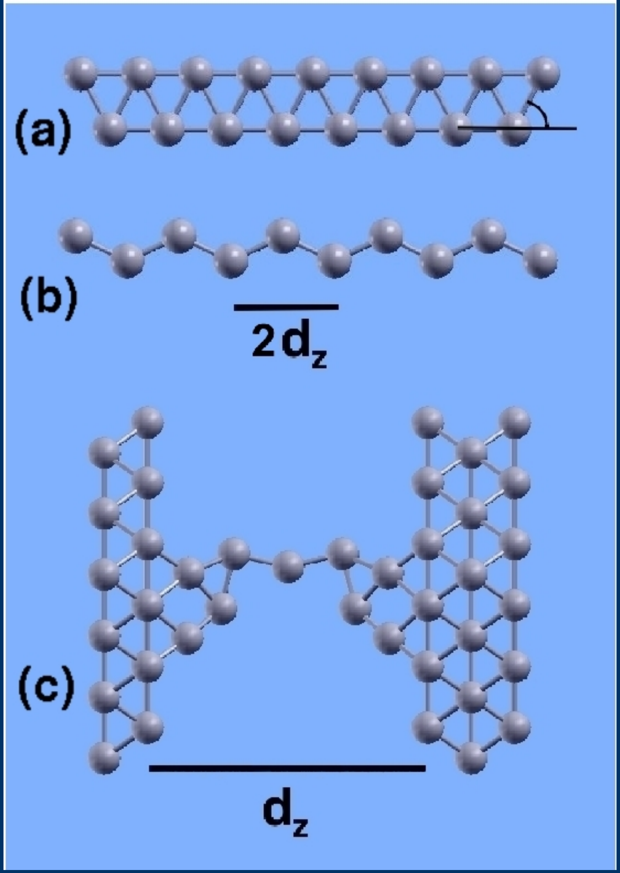
Large Magnetic Anisotropy of a Single Atomic Spin Embedded in a Surface Molecular Network. C. F. Hirjibehedin, et al., Science (2007)

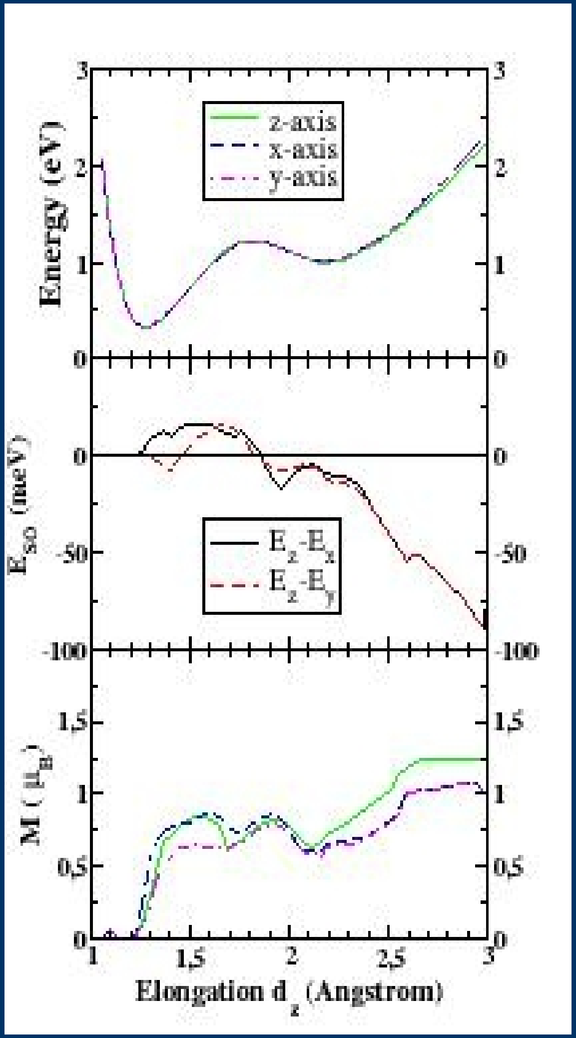
$E_{SO} \sim 2$ meV

Look at 5d nanostructures: atomic chains, clusters and molecules !

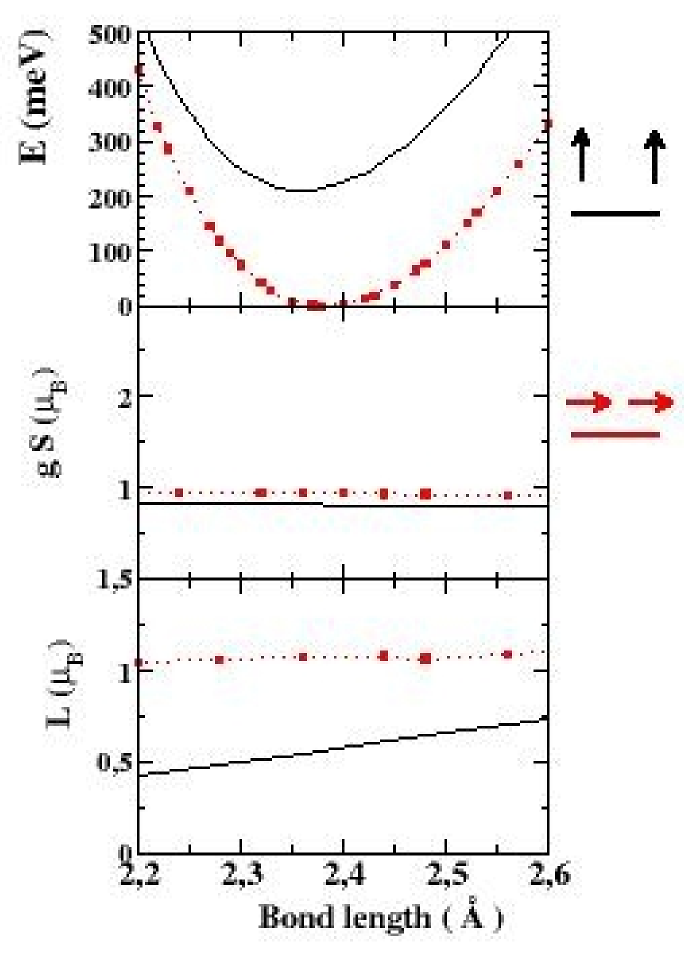
The MAE of Pt atomic chains

Fernandez-Seivane, Garcia-Suárez and Ferrer	PRB 2007
Smogunov, Corso, Weht, Delin and Tosatti	Nature Nano 2008



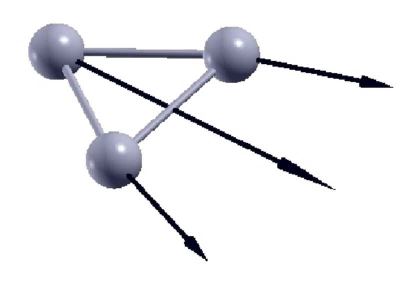


The MAE of atomic clusters

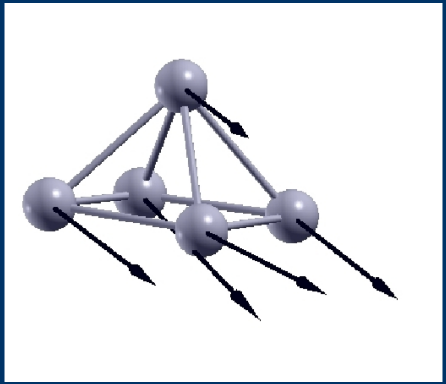


Fernandez-Seivane and Ferrer	4d & 5d clusters	PRL 2007
Strandberg et al.	3d & 4d dimers	Nature Mat 2007

Smallest MAE unit: the dimer

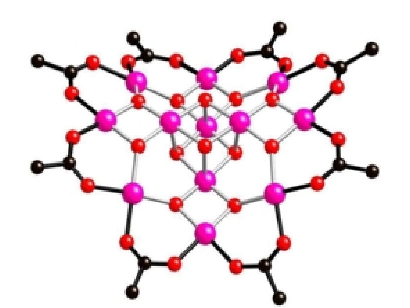


Pt_3

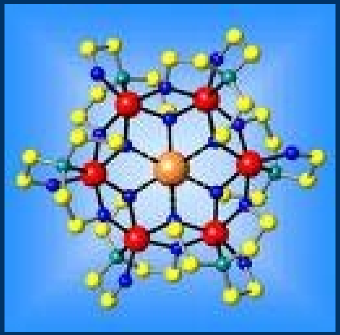


Pt_5

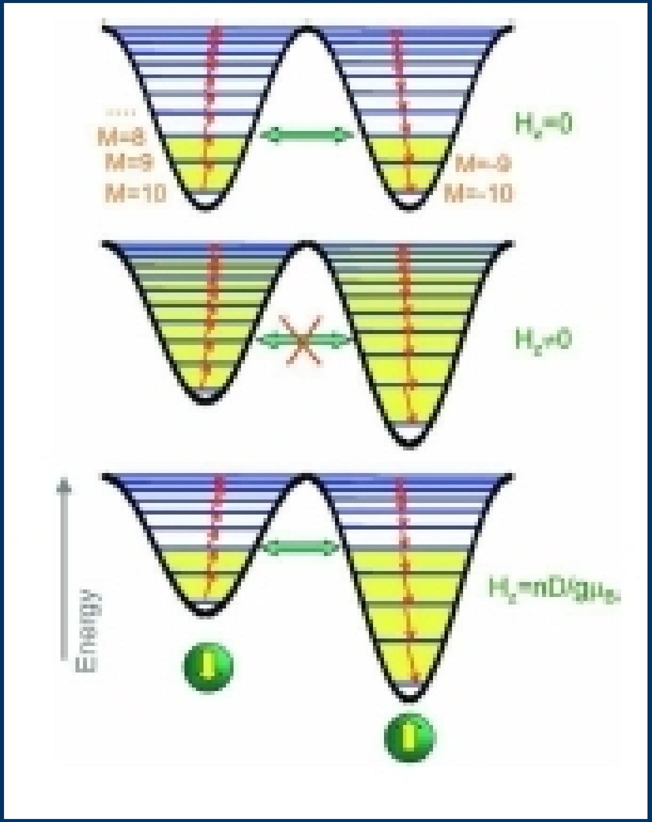
Magnetism and MAE in Molecular Magnets



Mn_{12}



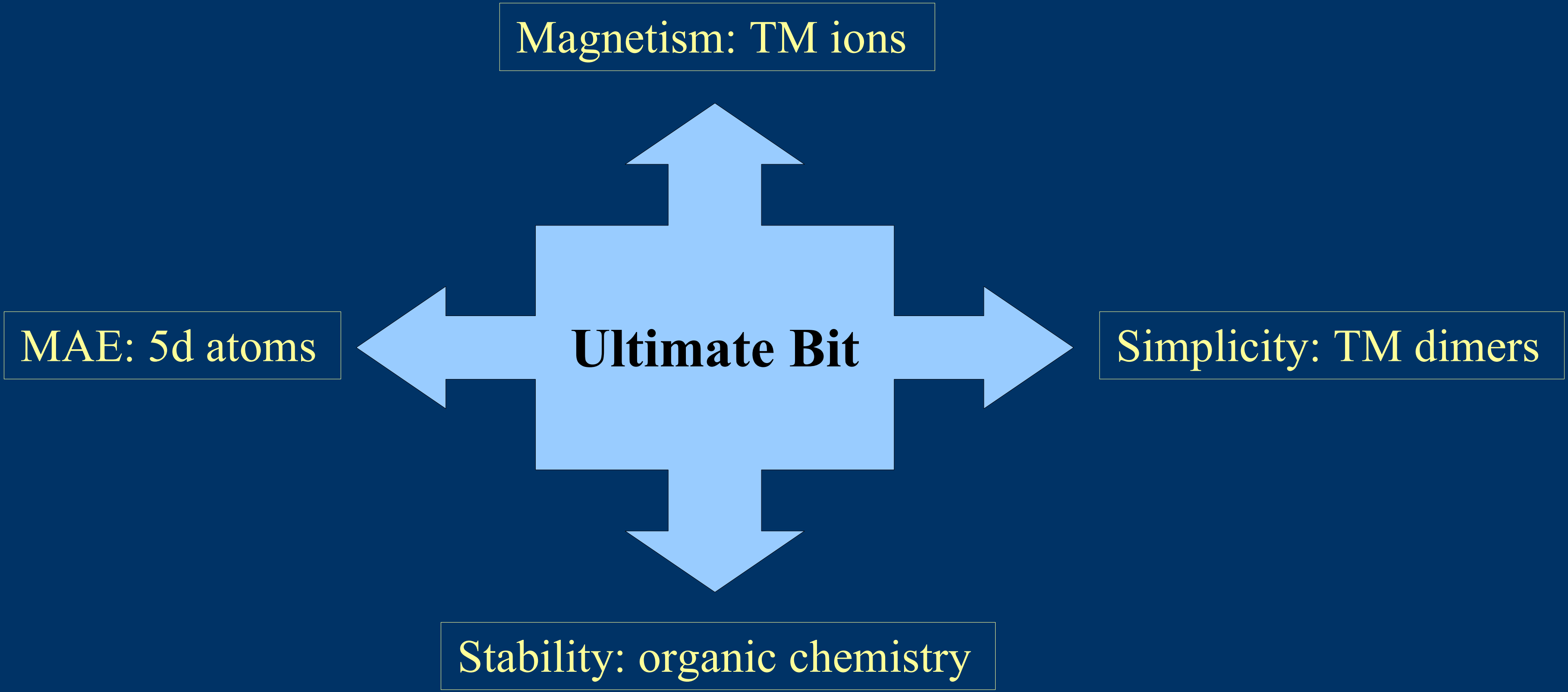
Ferric wheel



Drawbacks:

- Too complex: too many atoms
- Too many states – tunneling events
- E_{MAE} ~ 5 meV

Searching for the Ultimate Bit



Magnetism: TM ions

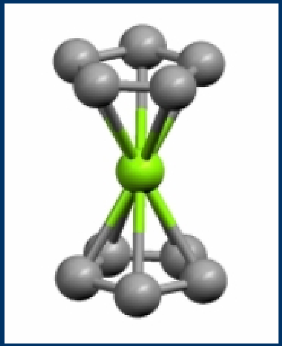
MAE: 5d atoms

Ultimate Bit

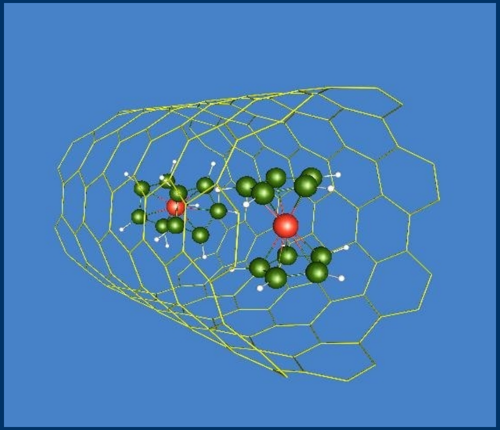
Simplicity: TM dimers

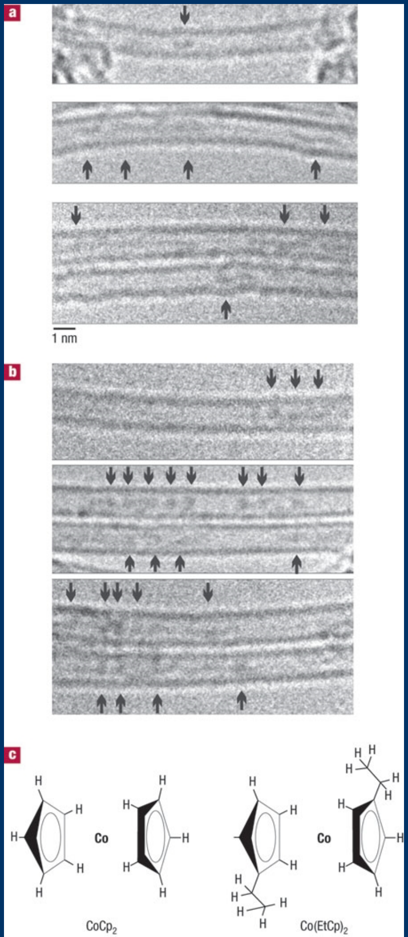
Stability: organic chemistry

Searching for the Ultimate Molecular Magnet



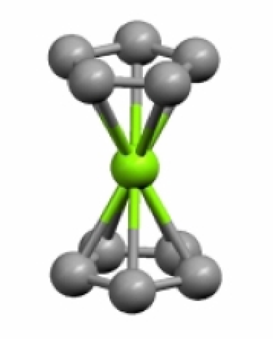
TMCp_2





CoCp2@SWCNT Briggs et al, Nat. Mat. 2006
Garcia-Suarez et al, PRL 2006

Searching for the Ultimate Molecular Magnet



$TMCp_2$

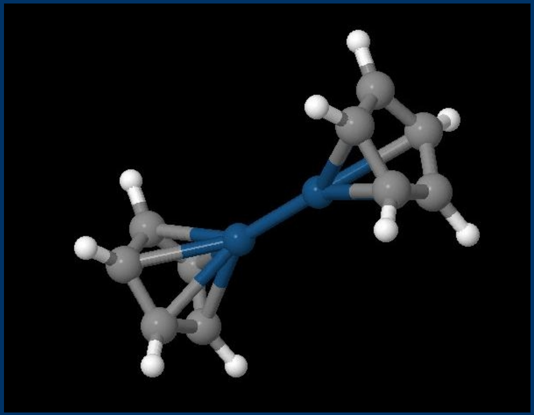
Spin S

0 ½ 1 ½ 0

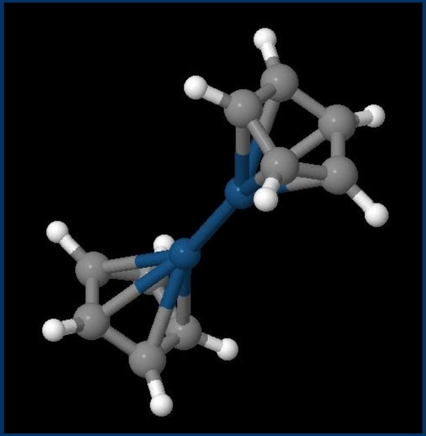
Sc	Ti	V	Cr	Mn	Fe	Co	Ni	Cu	Zn
Y	Zr	Nb	Mo	Te	Ru	Rh	Pd	Ag	Cd
La	Hf	Ta	W	Re	Os	Ir	Pt	Au	Hg

Synthesis of Zn_2Cp_2 - Dizincocene

Resta et al., Science 2004

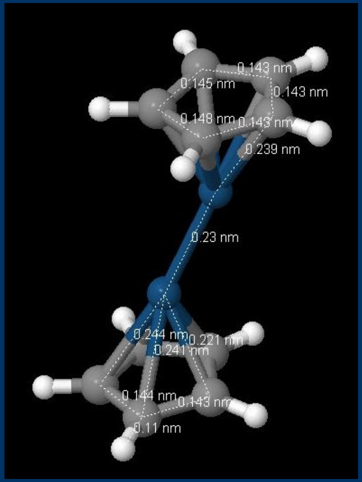


Eclipsed

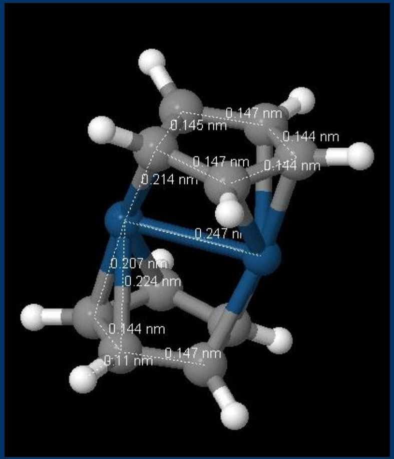


Staggered

Zn_2Cp_2 is non-magnetic



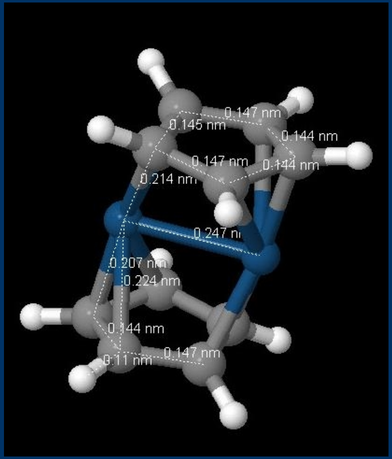
Slanted



Perpendicular

Magnetism & geometry of TM_2Cp_2

TM = Ir, Pt, Co



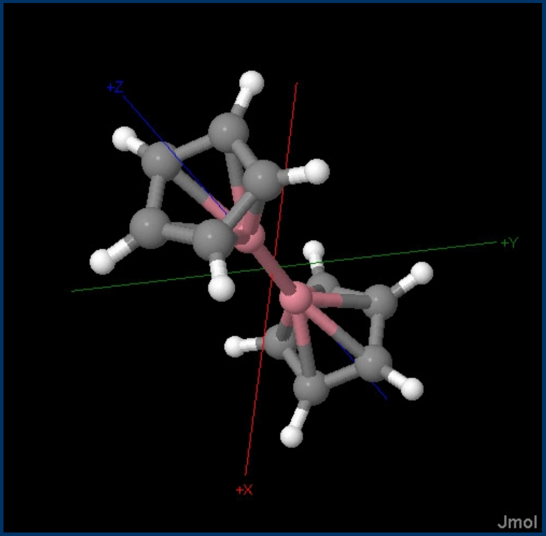
Ground-state geometry

5d: Ir_2Cp_2 & Pt_2Cp_2 are non-magnetic

3d: Co_2Cp_2 is magnetic ($S_T = 1.1$)
$E_{MAE} \sim 1$ meV

Magnetism & geometry of Mixed TM-TM'-Cp2

TM, TM' = Ir, Pt, Au



Even # of electrons: Ir-Au-Cp_2 is non-magnetic

Odd #: Pt-Ir-Cp_2 & Pt-Au-Cp_2 are magnetic

$E_{MAE} \sim 1$ meV

Staggered geometry

Summary

- ➔ MAEs of 500 meV must be achieved to beat the SP limit
- ➔ MAE due to the Spin-Orbit interaction increases at the atomic scale
- ➔ 5d (Ir & Pt) nanostructures may beat the super-paramagnetic limit
- ➔ Ir and Pt chains and clusters have MAEs ~ 100 – 200 meV
- ➔ Ultimate bit --> Simple organic molecule with a 5d TM dimer unit
- ➔ Dimetallocenes are generically non-magnetic
- ➔ Significant Anisotropic magnetorresistances (not shown)

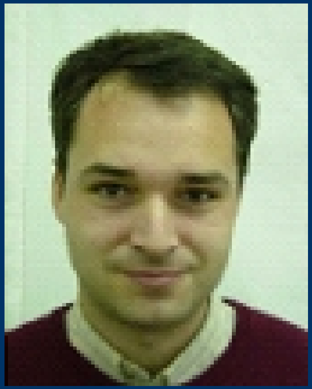
What's next ?

- ➔ Porphyrines
- ➔ ....

Thanks to

Lucas Fernandez-Seivane

Víctor García-Suárez



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