

# Magnetismo



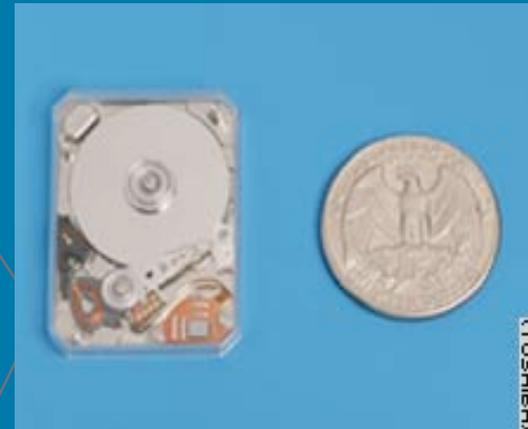
# Magnetismo no dia a dia...



Produção de Energia



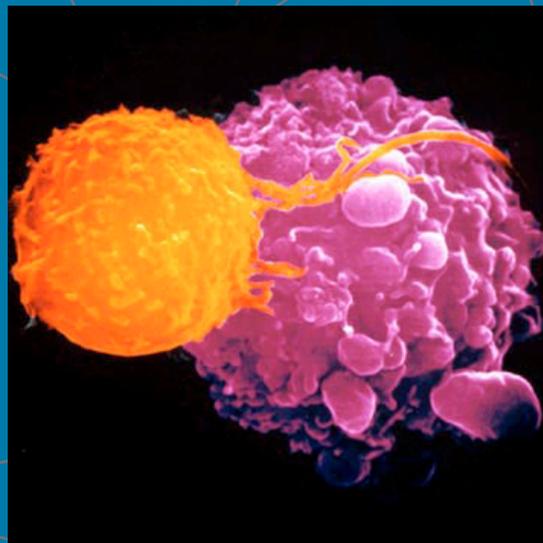
Transporte MAGLEV



Discos Rígidos



Ressonância Magnética



Medicina do Câncer



Meio Ambiente

e...

# ... fazer um sapo voar !!!



- **The flying dutch frog** levita em um campo magnético de 16 T no laboratório de altos campos magnéticos em Nijmegen.

# MAGNETISMO = Reconhecimento



Curies



Gauß



Faraday



Tesla

# Um pouco de história...

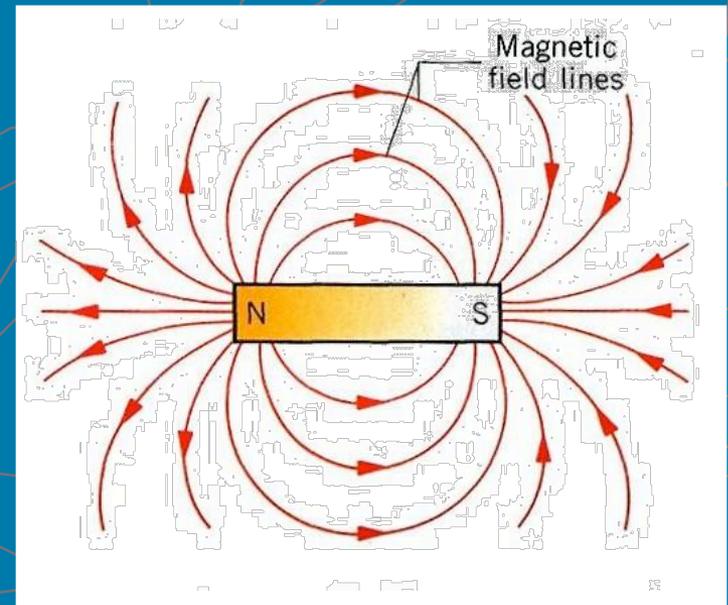
- **MAGNETISMO** é uma palavra originária da antiga cidade grega de Magnesia, onde o material magnético,  $\text{Fe}_3\text{O}_4$ , a magnetita, era abundante.
- **Plínio, o antigo**, (23-79 AD Romano) já escrevia sobre uma montanha próxima ao rio Indus que era composta inteiramente de uma rocha que atraía ferro.
- **Bússola chinesa** (121 AD) - uma barra de ferro próxima a um destes magnetos naturais poderia adquirir e **reter a propriedade magnética...** e tal barra, quando suspensa por um fio, se alinharia na direção norte-sul.

# O Conceito de "Campos"



Michael Faraday percebeu que ...

Um magneto produz um  
'campo magnético'  
distribuído por todo  
o espaço ao redor

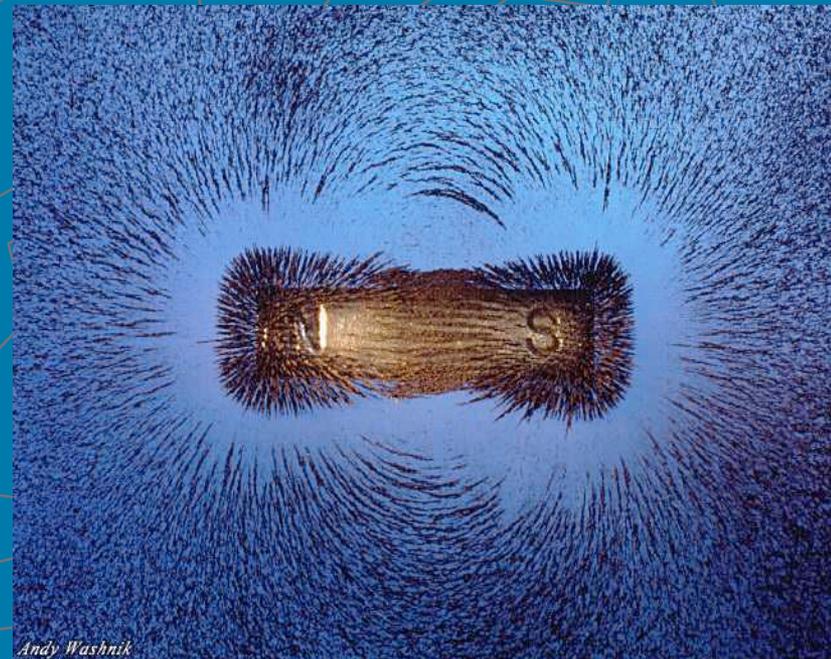


# O Conceito de "Campos"

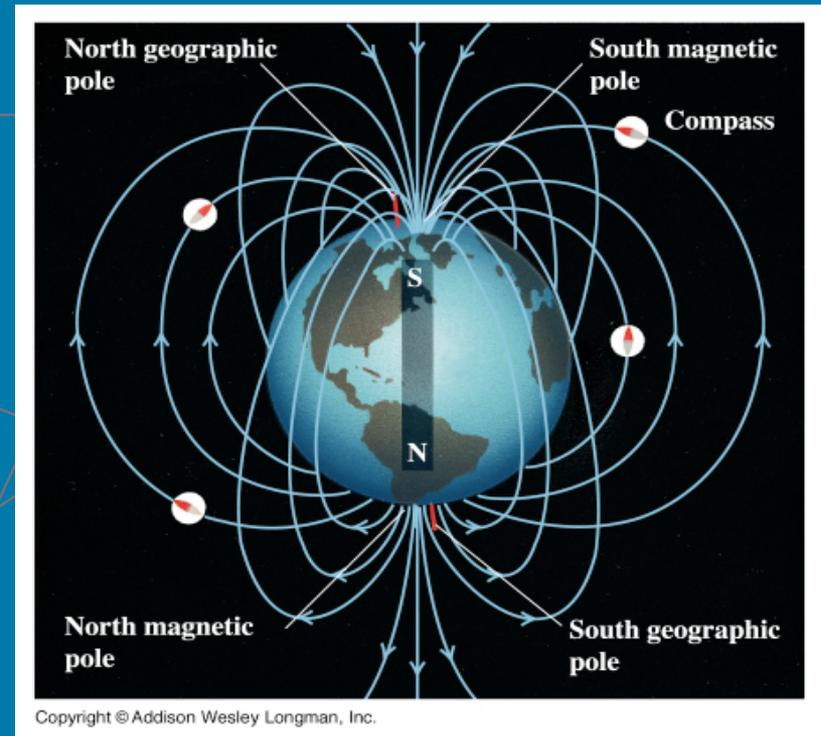


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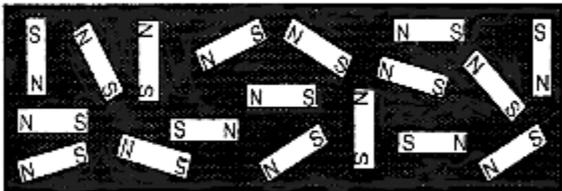
# A Bússola Moderna



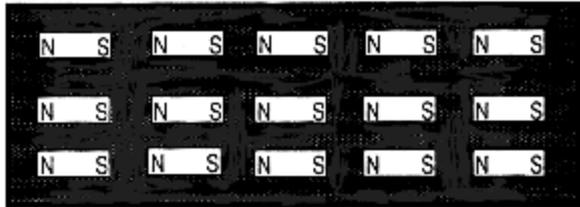
- O pólo norte da bússola aponta na direção do pólo sul do campo magnético da terra.

# De volta à bússola chinesa ...

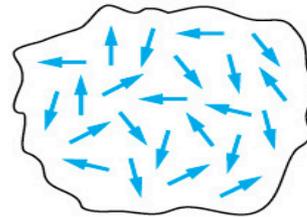
MAGNETIC MATERIAL



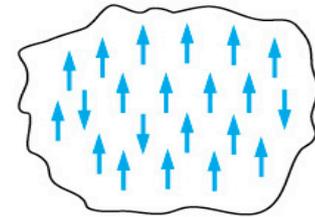
MAGNET



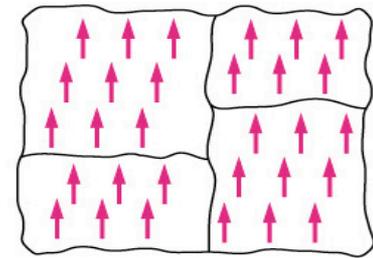
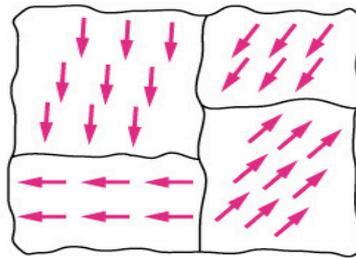
Magnetic field absent



In presence of magnetic field



Paramagnetism



Ferromagnetism

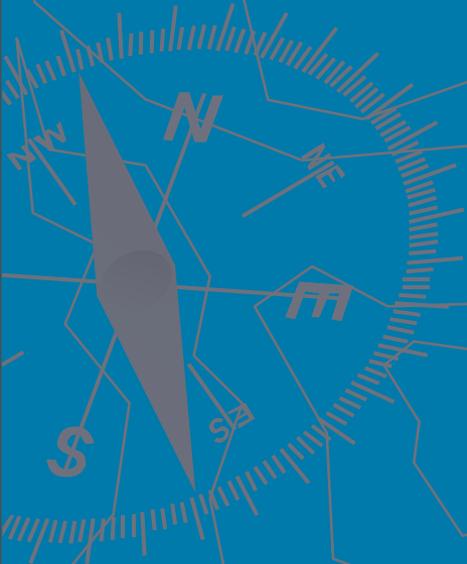
Campo Magnético Aplicado

A barra de ferro usada pelos chineses é um ótimo **FERROMAGNETO!**

# Compreendendo o Magnetismo

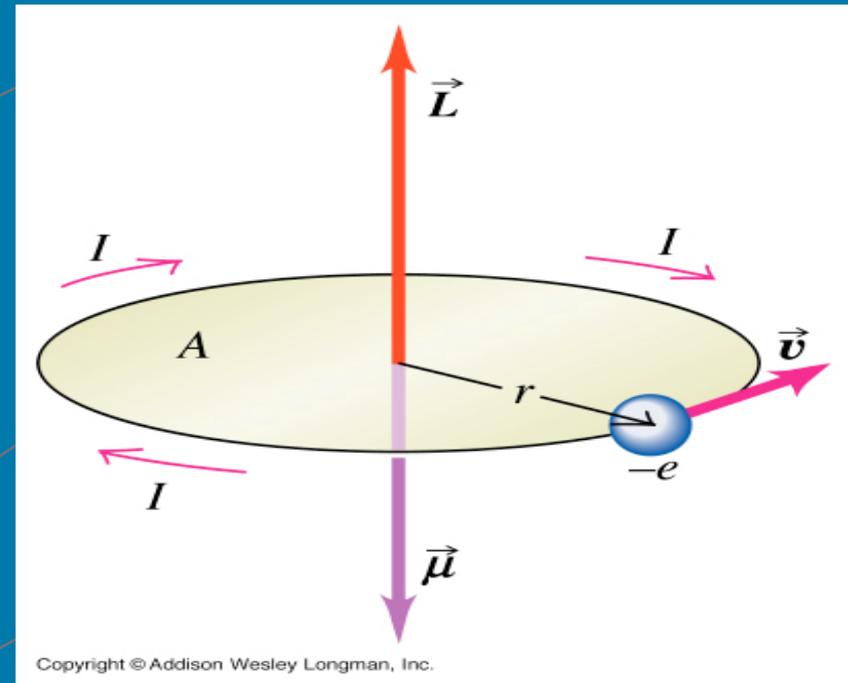
- O que são estas **flechas magnéticas** ?
- Como elas **interagem** entre si ?
- **Exemplos** de sistemas magnéticos !
- Conclusões

O que são estas flechas magnéticas?



# O que são estas flechas magnéticas?

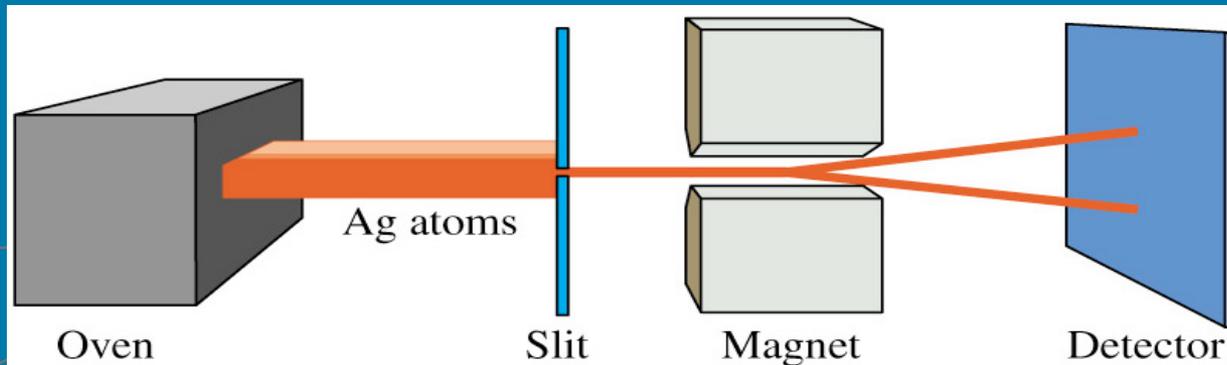
- **Oersted** (1819) – agulha próxima a um fio é defletida.
- **Faraday** (1831) – magneto em movimento produz corrente elétrica.



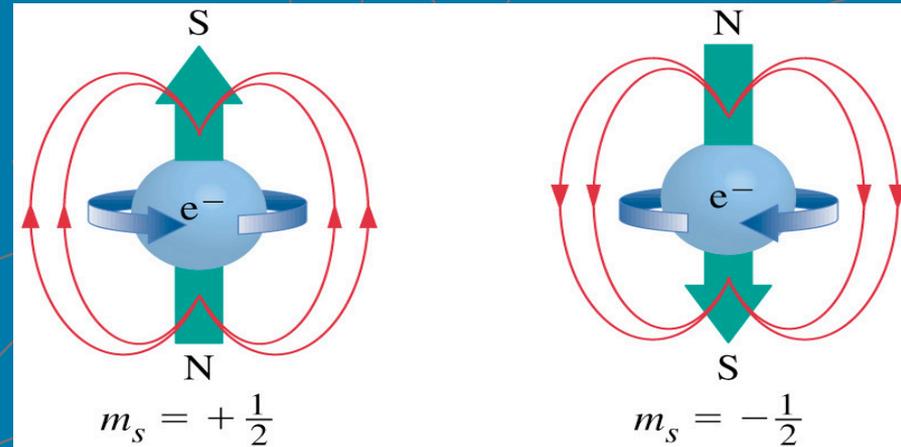
TODO fenômeno magnético resulta de forças entre cargas elétricas em movimento !!!

L – o momento angular ORBITAL

# A experiência de Stern e Gerlach

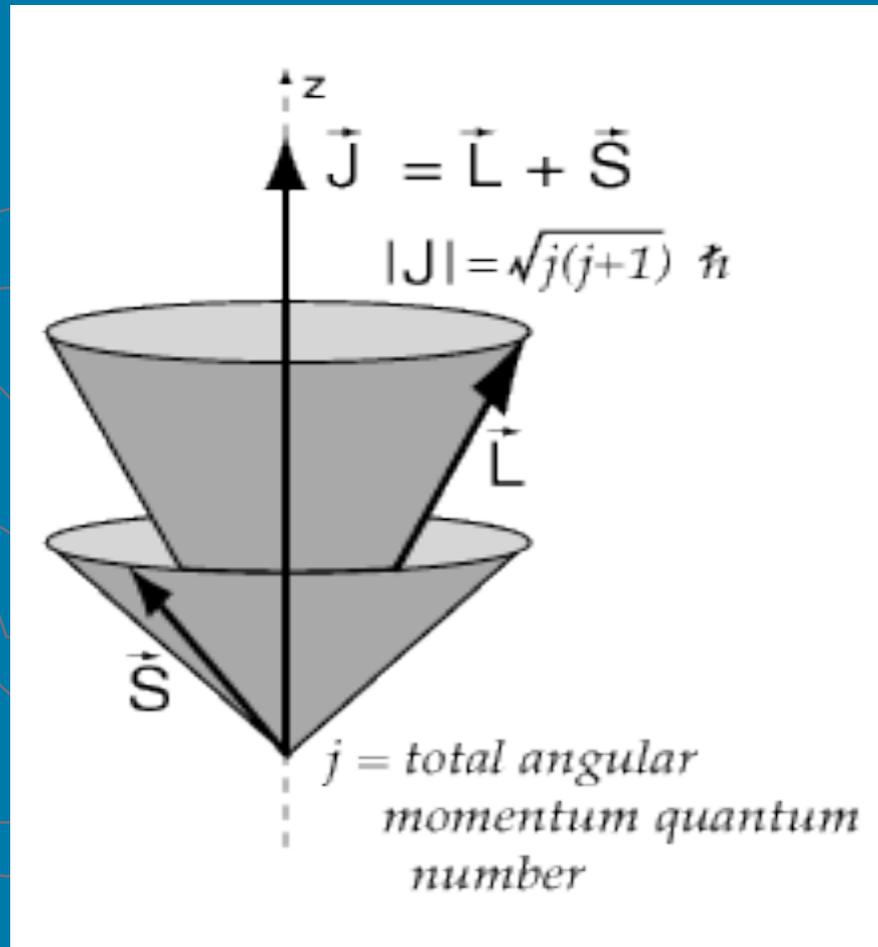


- Mesmo sem movimento orbital os átomos podem ter um momento magnético: o **SPIN**.
- O spin é uma propriedade intrínseca das partículas, como sua massa e carga.



**S – o momento angular de SPIN**

# 0 momento angular total $J=L+S$



$$\mu_{\text{eff}} = g \sqrt{J(J+1)} \mu_B$$

$$\mu_B = \frac{e\hbar}{2mc}$$

# Valores Experimentais

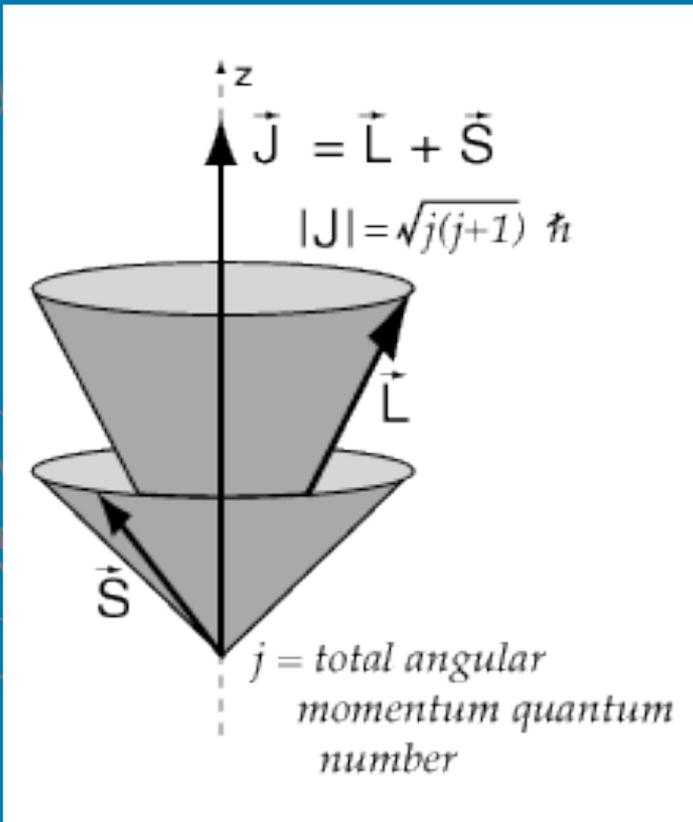
<b>Ion</b>	<b><math>d^n</math></b>	<b>S</b>	<b><math>\mu_s</math> (BM)</b>	<b><math>\mu_{\text{eff}}</math> (obs. BM)</b>
Sc <sup>3+</sup> , Ti <sup>4+</sup>	0	0	0	0
Ti <sup>3+</sup>	1	1/2	1.73	1.7-1.8
V <sup>3+</sup>	2	1	2.83	2.8-3.1
V <sup>2+</sup> , Cr <sup>3+</sup>	3	3/2	3.87	3.7-3.9
Cr <sup>2+</sup> , Mn <sup>3+</sup>	4	2	4.90	4.8-4.9
Mn <sup>2+</sup> , Fe <sup>3+</sup>	5	5/2	5.92	5.7-6.0
Fe <sup>2+</sup> , Co <sup>3+</sup>	6	2	4.90	<b>5.0-5.6</b>
Co <sup>2+</sup>	7	3/2	3.87	<b>4.3-5.2</b>
Ni <sup>2+</sup>	8	1	2.83	<b>2.9-3.9</b>
Cu <sup>2+</sup>	9	1/2	1.73	1.9-2.1
Zn <sup>2+</sup>	10	0	0	0

# Valores Experimentais

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Contribuição ORBITAL irrelevante !!!

# Quenching da componente orbital L



$$\langle \vec{L} \rangle = 0$$

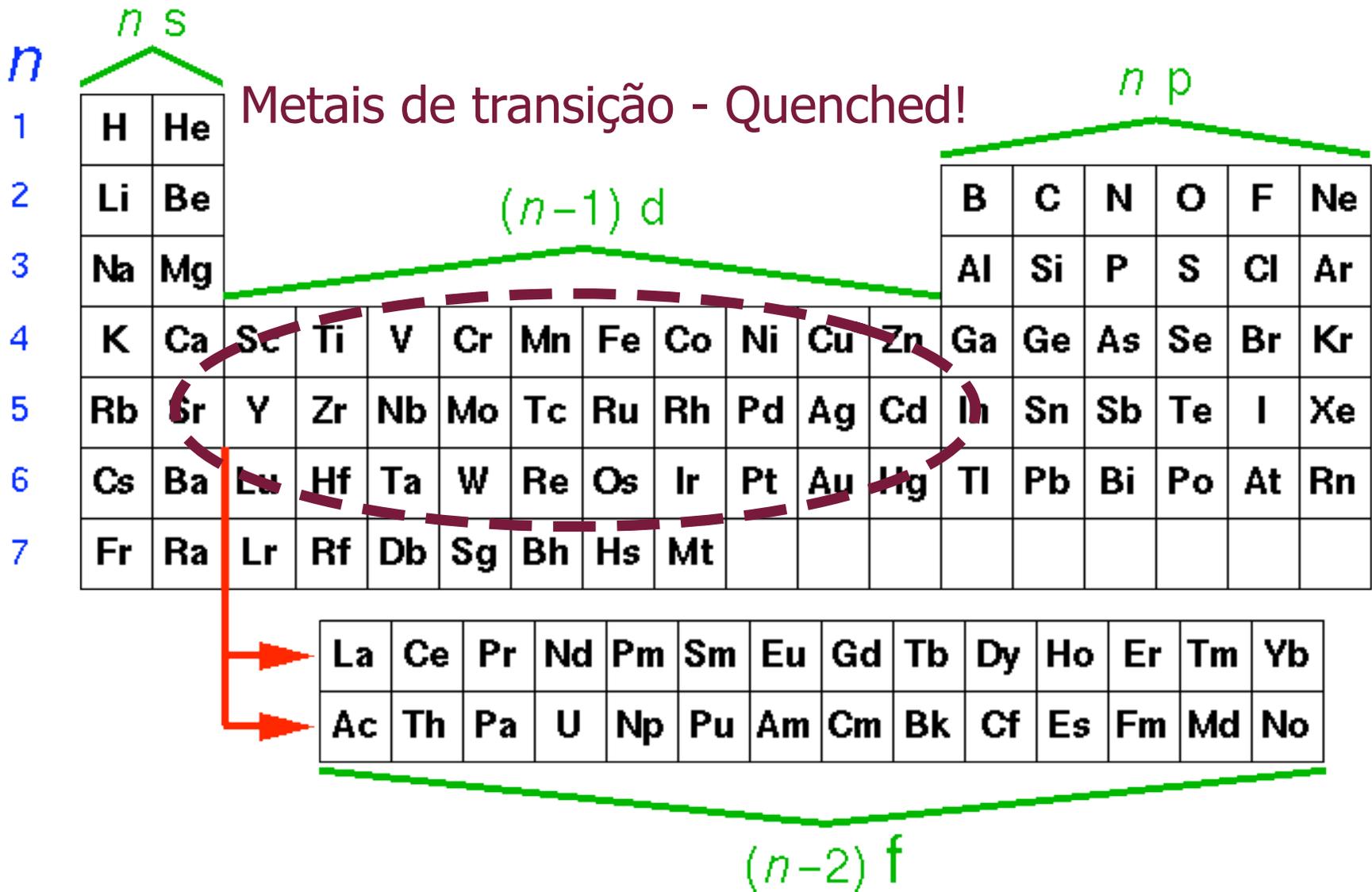
A componente orbital é **quenched**.  
Somente o spin é relevante.

$$\langle \vec{L} \rangle \neq 0$$

A componente orbital **Não é quenched**.  
O spin TOTAL J é o objeto relevante.



# To quench or not to quench...



# To quench or not to quench...

$n$   $n s$

Metals de transição - Quenched!

$(n-1) d$

$n p$

1	H	He																
2	Li	Be											B	C	N	O	F	Ne
3	Na	Mg											Al	Si	P	S	Cl	Ar
4	K	Ca	Sc	Ti	V	Cr	Mn	Fe	Co	Ni	Cu	Zn	Ga	Ge	As	Se	Br	Kr
5	Rb	Sr	Y	Zr	Nb	Mo	Tc	Ru	Rh	Pd	Ag	Cd	In	Sn	Sb	Te	I	Xe
6	Cs	Ba	La	Hf	Ta	W	Re	Os	Ir	Pt	Au	Hg	Tl	Pb	Bi	Po	At	Rn
7	Fr	Ra	Lr	Rf	Db	Sg	Bh	Hs	Mt									

La	Ce	Pr	Nd	Pm	Sm	Eu	Gd	Tb	Dy	Ho	Er	Tm	Yb
Ac	Th	Pa	U	Np	Pu	Am	Cm	Bk	Cf	Es	Fm	Md	No

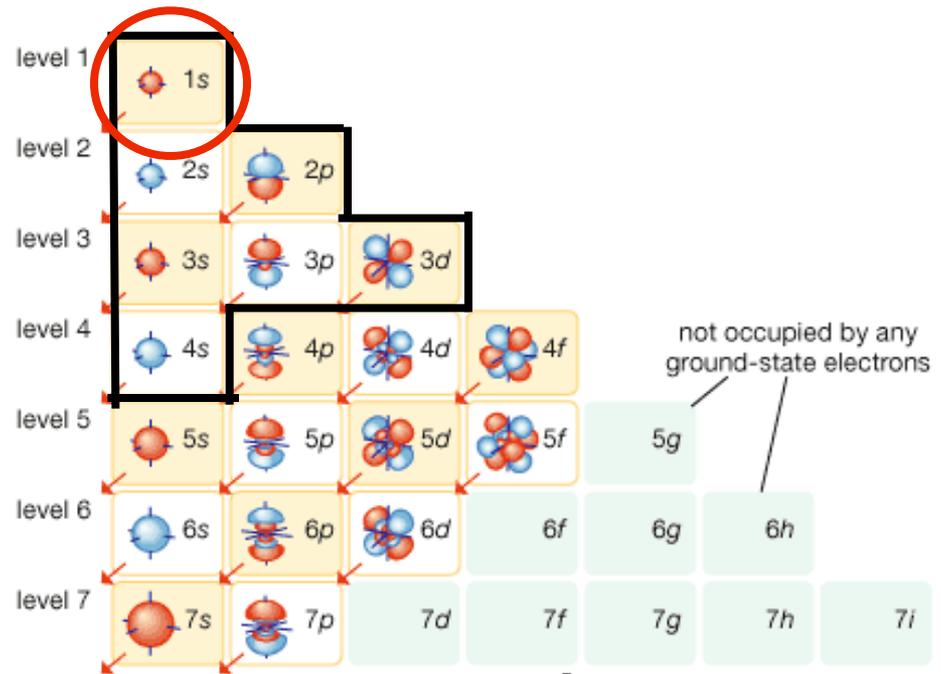
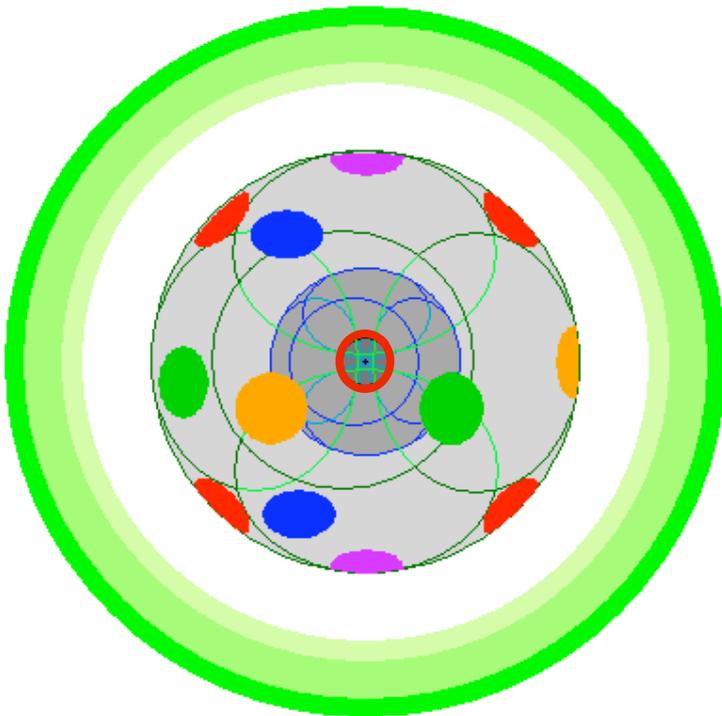
$(n-2) f$

Terras raras – NÃO quenched!



# Afinal de contas: o que é quenching?

**Metal**

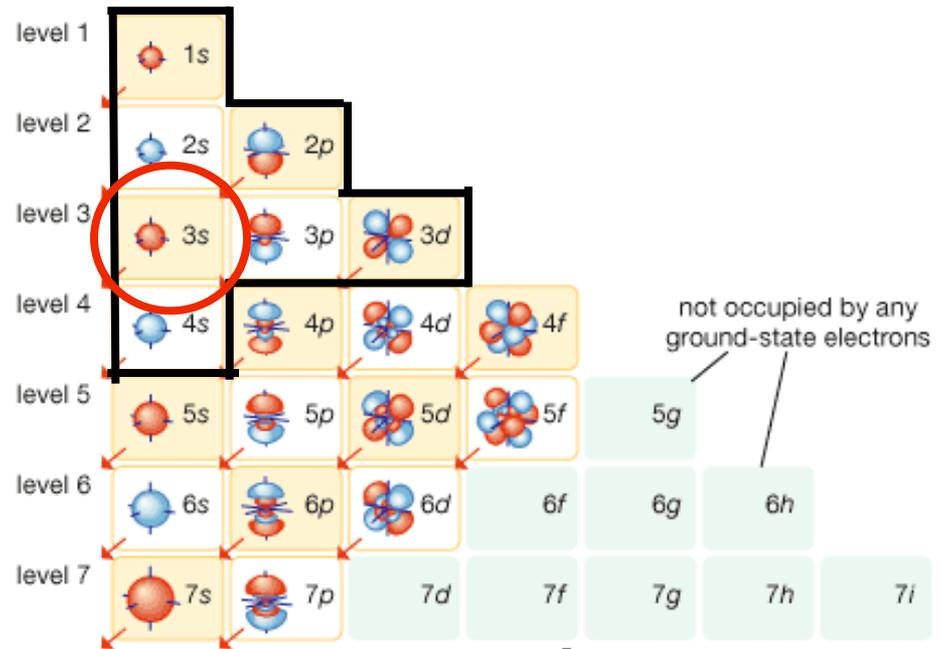
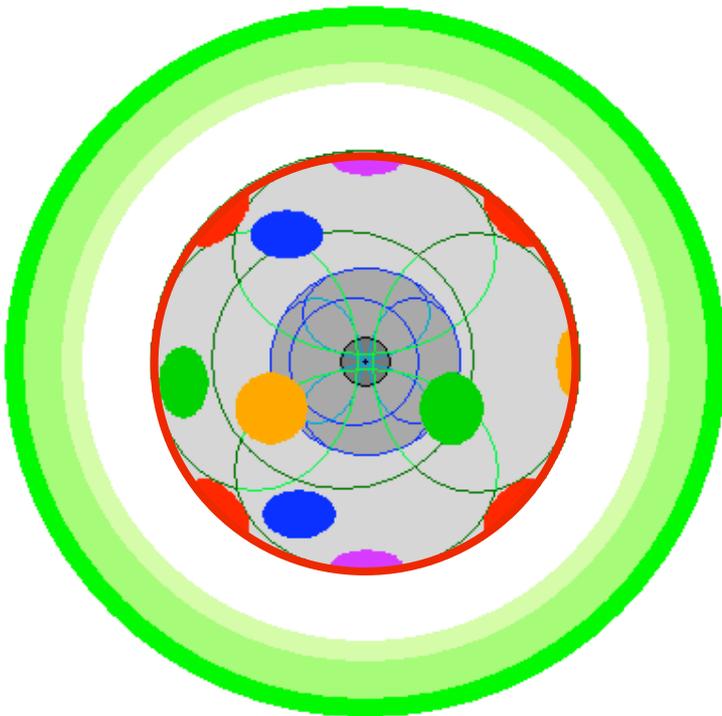


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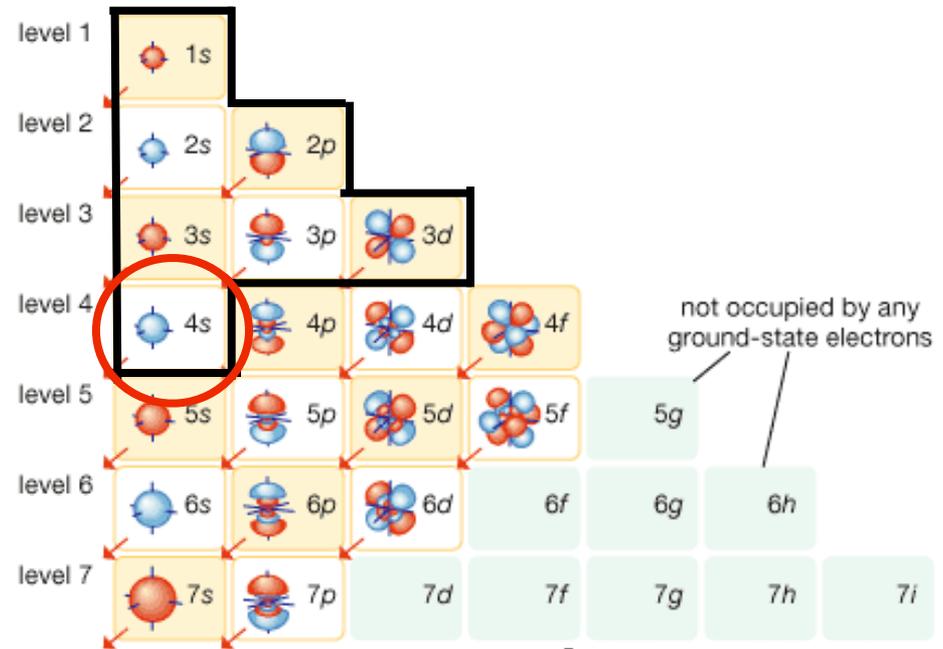
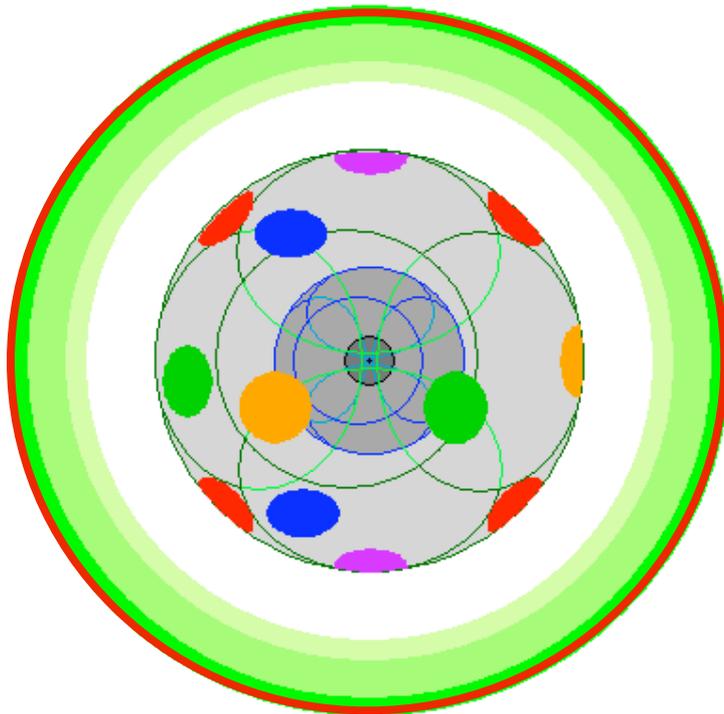
**Metal**



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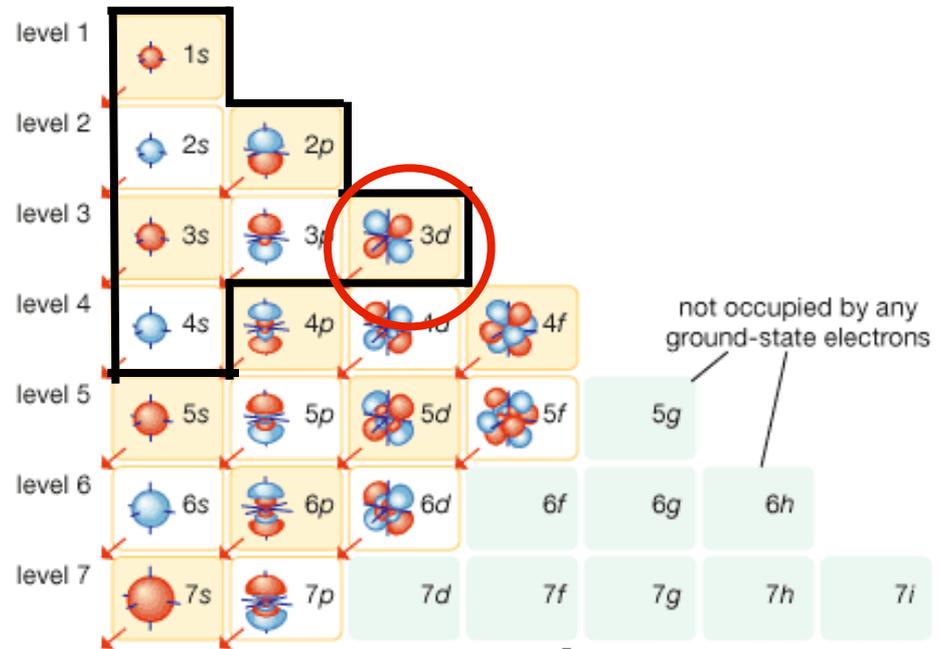
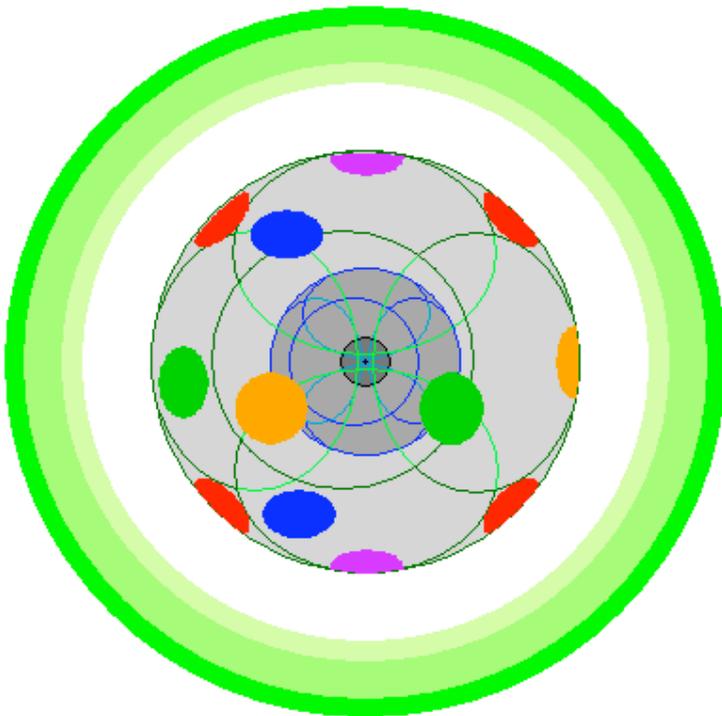




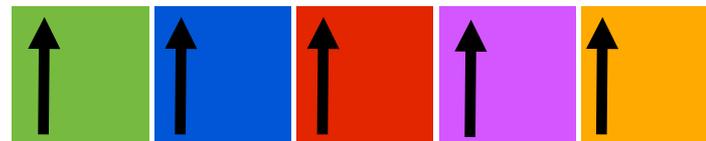
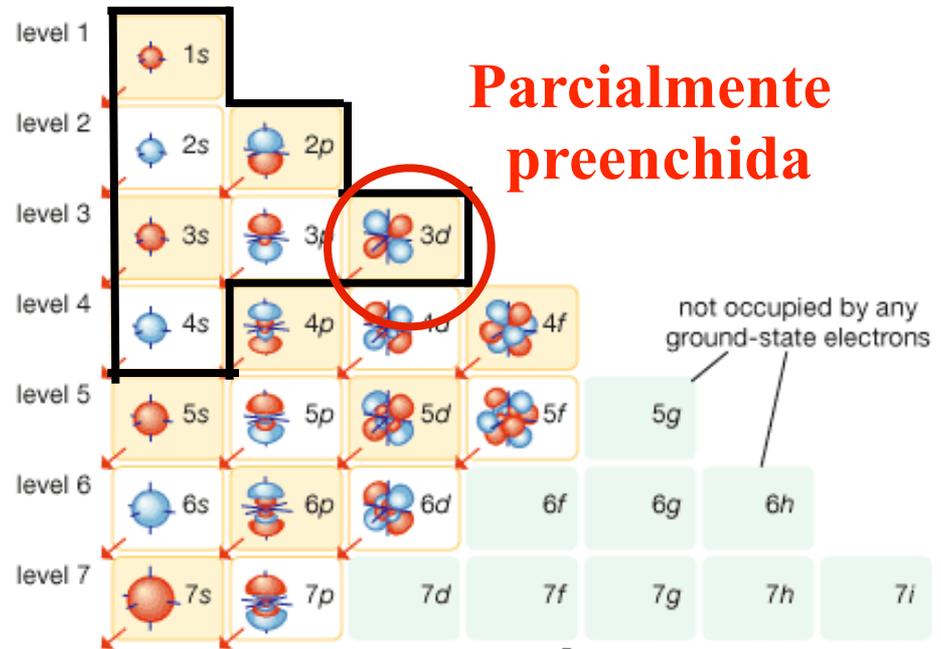
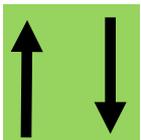
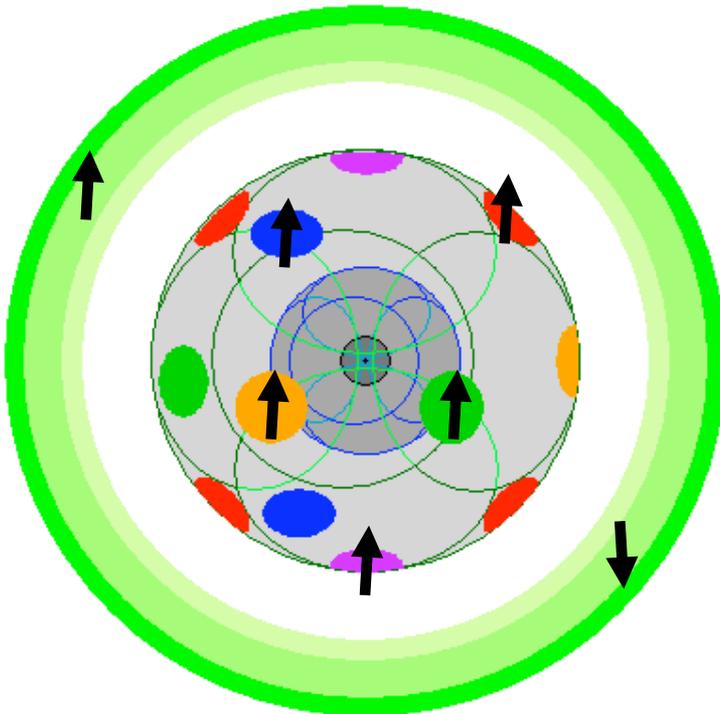
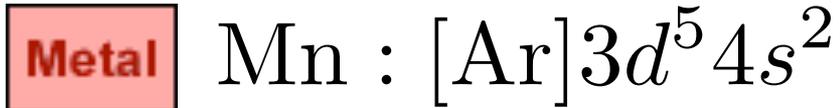


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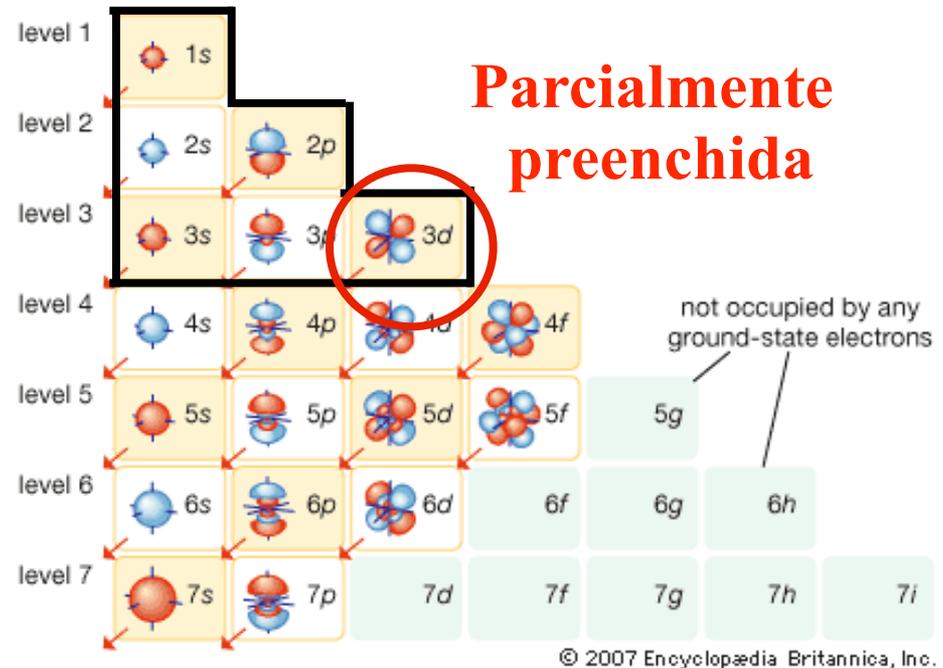
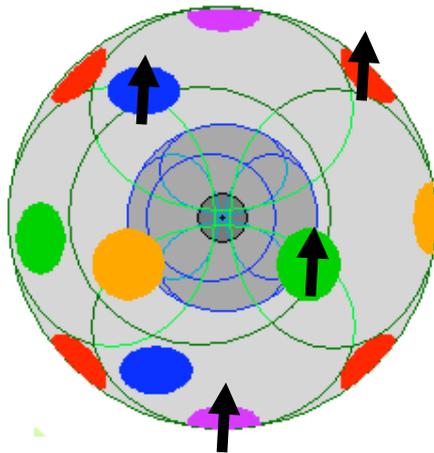
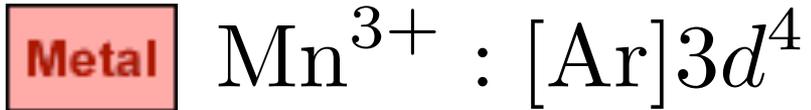
**Metal**



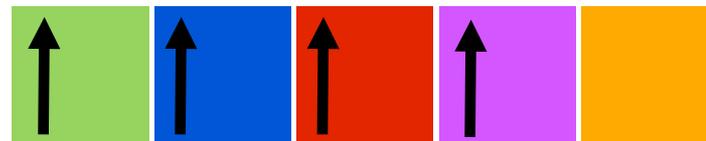
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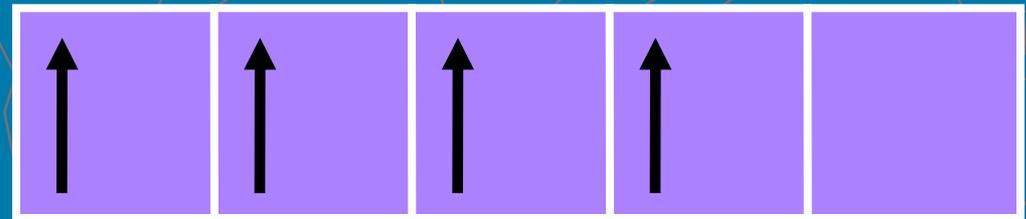
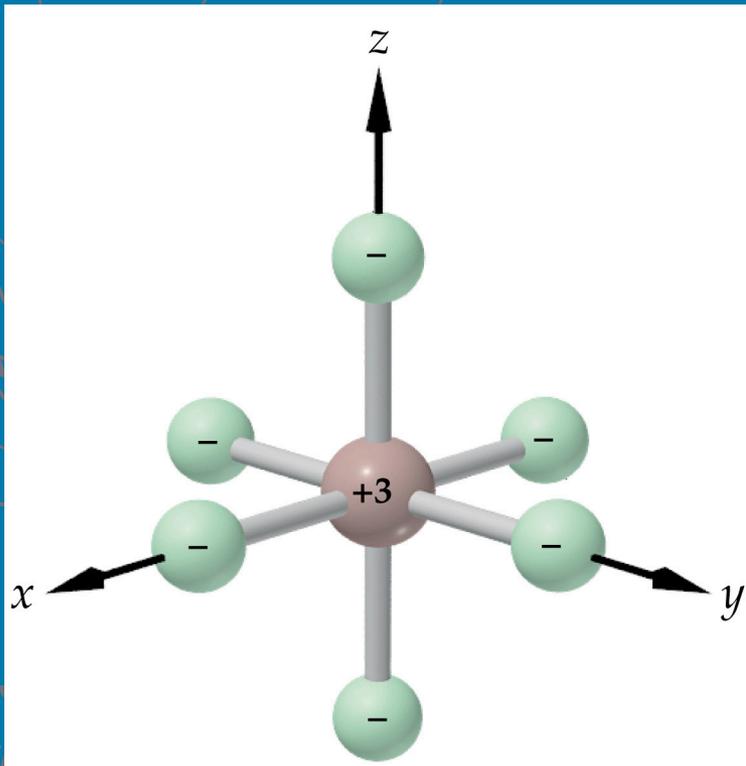
**Camada 3d<sup>4</sup> - Exposta!!!**



# Quenching de L - metais de transição

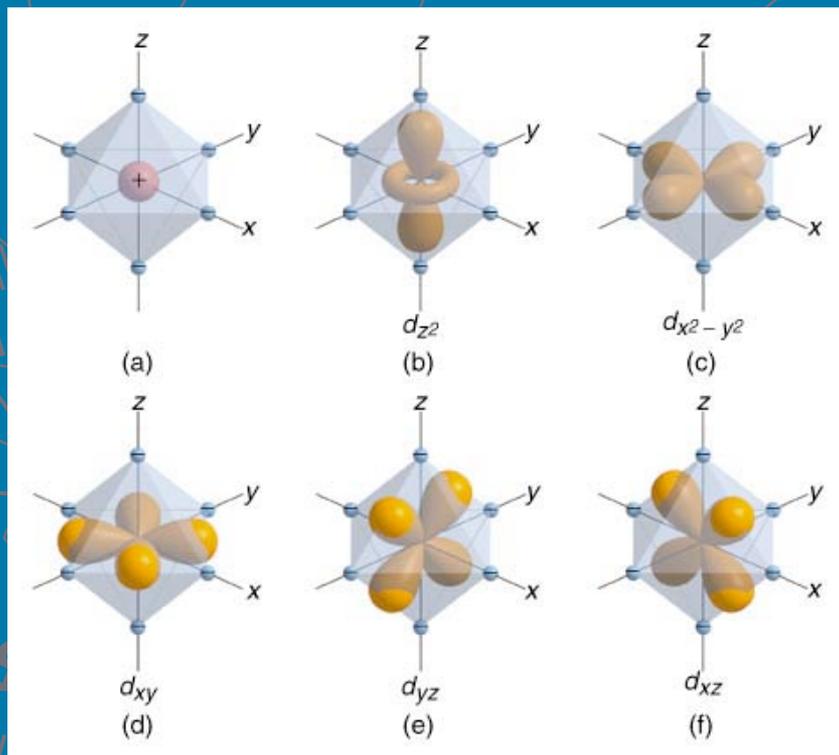


$$\leftarrow S = 2, L = 2$$

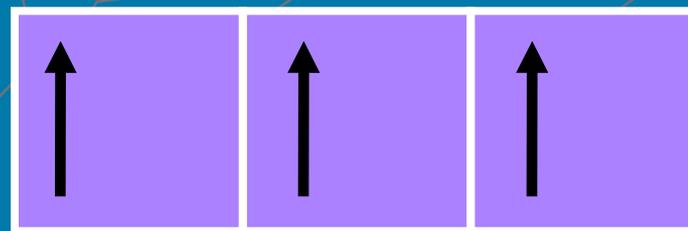
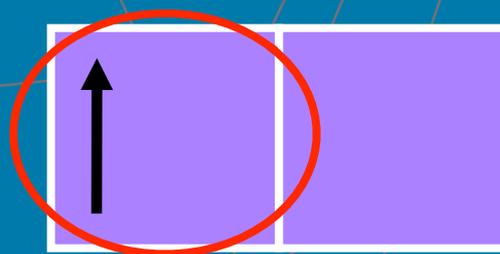


Os elétrons da camada-d sentem  
**FORTEMENTE** o campo cristalino

# Quenching de L - metais de transição

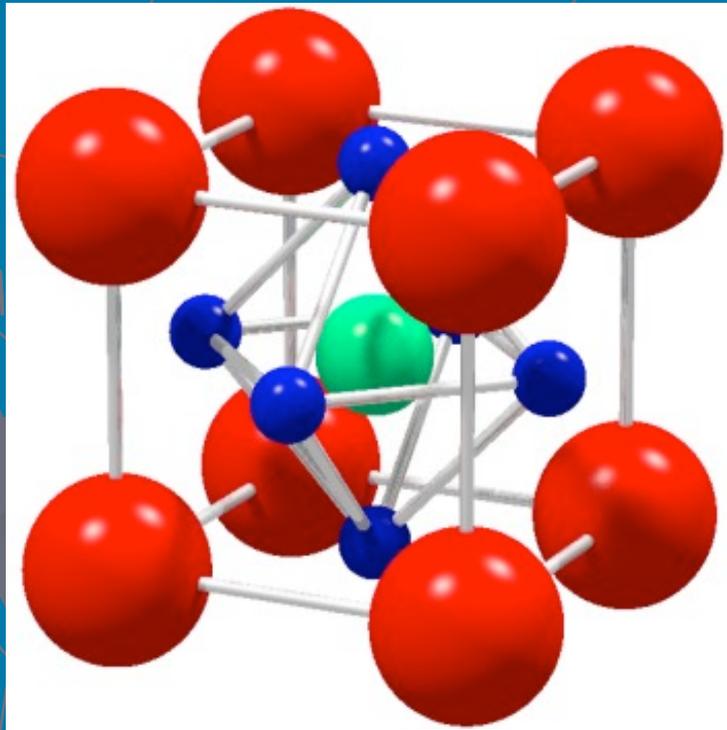


$$E \quad \langle \vec{L} \rangle \approx 0$$

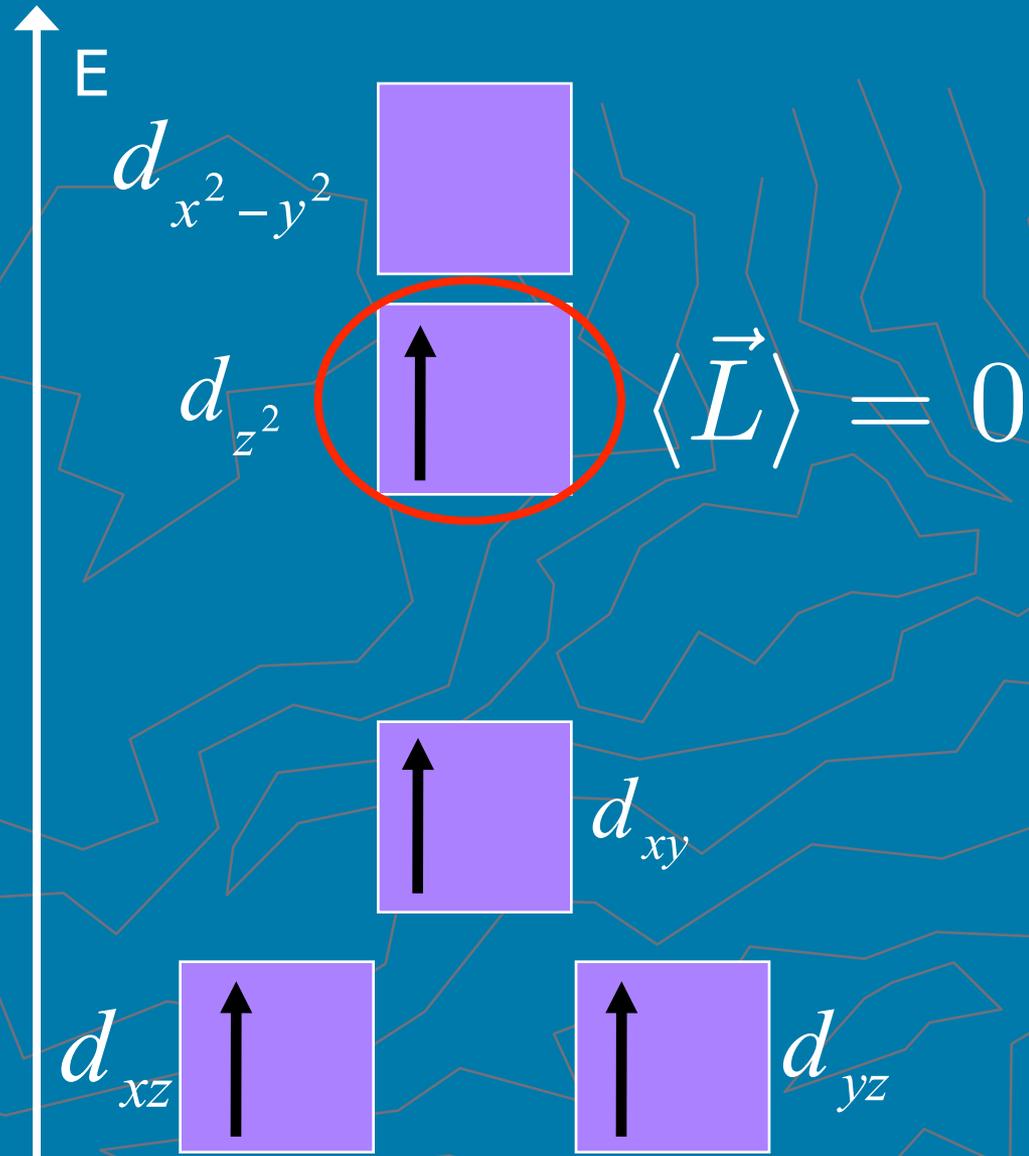


$t_{2g}$

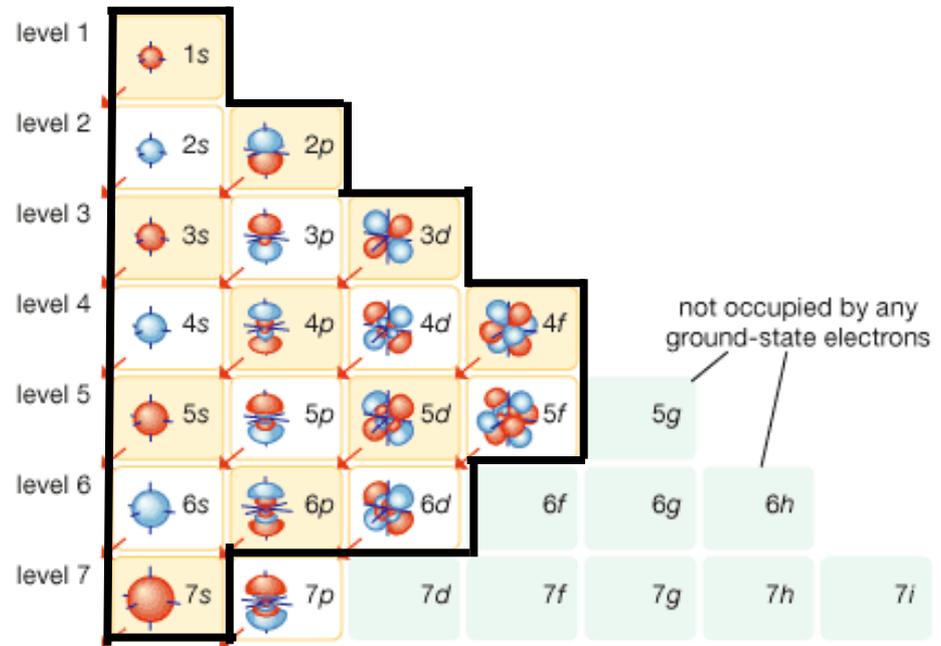
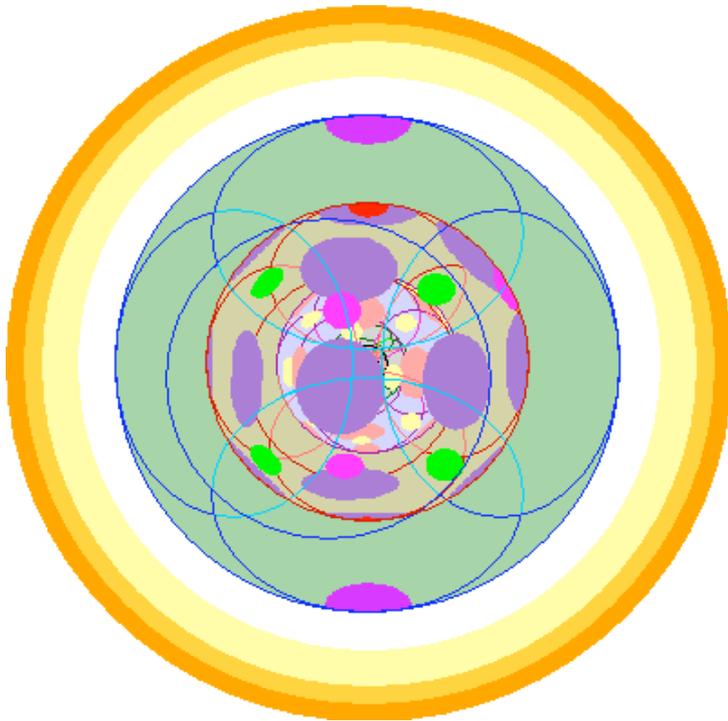
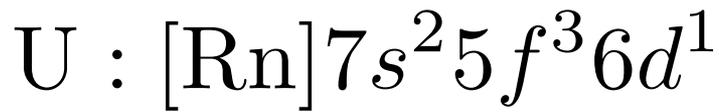
# Quenching de L - metais de transição



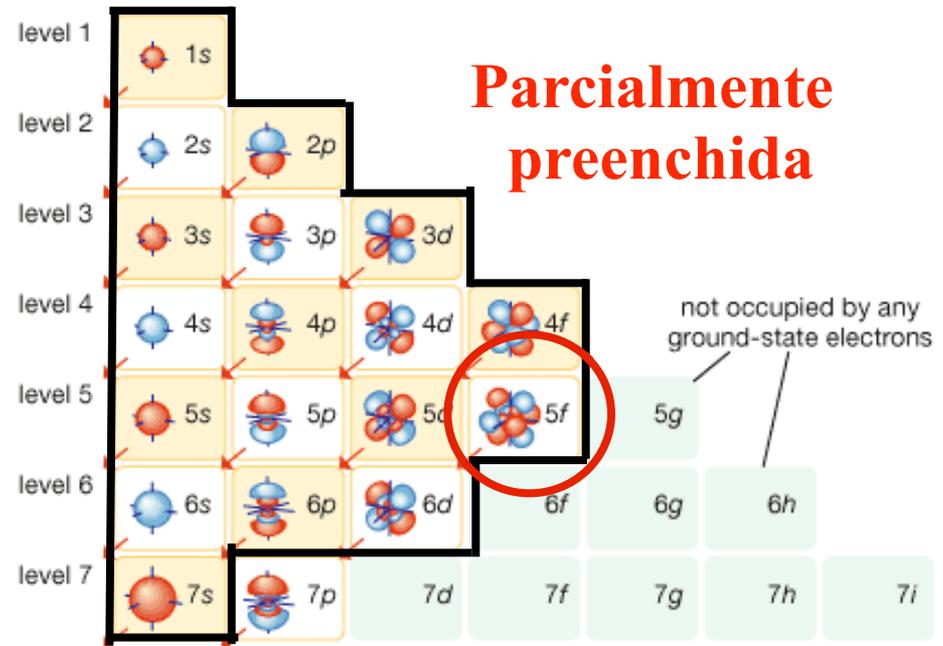
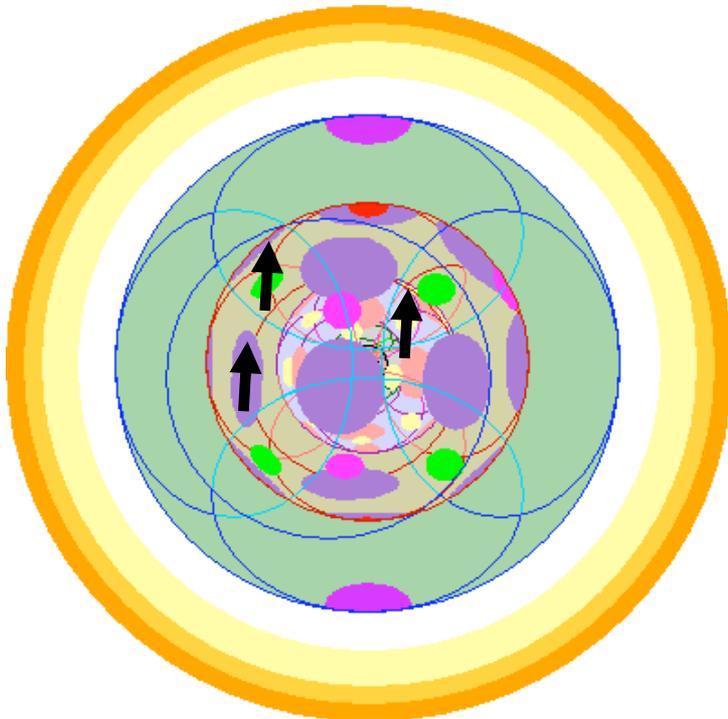
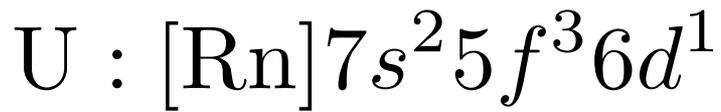
$LaMnO_3$



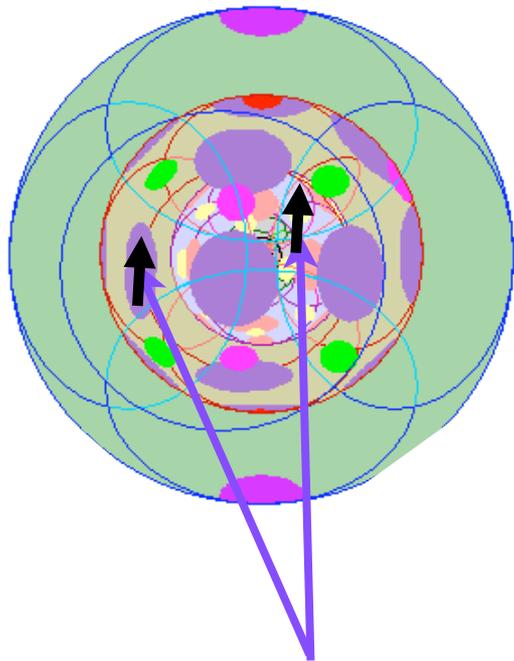
# Não quenching de L nos terras raras



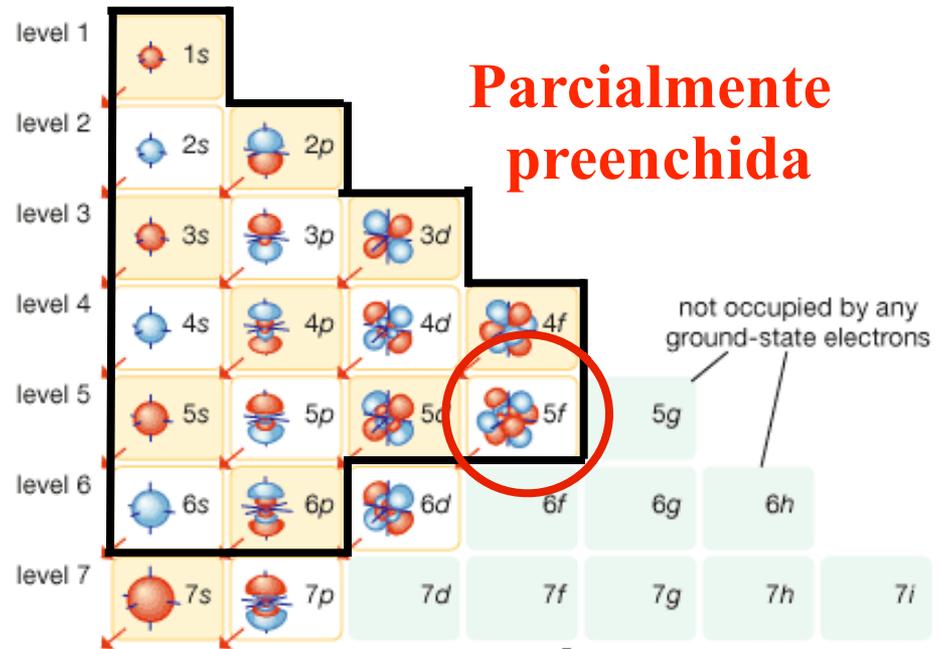
# Não quenching de L nos terras raras



# Não quenching de L nos terras raras

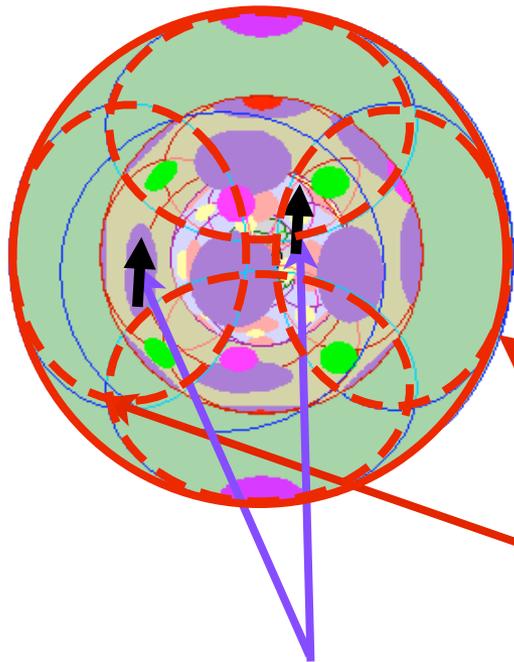


**Camada 5f incompleta**

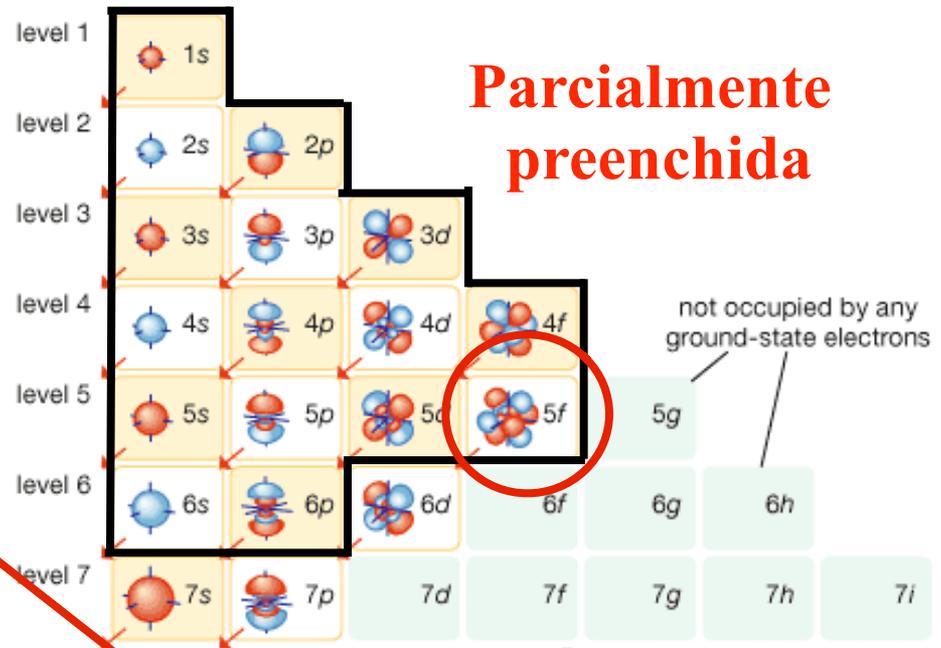


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# Não quenching de L nos terras raras



**Camada 5f incompleta**

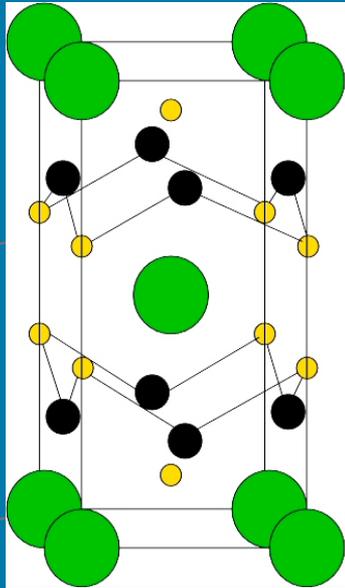


**Parcialmente preenchida**

**5p, 6s - Completas  
Blindagem!!!**

# Não quenching de L nos terras raras

U 

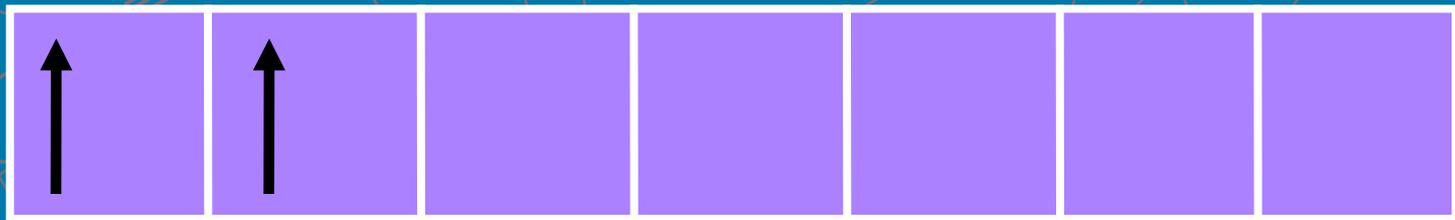


$$U^{4+} : [Rn]5f^2$$

$$S = 1, L = 5$$



$$J = |L - S| = 4$$



3

2

1

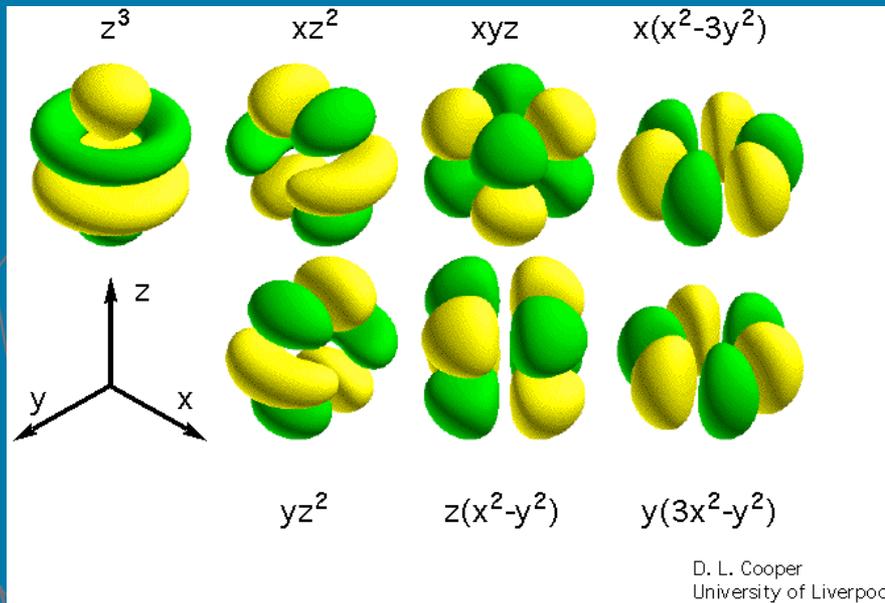
0

-1

-2

-3

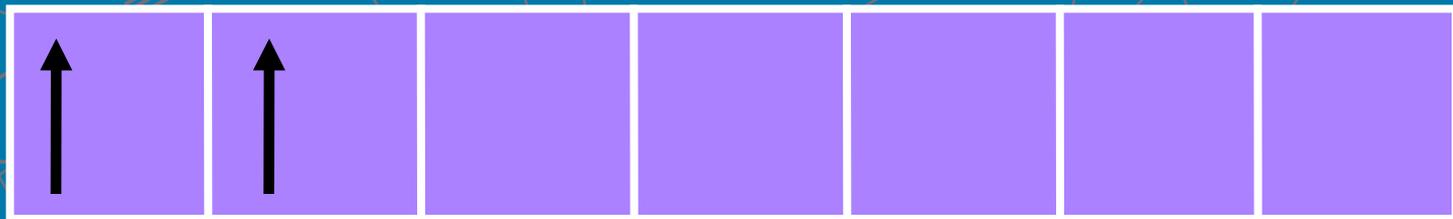
# Não quenching de L nos terras raras



$$S = 1, L = 5$$



$$J = |L - S| = 4$$



3

2

1

0

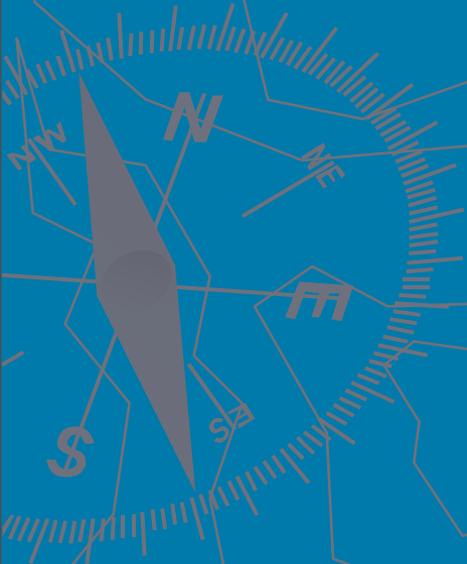
-1

-2

-3

Os elétrons da camada-f são **BLINDADOS** pelos elétrons 5p e 6s e **NÃO SENTEM** o campo cristalino

Como as flechas magnéticas  
interagem entre si ?



# Como se dá a interação magnética ?

- Configurações magnéticas diferentes podem surgir à partir de diferentes tipos de interação.

$$H = \sum_{R, R'} J_{ab}(R, R') S_a(R) S_b(R')$$

$$[J_{ab}] = \begin{pmatrix} J & 0 & 0 \\ 0 & J & 0 \\ 0 & 0 & J \end{pmatrix}$$

**Modelo de Heisenberg**

$$[J_{ab}] = \begin{pmatrix} J & 0 & 0 \\ 0 & J & 0 \\ 0 & 0 & 0 \end{pmatrix}$$

**Modelo XY**

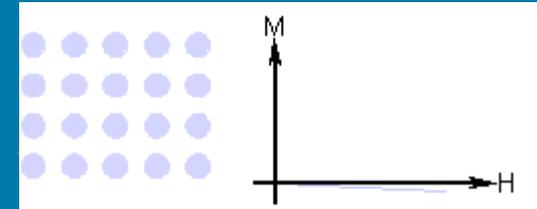
$$[J_{ab}] = \begin{pmatrix} 0 & 0 & 0 \\ 0 & 0 & 0 \\ 0 & 0 & J \end{pmatrix}$$

**Modelo de Ising**

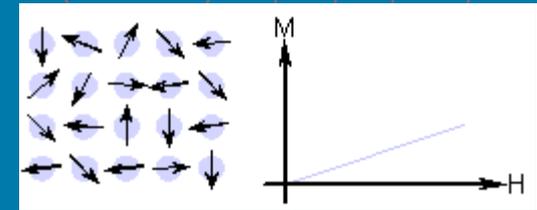
- Diamagnetismo, Paramagnetismo, Ferromagnetismo, Antiferromagnetismo e Ferrimagnetismo.

# Exemplos de estados magnéticos

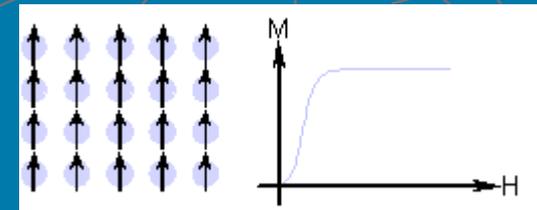
**Diamagnetismo:** os átomos não possuem momento magnético.



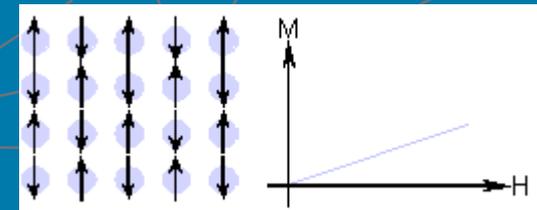
**Paramagnetismo:** os átomos possuem momentos magnéticos aleatórios.



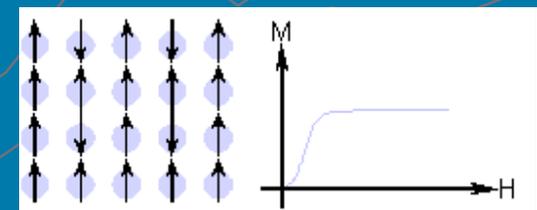
**Ferromagnetismo:** os átomos possuem momentos magnéticos paralelos.



**Anti-ferromagnetismo:** os átomos possuem momentos magnéticos antiparalelos.



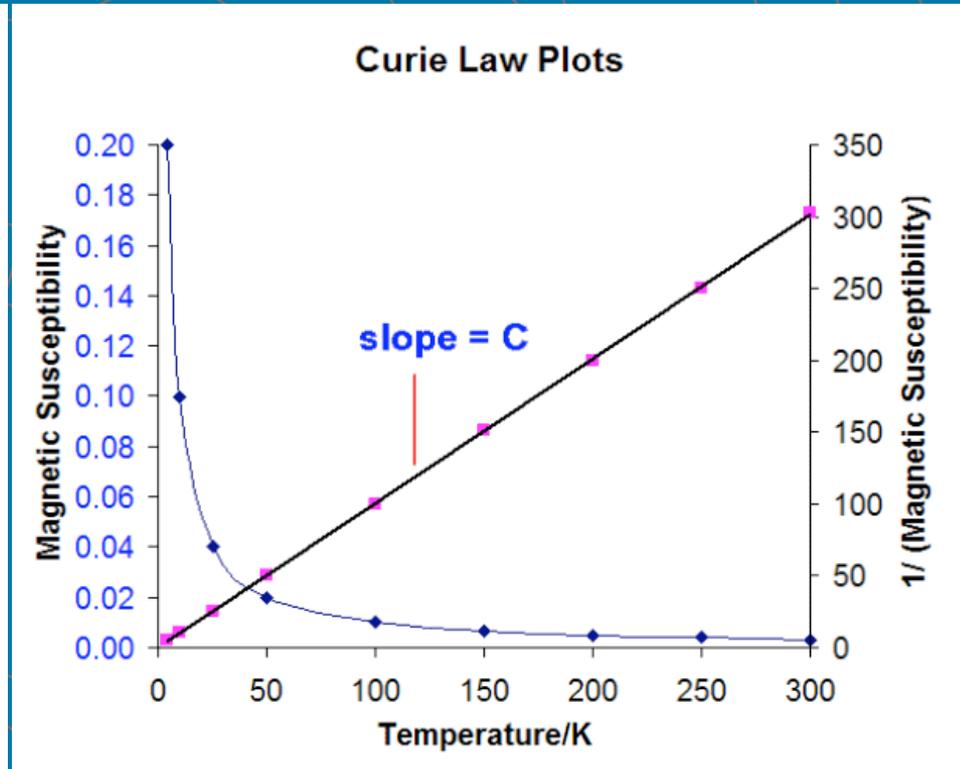
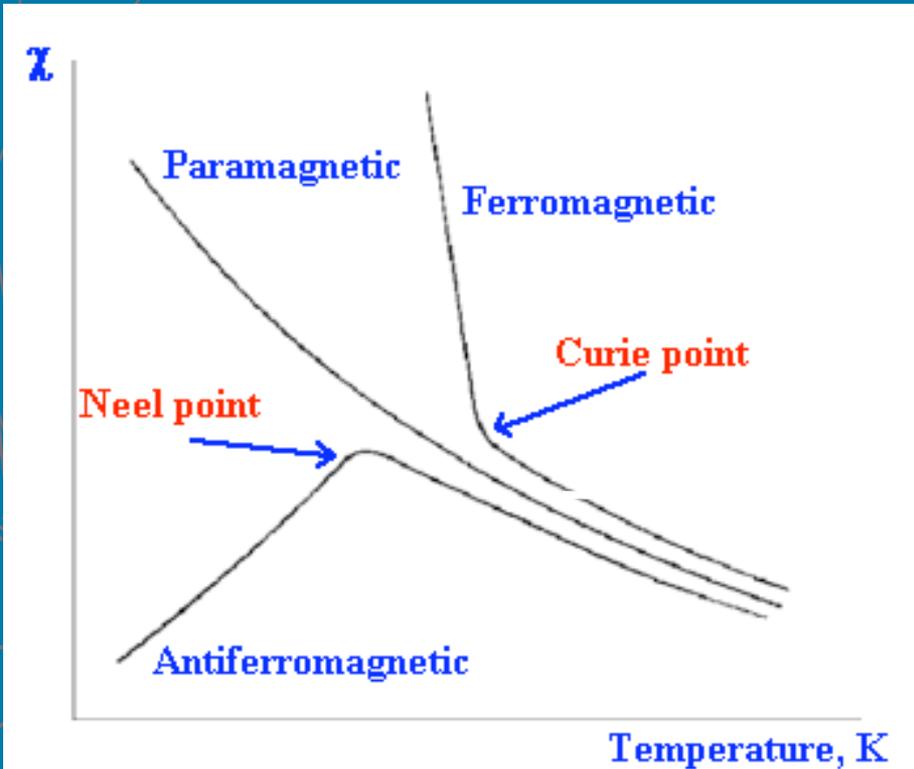
**Ferrimagnetismo:** os átomos possuem momentos magnéticos antiparalelos, mas com magnitudes diferentes.



# Algumas propriedades gerais...

## Suscetibilidade Magnética

## Lei de Curie-Weiss



$$\chi = \frac{M}{H}$$

$$\chi = \frac{C}{T - \Theta}$$

# Momento Magnético em Terras Raras



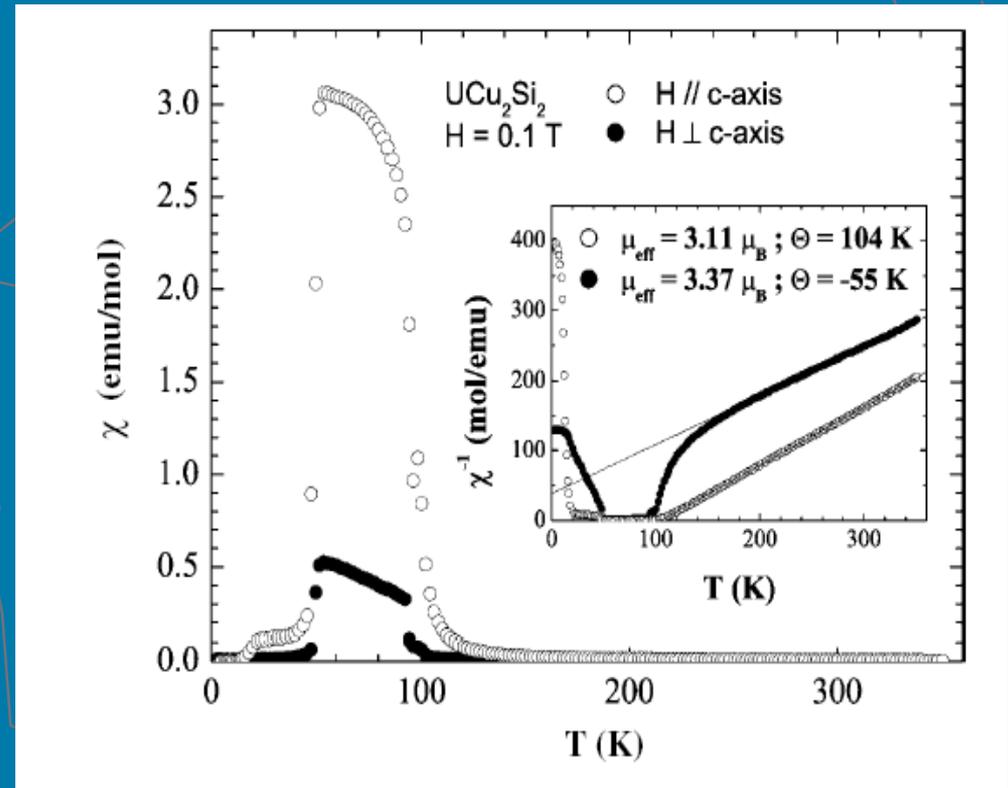
$$S = 1, L = 5$$

$$J = |L - S| = 4$$

$$\chi \propto \frac{C}{T - \Theta}$$

$$C \sim \mu_{eff}^2$$

$$\mu_{eff} = g \sqrt{J(J+1)} \mu_B \approx 3.5 \mu_B$$



# Momento Magnético em Terras Raras



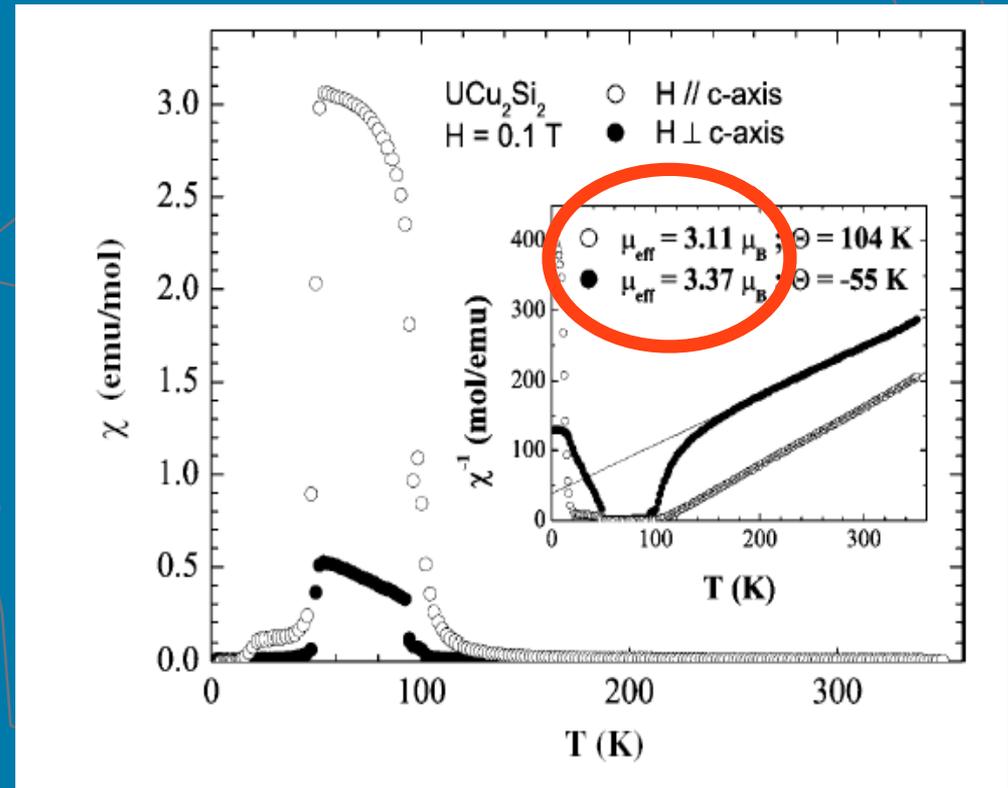
$$S = 1, L = 5$$

$$J = |L - S| = 4$$

$$\chi \propto \frac{C}{T - \Theta}$$

$$C \sim \mu_{eff}^2$$

$$\mu_{eff} = g \sqrt{J(J+1)} \mu_B \approx 3.5 \mu_B$$



# Sistemas da Matéria Condensada com Interações de Troca Distintos

- Miragem Quântica - ressonância Kondo
- Magnetoresistência - hard drives
- Ferromagnetismo fraco - cupratos
- Spin-Ice - monopolos magnéticos

# Sistemas da Matéria Condensada com Interações de Troca Distintos

- Miragem Quântica - ressonância Kondo  
Troca **INDIRETA - RKKY**
- Magnetoresistência - hard drives
- Ferromagnetismo fraco - cupratos
- Spin-Ice - monopolos magnéticos

# Sistemas da Matéria Condensada com Interações de Troca Distintos

- Miragem Quântica - ressonância Kondo  
Troca **INDIRETA - RKKY**
- Magnetoresistência - hard drives  
**DUPLA Troca**
- Ferromagnetismo fraco - cupratos
- Spin-Ice - monopolos magnéticos

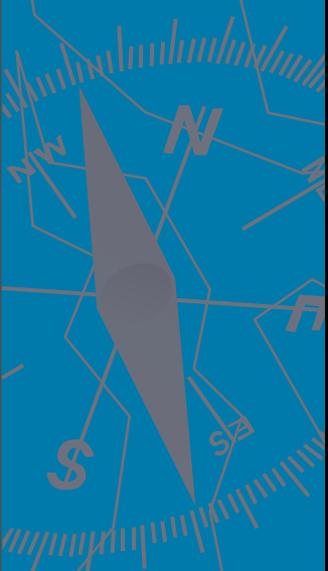
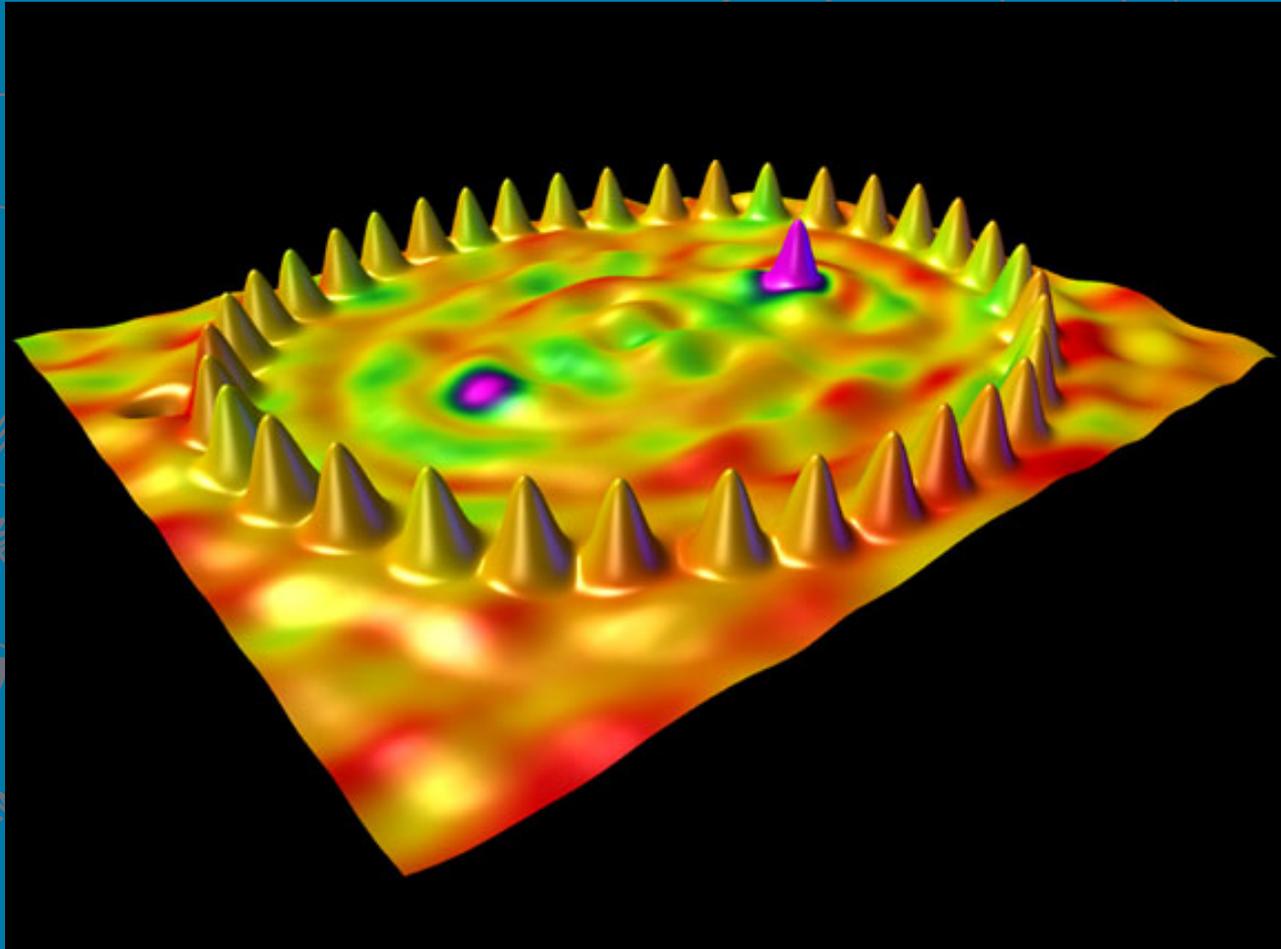
# Sistemas da Matéria Condensada com Interações de Troca Distintos

- Miragem Quântica - ressonância Kondo  
Troca **INDIRETA - RKKY**
- Magnetoresistência - hard drives  
**DUPLA Troca**
- Ferromagnetismo fraco - cupratos  
**SUPER Troca**
- Spin-Ice - monopolos magnéticos

# Sistemas da Matéria Condensada com Interações de Troca Distintos

- **Miragem Quântica** - ressonância Kondo  
Troca **INDIRETA - RKKY**
- **Magnetoresistência** - hard drives  
**DUPLA Troca**
- **Ferromagnetismo fraco** - cupratos  
**SUPER Troca**
- **Spin-Ice** - monopolos magnéticos  
**Troca DIPOLAR**

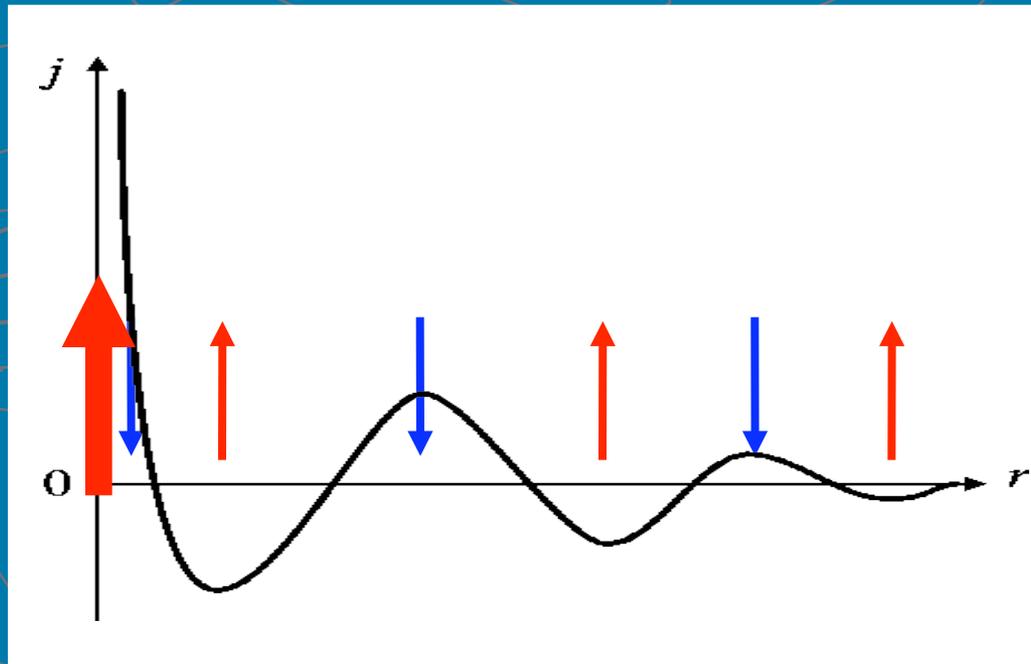
# Miragem Quântica



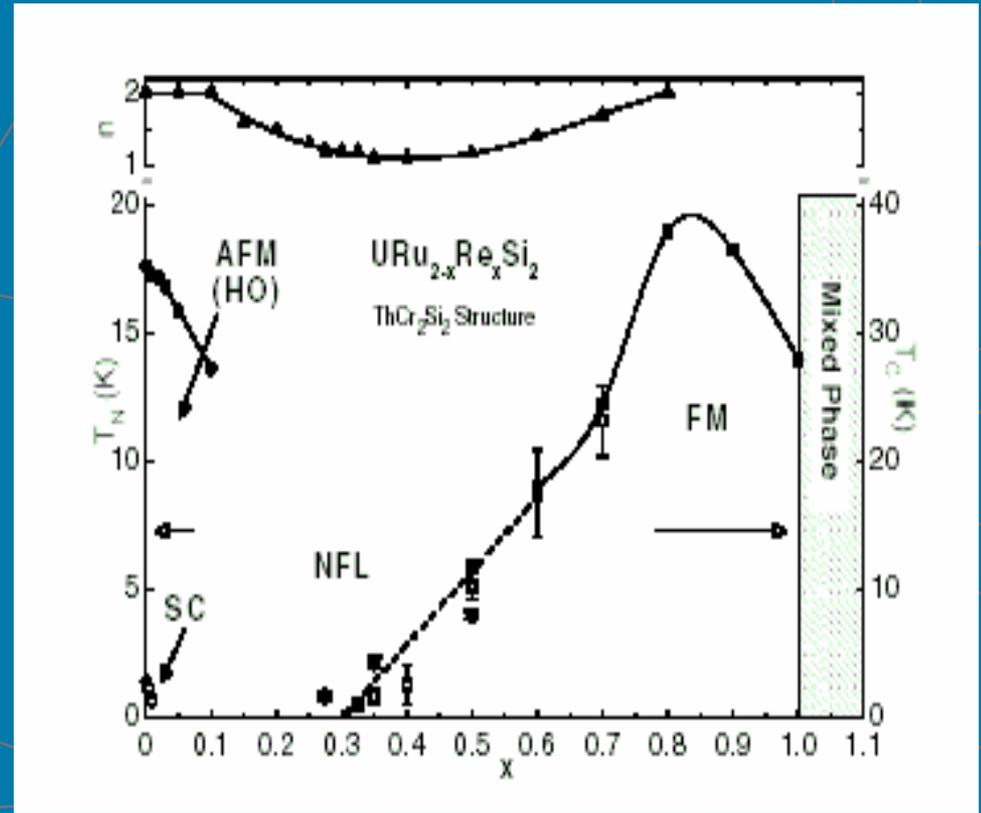
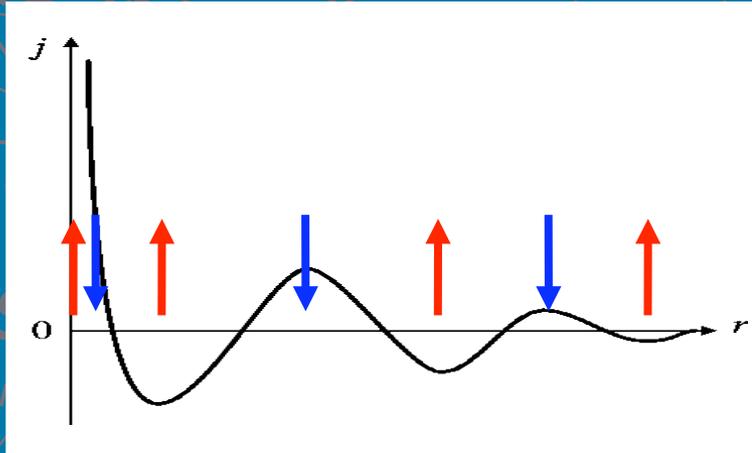
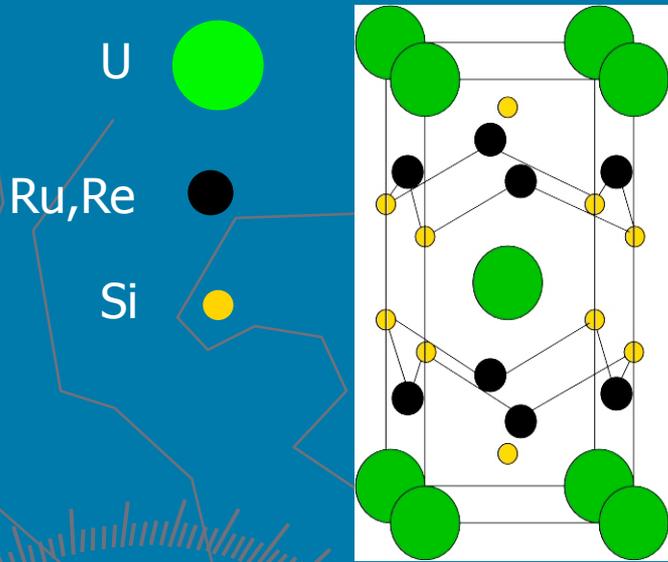
# Troca Indireta (RKKY) - oscilações de Fridel

$$H = \sum_{R, R'} J(R, R') S(R) \cdot S(R')$$

$$J(R, R') = \Gamma \frac{\sin(r) - r \cos(r)}{r^4}$$

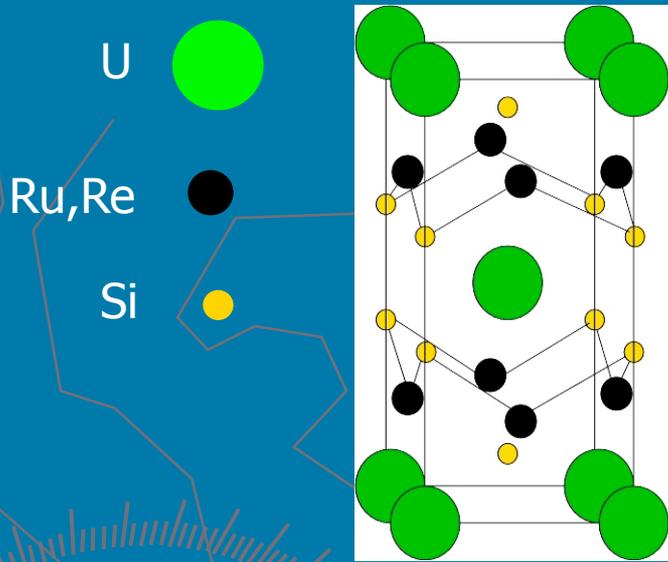


# Criticalidade Quântica - Férmions Pesados

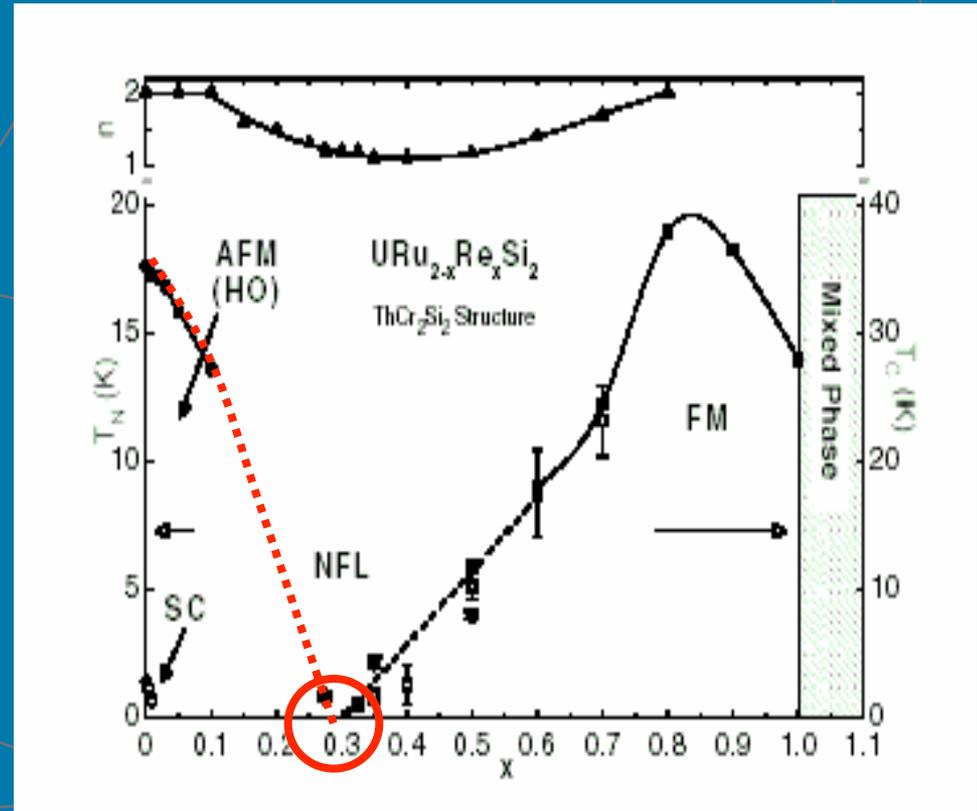
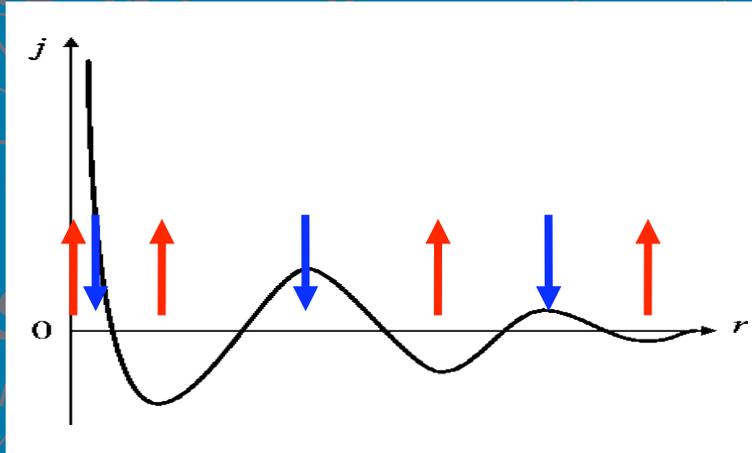


$$H = \sum_{R, R'} J(R, R') S(R) \cdot S(R')$$

# Criticalidade Quântica - Férmions Pesados



## Ponto Crítico Quântico ?



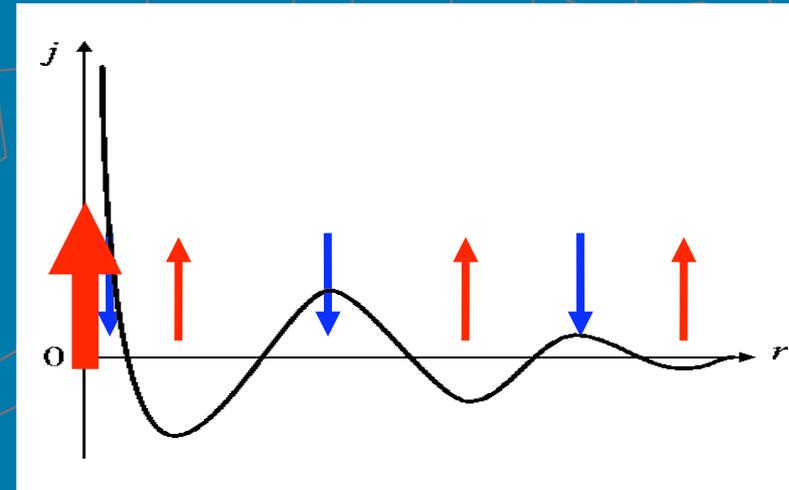
$$H = \sum_{R, R'} J(R, R') S(R) \cdot S(R')$$

# Ressonância Kondo e Oscilações RKKY

$$H = \sum_{R, R'} J(R, R') S(R) \cdot S(R')$$



$$J(R, R') = \Gamma \frac{\sin(r) - r \cos(r)}{r^4}$$



**Oscilações de Friedel  
na densidade eletrônica**

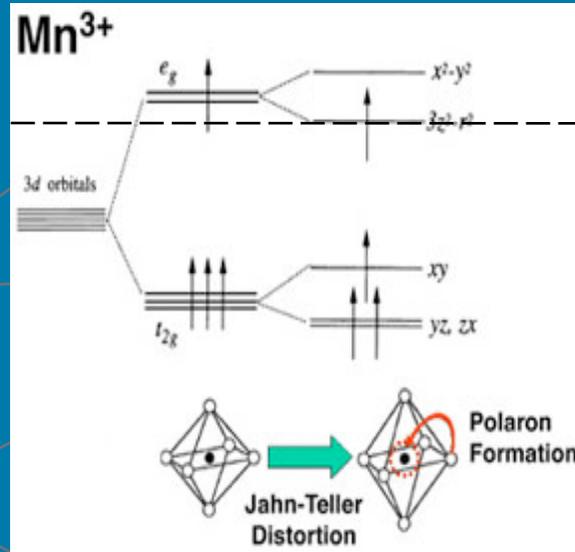
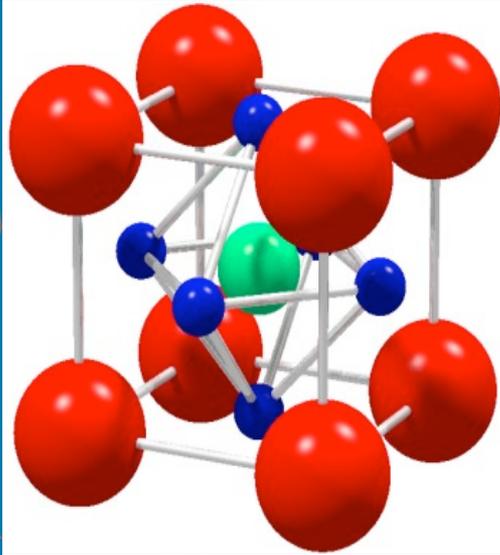
**Aumento da densidade eletrônica  
ao redor da impureza magnética**



# Magnetoresistência Gigante/Colossal



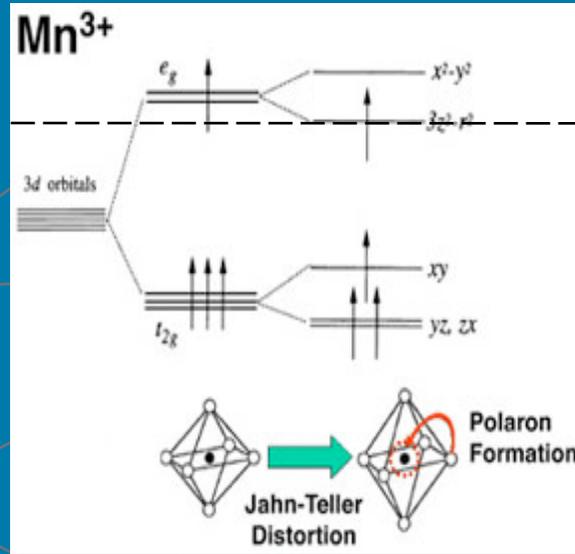
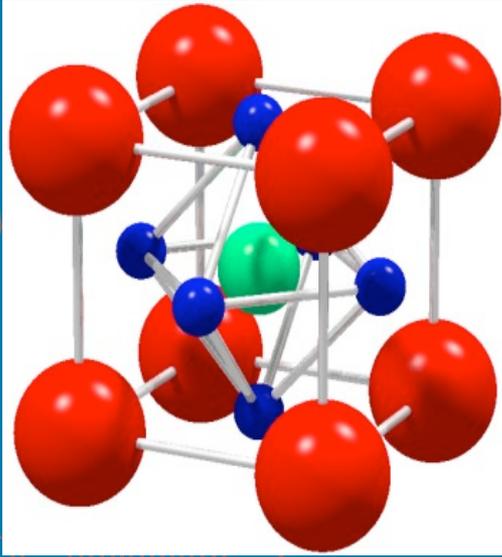
# Dupla Troca nas manganitas $LaMnO_3$



Itinerante

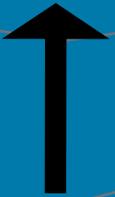
Localizado

# Dupla Troca nas manganitas $LaMnO_3$

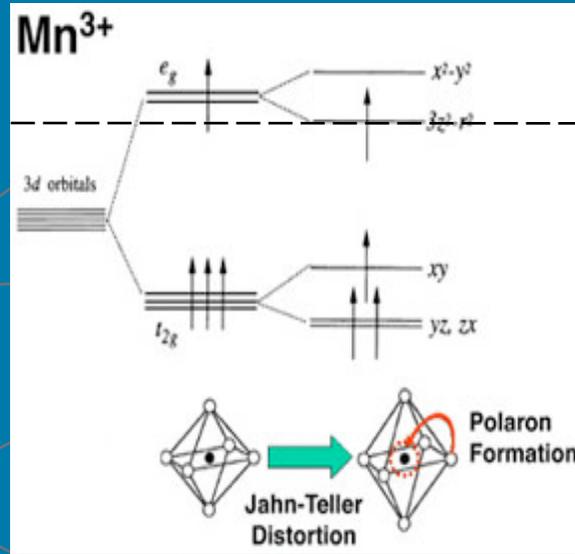
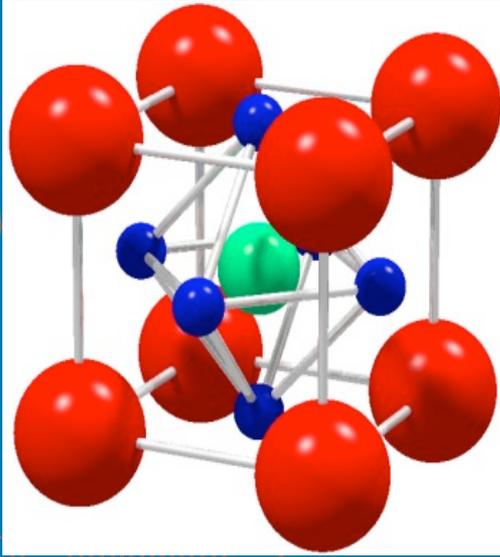


Itinerante

Localizado

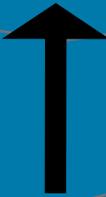


# Dupla Troca nas manganitas $LaMnO_3$

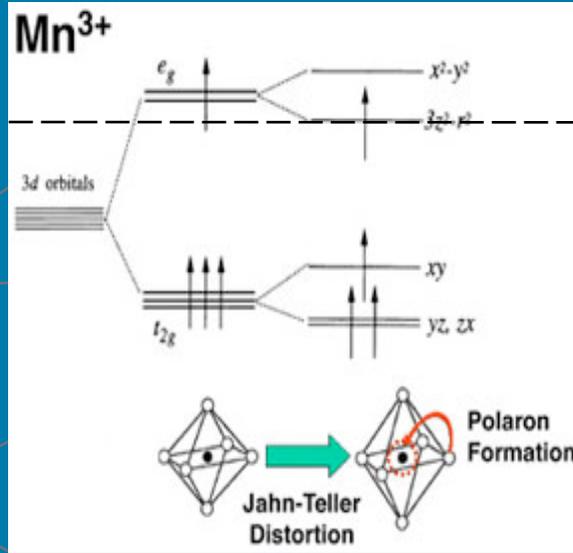
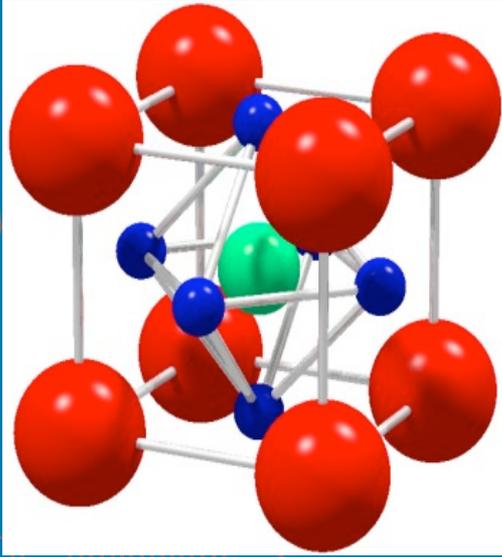


Itinerante

Localizado



# Dupla Troca nas manganitas $LaMnO_3$

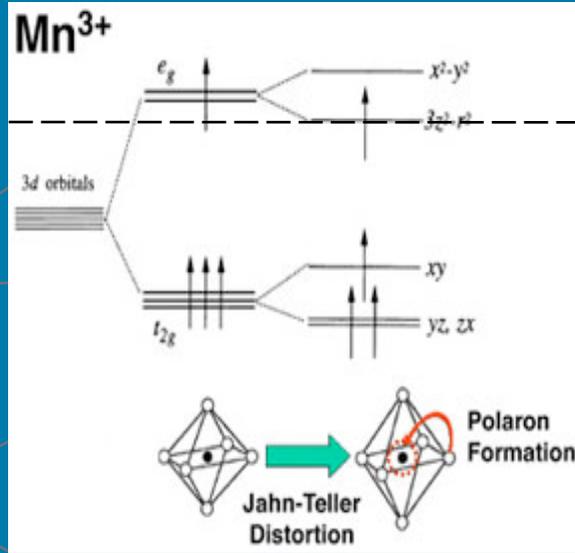
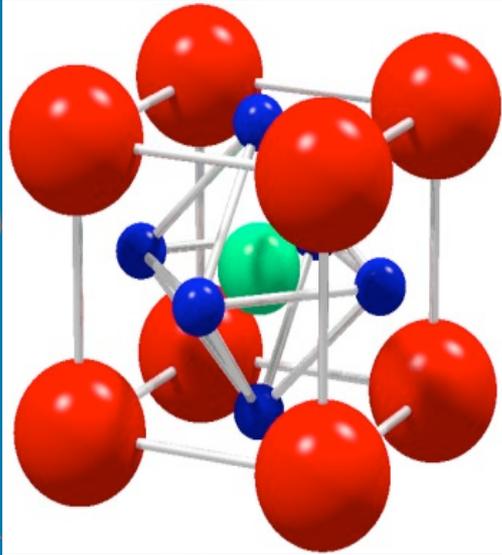


↑ Itinerante

↑ Localizado

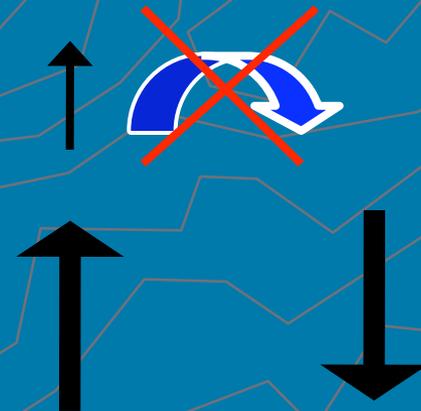
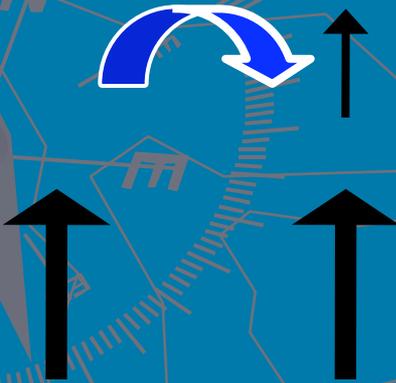


# Dupla Troca nas manganitas $LaMnO_3$

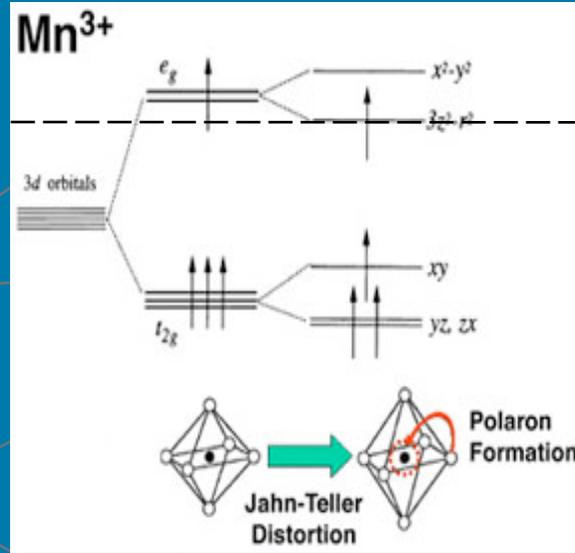
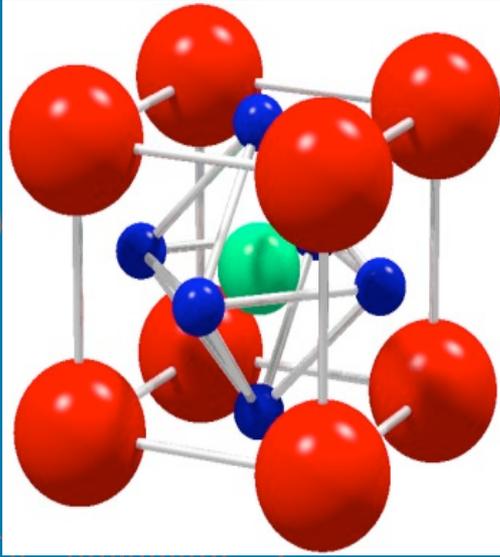


↑ Itinerante

↑ Localizado

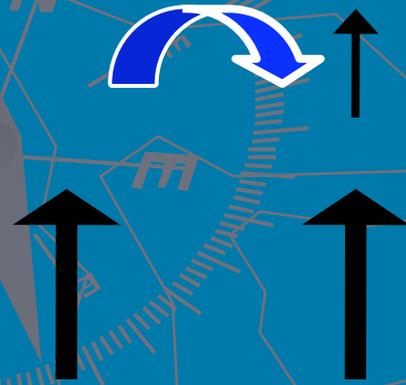


# Dupla Troca nas manganitas $LaMnO_3$

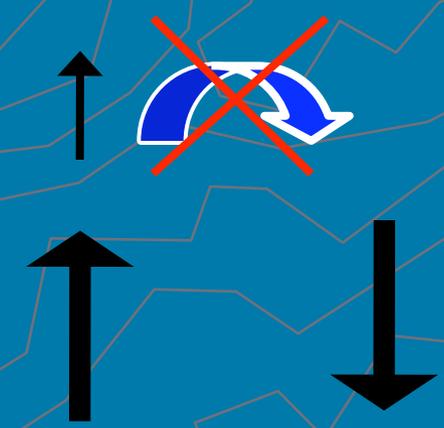


↑ Itinerante

↑ Localizado



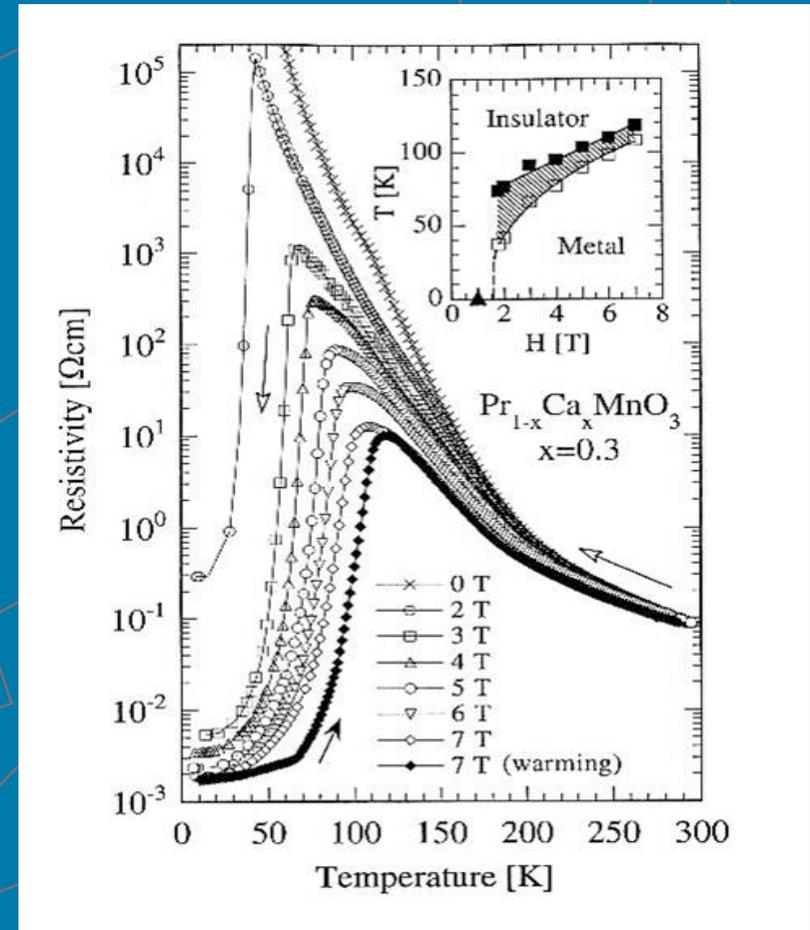
$$E_{ij} = -t \cos \theta_{ij}$$



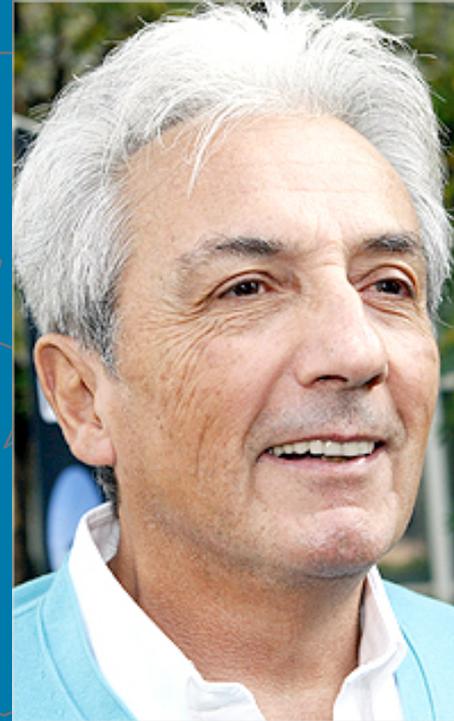
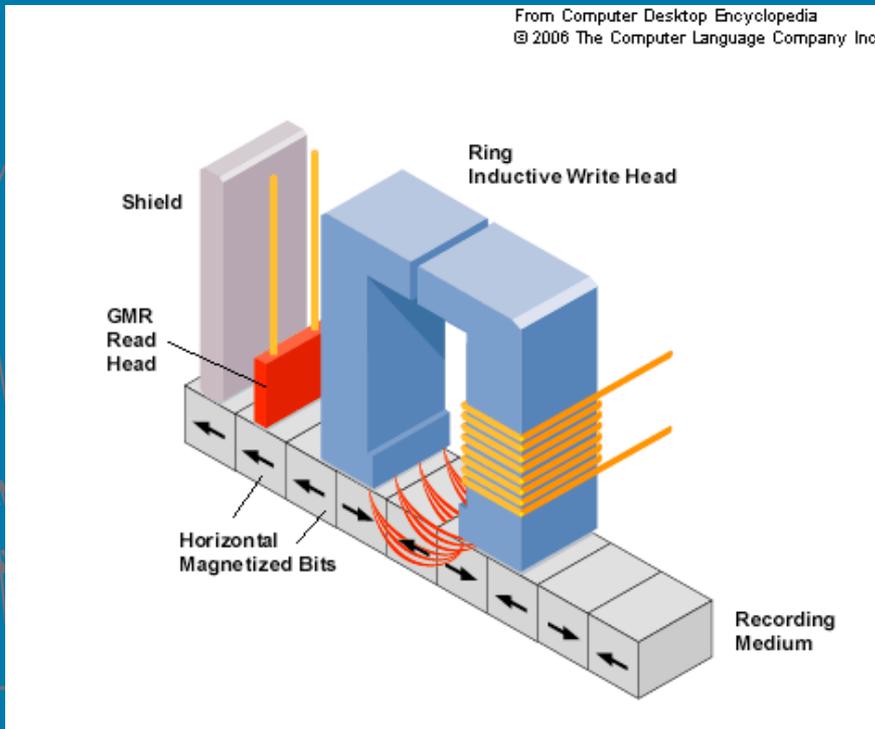
O transporte é favorecido pelo alinhamento ferromagnético!

# Magnetoresistência Colossal

- O campo magnético alinha todos os íons  $Mn^{3+}$ .
- Redução Drástica na resistividade: 100,000 %
- Enorme potencial para aplicações como sensores de leitura nasensors na eletrônica.



# O prêmio Nobel de 2007



Albert Fert

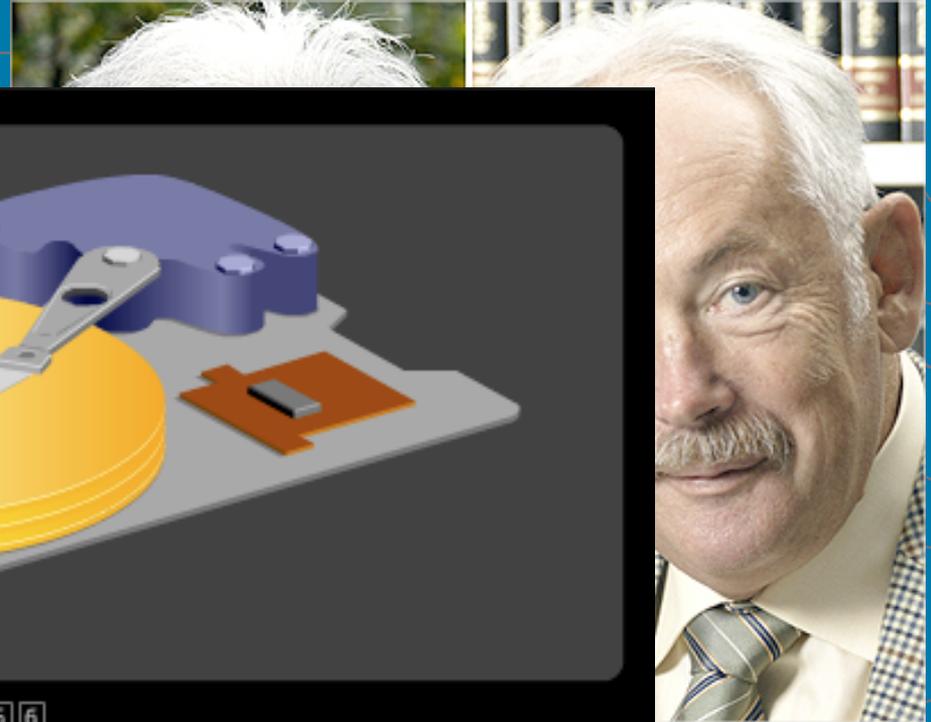


Peter Grünberg

**Cabeça de leitura  
Magnetoresistência**

# O prêmio Nobel de 2007

From Computer Desktop Encyclopedia  
© 2006 The Computer Language Company Inc.



Shield

GMR  
Read  
Head

Horiz  
Magr

## THE HARD DISK DRIVE

1 2 3 4 5 6

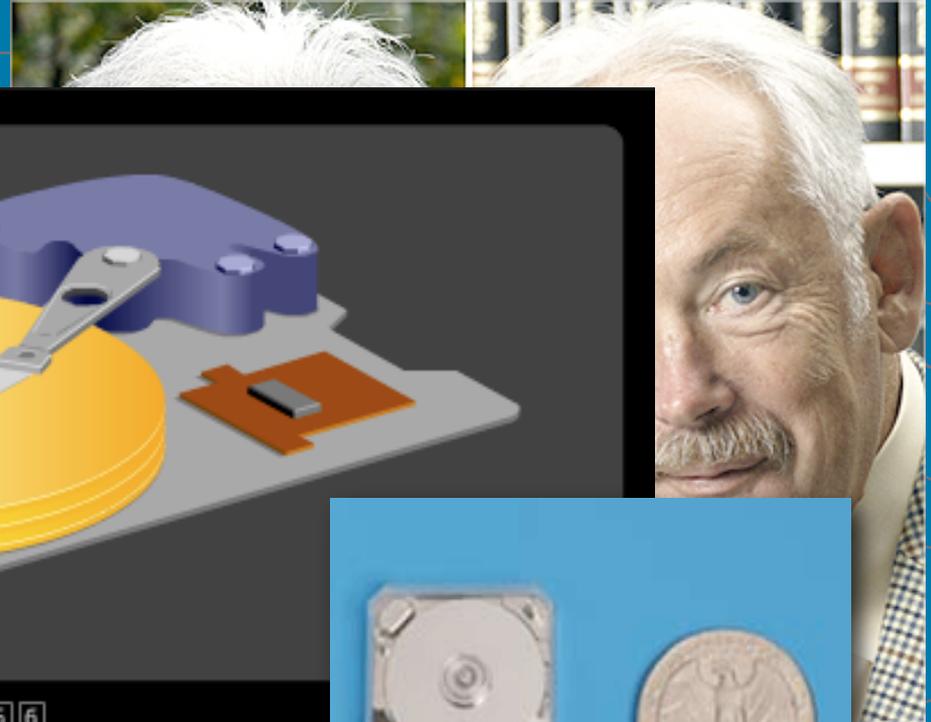
You are looking at the inside of a hard disk drive. The head is located at the end of the actuator arm, and flies over the disk to read and write data. Click the next button to take a closer look at the read/write element. [NEXT]

Cal  
Mag

Grünberg

# O prêmio Nobel de 2007

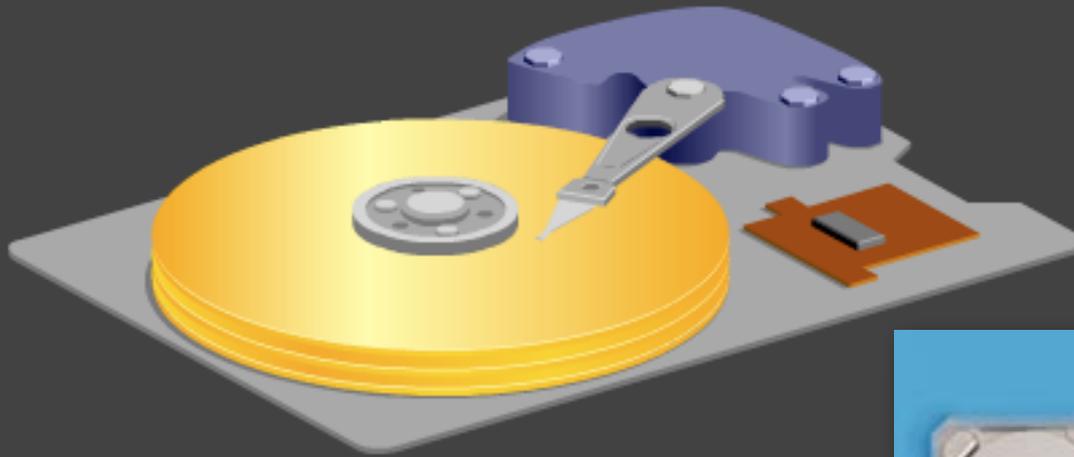
From Computer Desktop Encyclopedia  
© 2006 The Computer Language Company Inc.



Shield

GMR  
Read  
Head

Horiz  
Magr



## THE HARD DISK DRIVE

1 2 3 4 5 6

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]

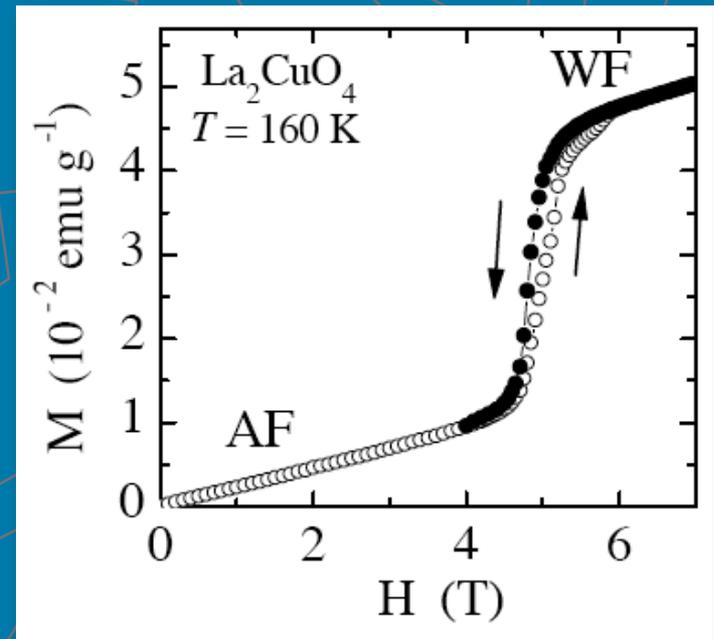
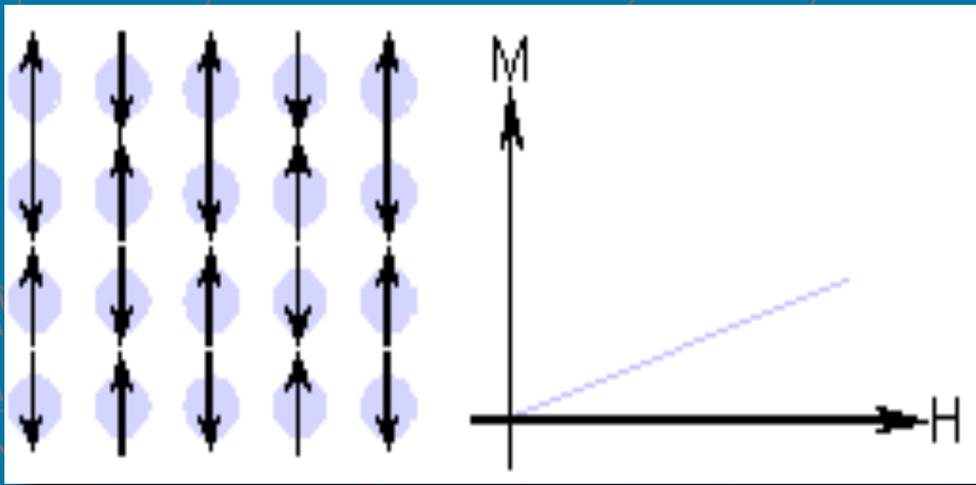


TOSHIBA

Cal  
Mag

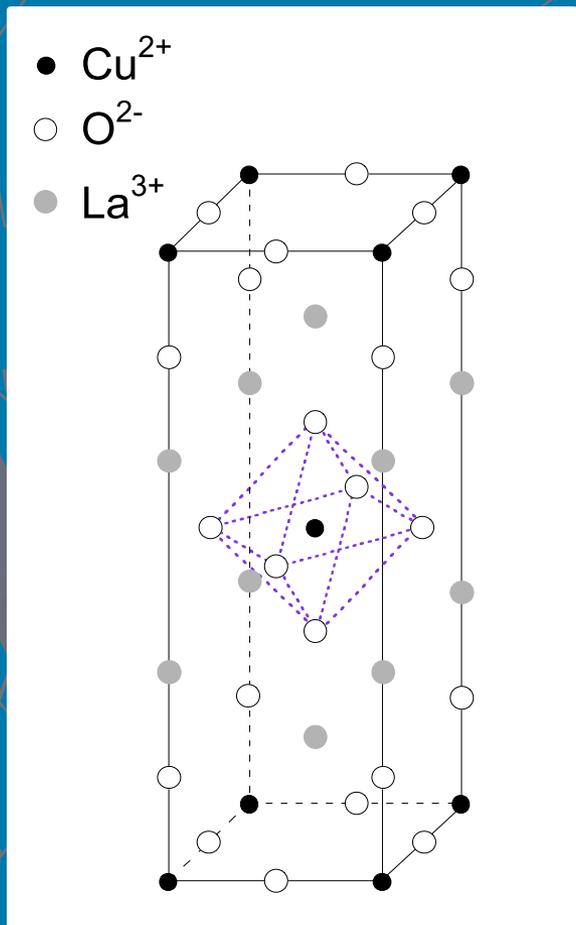
rg

# Ferromagnetismo Fraco - Cupratos



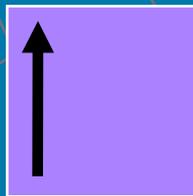
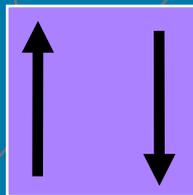
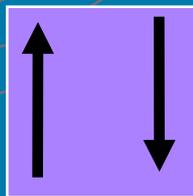
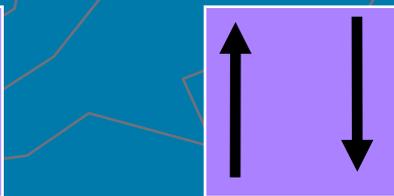
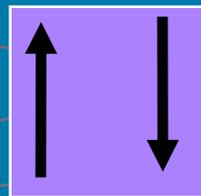
Transição de fase de 1ª ordem!!!

# Super-Troca nos Supercondutores de Altas Temperaturas



E

$d_{xz}$



$d_{x^2-y^2}$

$d_{z^2}$

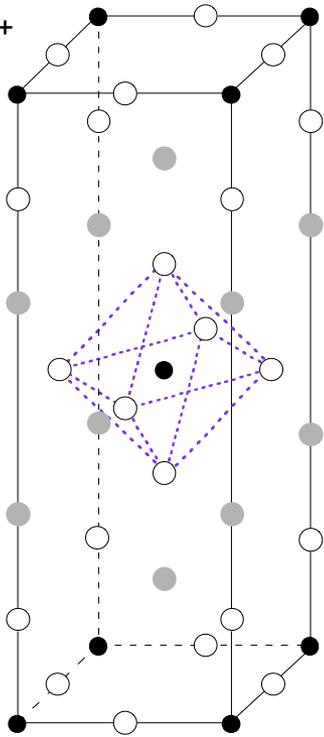
$d_{xy}$

$d_{yz}$

# Super-Troca nos Supercondutores de Altas Temperaturas

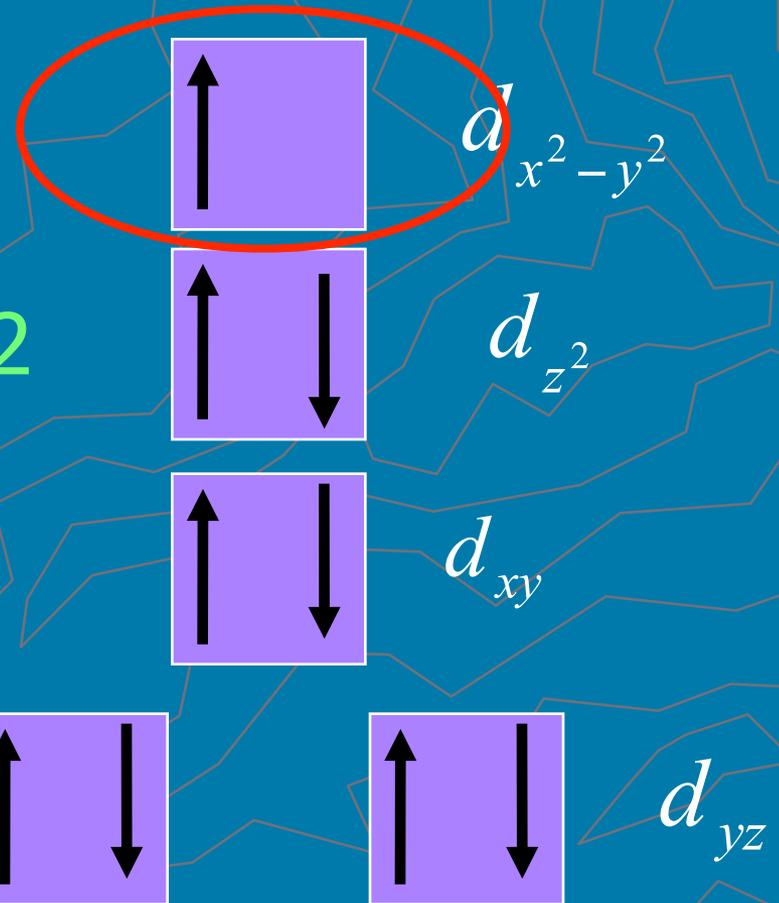


- $\text{Cu}^{2+}$
- $\text{O}^{2-}$
- $\text{La}^{3+}$

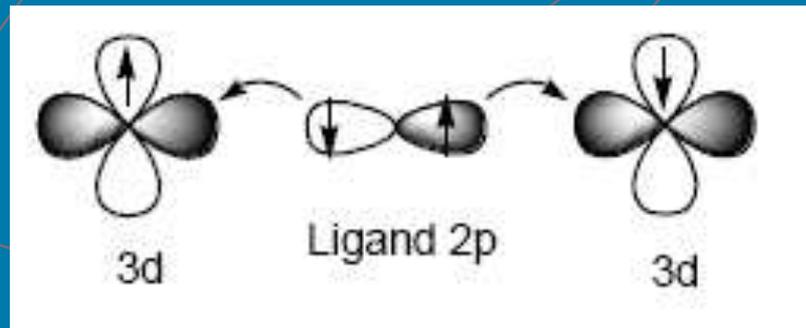


E

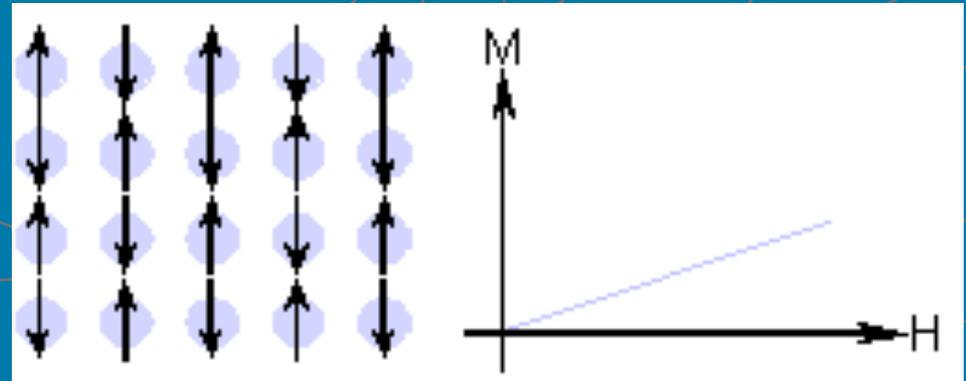
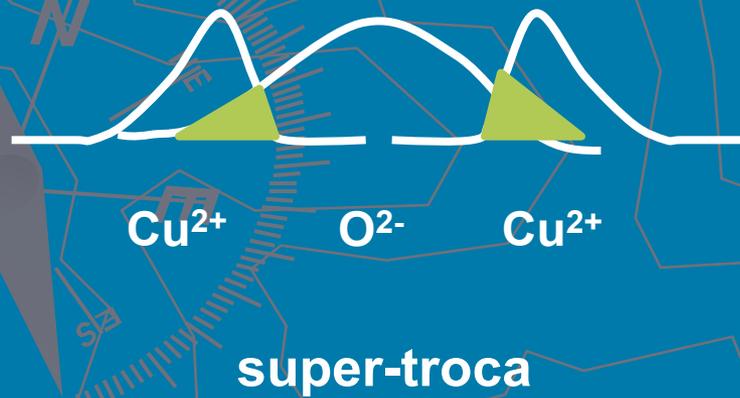
$S=1/2$



# Super-Troca nos Supercondutores de Altas Temperaturas



Ordem Anti-ferromagnética!  
Néel State



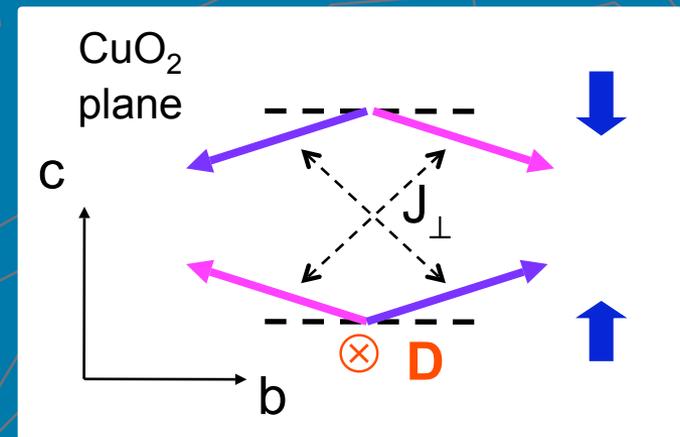
# Acoplamento SPIN-ÓRBITA nos HTSC

$$H = \sum_{R,R'} J_{ab}(R,R') S_a(R) S_b(R')$$

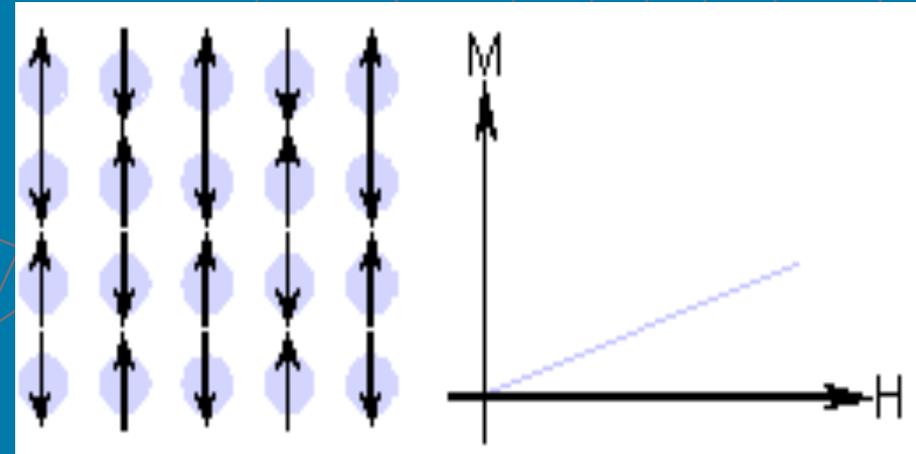
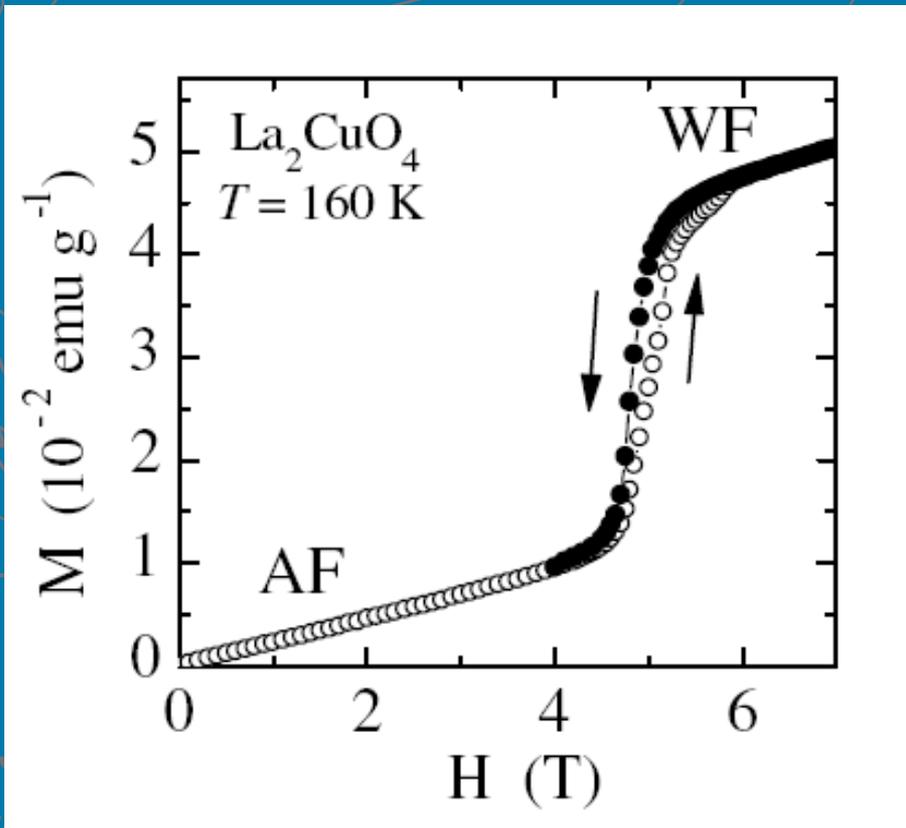
$$[J_{ab}] = \begin{pmatrix} J_x & D & 0 \\ -D & J_y & 0 \\ 0 & 0 & J_z \end{pmatrix}$$

Interação de Dzyaloshinskii-Moriya

Ferromagnetismo FRACO por plano!

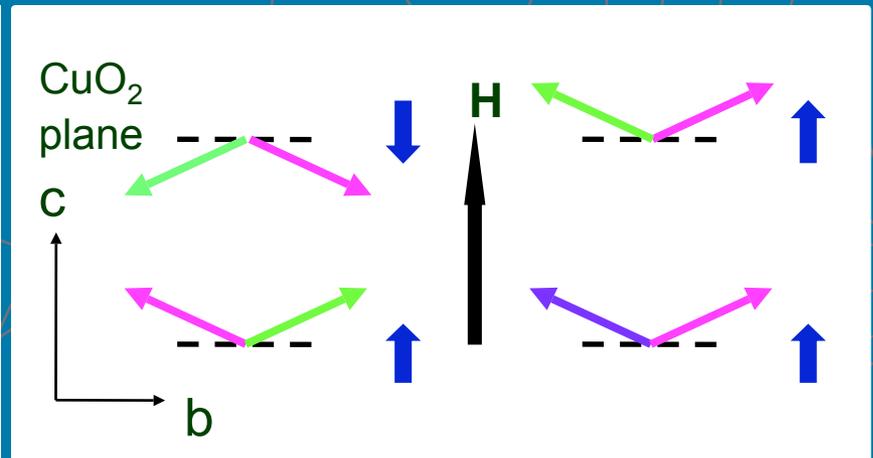
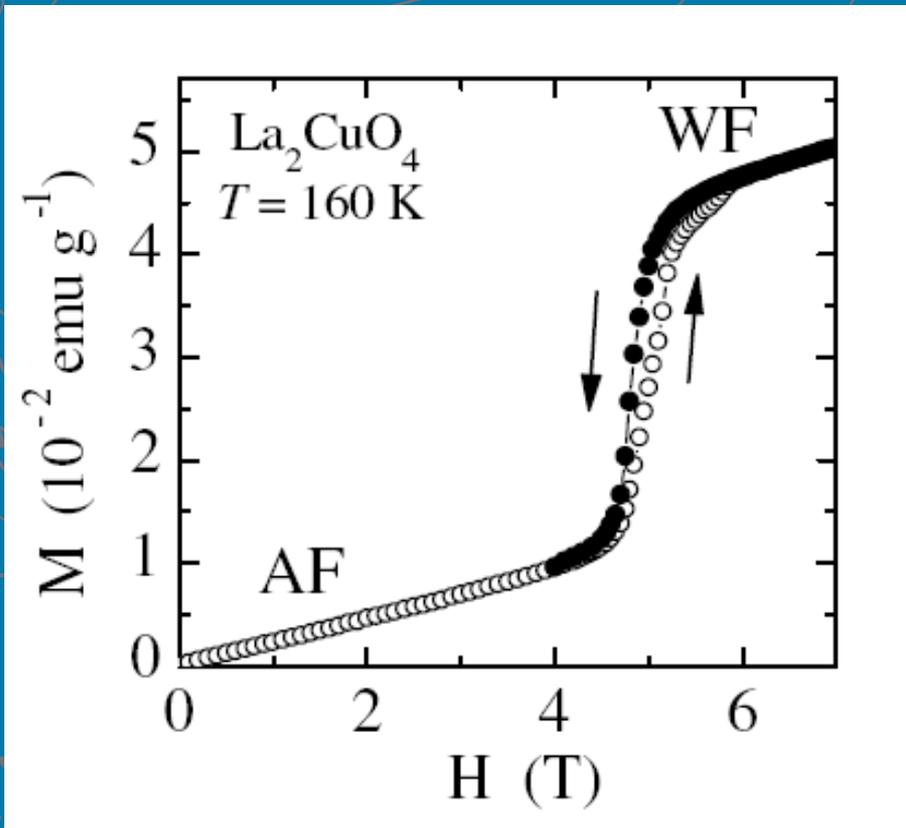


# Transição de Spin-flop no $\text{La}_2\text{CuO}_4$



# Transição de Spin-flop no $\text{La}_2\text{CuO}_4$

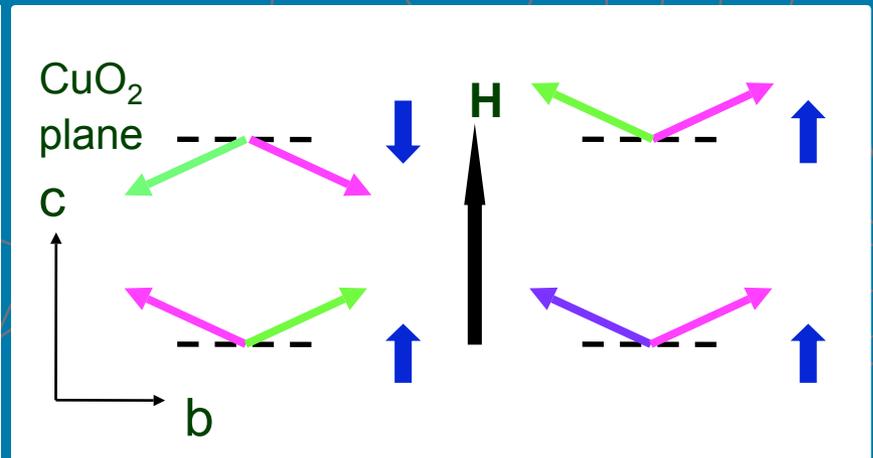
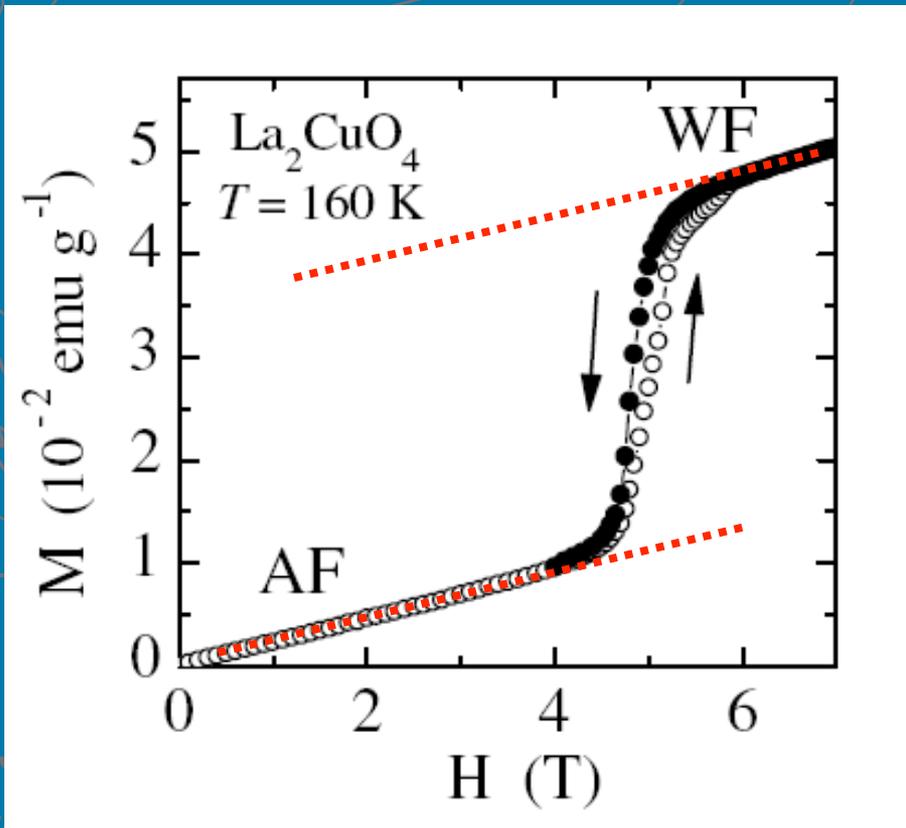
Anti-ferromagnetismo Canted!



$$[J_{ab}] = \begin{pmatrix} J_x & D & 0 \\ -D & J_y & 0 \\ 0 & 0 & J_z \end{pmatrix}$$

# Transição de Spin-flop no $\text{La}_2\text{CuO}_4$

Anti-ferromagnetismo Canted!



$$[J_{ab}] = \begin{pmatrix} J_x & D & 0 \\ -D & J_y & 0 \\ 0 & 0 & J_z \end{pmatrix}$$

Transição de 1ª ordem!

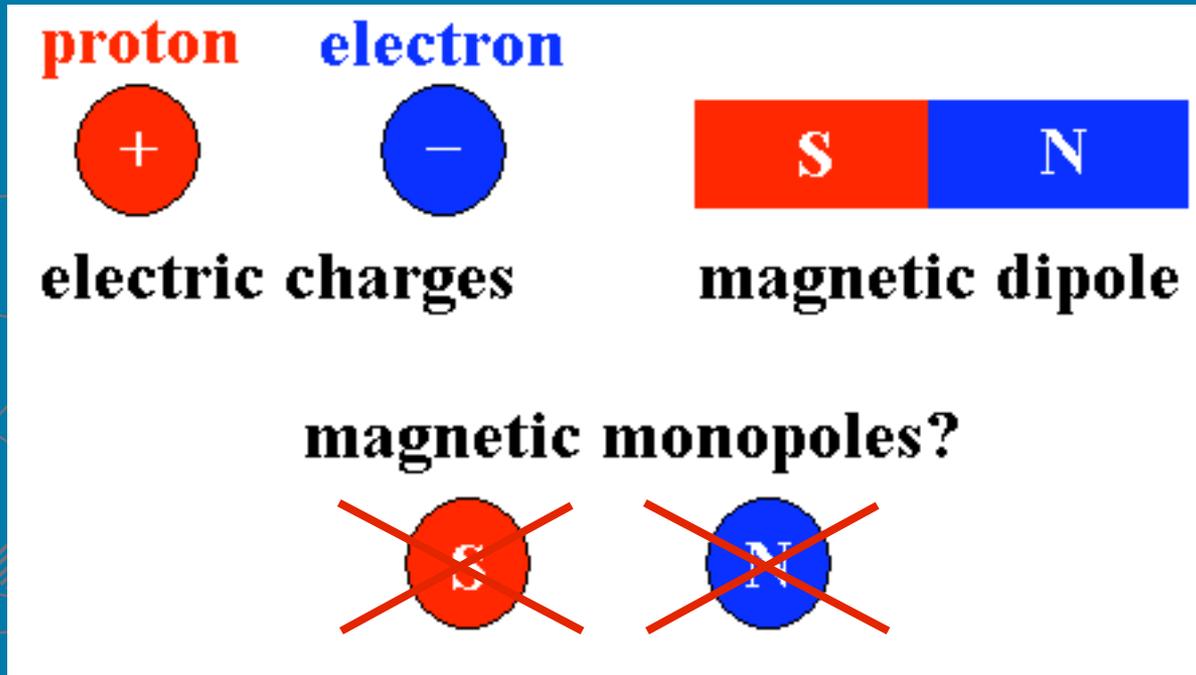
# Monopolos Magnéticos

Propostos em  
Janeiro / 2008



Medidos em  
Abril / 2009

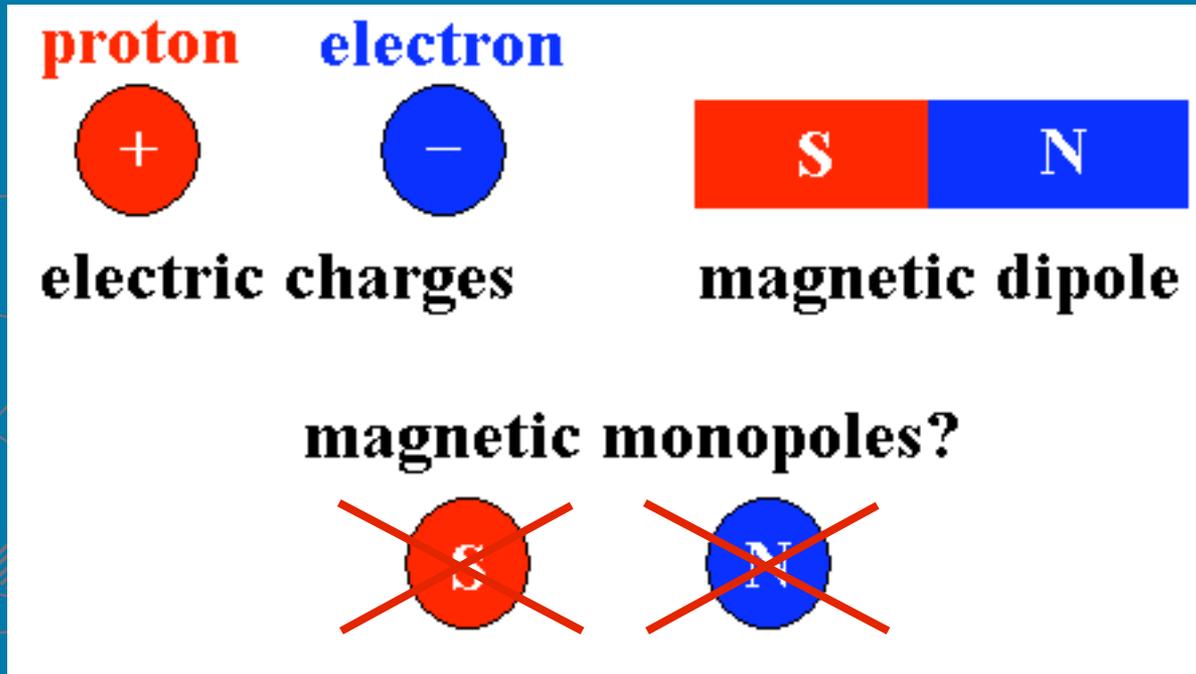
# Polos Norte e Sul - ~~Monopolos~~



Leis de Gauß - Eletrostática e Magnetostática

$$\nabla \cdot \mathbf{E} = \frac{\rho}{4\pi\epsilon_0} \qquad \nabla \cdot \mathbf{B} = 0$$

# Polos Norte e Sul - ~~Monopolos~~



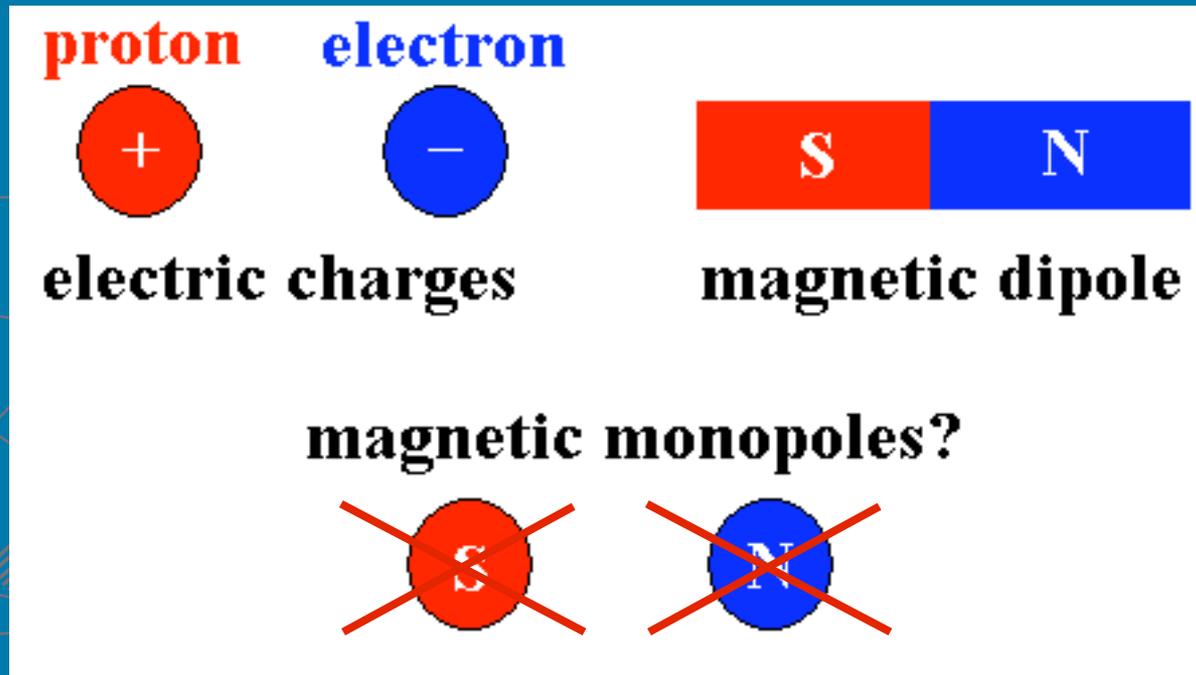
Leis de Gauß - Eletrostática e Magnetostática

$$\nabla \cdot \mathbf{E} = \frac{\rho}{4\pi\epsilon_0}$$

$$\nabla \cdot \mathbf{B} = 0$$

No Vácuo!!!

# Monopolos - Física EMERGENTE



Sólidos proveem MEIOS para monopolos

$$\nabla \cdot \mathbf{B} = \nabla \cdot (\mathbf{H} + 4\pi\mathbf{M}) = 0$$

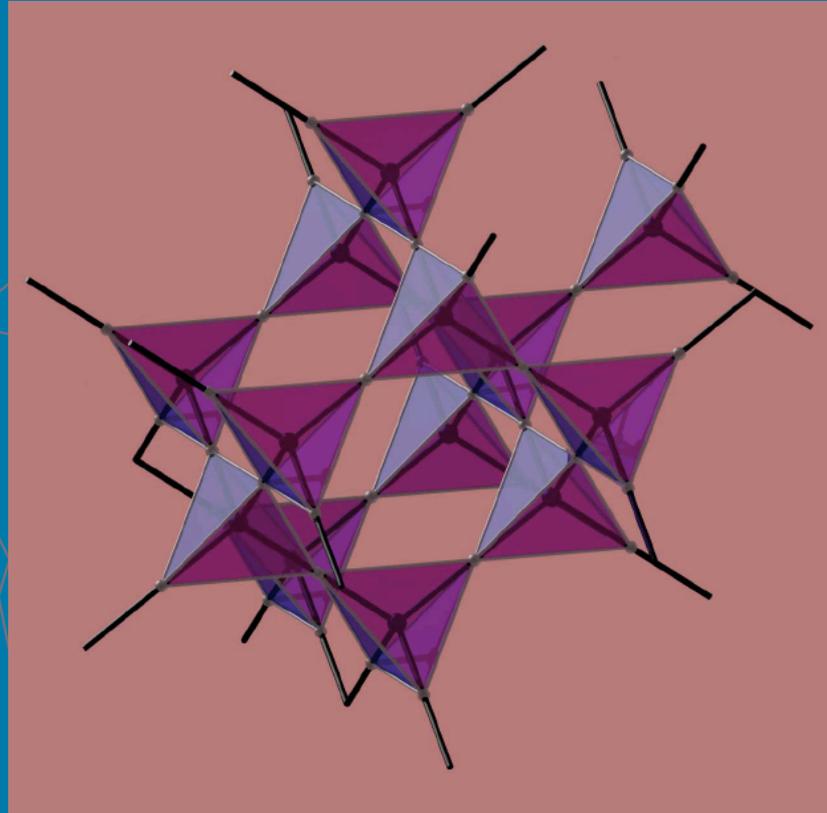
H e M podem ter divergentes NÃO nulos

# Monopolos de Dirac em Spin-Ice

$\text{Dy}_2\text{Ti}_2\text{O}_7$

$\text{Ho}_2\text{Ti}_2\text{O}_7$

$\mu_{eff} \approx 10\mu_B$



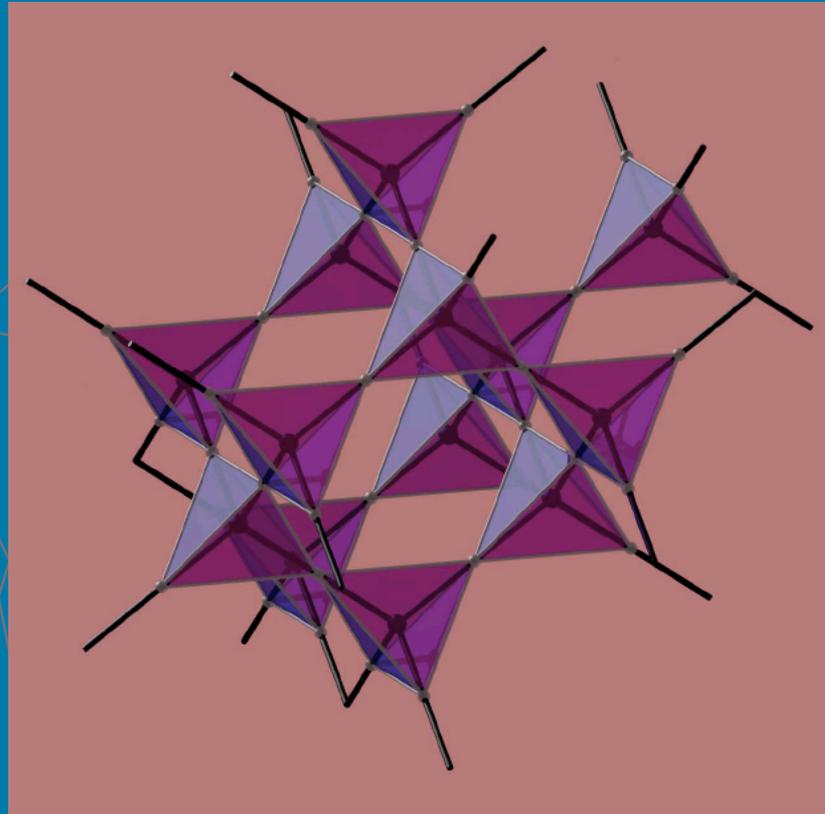
$$\mathcal{H} = J\mu^2 \sum_{\langle i,j \rangle} \mathbf{S}_i \cdot \mathbf{S}_j + D\mu^2 \sum_{\langle i,j \rangle} \left[ \frac{\mathbf{S}_i \cdot \mathbf{S}_j}{|\mathbf{r}_{ij}|^3} - \frac{3(\mathbf{S}_i \cdot \mathbf{r}_{ij})(\mathbf{S}_j \cdot \mathbf{r}_{ij})}{|\mathbf{r}_{ij}|^5} \right]$$

# Monopolos de Dirac em Spin-Ice

$\text{Dy}_2\text{Ti}_2\text{O}_7$

$\text{Ho}_2\text{Ti}_2\text{O}_7$

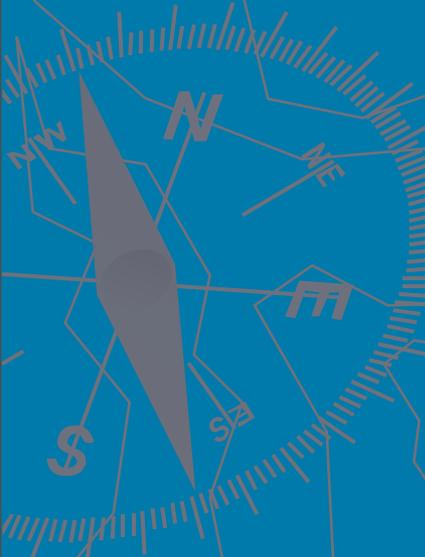
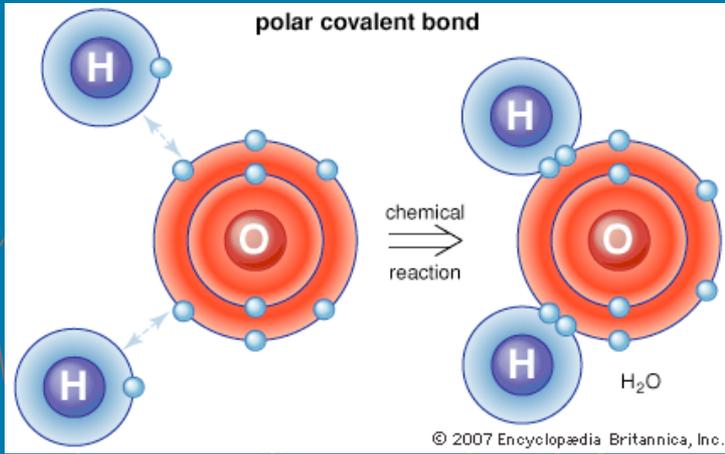
$\mu_{eff} \approx 10\mu_B$



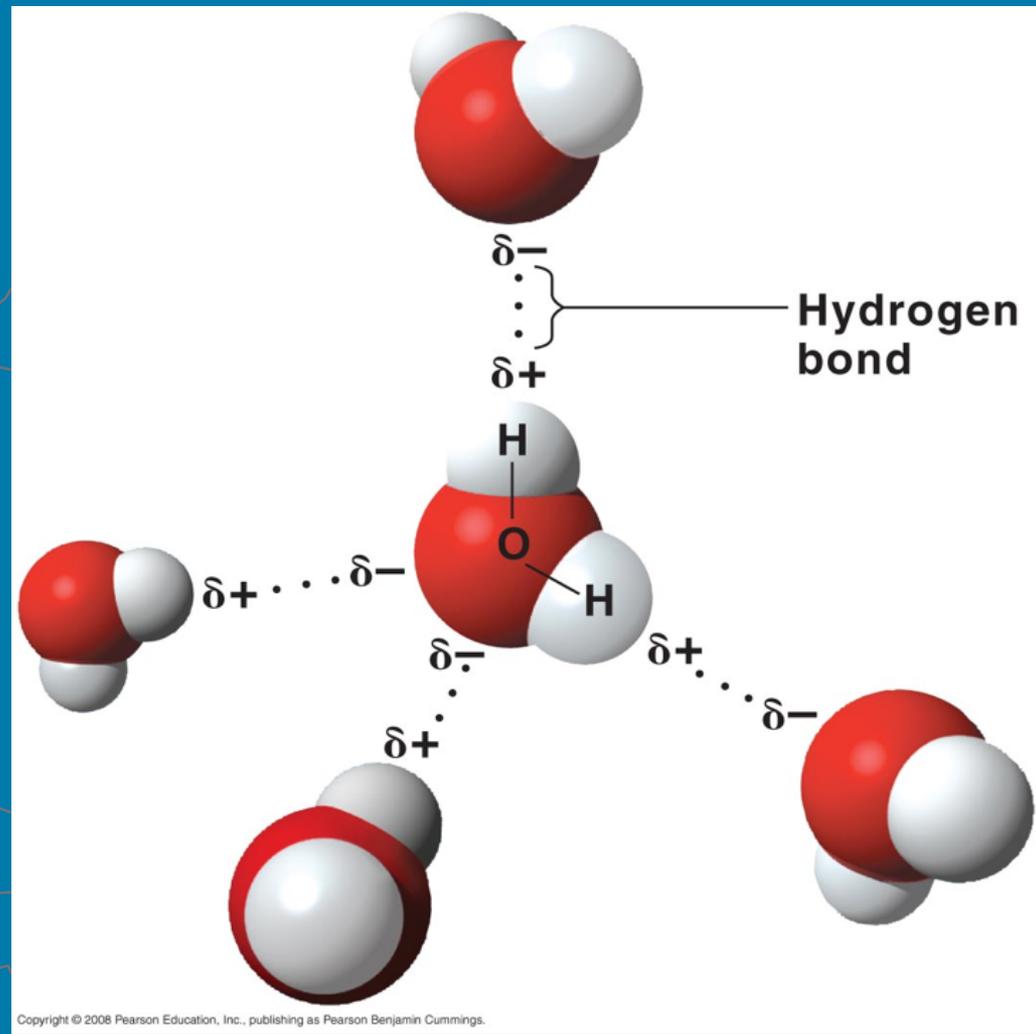
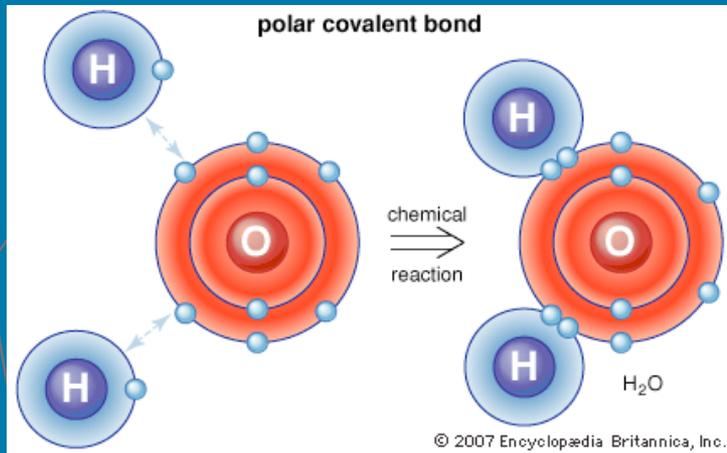
**Interações DIPOLARES**

$$\mathcal{H} = J\mu^2 \sum_{\langle i,j \rangle} \mathbf{S}_i \cdot \mathbf{S}_j + D\mu^2 \sum_{\langle i,j \rangle} \left[ \frac{\mathbf{S}_i \cdot \mathbf{S}_j}{|\mathbf{r}_{ij}|^3} - \frac{3(\mathbf{S}_i \cdot \mathbf{r}_{ij})(\mathbf{S}_j \cdot \mathbf{r}_{ij})}{|\mathbf{r}_{ij}|^5} \right]$$

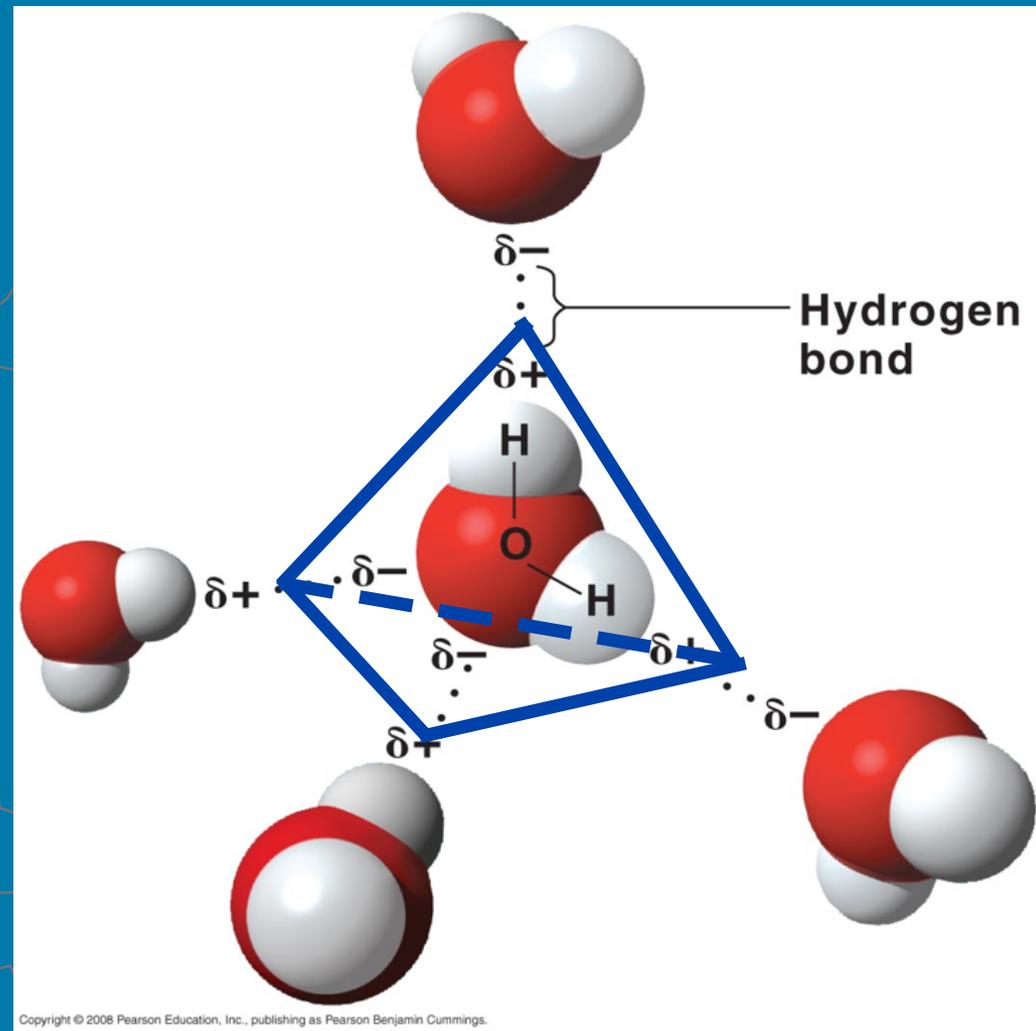
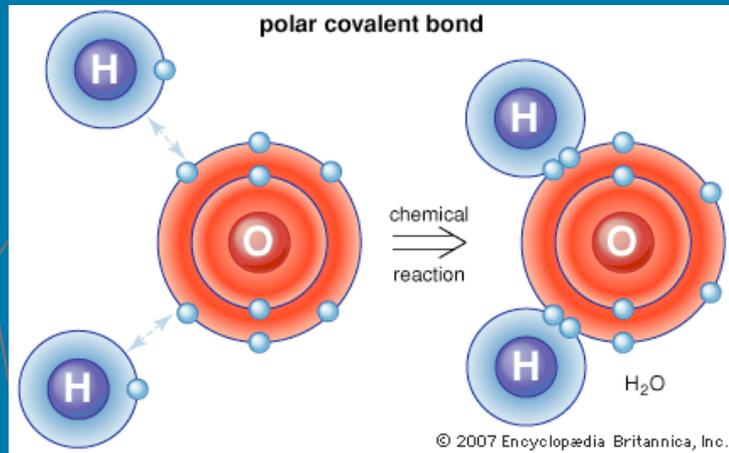
# Estrutura molecular tipo ICE



# Estrutura molecular tipo ICE



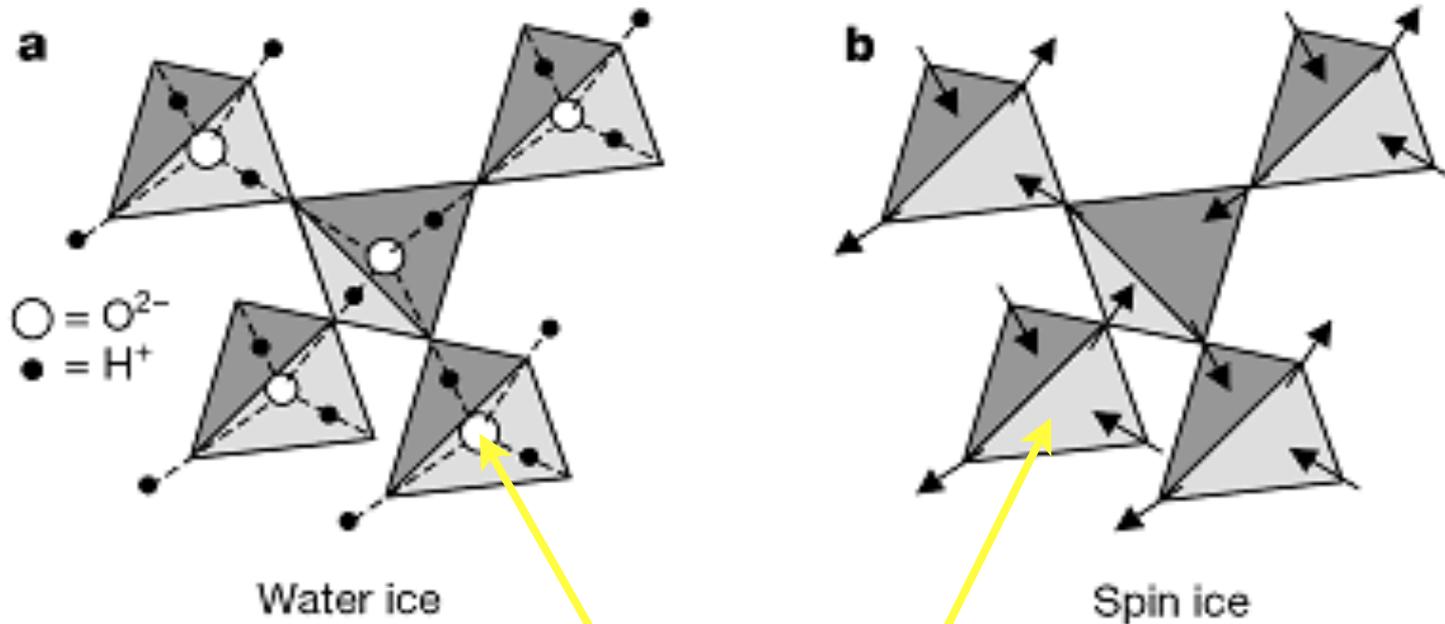
# Estrutura molecular tipo ICE



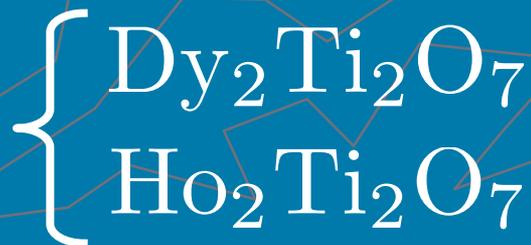
Ice-rule: entram 2 saem 2



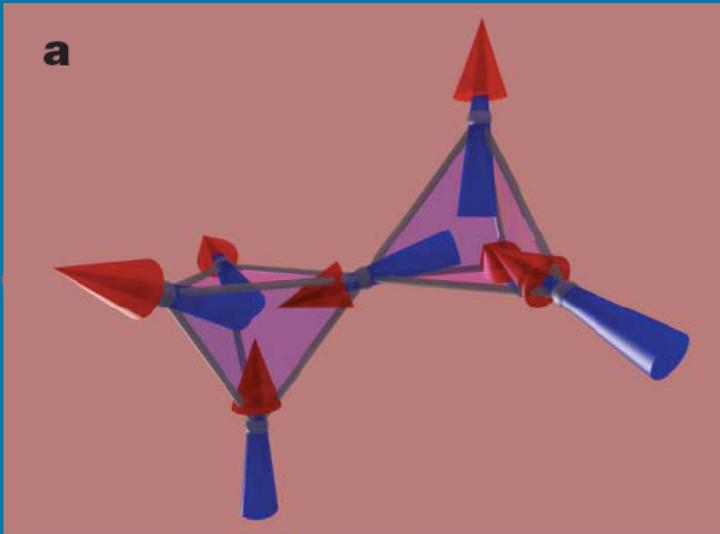
# Estrutura molecular tipo ICE



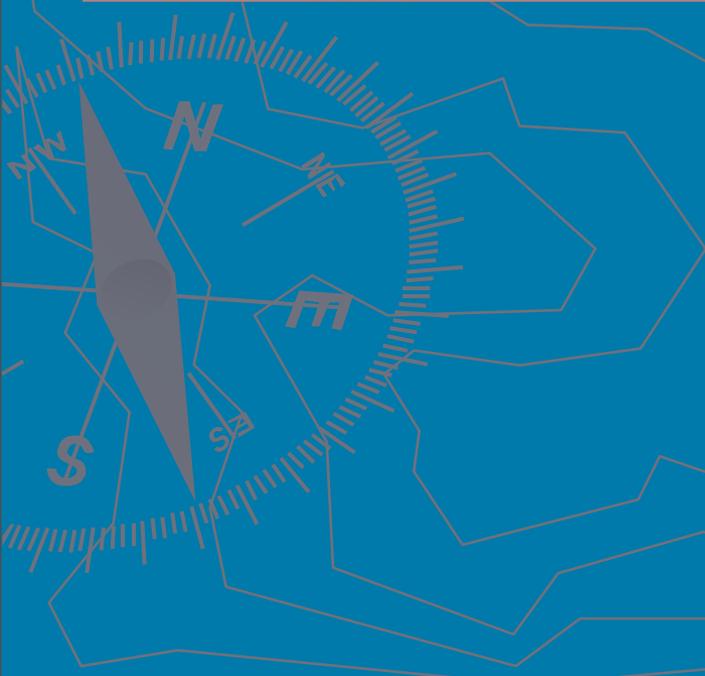
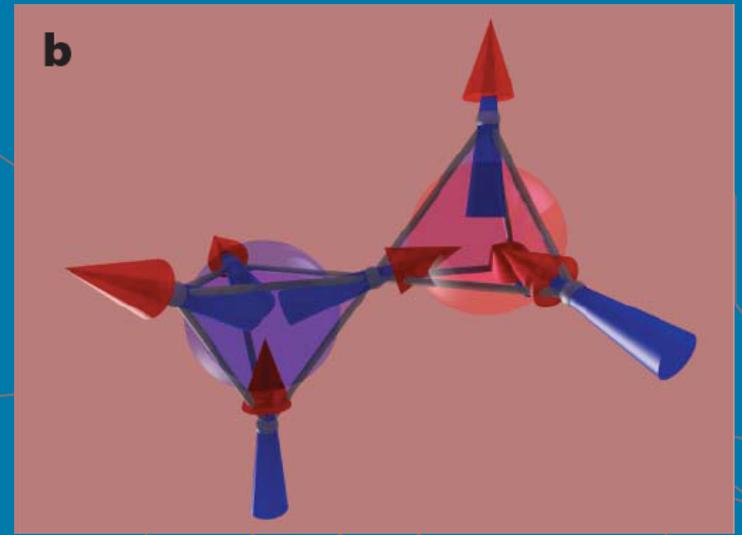
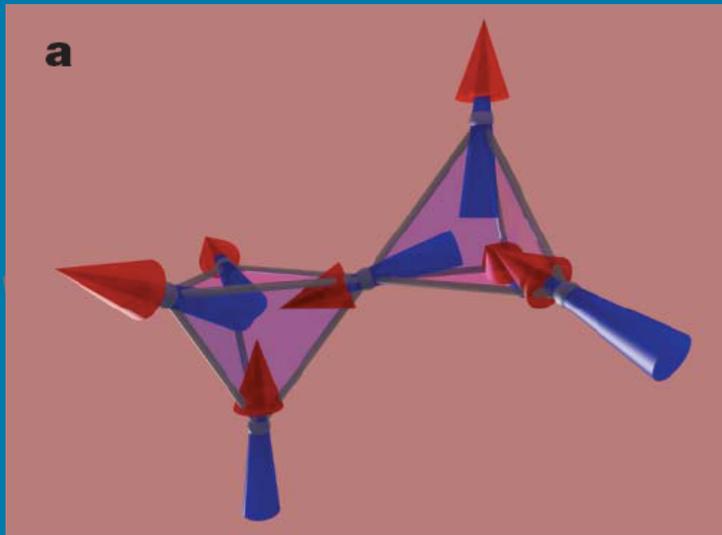
**Ice-rule: entram 2 saem 2**



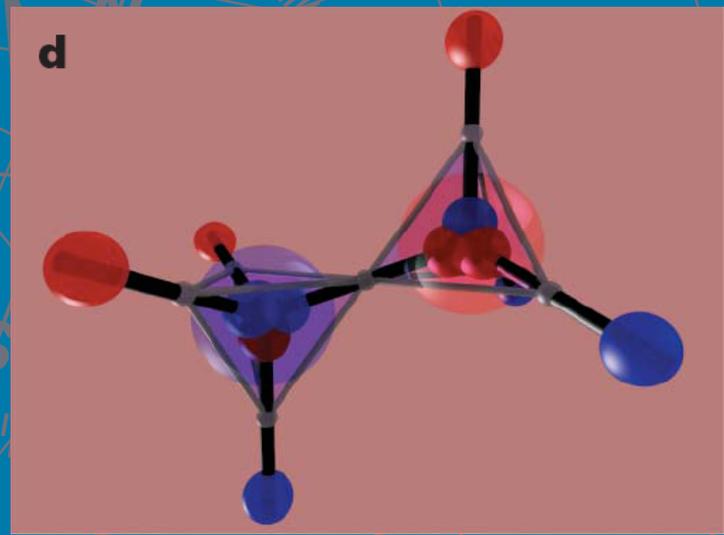
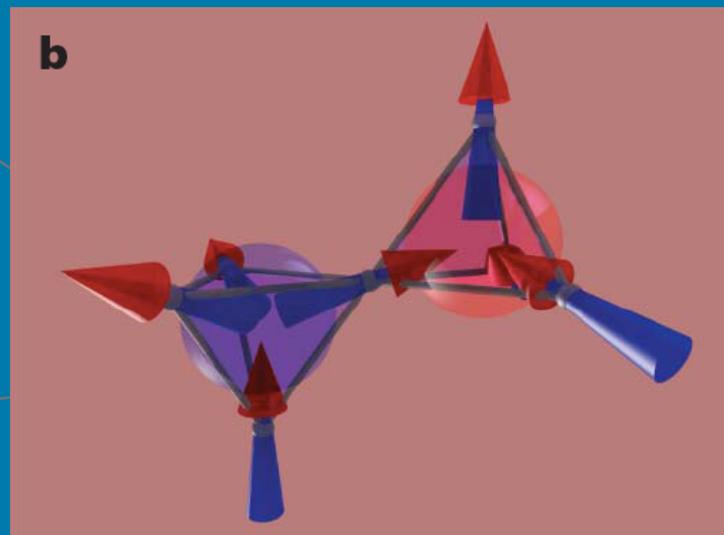
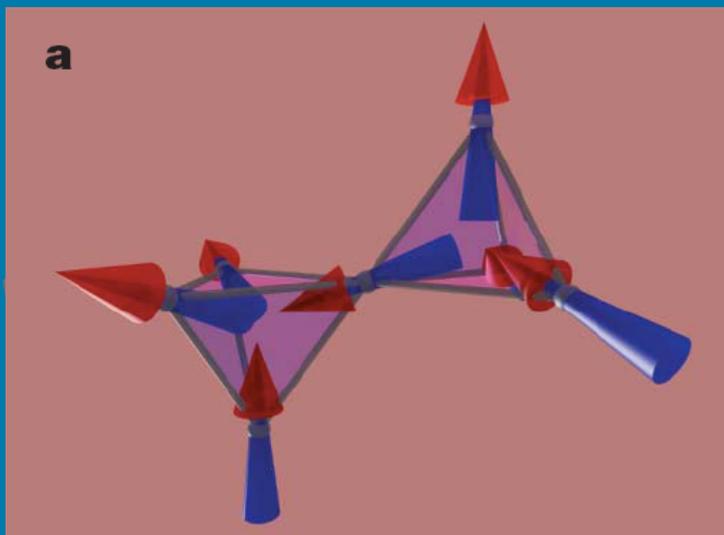
# Monopolos de Dirac em Spin-Ice



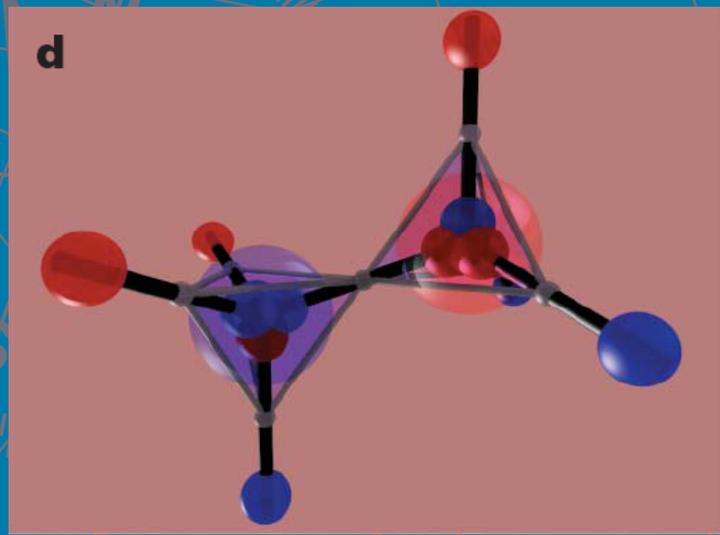
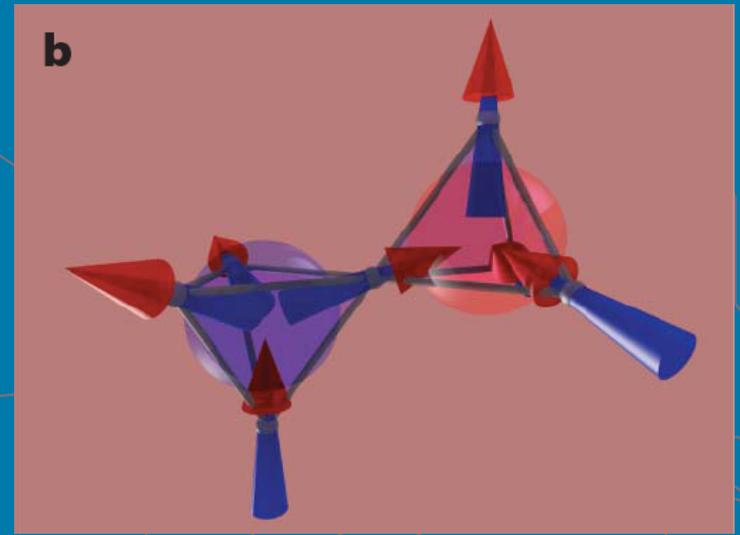
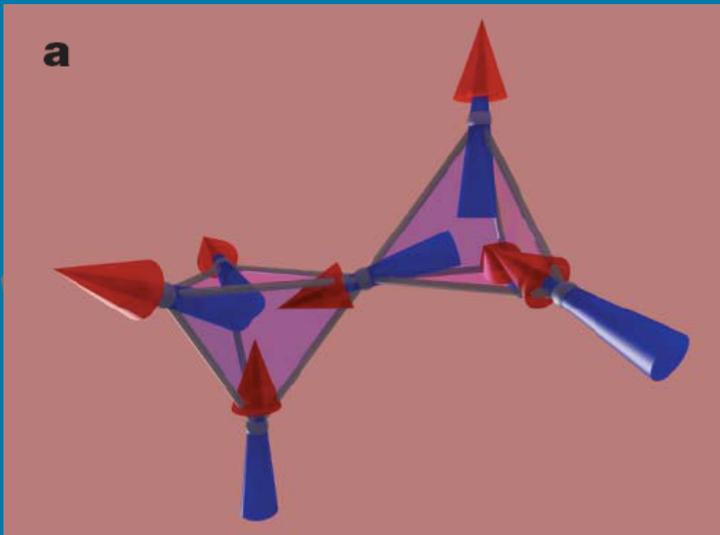
# Monopolos de Dirac em Spin-Ice



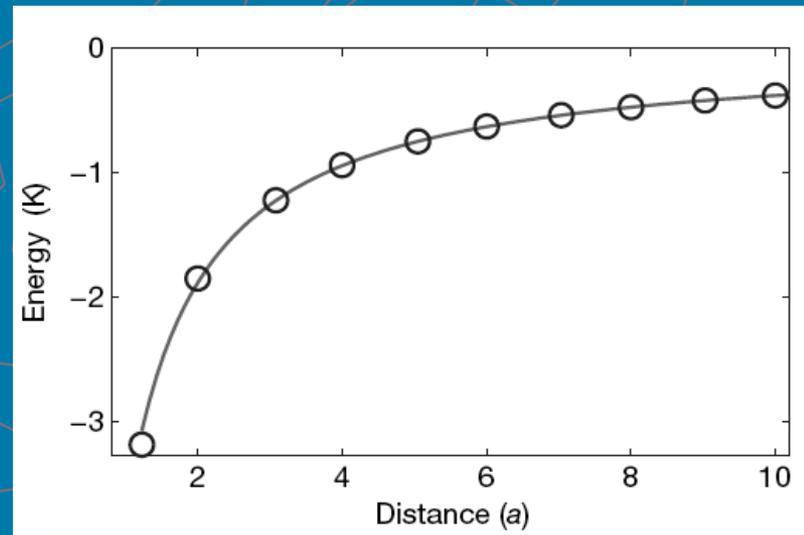
# Monopolos de Dirac em Spin-Ice



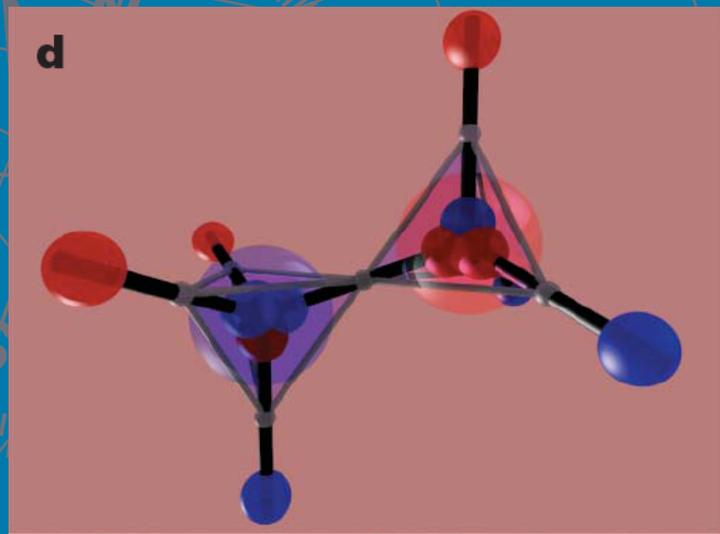
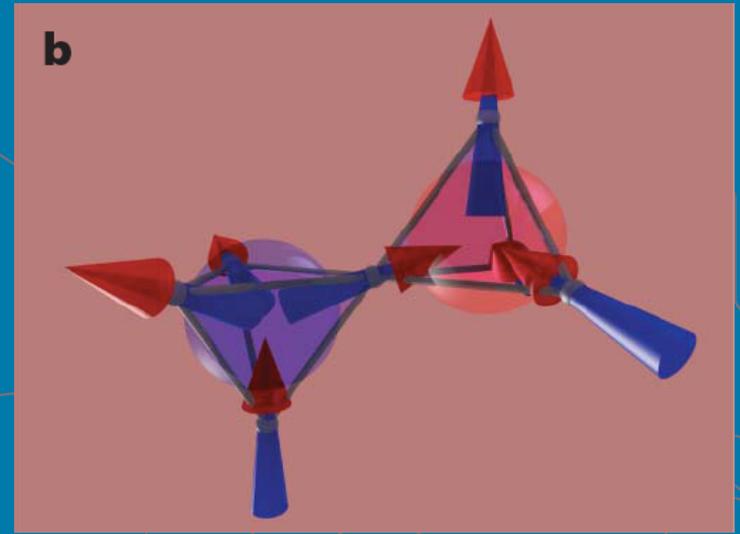
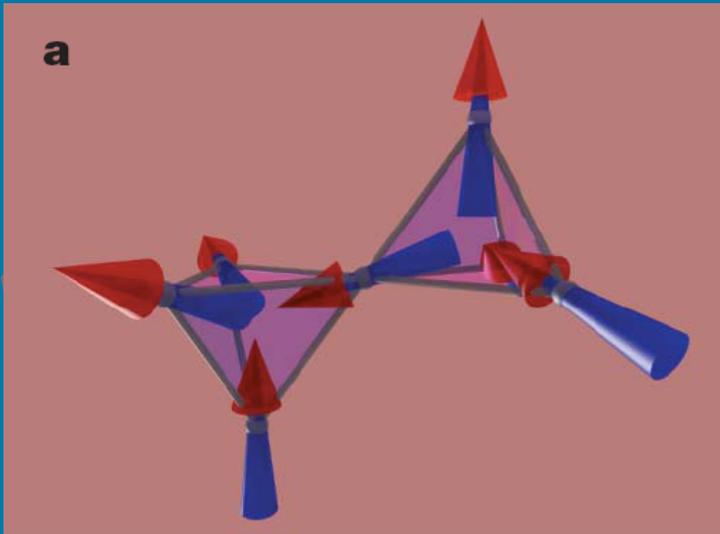
# Monopolos de Dirac em Spin-Ice



Gás de Coulomb / Monopolos

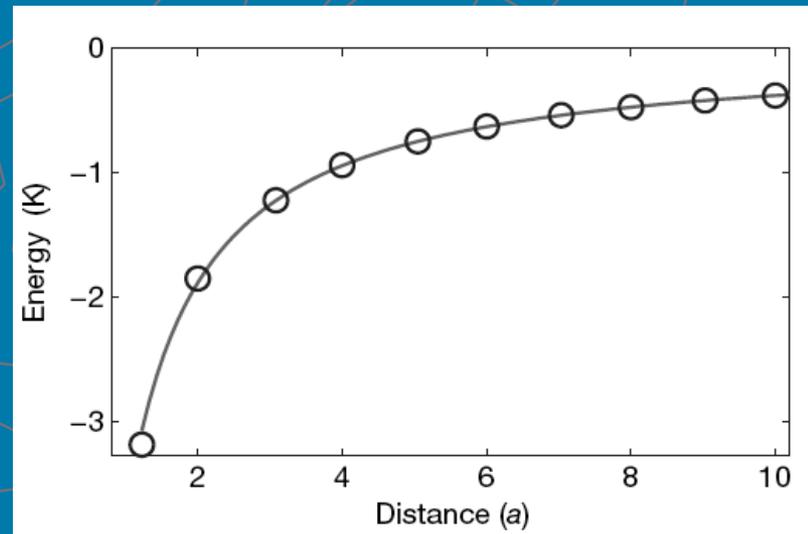


# Monopolos de Dirac em Spin-Ice

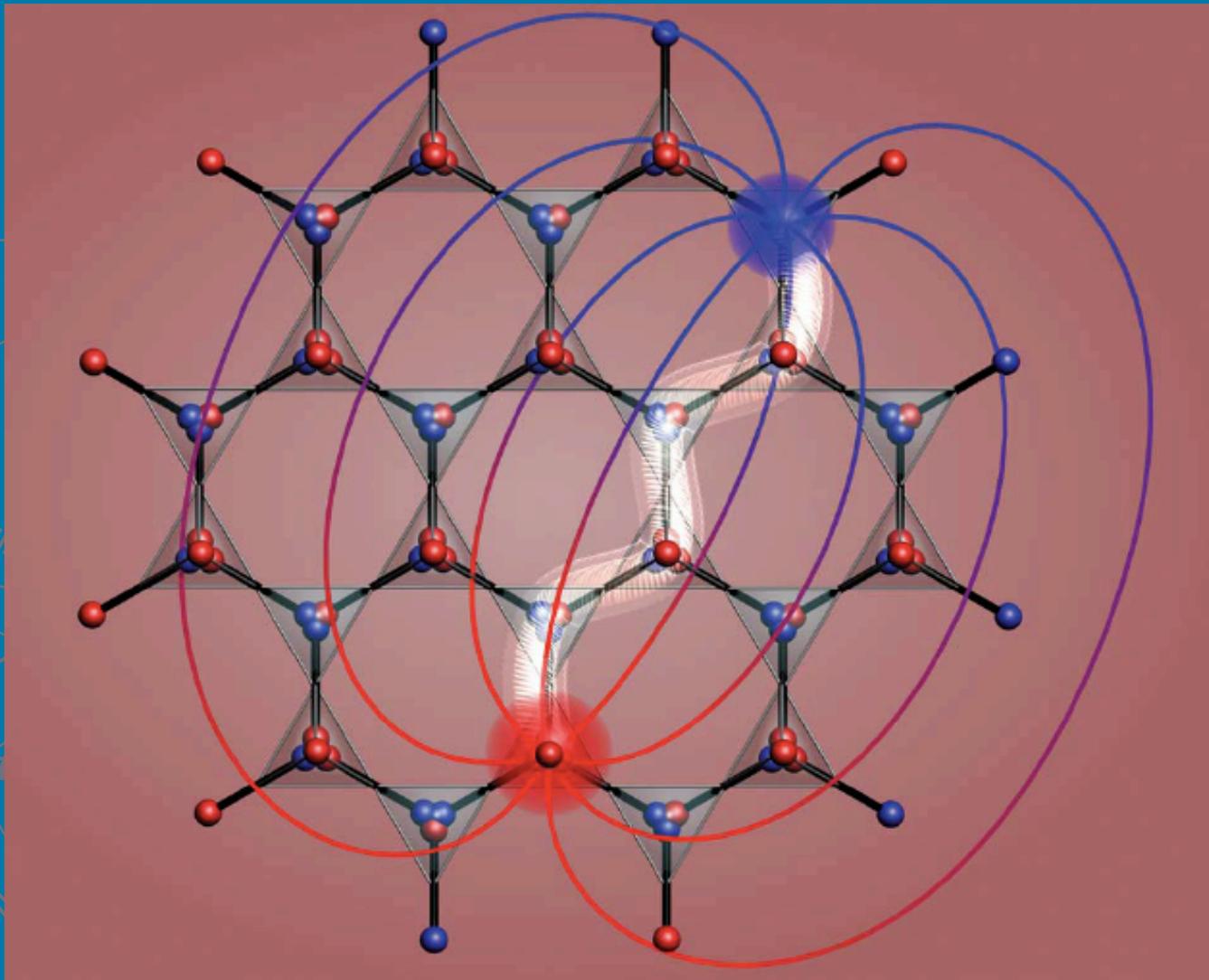


$$\frac{-\mu_0 q_m^2}{4\pi r}$$

Gás de Coulomb / Monopolos

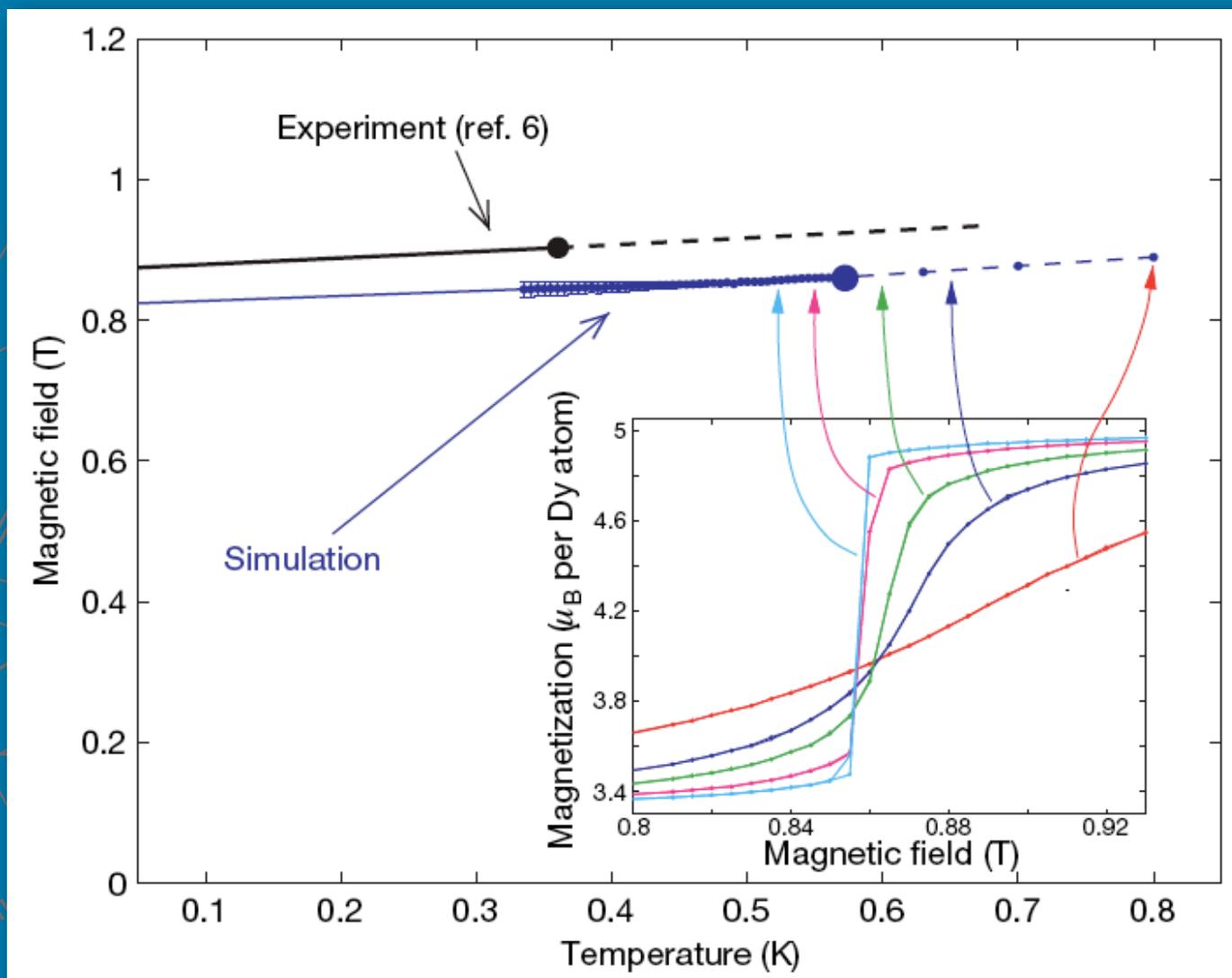


# Strings de Dirac no vácuo magnético



O custo energético para separar os monopolos é FINITO!!!

# Evidência experimental em $\text{Dy}_2\text{Ti}_2\text{O}_7$



**Transição gás-líquido de 1ª ordem dos monopolos magnéticos!!**

# Outras aplicações



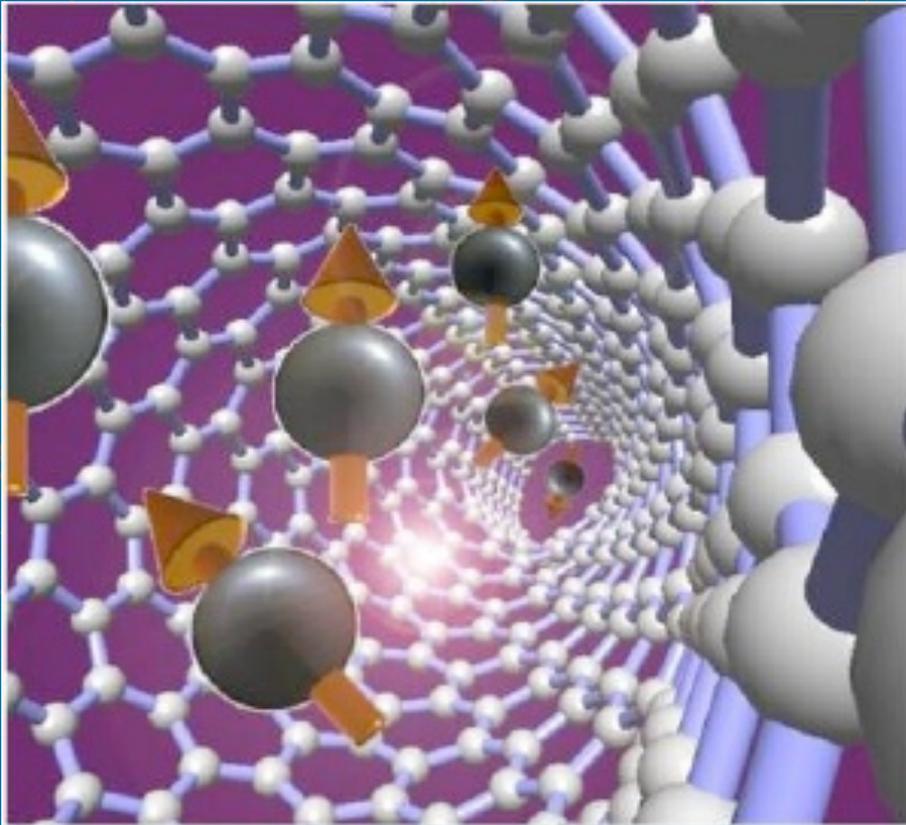
do



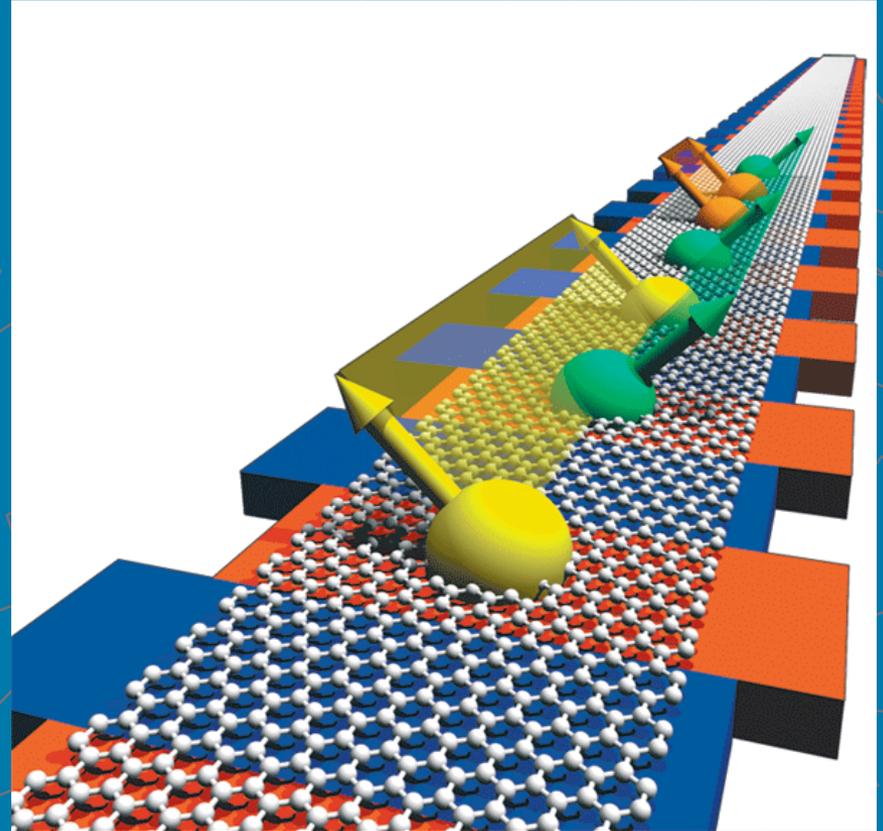
# MAGNETISMO!

# Aplicações futuras...

Co em nanotubos



q-bits no grafeno

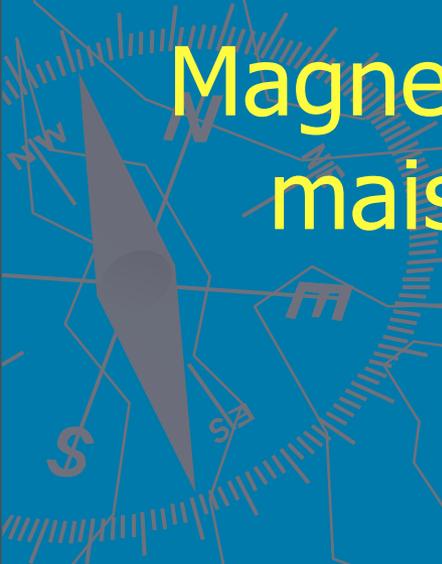


# Conclusões



# Conclusões

Magnetismo pode ser usado para fins mais nobres que levitar sapos !!!



# Que tal morangos ?



O moranguês voador !

# Muito Obrigado!!!



# Muito Obrigado!!!

