Magnetic Susceptibility Balance

Physics tell us that moving electrical charges create magnetic fields. This means that unpaired electrons will create magnetic fields as a result of their property that is called “spin”. This magnetic field can be measured with a suitable instrument. This instrument is called the magnetic susceptibility balance. The spin of the positively charged nucleus also creates a magnetic field that is measured using a nuclear magnetic resonance (NMR) spectrometer to determine the nature and number of the nuclei.

The electrons also can possess orbital motion that can contribute to the magnetic field but this motion is largely quenched or removed by the presence of ligands that surround the metal ion and lift the degeneracy of the metal’s d orbitals.

The magnetic susceptibility balance places the sample between two permanent magnets that are mounted on a torsion bar that allows for calibrated motion of the magnets. The permanent magnets will move in response to the force created by the magnetic field of the sample and this motion will be measured by the electronics within the instrument. There will be some movement of the magnets on the torsion bar even for samples that have all of the electrons paired. In this case the magnetic force from the sample is induced by the presence of the permanent magnetic field. The strength of the induced magnetic field in the presence of a permanent magnetic field is the property given by the magnetic susceptibility.

The magnetic susceptibility \( \chi_g \) of the sample is given by:
\[
\chi_g = \frac{C_{bal} \times l \times (R - R_o)}{10^9 \times m},
\]
where \( C_{bal} \) is the balance calibration constant (and should be equal to 1.0),
\( l \) is the sample length in centimeters,
\( R \) is the reading for the tube filled with the sample,
\( R_o \) is the reading for the tube empty, and
\( m \) is the mass of the sample.

The molar susceptibility is \( \chi_M \) and is equal to \( \chi_g \) multiplied by the formula weight of the substance.

Diamagnetic (spin paired) components of the sample such as ligands and counterions will also make small contributions to the magnetic susceptibility. The molar susceptibilities of these components can be subtracted out from that of the sample in order to get the value that is solely due to the unpaired electrons on the metal ion. Some values that we can use are: \( \text{Cl} \rightarrow 10^6 \chi_M = 23 \), \( \text{H}_2\text{O} \rightarrow 10^6 \chi_M = 13 \), and \( \text{H}_2\text{NCH}_2\text{CH}_2\text{NH}_2 \rightarrow 10^6 \chi_M = 47 \).

The spin only magnetic moment \( \mu_{eff} \) of an atom with unpaired electrons is given by
\[
\mu_{eff} = (n^2(n+2))^{1/2},
\]
where \( n \) is the number of unpaired electrons. This is related to the molar susceptibility by the formula,
\[
\mu_{eff} = \frac{3kT \chi_M}{NB}^{1/2},
\]
where
\( k \) is the Boltzmann constant \((1.38 \times 10^{-23} \text{ J/K})\),
\( T \) is the absolute temperature in Kelvin,
\( N \) is Avogadro’s number \((6.02 \times 10^{-23} \text{ /mol})\), and
\( B \) is the Bohr magneton \((9.27 \times 10^{-24} \text{ J/Tesla})\).

The constants are easily dealt with to give \( \mu_{eff} = 2.828 \times (T \chi_M)^{1/2} \), which will allow the number of unpaired electrons on a metal ion in a complex to be calculated. The magnetic moment calculated from the molar magnetic susceptibility will be slightly larger than the spin-only quantity due to some orbital contribution to the magnetic moment.