

# MAGNETIC MATERIALS

1/ What features of atomic structure determine whether an element is diamagnetic or paramagnetic? Explain. Consider two examples: Cl and Zn atoms.

The magnetic form of a substance can be determined by examining its electron configuration: if it shows unpaired electrons, then the substance is paramagnetic; if all electrons are paired, the substance is diamagnetic. Paramagnetism requires a net magnetic moment per atom, whereas diamagnetism requires zero net magnetic moment of the atom current loops, in absence of external field, and induced magnetic moment per atom in external field which opposes the external field.

The analysis process can be broken into four steps:

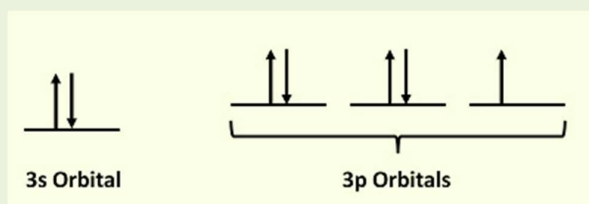
## Ex 1. Chlorine atom

Step 1: Find the electron configuration

For Cl atoms, the electron configuration is ( $Z=17$ )  
 $1s^2 2s^2 2p^6 3s^2 3p^5$

Step 2: Draw the valence orbitals

*Ignore the core electrons and focus on the valence electrons only.*



Step 3: Look for unpaired electrons

There is one unpaired electron.

Step 4: Determine whether the substance is paramagnetic or diamagnetic

Since there is an unpaired electron, Cl atoms are paramagnetic (but is quite weak).

## Ex.2 Zn atom

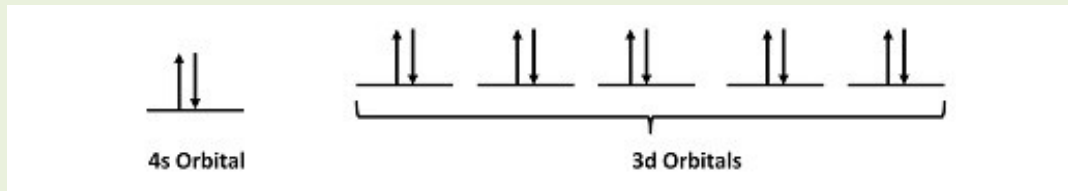
Find the electron configuration ( $Z=30$ )

$1s^2 2s^2 2p^6 3s^2 3p^6 4s^2 3d^{10}$

For Zn atoms, the electron configuration is  $4s^2 3d^{10}$

## MAGNETIC MATERIALS

### Step 2: Draw the valence orbitals



### Step 3: Look for unpaired electrons

There are no unpaired electrons.

### Step 4: Determine whether the substance is paramagnetic or diamagnetic

Because there are no unpaired electrons, Zn atoms are diamagnetic.

**2/ Application:** If a magnet is suspended over a container of liquid air, it attracts droplets to its poles. The droplets contain only liquid oxygen; even though nitrogen is the primary constituent of air, it is not attracted to the magnet. Explain what this tells you about the magnetic susceptibilities of oxygen and nitrogen, and explain why a magnet in ordinary, room-temperature air doesn't attract molecules of oxygen gas to its poles.

- See mp4 movie with the experiment of liquid O<sub>2</sub> and liquid N<sub>2</sub> between the two poles of an electromagnet.

**3/ Why should the permeability of a paramagnetic material be expected to decrease with increasing temperature?**

**Answer:** When a paramagnetic material is submitted to an external magnetic field  $\vec{B}_0$ , the individual magnetic moments of atoms  $\vec{\mu}_i$  will tend to align along the external field. This will give rise to an additional magnetic field  $\mu_0 \vec{M}$  where the magnetization  $\vec{M} = (\sum_i \vec{\mu}_i) / V$ :

$$\vec{B} = \vec{B}_0 + \mu_0 \vec{M} = K_M \vec{B}_0$$

The magnetic permeability  $K_M$  is a dimensionless factor which describes the ratio between  $B$  and  $B_0$ .

$$K_M = \frac{B_0 + \mu_0 M}{B_0} = 1 + \frac{\mu_0 M}{B_0}$$

The magnetic susceptibility is then defined as:  $\chi_M = K_M - 1 = \frac{\mu_0 M}{B_0}$  (ratio effect ( $M$ ) / cause ( $B_0$ ))

Discussing the  $M(T)$  for a paramagnetic material, one can understand the dependence of  $K_M$  with  $T$  (discuss phenomenologically the Curie's law).

## MAGNETIC MATERIALS

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4/ The magnetic susceptibility of paramagnetic materials is quite strongly temperature dependent, but that of diamagnetic materials is nearly independent of temperature. Why the difference?

**Answer:**

Whether a substance is paramagnetic or diamagnetic is determined primarily by the presence or absence of free magnetic dipole moments (i.e., those free to rotate) in its constituent atoms. When there are no free moments, the magnetization is produced by currents of the electrons in their atomic orbits, induced when experiencing an external magnetic field. The substance is then diamagnetic, with a negative susceptibility independent of both field strength and temperature.

From the previous problem one can understand the strong variation of  $M(T)$  in a paramagnetic material. This implicates a strong variation of variation  $\chi(T)$  - discuss phenomenologically the  $M(T)$  - Curie law.

In diamagnetic materials the magnetic susceptibility is negative. Usually its magnitude is of the order of  $-10^{-6}$  to  $-10^{-5}$ . The negative value of the susceptibility means that in an applied magnetic field diamagnetic materials acquire the magnetization, which is pointed opposite to the applied field. The negative sign of this susceptibility is a direct consequence of Lenz's law (see above). When  $B$  is switched on, the change in motion of each orbit is equivalent to an induced circulating electric current in such a direction that its own magnetic flux opposes the change in magnetic flux through the orbit; i.e., the induced magnetic moment is directed opposite to  $B$  (see Lenz law, course next week).

In diamagnetic materials the susceptibility nearly has a constant value independent of temperature. Ionic crystals and inert gas atoms are diamagnetic. These substances have atoms or ions with complete shells, and their diamagnetic behavior is because a magnetic field acts to distort the orbital motion. Another class of diamagnetic materials is noble metals.