

# Magnetism

**Transition & Lanthanide ions  
and their complexes**

# Magnetism - Background

From paired & unpaired electron spins

**Each spinning electron causes a magnetic field around it. In most cases, the magnetic field of one electron is cancelled by an opposite magnetic field produced by the other electron in the pair.**

**In metals, such as, iron, cobalt and nickel, there are several unpaired electrons, so they do not cancel all the electrons' magnetic fields.**

**As a result, each atom of these metals acts like a small magnet.**

# Magnetochemistry -- Introduction

**Electron spin:** An electron has two intrinsic spin states, which are referred as up and down or alpha and beta.

**Electron orbital motion:** A magnetic field is generated due to the electron moving around the nucleus.

**Nuclear spin:** Some nuclei, such as hydrogen, have a net spin, which generates a magnetic field.

Each of these magnetic fields interact with one another and with the external magnetic fields. However, some of these interactions are strong, some are weak and some are negligible.

# Dia and Paramagnetic compounds

*N<sub>2</sub> diamagnetic*

Pouring liquid dinitrogen



liquid dinitrogen  
does NOT stick



Dia.M. ex. H<sub>2</sub>O, KCl organic ligands,  
etc.

Bismuth metal (most diamagnetic  
of all metals)

diamagnetic

## ***$O_2$ paramagnetic***

when dioxygen is in its ground state it is a triplet (spin  $S=1$ )  
and its reactivity is weak.



Liquid  $O_2$



liquid dioxygen  
does stick

$O_2$  is paramagnetic

## Magnetic Levitation: Property of diamagnetic molecules



## Magnetisation

The classical theory of magnetism was well developed before quantum mechanics. Lenz's Law (~1834), states that:

When a substance is placed within a magnetic field,  $H$ , the field within the substance,  $B$ , differs from  $H$  by the induced field,  $4\pi I$ , which is proportional to the intensity of magnetization,  $I$ .

That is;  $B = H + 4\pi I$

$B$  = the magnetic field within the substance

$H$  = the applied magnetic field

$I$  = the intensity of magnetisation

$$B/H = 1 + 4\pi I/H \quad \text{or} \quad B/H = 1 + 4\pi \kappa$$

where  $B/H$  is called the magnetic permeability of the material and  $\kappa$  is the magnetic susceptibility per unit volume,  $(I/H)$

By definition,  $\kappa$  in a vacuum is zero,

so,  **$B = H$ .**



## Molar Susceptibility

It is usually more convenient to measure mass (gram) susceptibility,  $\chi_g$ , which is related to the volume susceptibility through the density.

$$\chi_g = \kappa/\rho \quad \text{where } \rho \text{ is density}$$

Finally to get our measured quantity on a basis that can be related to atomic properties, we convert it to molar susceptibility

$\chi_m = \chi_g \times \text{M.Wt.}$  Where, M. Wt. is molecular weight of the sample

Volume  $\rightarrow$  mass  $\rightarrow$  molar **SUSCEPTIBILITY**



## Magnetic moment ( $\mu$ ) from susceptibility ( $\chi$ )

### Calculation of $\mu$ from $\chi$

$$\chi_m = N\mu^2 / 3kT$$

where N is Avogadro's No.; k is the Boltzmann and T the absolute temp

Rewriting this gives the magnetic moment as

$$\mu_{so} = \sqrt{\frac{3k}{N\beta^2}} \sqrt{\chi T} = 2.828 \sqrt{\chi T}$$

# Magnetism in Metal Complexes

Many transition metal salts and complexes are paramagnetic due to partially filled d-orbitals.

The experimentally measured magnetic moment ( $\mu$ ) (and from the equation in the previous page) can provide some important information about the compounds themselves:

- No of unpaired electrons present
- Distinction between HS and LS octahedral complexes
- Spectral behavior, and
- Structure of the complexes

# Sources of Paramagnetism

Orbital motion of the electron generates ORBITAL MAG. MOMENT ( $\mu_l$ )

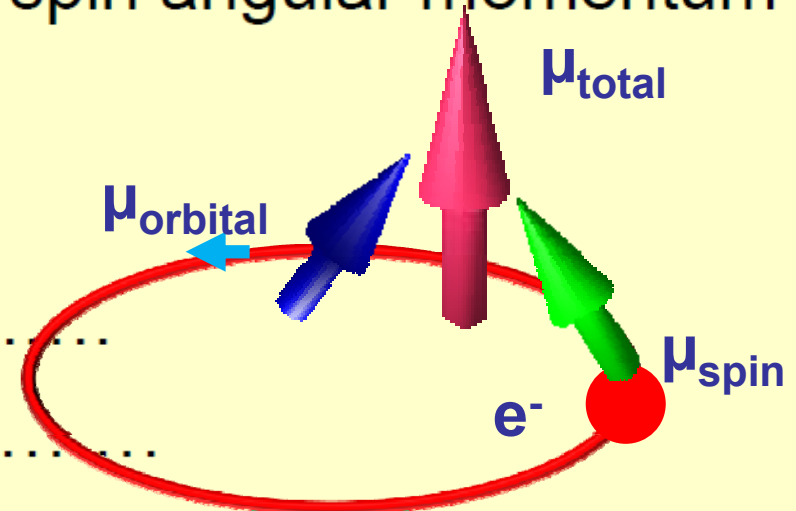
Spin motion of the electron generates SPIN MAG. MOMENT ( $\mu_s$ )

$l$  = orbital angular momentum;  $s$  = spin angular momentum

For multi-electron systems

$$L = l_1 + l_2 + l_3 + \dots$$

$$S = s_1 + s_2 + s_3 + \dots$$



$$\mu_{l+s} = [4S(S+1) + L(L+1)]^{1/2} \text{ B.M.}$$

$$\mu_{L+S} = [4S(S+1) + L(L+1)]^{1/2} \text{ B.M.}$$

For TM-complexes, the magnetic properties arise mainly from the exposed *d*-orbitals. The *d*-orbitals are perturbed by ligands.

∴ The rotation of electrons about the nucleus is restricted which leads to  $L = 0$

$$\mu_s = [4S(S+1)]^{1/2} \text{ B.M.}$$

$S = n(1/2) = n/2$ ;  $n$  = no of unpaired electrons

Hence

$$\mu_s = [4(n/2)(n/2+1)]^{1/2} \text{ B.M.}$$

$$= [n(n+2)]^{1/2} \text{ B.M.}$$

This is called Spin-Only Formula

$\mu_s = 1.73, 2.83, 3.88, 4.90, 5.92 \text{ BM}$  for  $n = 1$  to  $5$ , respectively

## Conditions to exhibit orbital angular momentum ( $\mu_L$ )

- The orbitals should be degenerate ( $t_{2g}$  or  $e_g$ )
- The orbitals should be similar in shape and size. Should be possible to transform an orbital into an equivalent one by rotation. This is indeed possible to transform the  $t_{2g}$  orbitals into each other by  $90^\circ$  rotation. Such transformation is not possible with the orbitals of  $e_g$ .
- The orbitals must not contain electrons of identical spin during this transformation and the movement of electron

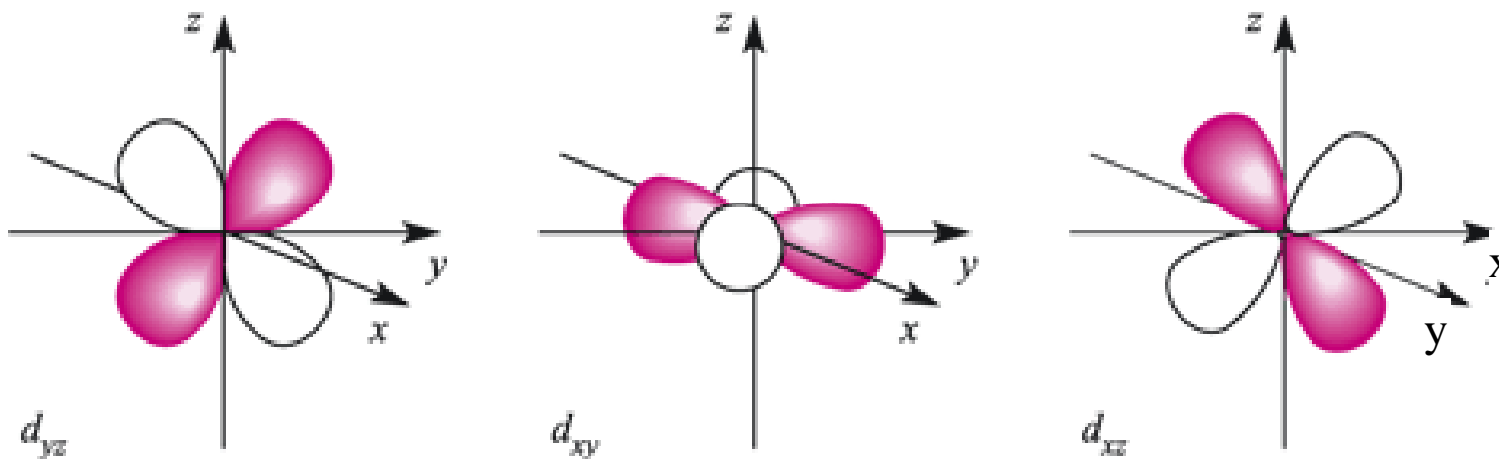
These conditions are fulfilled only when one or two orbitals contain partially filled electrons in  $t_{2g}$  and NOT in  $e_g$

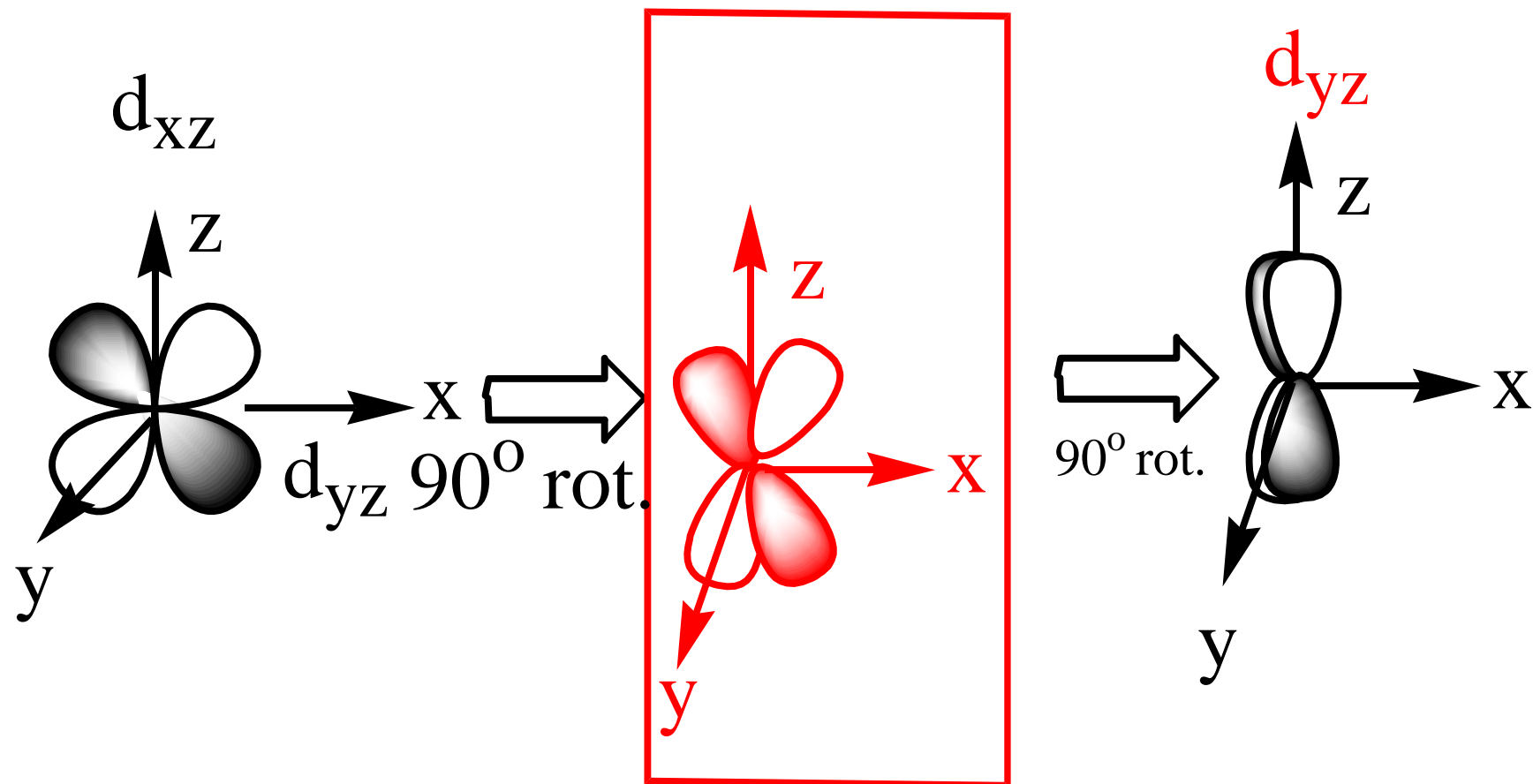
## Octahedral complexes

The degenerate  $t_{2g}$  orbitals ( $d_{xy}$ ,  $d_{xz}$ ,  $d_{yz}$ ) can be interconverted by  $90^\circ$  rotations

e.g. the  $d_{xz}$  orbital is transformed into the  $d_{yz}$  orbital by a rotation of  $90^\circ$  about the z-axis – during this rotation the electron is orbiting the nucleus

Thus, an electron in a  $t_{2g}$  orbital **can** contribute to orbital angular momentum



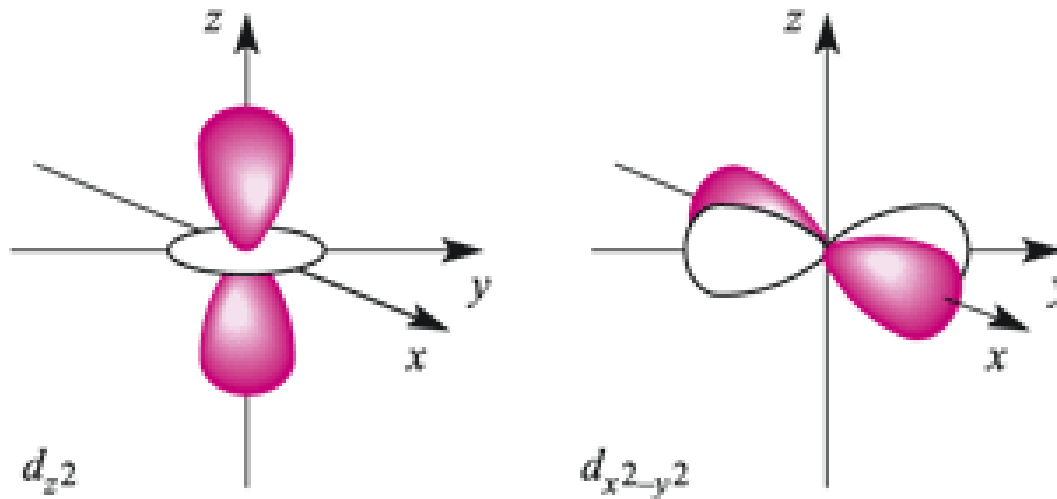




## Octahedral complexes

However the  $e_g$  orbitals ( $d_{z^2}$  and  $d_{x^2-y^2}$ ) cannot be interconverted by rotation as they are different shapes

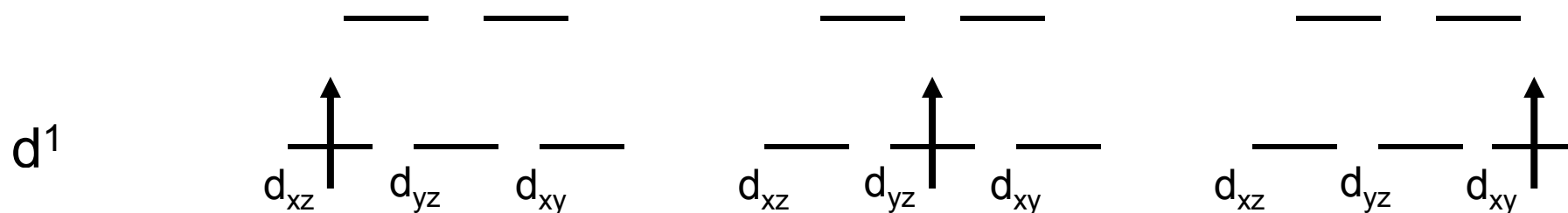
Thus an electron in an  $e_g$  orbital **can not** contribute to orbital angular momentum



# Orbital contribution to the magnetic moment

## high spin octahedral $d^n$ ions

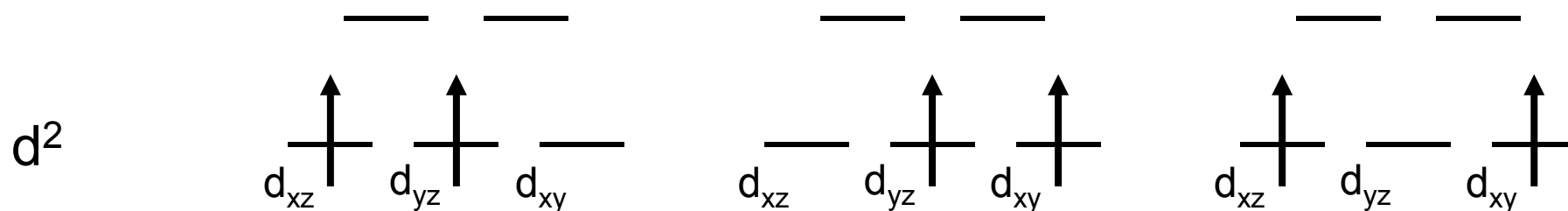
think of **possible**  $t_{2g}$  electron arrangements



Possible  $t_{2g}$  arrangements = 3

Orbital contribution = **YES**

$d^1$  e.g. Ti(III)



Possible  $t_{2g}$  arrangements = 3

Orbital contribution = **yes**

$d^2$  e.g. V(III)

# Quenched orbital angular momentum

$d^n$	Octahedral		Tetrahedral
	high-spin low-spin		
$d^1$			$e^1$
$d^2$			$e^2$
$d^3$	$t_{2g}^3$		
$d^4$		$t_{2g}^3 e_g^1$	
$d^5$		$t_{2g}^3 e_g^2$	
$d^6$			$t_{2g}^6$
$d^7$			$e^3 t_2^3$
$d^8$	$t_{2g}^6 e_g^2$		$e^4 t_2^3$
$d^9$	$t_{2g}^6 e_g^3$		

## High spin complexes

<b>Ion</b>	<b>Number of unpaired electrons</b>	<b>Spin-only moment /<math>\mu_B</math></b>	<b>observed moment /<math>\mu_B</math></b>
<b>Ti<sup>3+</sup></b>	<b>1</b>	<b>1.73</b>	<b>1.73</b>
<b>V<sup>4+</sup></b>	<b>1</b>		<b>1.68–1.78</b>
<b>Cu<sup>2+</sup></b>	<b>1</b>		<b>1.70–2.20</b>
<b>V<sup>3+</sup></b>	<b>2</b>	<b>2.83</b>	<b>2.75–2.85</b>
<b>Ni<sup>2+</sup></b>	<b>2</b>		<b>2.8–3.5</b>
<b>V<sup>2+</sup></b>	<b>3</b>	<b>3.87</b>	<b>3.80–3.90</b>
<b>Cr<sup>3+</sup></b>	<b>3</b>		<b>3.70–3.90</b>
<b>Co<sup>2+</sup></b>	<b>3</b>		<b>4.3–5.0</b>
<b>Mn<sup>4+</sup></b>	<b>3</b>		<b>3.80–4.0</b>
<b>Cr<sup>2+</sup></b>	<b>4</b>	<b>4.90</b>	<b>4.75–4.90</b>
<b>Fe<sup>2+</sup></b>	<b>4</b>		<b>5.1–5.7</b>
<b>Mn<sup>2+</sup></b>	<b>5</b>	<b>5.92</b>	<b>5.65–6.10</b>
<b>Fe<sup>3+</sup></b>	<b>5</b>		<b>5.7–6.0</b>

# Orbital Contributions in Octahedral Complexes

Ion	Config	OAM ?	$\mu_{so}$	$\mu_{obs}$
Ti(III)	d1	yes	1.73	1.6-1.7
V(IV)	d1	yes	1.73	1.7-1.8
V(III)	d2	yes	2.83	2.7-2.9
Cr(IV)	d2	yes	2.83	2.8
V(II)	d3	no	3.88	3.8-3.9
Cr(III)	d3	no	3.88	3.7-3.9
Mn(IV)	d3	no	3.88	3.8-4.0
Cr(II)	d4 h.s	no	4.90	4.7-4.9
Cr(II)	d4 l.s.	yes	2.83	3.2-3.3
Mn(III)	d4 h.s	no	4.90	4.9-5.0
Mn(III)	d4 l.s.	yes	2.83	3.2
Mn(II)	d5 h.s	no	5.92	5.6-6.1
Mn(II)	d5 l.s	yes	1.73	1.8-2.1
Fe(III)	d5 h.s	no	5.92	5.7-6.0
Fe(III)	d5 l.s	yes	1.73	2.0-2.5
Fe(II)	d6 h.s	yes	4.90	5.1-5.7
Co(II)	d7 h.s	yes	3.88	4.3-5.2
Co(II)	d7 l.s	no	1.73	1.8
Ni(III)	d7 l.s	no	1.73	1.8-2.0
Ni(II)	d8	no	2.83	2.9-3.3
Cu(II)	d9	no	1.73	1.7-2.2

# High & Low – Spin Octahedral complexes & Spin Cross-Over

## High and low -spin octahedral complexes

d-count	Number of unpaired electrons		examples
	high-spin	low-spin	
d <sup>4</sup>	4	2	Cr <sup>2+</sup> , Mn <sup>3+</sup>
d <sup>5</sup>	5	1	Mn <sup>2+</sup> , Fe <sup>3+</sup>
d <sup>6</sup>	4	0	Fe <sup>2+</sup> , Co <sup>3+</sup>
d <sup>7</sup>	3	1	Co <sup>2+</sup>

With one unpaired electron  $\mu_{\text{eff}}$  values range from 1.8 to 2.5  $\mu_{\text{B}}$  and with two unpaired electrons the range is 3.18 to 3.3  $\mu_{\text{B}}$ .

## Spin cross-over

When the energy difference between the high-spin and low-spin states is comparable to  $kT$  ( $k$  is the Boltzmann constant and  $T$  the temperature) an equilibrium is established between the spin states, involving what have been called "electronic isomers".

Tris-dithiocarbamate iron(III),  $\text{Fe}(\text{S}_2\text{CNR}_2)_3$ , is a well-documented example. The effective moment varies from a typical d<sup>5</sup> low-spin value of 2.25  $\mu_{\text{B}}$  at 80 K to more than 4  $\mu_{\text{B}}$  above 300 K.

## Orbital Contributions in tetrahedral Complexes

Ion	Config	OAM ?	$\mu_{so}$	$\mu_{obs}$
Cr(V)	d1	no	1.73	1.7-1.8
Mn(VI)	d1	no	1.73	1.7-1.8
Cr(IV)	d2	no	2.83	2.8
Mn(V)	d2	no	2.83	2.6-2.8
Fe(V)	d3	yes	3.88	3.6-3.7
-	d4	yes	4.90	-
Mn(II)	d5	no	5.92	5.9-6.2
Fe(II)	d6	no	4.90	5.3-5.5
Co(II)	d7	no	3.88	4.2-4.8
Ni(II)	d8	yes	2.83	3.7-4.0
Cu(II)	d9	yes	1.73	



**GS = Ground electronic State; ES = Excited electronic State**

## Other Reasons for Orbital Contribution:

Although  $\mu$  normally develops from GS, sometimes ES also may contribute, especially the GS-ES energy difference is very small.

Example:

Take  $\text{Ni}^{2+}$  octahedral;  $d^8$ ; GS:  $t_{2g}^6 e_g^2$  no  $\mu_l$

ES:  $t_{2g}^5 e_g^3$   $\mu_l$  contributes

Similarly,

Take  $\text{Co}^{2+}$  tetrahedral;  $d^7$  GS:  $e^4 t_2^3$  no  $\mu_l$

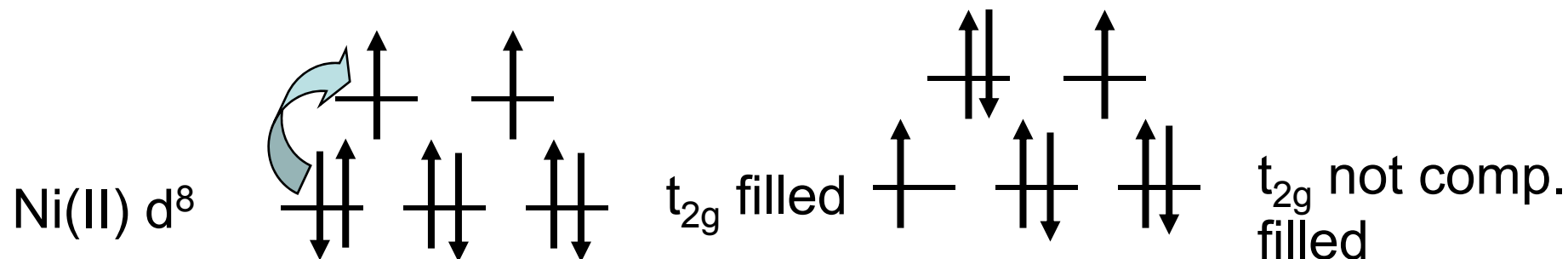
ES:  $e^3 t_2^4$   $\mu_l$  contributes

Therefore;  $\mu_{\text{obs}} > \mu_s$  for both  $O_h \text{ Ni}^{2+}$  and  $T_d \text{ Co}^{2+}$

# Orbital contribution to the magnetic moment

## Contribution due to the excited state(s)

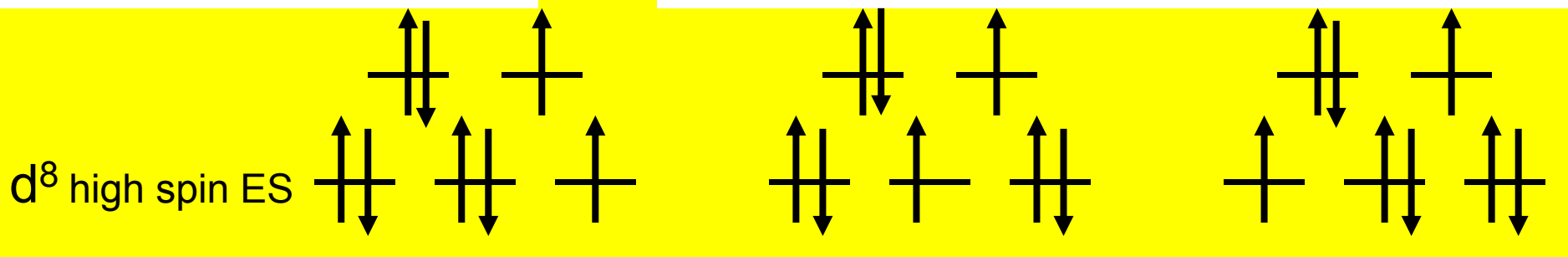
think of **possible**  $t_{2g}$  electron arrangements



**Excited state**

Possible  $t_{2g}$  arrangements = 1

**Orbital contribution = NO**



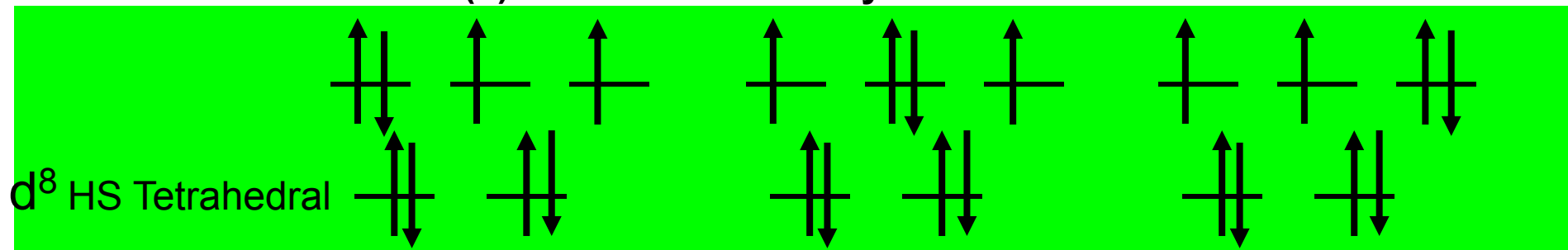
Possible  $t_{2g}$  arrangements = 3

**Orbital contribution = YES**

$$\mu_{\text{exp}} > \mu_s \text{ for Oct. Ni}^{2+}$$

Therefore for  $O_h$  Ni(II) the magnetic moments are larger if the GS-ES gap is small.

BUT FOR Tetrahedral Ni(II) situation is entirely different ....



Possible  $t_{2g}$  arrangements = 3

Orbital contribution = YES

$M_{\text{exp}} O_h \text{ Ni(II)}$  is smaller than  $M_{\text{exp}} T_d \text{ Ni(II)}$

Exp.  $\text{NiCl}_4^{2-}$ ,  $\text{Ni(HMPA)}_4^{2+}$  (HMPA=hexamethyl phosphoramidate) have mag. moment larger than 4 BM.

(Larger the distortion smaller the mag.moment )

USEFUL IN DISCRIMINATING  $O_h$  vs  $T_d$  structures.

# Magnetic properties of lanthanides

- The f electrons in lanthanides are buried in the (n-2) shell

- $\therefore$  Thus 4f normally unaffected by surrounding ligands
- Hence, the magnetic moments of  $\text{Ln}^{3+}$  ions are generally well-described from the coupling of spin and orbital angular momenta  $\sim$  Russell-Saunders Coupling to give J vector
- spin orbit coupling constants are large (ca.  $1000 \text{ cm}^{-1}$ )
- ligand field effects are very small (ca.  $100 \text{ cm}^{-1}$ )
  - only ground J-state is populated
  - spin-orbit coupling  $\gg$  ligand field splittings
- magnetism is essentially independent of environment

# **Spectroscopic Terms (& Term Symbols)**

Different microstates exist for the same electronic configuration.

Russel-Saunders coupling is used to describe the terms.

The symbol will represent the total value of azimuthal quantum numbers ( $L = \sum l_i$ ) and it takes the letters, 'S, P, D, F, G, H, I, K, L, M, N' respectively for L values of 0, 1, 2, 3, 4, 5, 6, 7, 8, 9 and 10.

The degeneracy  $(2S+1)$  {S = sum of all the spins} is shown on the left superscript.

The term symbol is shown as  $(2S+1)L$  {for eg.,  $^3F$  corresponds to  $S = 1$  and  $L = 3$ }

No. of microstates for  $^3F$  is,  $(2S+1) \times (2L+1) = 3 \times 7 = 21$

Magnetic moment of a J-state is expressed by:

$$\mu = g_J \sqrt{J(J+1)} \mu_B \quad g_J = \frac{3}{2} + \frac{S(S+1) - L(L+1)}{2J(J+1)}$$

$$J = L+S, L+S-1, \dots, L-S$$

*For the calculation of g value, we use*

*minimum* value of J for the configurations up to half-filled;

i.e.  $J = L-S$  for  $f^0$ - $f^7$  configurations

*maximum* value of J for config. more than half-filled;

i.e.  $J = L+S$  for  $f^8$ - $f^{14}$  configurations

*For  $f^0$ ,  $f^7$ , and  $f^{14}$ ,  $L = 0$ , hence  $\mu_J$  becomes  $\mu_S$*

	config	g.s.	No. e-	color	calcd	obsd
La	4f <sup>0</sup>	<sup>1</sup> S <sub>0</sub>	0	Colorless	0	0
Ce	4f <sup>1</sup>	<sup>2</sup> F <sub>5/2</sub>	1	Colorless	2.54	2.3 - 2.5
Pr	4f <sup>2</sup>	<sup>3</sup> H <sub>4</sub>	2	Green	3.58	3.4 - 3.6
Nd	4f <sup>3</sup>	<sup>4</sup> I <sub>9/2</sub>	3	Lilac	3.62	3.5 - 3.6
Pm	4f <sup>4</sup>	<sup>5</sup> I <sub>4</sub>	4	Pink	2.68	-
Sm	4f <sup>5</sup>	<sup>6</sup> H <sub>5/2</sub>	5	Yellow	0.85	1.4 - 1.7
Eu	4f <sup>6</sup>	<sup>7</sup> F <sub>0</sub>	6	Pale pink	0	3.3 - 3.5
Gd	4f <sup>7</sup>	<sup>8</sup> S <sub>7/2</sub>	7	Colorless	7.94	7.9 - 8.0
Tb	4f <sup>8</sup>	<sup>7</sup> F <sub>6</sub>	6	Pale pink	9.72	9.5 - 9.8
Dy	4f <sup>9</sup>	<sup>6</sup> H <sub>15/2</sub>	5	Yellow	10.65	10.4 - 10.6
Ho	4f <sup>10</sup>	<sup>5</sup> I <sub>8</sub>	4	Yellow	10.6	10.4 - 10.7
Er	4f <sup>11</sup>	<sup>4</sup> I <sub>15/2</sub>	3	Rose-pink	9.58	9.4 - 9.6
Tm	4f <sup>12</sup>	<sup>3</sup> H <sub>6</sub>	2	pale green	7.56	7.1 - 7.6
Yb	4f <sup>13</sup>	<sup>2</sup> F <sub>7/2</sub>	1	Colorless	4.54	4.3 - 4.9
Lu	4f <sup>14</sup>	<sup>1</sup> S <sub>0</sub>	0	Colorless	0	0



# Sample Landé Calculation for a $\text{Ln}^{3+}$ ion

e.g.  $\text{Pr}^{3+} [\text{Xe}]4f^2$ ; find Ground State from Hund's Rules

- $S = 1/2 + 1/2 = 1$
- $L = 3 + 2 = 5$
- $J = 6, 5, 4$ ;  $J = 4$  is chosen for  $f^2$
- $g = (3/2) + [1(1+1) - 5(5+1)/2(4)(4+1)] = 0.8$

□  $\mu_J = 3.577 \text{ B.M.}$       Experiment = 3.4 - 3.6 B.M

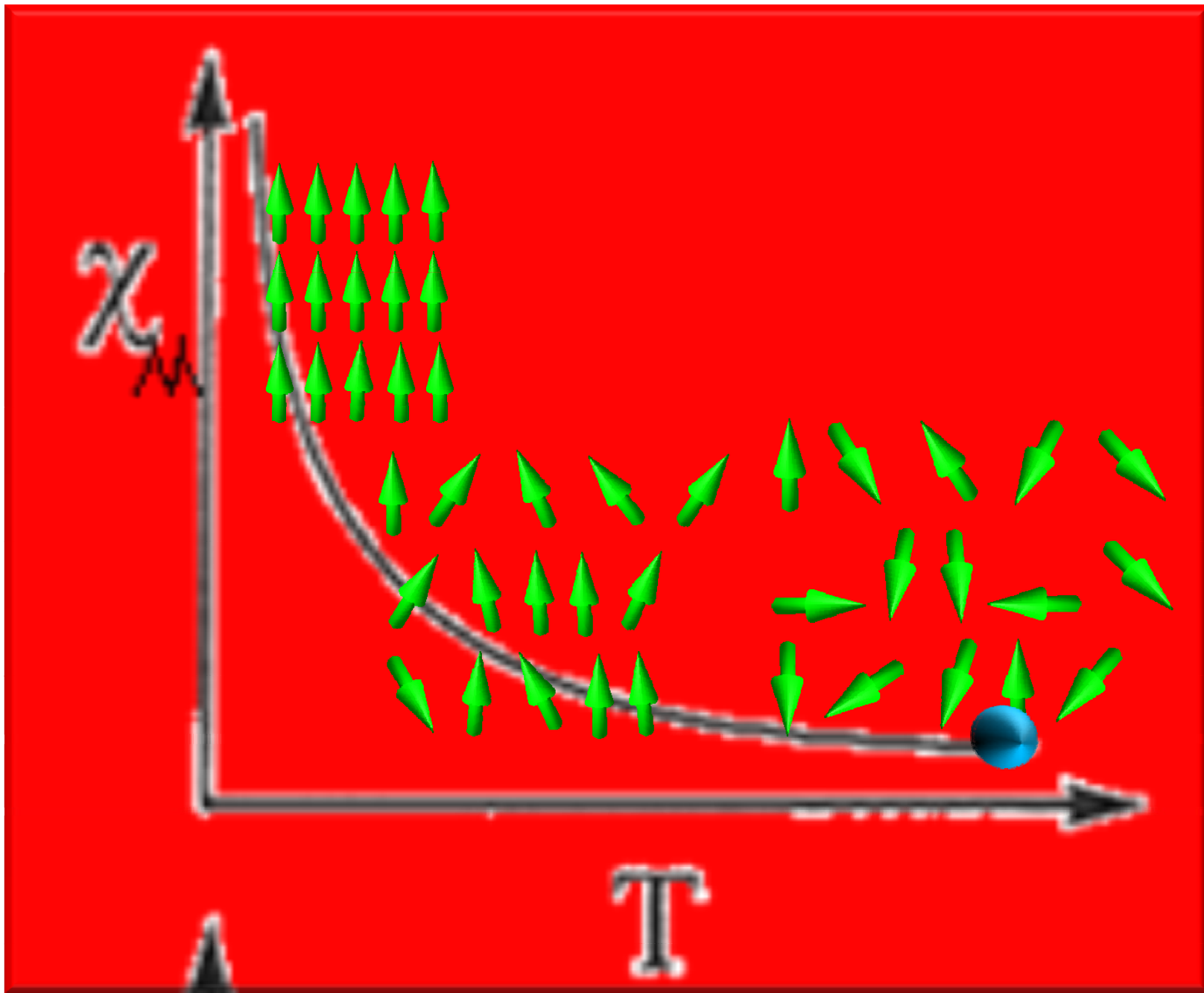
- Landé formula fits well with observed magnetic moments for all but  $\text{Sm}^{\text{III}}$  and  $\text{Eu}^{\text{III}}$  ions.
- Moments of these ions are altered from the Landé expression by temperature-dependent population of low-lying excited J-state(s)

# Magnetic States of Matter

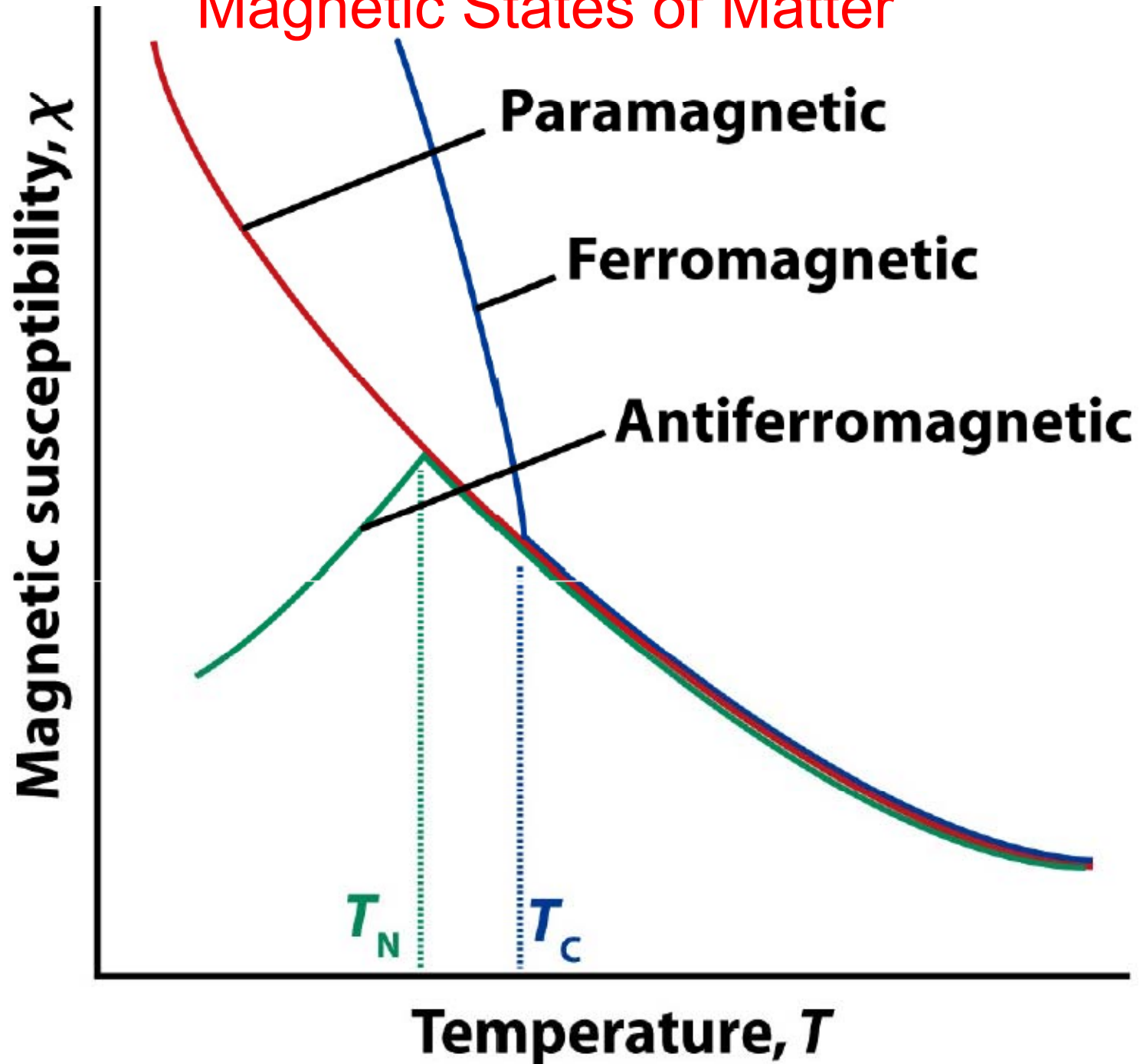
**Diamagnet** - A diamagnetic compound has all of its electron spins paired giving a net spin of zero. Diamagnetic compounds are weakly repelled by a magnet.

**Paramagnet** - A paramagnetic compound will have some electrons with unpaired spins. Paramagnetic compounds are attracted by a magnet. Paramagnetism derives from the spin and orbital angular momenta of electrons. This type of magnetism occurs only in compounds containing unpaired electrons, as the spin and orbital angular momenta is cancelled out when the electrons exist in pairs.

Compounds in which the paramagnetic centres are separated by diamagnetic atoms within the sample are said to be magnetically dilute.



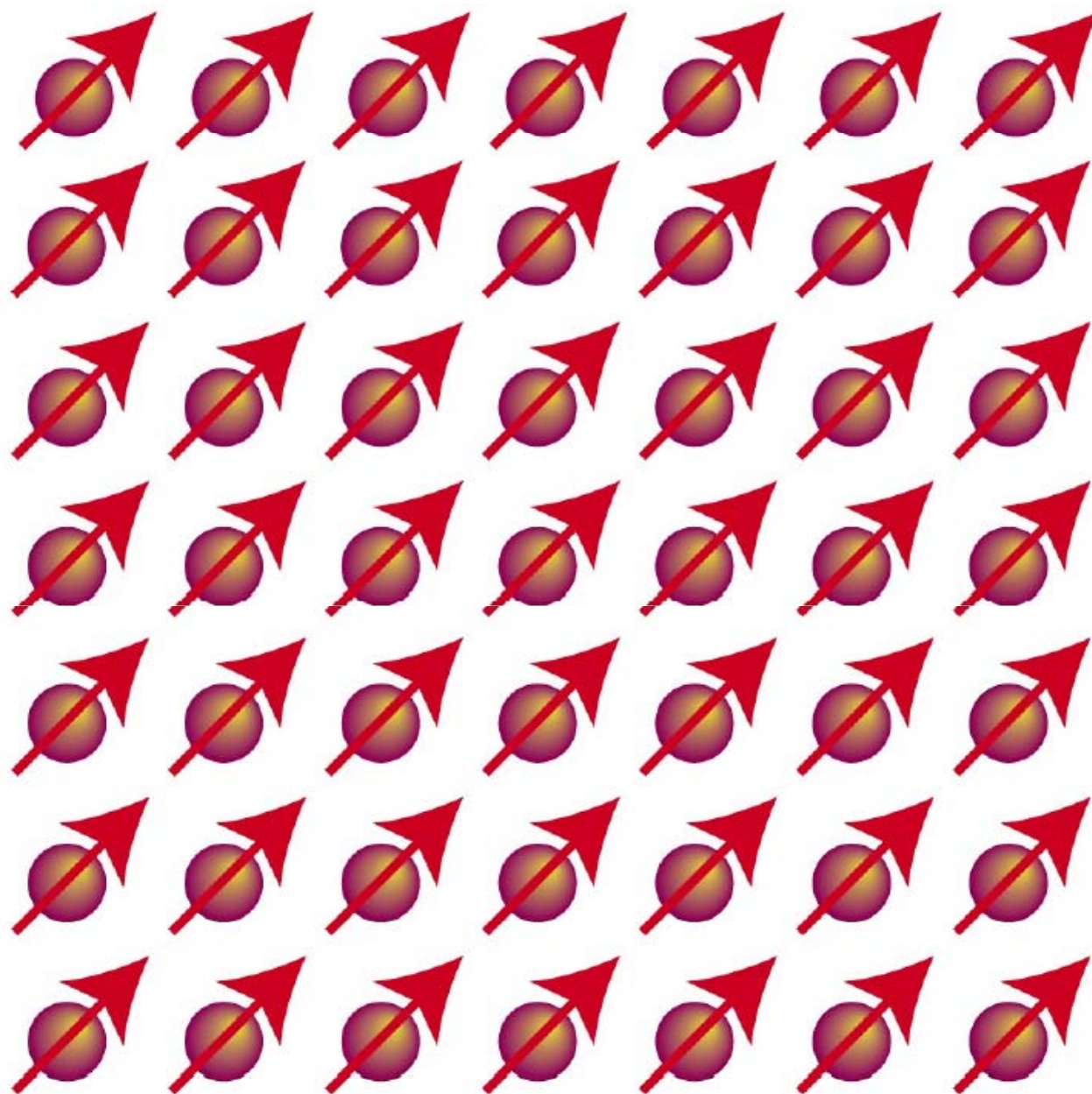
## Magnetic States of Matter

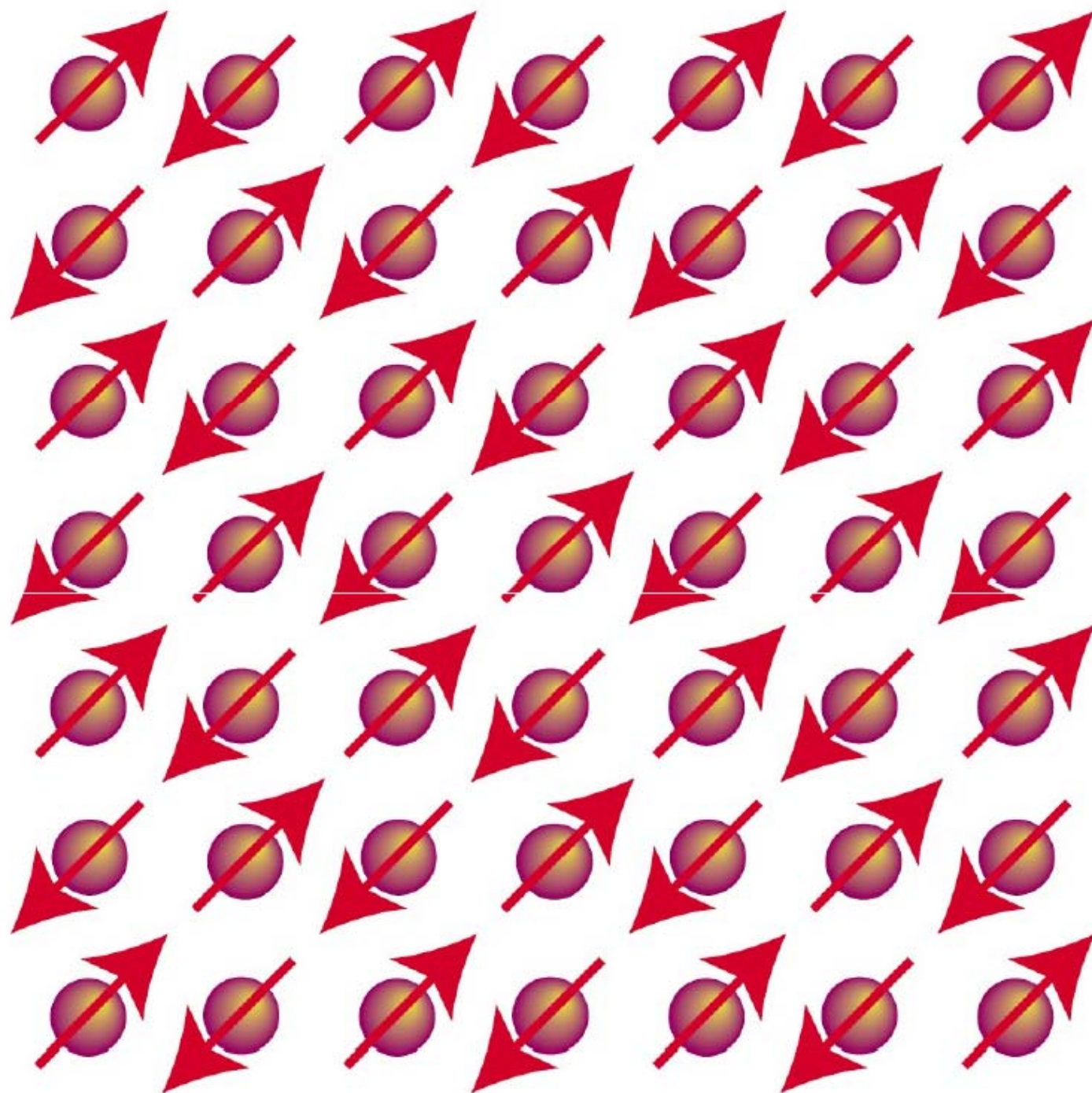


# Magnetic States of Matter

- These two forms of paramagnetism show characteristic variations of the magnetic susceptibility with temperature.
- In the case of ferromagnetism, above the Curie point the material displays "normal" paramagnetic behavior. Below the Curie point the material displays strong magnetic properties. Ferromagnetism is commonly found in compounds containing iron and in alloys.
- For antiferromagnetism, above the Neel point the material displays "normal" paramagnetic behavior. Below the Neel point the material displays weak magnetic properties which at lower and lower temperatures can become essentially diamagnetic. Antiferromagnetism is more common and is found to occur in transition metal halides and oxides, such as  $\text{TiCl}_3$  and  $\text{VCl}_2$ .

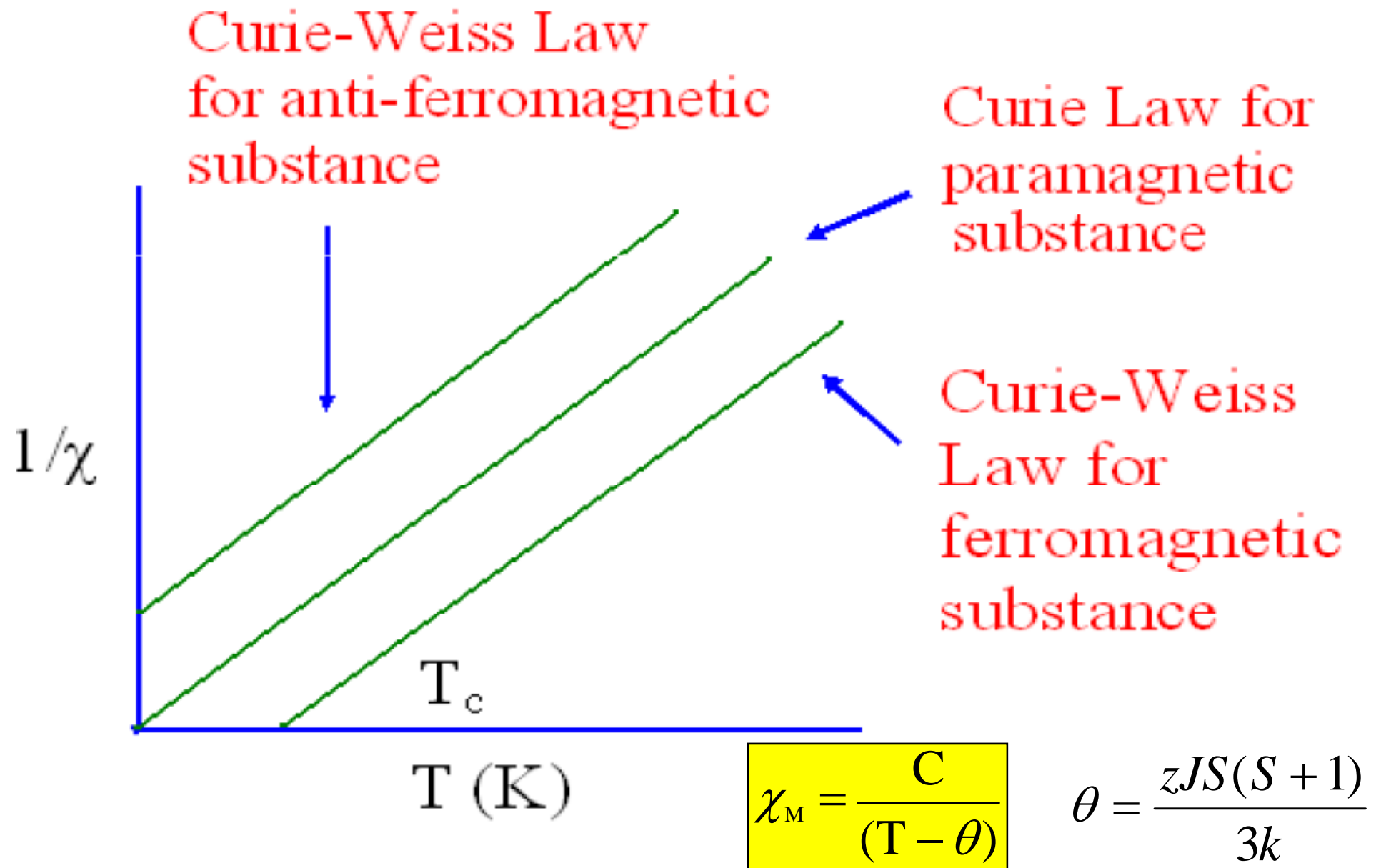


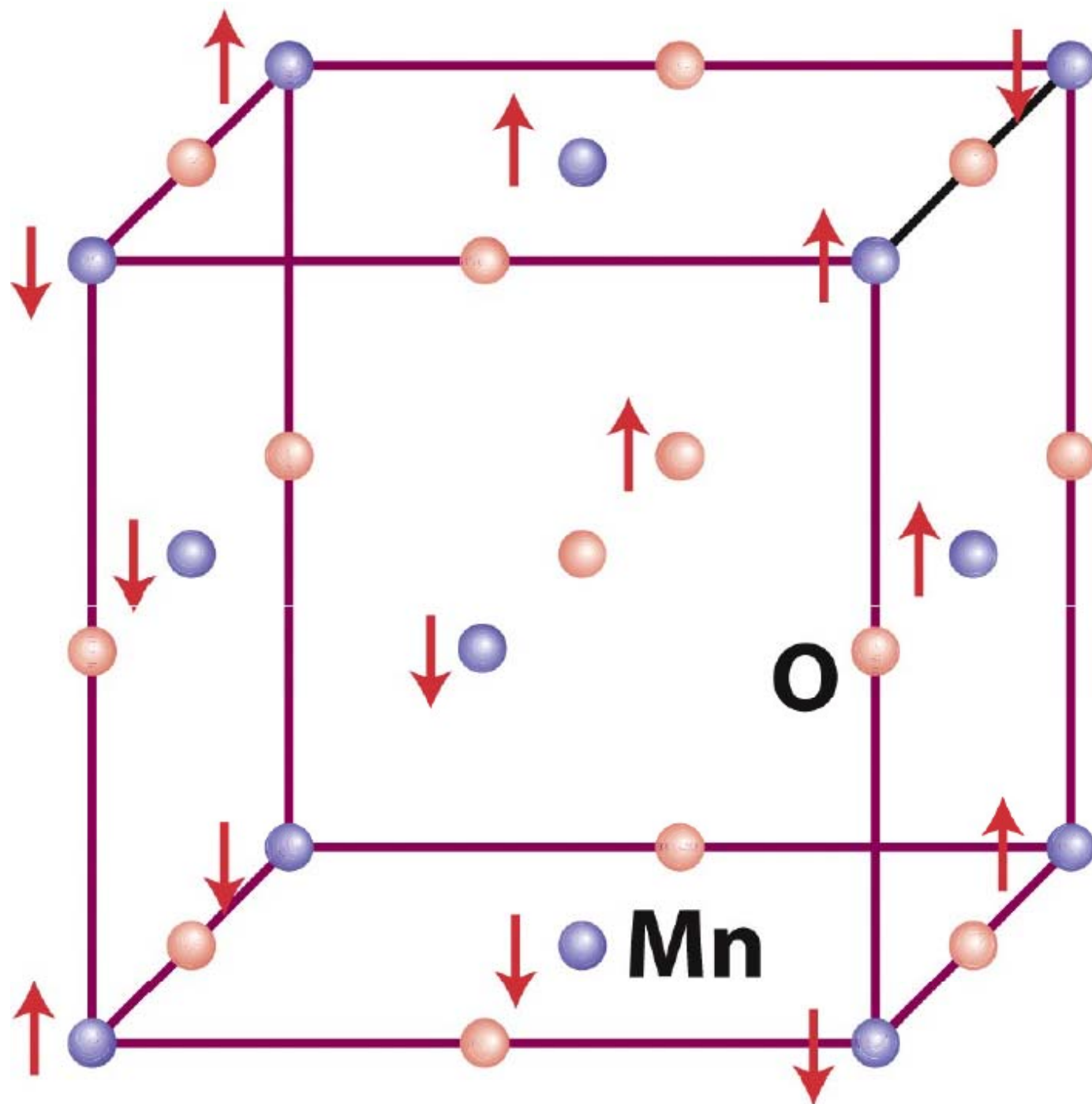




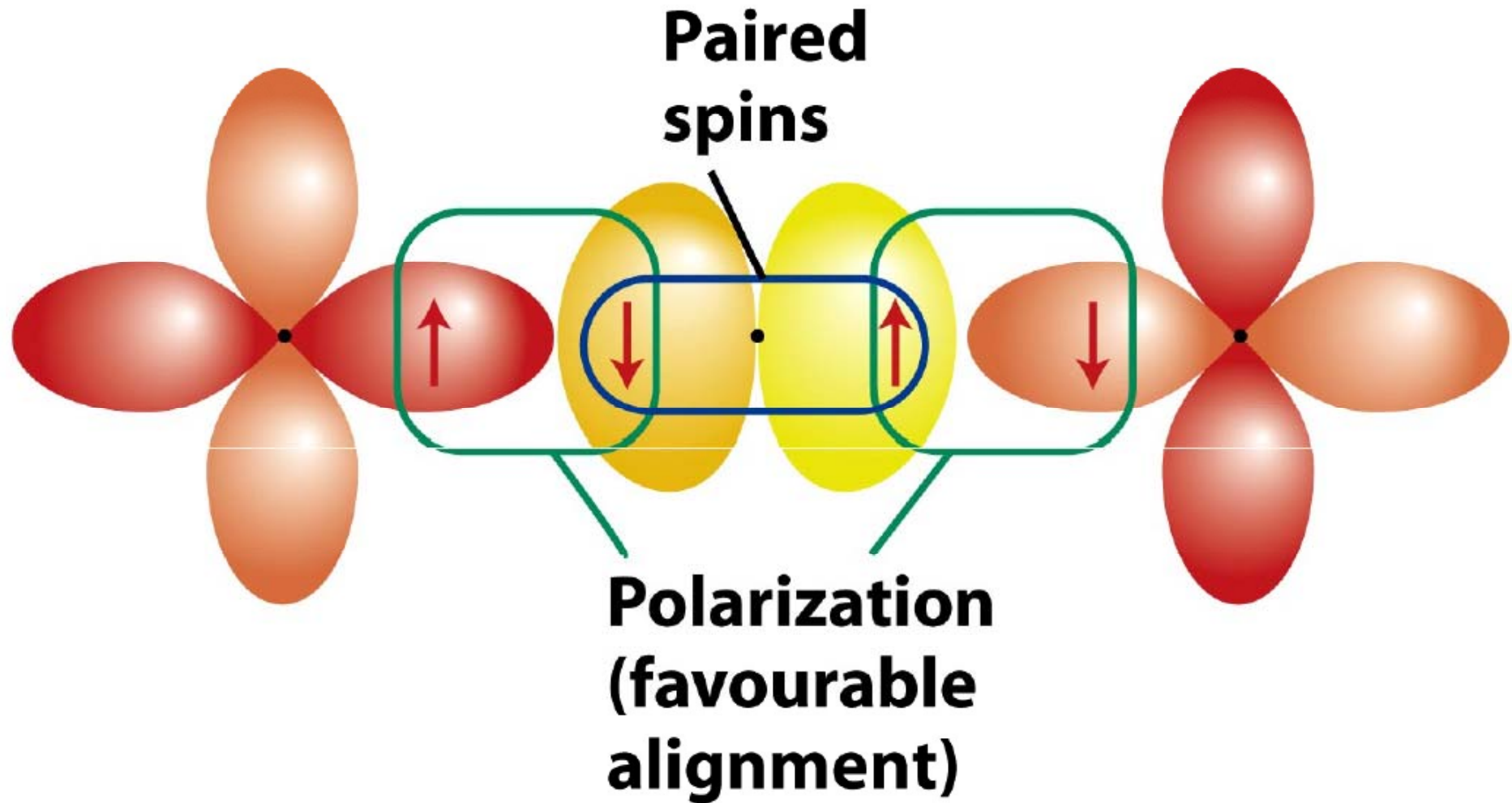


# Magnetic States of Matter





## Magnetic coupling: Origin of AF interaction



# Hard & Soft Magnetic Materials

## Hard Ferromagnet

As permanent magnet

Alnicos

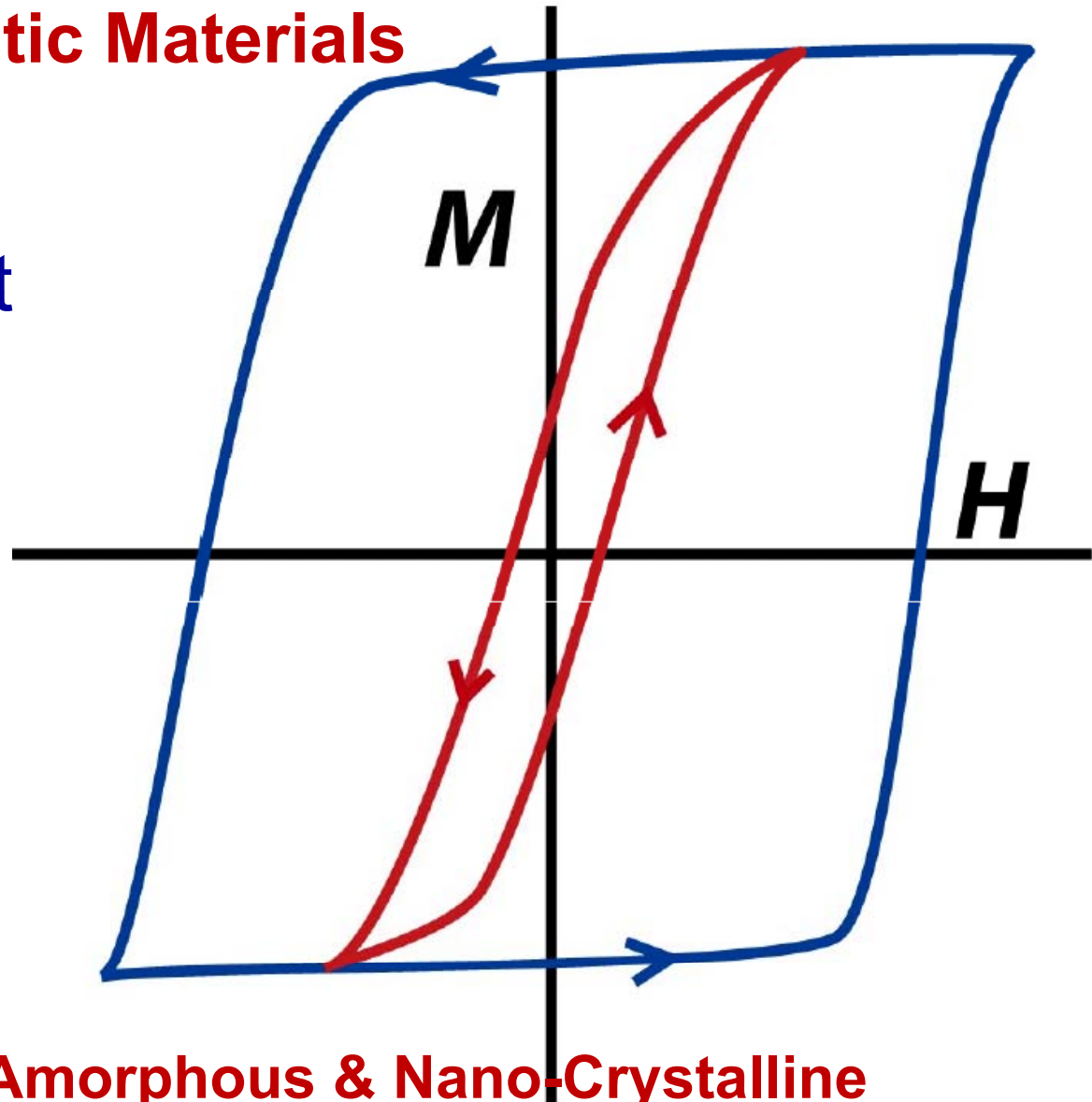
SmCo Type

NdFeB Type

## Soft Ferromagnet

Used in transformers

Iron-Silicon Alloys; Amorphous & Nano-Crystalline Alloys; Nickel-Iron Alloys;  
AC & DC Applications



# Applications of hard ferromagnetic materials

***Automotive:*** Starter motors, Anti-lock braking systems (ABS), Motor drives for wipers, Injection pumps, Fans and controls for windows, seats etc, Loudspeakers, Eddy current brakes, Alternators.

***Telecommunications:*** Loudspeakers, Microphones, Telephone ringers, Electro-acoustic pick-ups, Switches and relays.

***Data Processing:*** Disc drives and actuators, Stepping motors, Printers.

***Consumer Electronics:*** DC motors for showers, Washing machines, Drills, Low voltage DC drives for cordless appliances, Loudspeakers for TV and Audio, TV beam correction and focusing device, Compact-disc drives, Home computers, Video Recorders, Clocks.

***Electronic and Instrumentation:*** Sensors, Contactless switches, NMR spectrometer, Energy meter disc, Electro-mechanical transducers, Crossed field tubes, Flux-transfer trip device, Dampers.

***Industrial:*** DC motors for magnetic tools, Robotics, Magnetic separators for extracting metals and ores, Magnetic bearings, Servo-motor drives, Lifting apparatus, Brakes and clutches, Meters and measuring equipment.

***Astro and Aerospace:*** Frictionless bearings, Stepping motors, Couplings, Instrumentation, Travelling wave tubes, Auto-compass.

***Biosurgical:*** Dentures, Orthodontics, Orthopaedics, Wound closures, Stomach seals, Repulsion collars, Ferromagnetic probes, Cancer cell separators, Magnetomotive artificial hearts, NMR / MRI body scanner.

## Problem:

- Account for the magnetic moments of  $(\text{Et}_4\text{N})_2[\text{NiCl}_4]$  recorded at 80 and 300 K.
- 80K   300K
- 3.25   3.89 B.M.
- $\text{Ni}^{2+}$  is a  $d^8$  metal ion.
- The formula suggests a 4 coordinate complex and we can assume that the complex is tetrahedral with a d electron configuration of  $e^4 t_2^4$  therefore the spin-only magnetic moment can be calculated as 2.83 BM
- Why did we ignore the possibility of it being square-planar?
- The free ion Russell-Saunders ground term is  $^3F$  ( $L=3$  and  $S=1$ ) which will give rise to a lowest energy T term in a tetrahedral field and hence the resultant magnetic moment is expected to be temperature dependent and have a direct orbital contribution.

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This is understood from Spectroscopy. Without going into the spectroscopy related parameters, it can be said that the  $d^8$  will be diamagnetic if it were square planar.



## Problem: Continued

- The observed values may be quite different then to the calculated spin only magnetic moment.
- The value of  $\mu_{S+L}$  can be calculated as:  $\mu_{S+L} = \sqrt{4S(S+1)+L(L+1)}$
- $= \sqrt{8+12} = \sqrt{20} = 4.47 \text{ B.M.}$
- If you use the spin-only formula  $\mu_s = \sqrt{n(n+2)} = \sqrt{8} = 2.8 \text{ BM}$
- Now go back and check above the observed magnetic moments at the given temperatures. What do you conclude?
- From the observed values it can be seen that the magnetic moment of the  $d^8 \text{ Ni}^{2+}$  complex is intermediate between the  $\mu_s$  and  $\mu_{S+L}$  values (probably due to partial quenching of the orbital angular momentum contribution) and is dependent on temperature.