

MSJChem

Tutorials for IB Chemistry

Topic 13

Periodicity HL

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Transition elements

Transition elements

An element whose atom has an incomplete d sub-level, or can form positive ions with an incomplete d sub-level.

First row d-block elements

21 Sc 44.96	22 Ti 47.87	23 V 50.94	24 Cr 52.00	25 Mn 54.94	26 Fe 55.85	27 Co 58.93	28 Ni 58.69	29 Cu 63.55	30 Zn 65.38
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Zinc is not considered to be a transition element as it does not have an incomplete d sub-level as an atom or an ion.

Transition elements

First row d-block element	Electron configuration of atom	Ion formed	Electron configuration of ion
Sc	[Ar] 4s ² 3d ¹	Sc ³⁺	[Ne] 3s ² 3p ⁶
Ti	[Ar] 4s ² 3d ²	Ti ²⁺	[Ar] 3d ²
V	[Ar] 4s ² 3d ³	V ²⁺	[Ar] 3d ³
Cr	[Ar] 4s ¹ 3d ⁵	Cr ³⁺	[Ar] 3d ³
Mn	[Ar] 4s ² 3d ⁵	Mn ⁴⁺	[Ar] 3d ³
Fe	[Ar] 4s ² 3d ⁶	Fe ³⁺	[Ar] 3d ⁵
Co	[Ar] 4s ² 3d ⁷	Co ²⁺	[Ar] 3d ⁷
Ni	[Ar] 4s ² 3d ⁸	Ni ²⁺	[Ar] 3d ⁸
Cu	[Ar] 4s ¹ 3d ¹⁰	Cu ²⁺	[Ar] 3d ⁹
Zn	[Ar] 4s ² 3d ¹⁰	Zn ²⁺	[Ar] 3d ¹⁰

Transition elements

Physical properties	Chemical properties
High electrical and thermal conductivity	Have more than one oxidation state in compounds
High melting points	Form complex ions
Malleable and ductile	Form coloured compounds in solution
High tensile strength	Can act as catalysts (Fe in the Haber process)
Show magnetic properties (paramagnetic and ferromagnetic)	

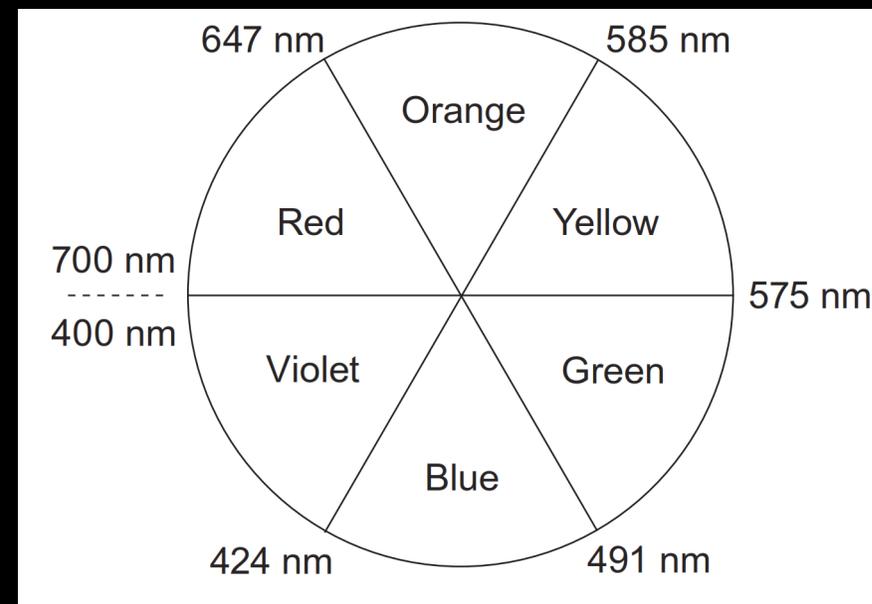
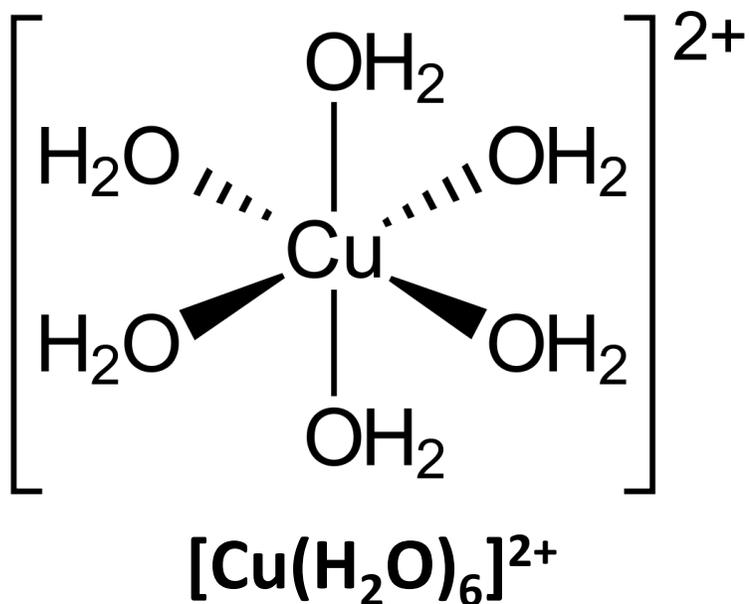
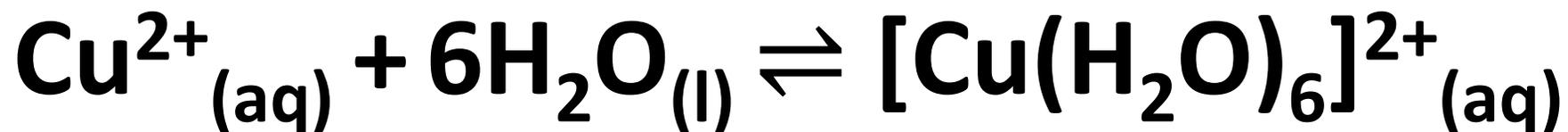
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Complex ions

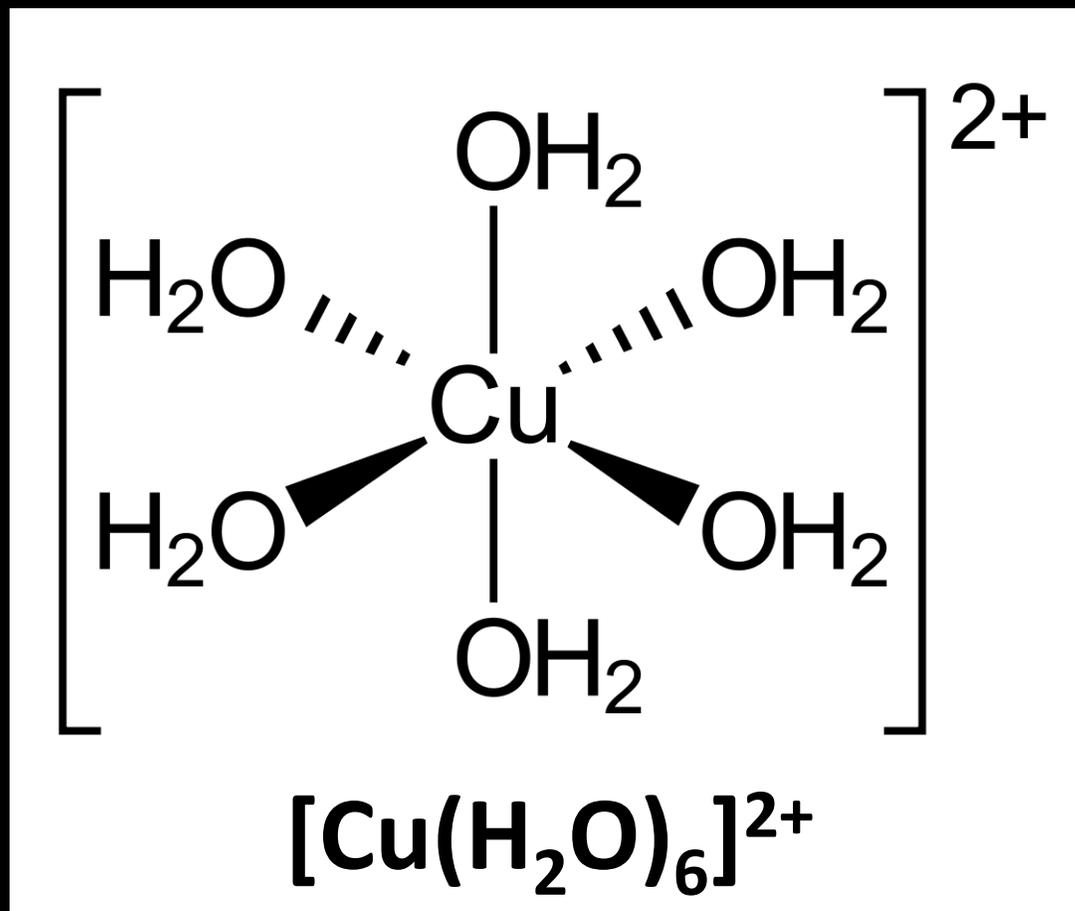
Complex ions

Complex ions are formed when the ions of a transition element bond with species called ligands.



Complex ions

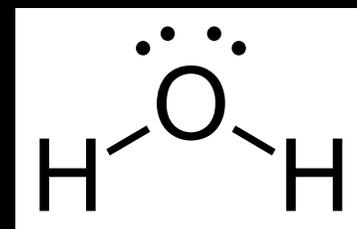
Complex ions consist of a central metal ion bonded to ligands by coordinate covalent bonds.



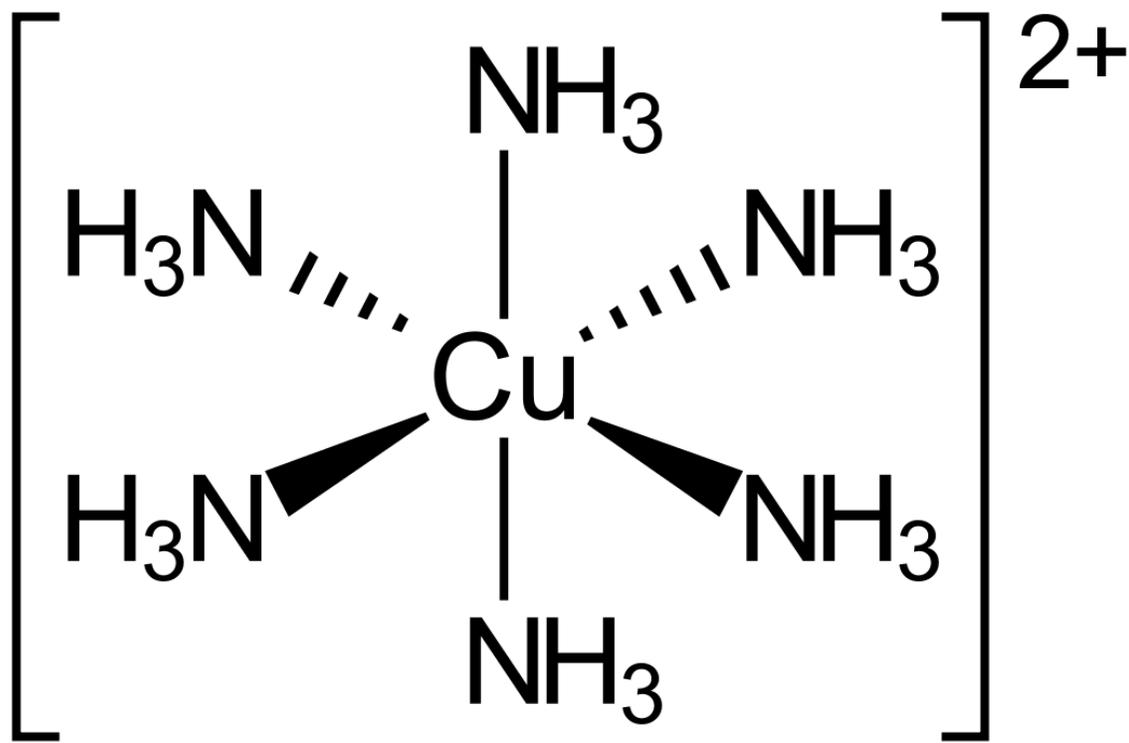
Central metal ion: Cu^{2+}

Ligands: H_2O

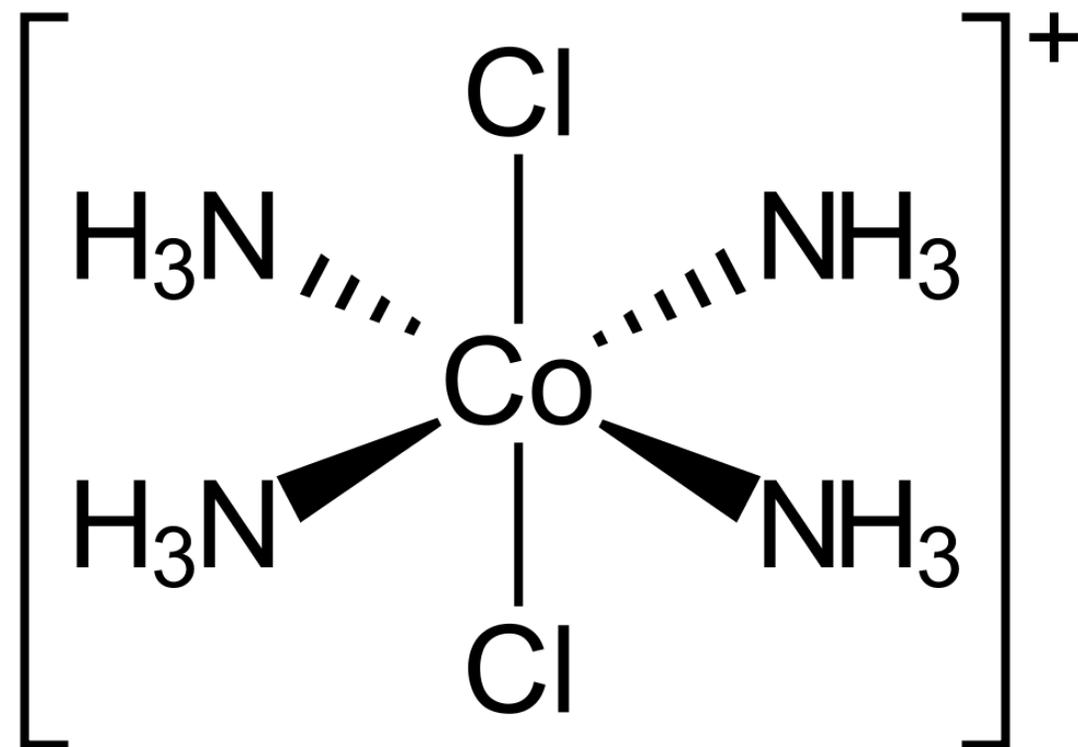
Ligands supply the bonding electrons forming a coordinate covalent bond with the central metal ion



Complex ions

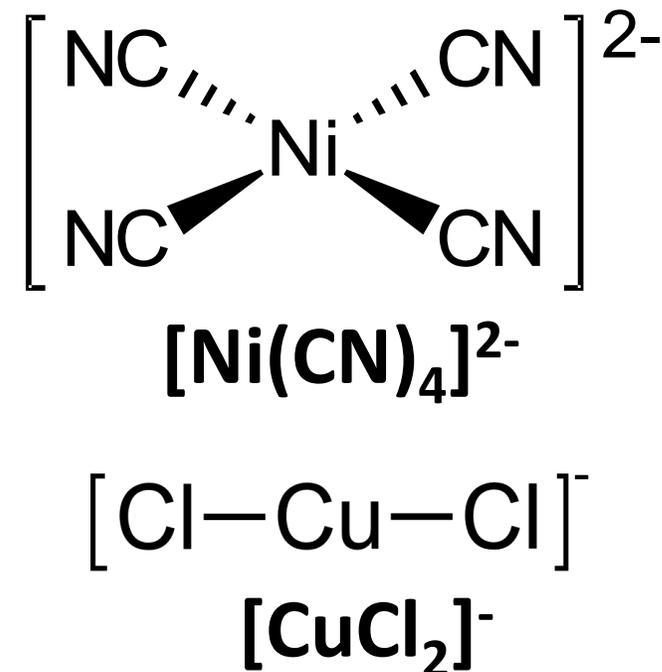
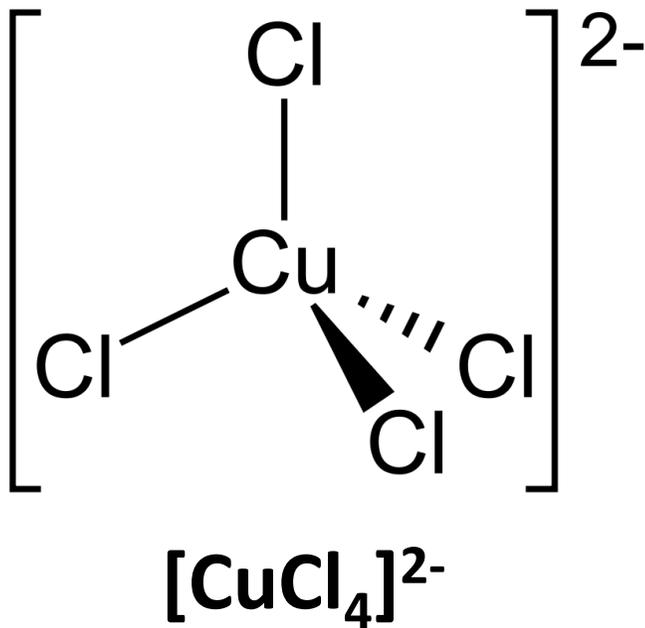
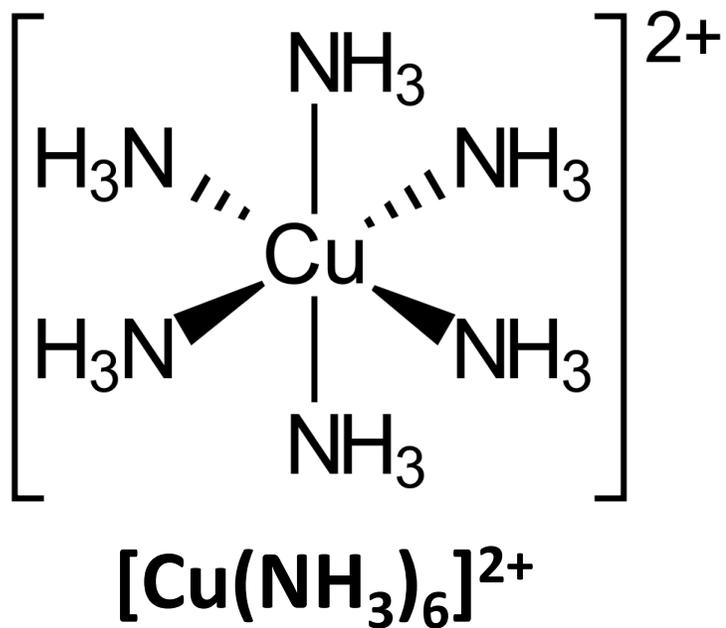


Central metal ion: Cu^{2+}
Ligands: NH_3



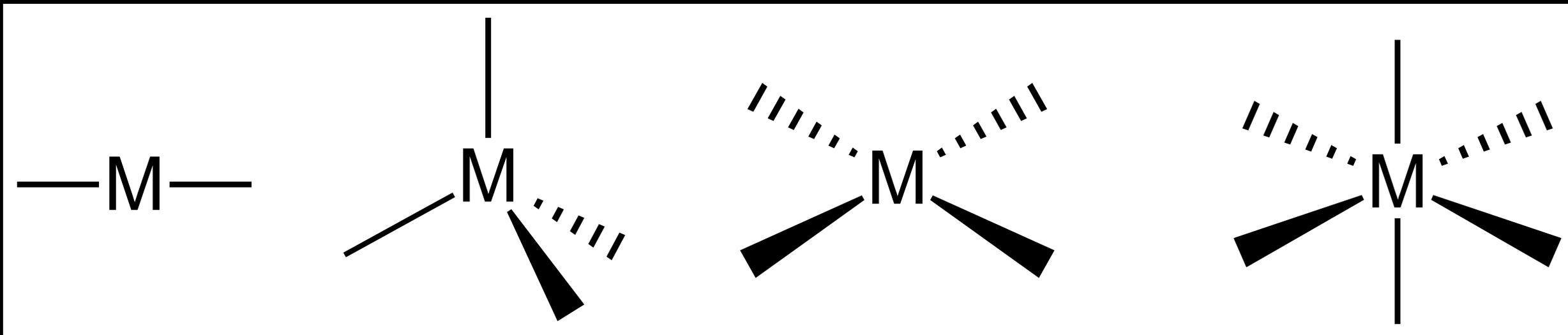
Central metal ion: Co^{3+}
Ligands: NH_3/Cl^-

Complex ions



Complex ion	Coordination number	Geometry
$[\text{Cu}(\text{NH}_3)_6]^{2+}$	6	octahedral
$[\text{CuCl}_4]^{2-}$ $[\text{Ni}(\text{CN})_4]^{2-}$	4	tetrahedral/square planar
$[\text{CuCl}_2]^{-}$	2	linear

Complex ions



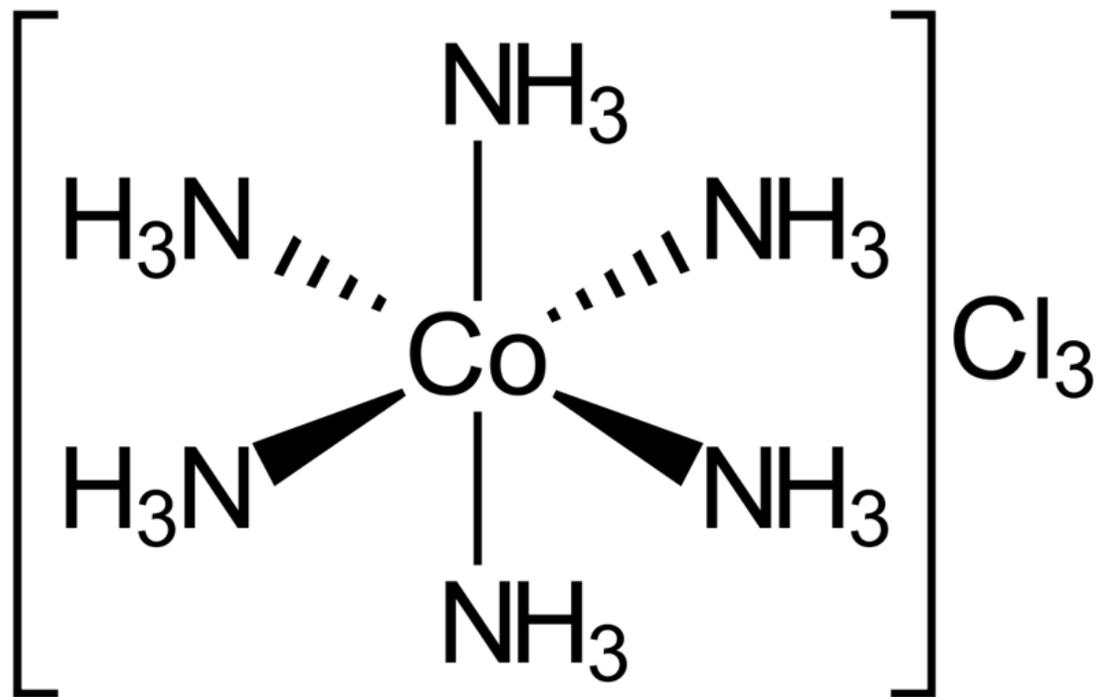
Complex ion	Coordination number	Geometry
$[\text{Cu}(\text{NH}_3)_6]^{2+}$	6	octahedral
$[\text{CuCl}_4]^{2-}$ $[\text{Ni}(\text{CN})_4]^{2-}$	4	tetrahedral/square planar
$[\text{CuCl}_2]^-$	2	linear

Coordination compounds

Coordination compounds consist of:

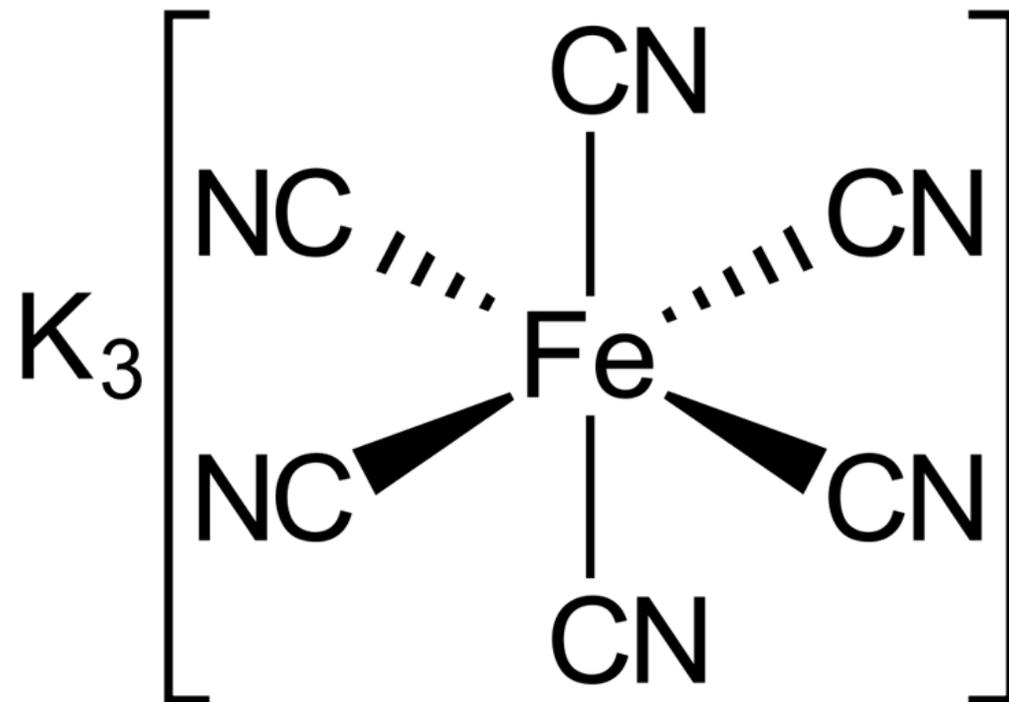
- a complex ion - central metal ion with ligands bonded by coordinate covalent bonds
- counter ions - ions that balance out the charge on the complex ion

Coordination compounds



Complex ion: $[\text{Co}(\text{NH}_3)_6]^{3+}$

Counter ions: 3Cl^-



Complex ion: $[\text{Fe}(\text{CN})_6]^{3-}$

Counter ions: 3K^+

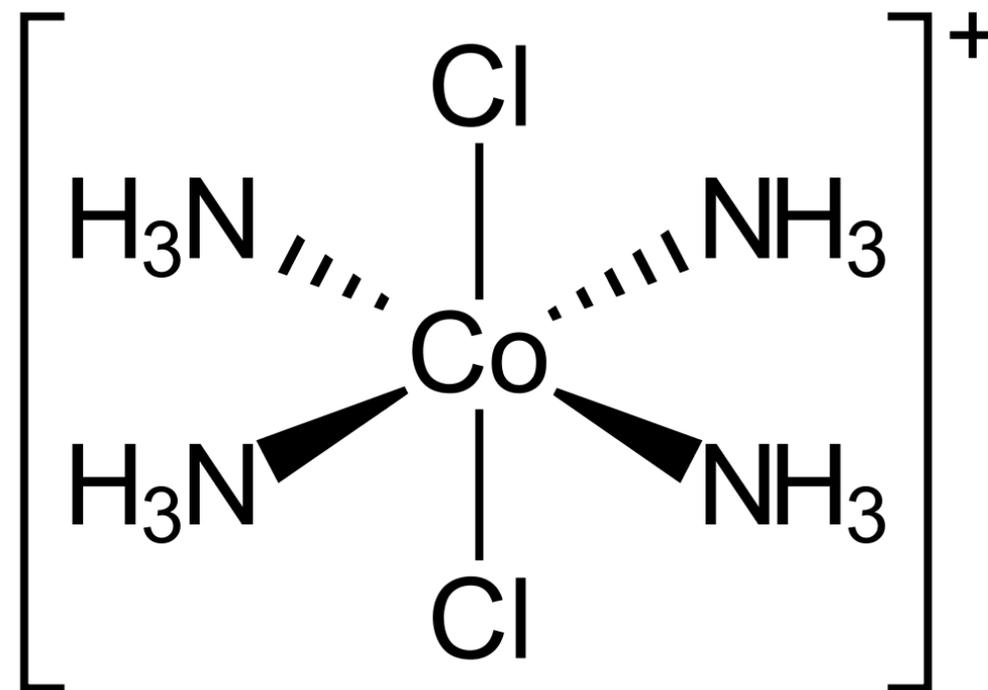
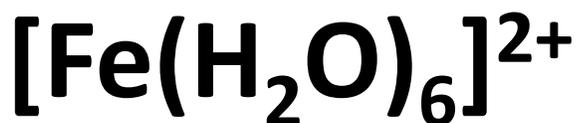
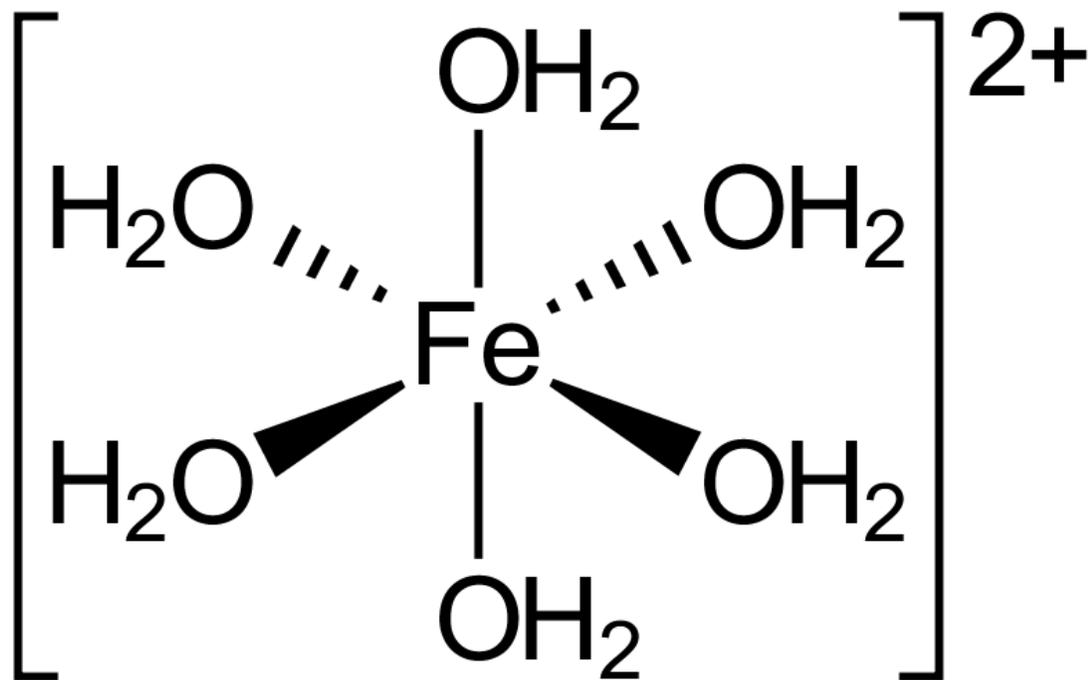
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Ligands

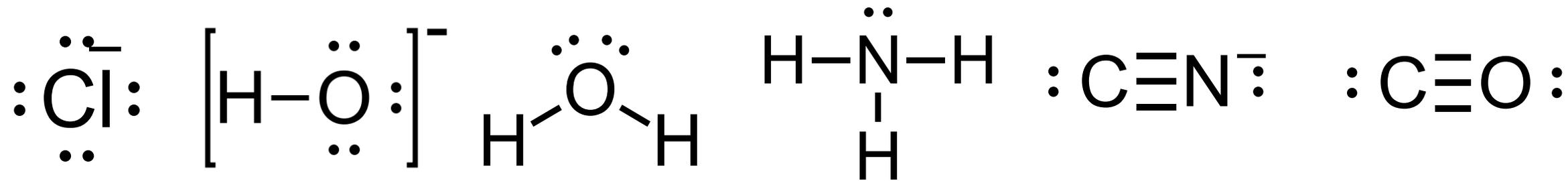
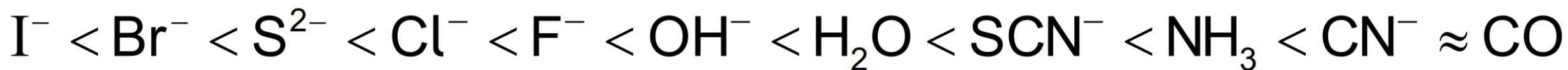
Ligands

Complex ions consist of a central metal ion bonded to ligands by coordinate covalent bonds.



Ligands

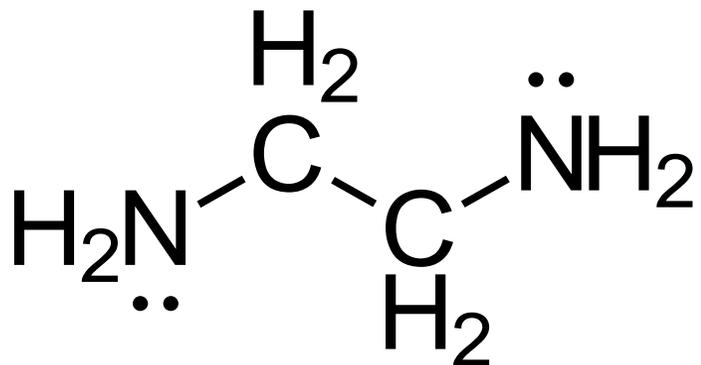
Ligands are species with lone pairs of electrons that form coordinate covalent bonds with a central metal ion (ligands are also Lewis bases).



Monodentate ligands use only one lone pair of electrons to bond to a central metal ion.

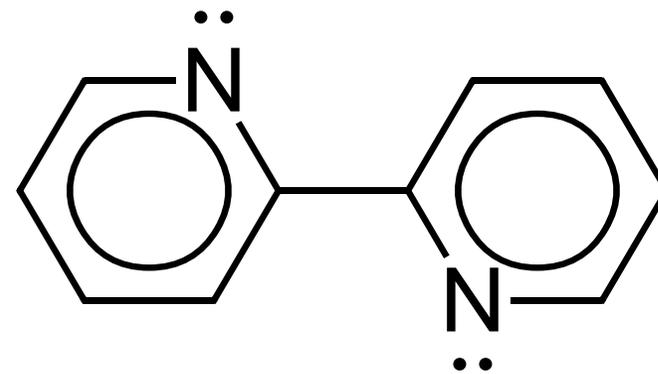
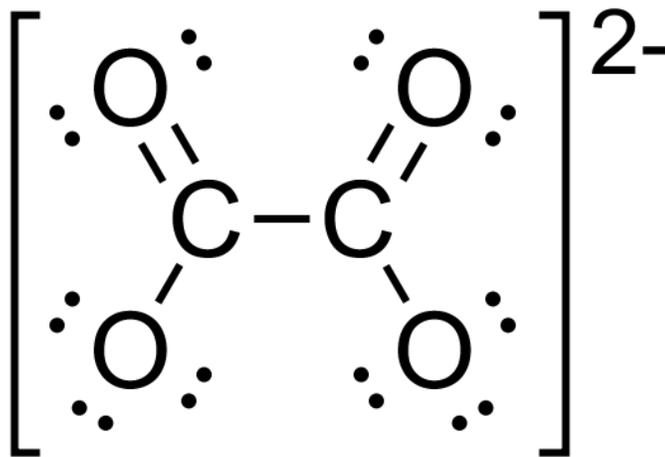
Ligands

Bidentate ligands use two lone pairs of electrons to bond to a central metal ion.



1,2-ethanediamine

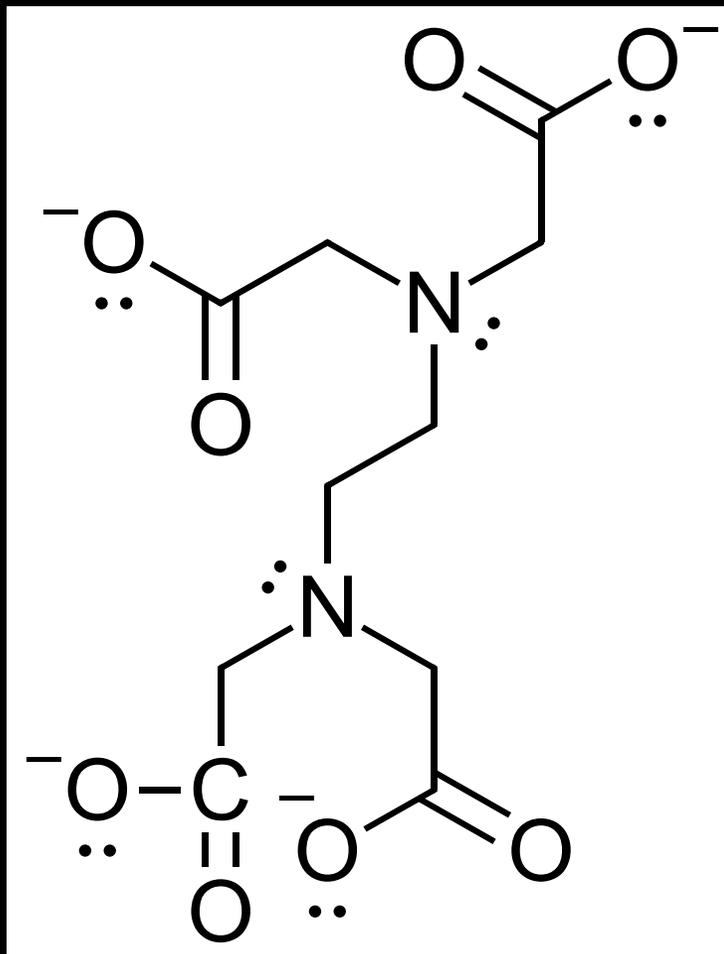
Ethanedioate ion



Bipyridine

Ligands

Polydentate ligands use multiple lone pairs of electrons to bond to a central metal ion.



EDTA⁴⁻ is a hexadentate ligand; it uses six lone pairs of electrons to form six coordinate covalent bonds to a central metal ion.

EDTA⁴⁻ is used as a food preservative as it binds to metal ions in enzymes that catalyse chemical reactions.

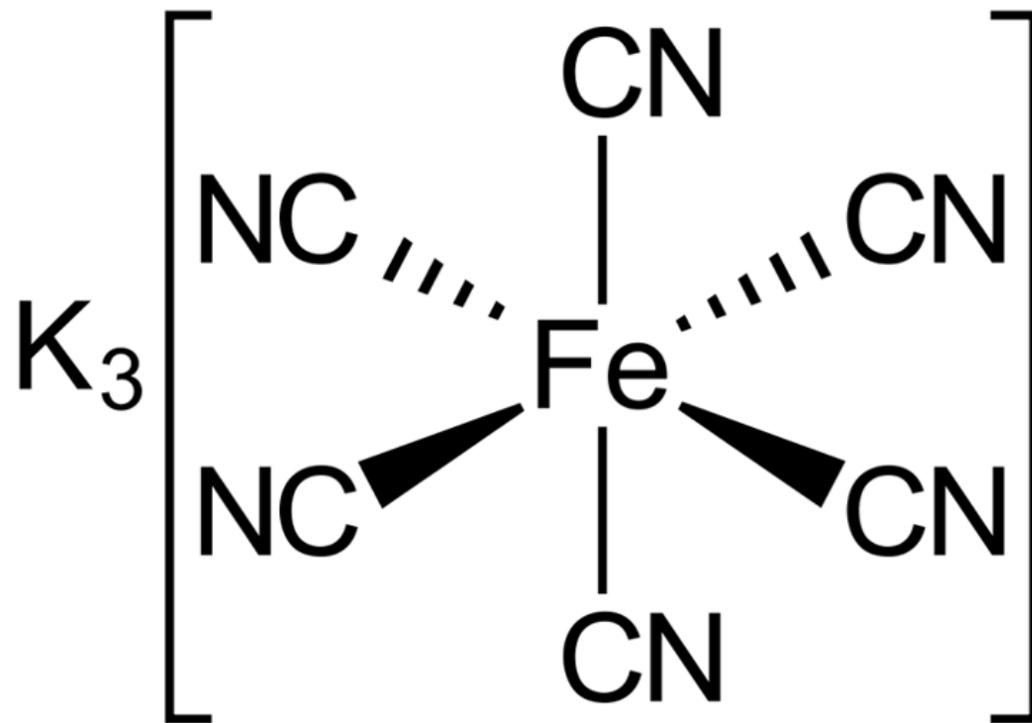
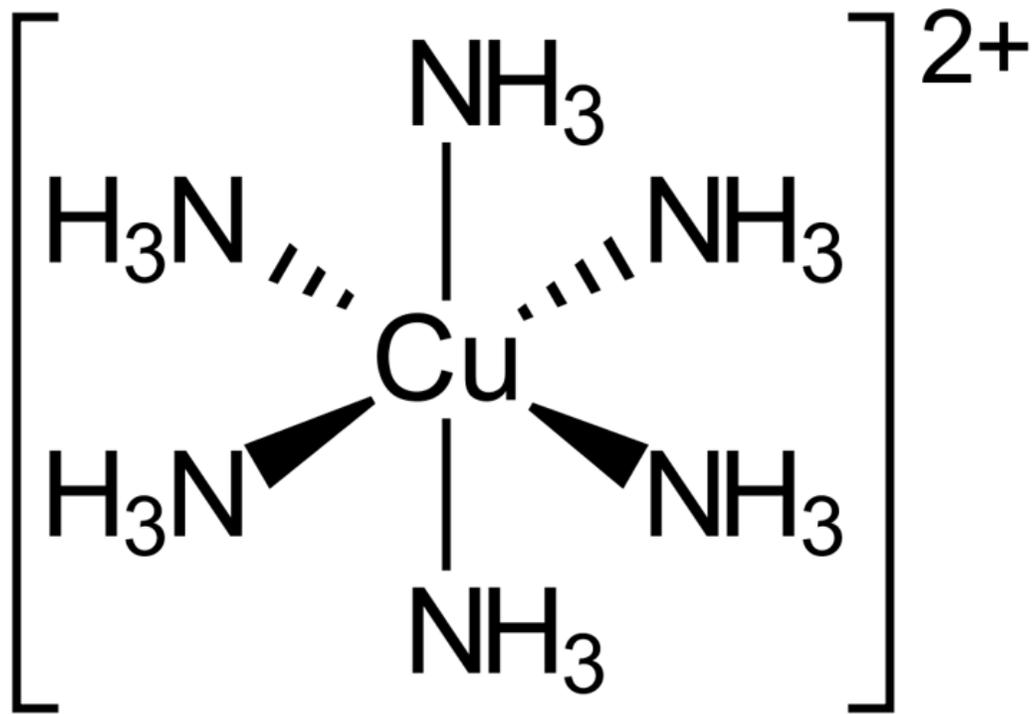
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**Deduce the charge on
a central metal ion**

Complex ion

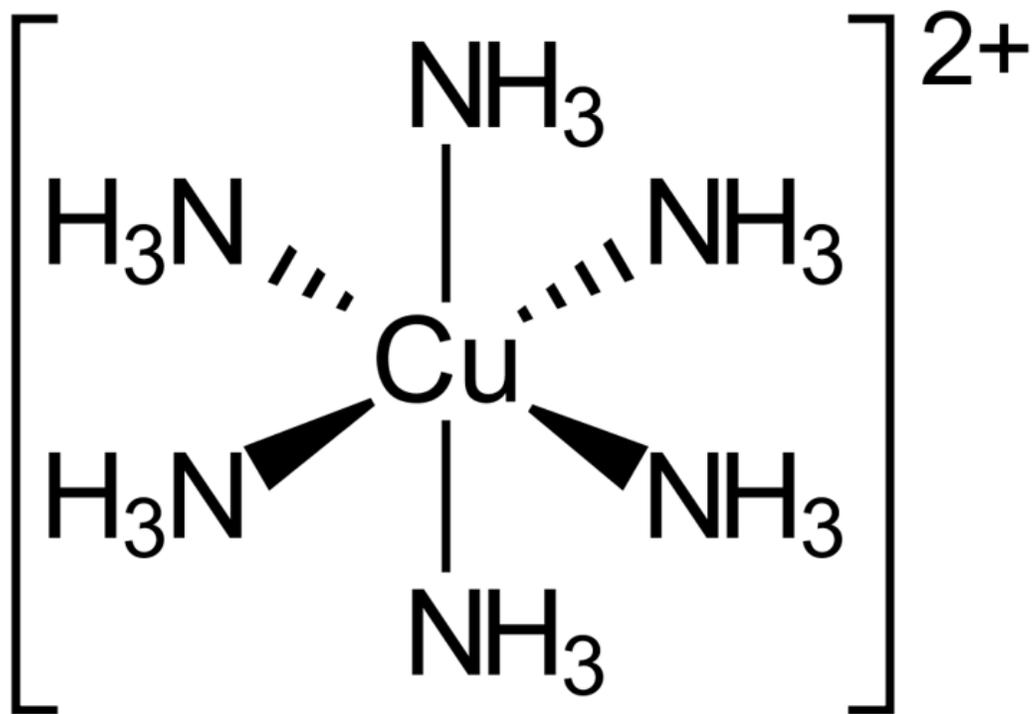
Coordination compound



Charge on a central metal ion

Transition element	Common ions formed	Oxidation state
Chromium	Chromium(II) Cr^{2+}	+2
	Chromium(III) Cr^{3+}	+3
Cobalt	Cobalt(II) Co^{2+}	+2
	Cobalt(III) Co^{3+}	+3
Copper	Copper(I) Cu^{+}	+1
	Copper(II) Cu^{2+}	+2
Iron	Iron(II) Fe^{2+}	+2
	Iron(III) Fe^{3+}	+3
Nickel	Nickel(II) Ni^{2+}	+2

Charge on a central metal ion



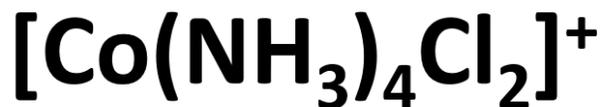
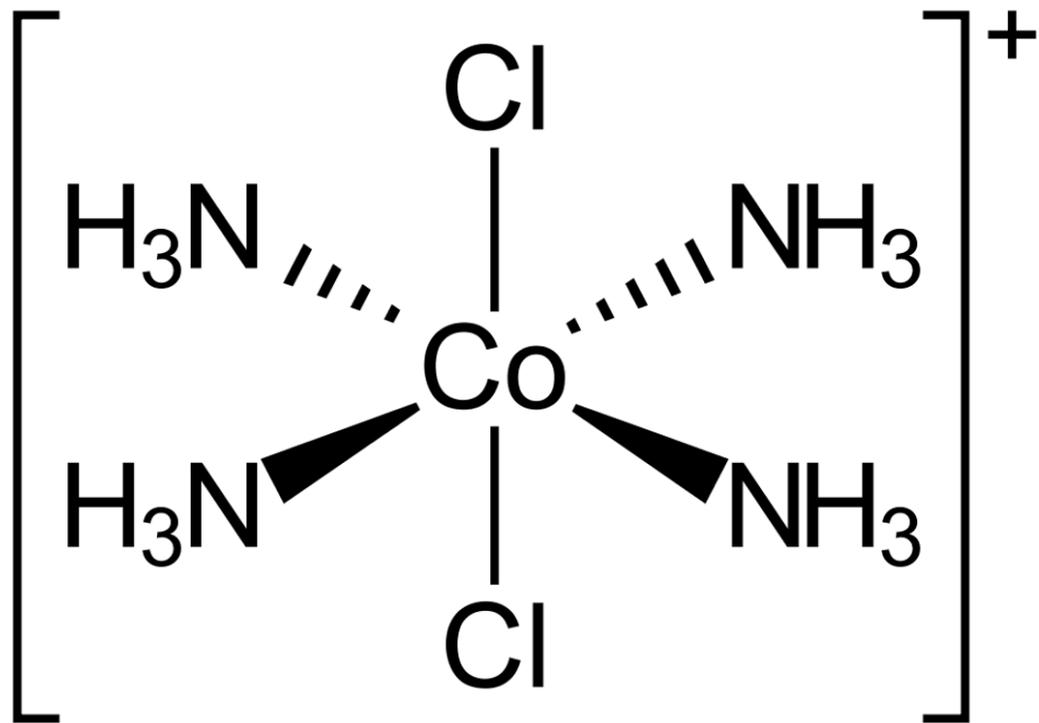
If the ligands are neutral, the charge on the complex ion is the same as the charge on the central metal ion.

The central metal ion is the Cu^{2+} ion (oxidation state +2).

Central metal ion: Cu^{x+}

Ligands: 6NH_3 molecules

Charge on a central metal ion



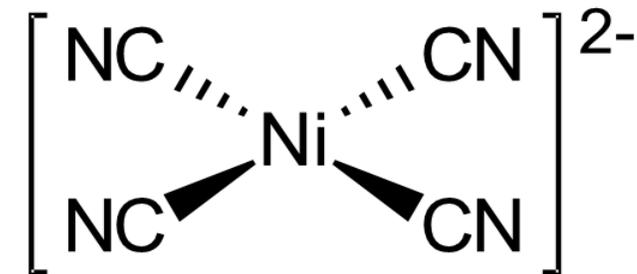
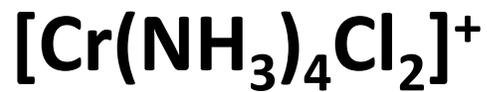
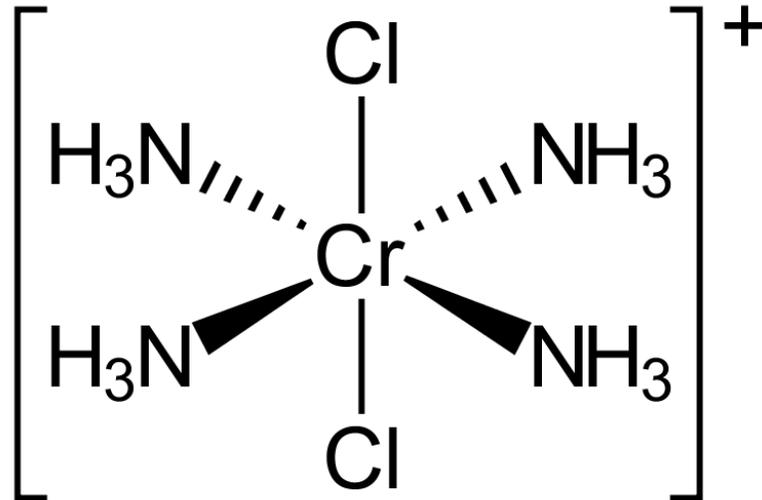
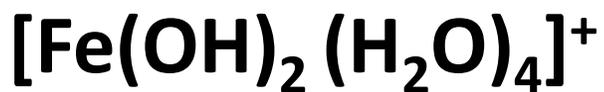
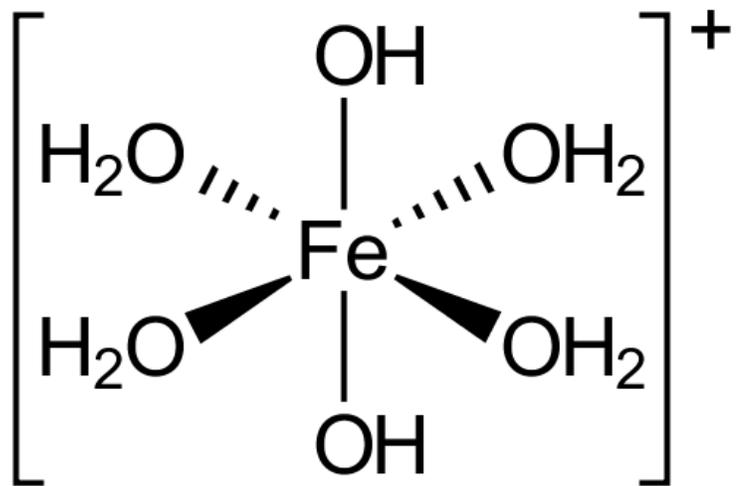
If the ligands are negatively charged, subtract the total charge of the ligands from the charge on the complex ion.

The central metal ion is the Co^{3+} (oxidation state +3).

Central metal ion: Co^{x+}

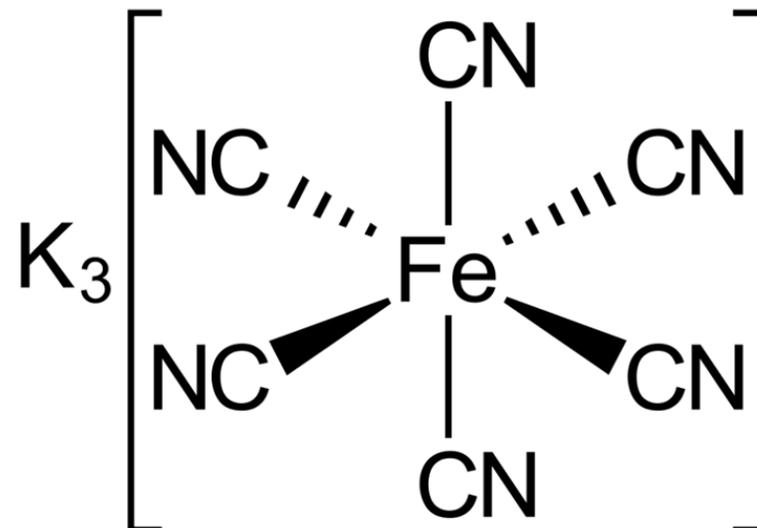
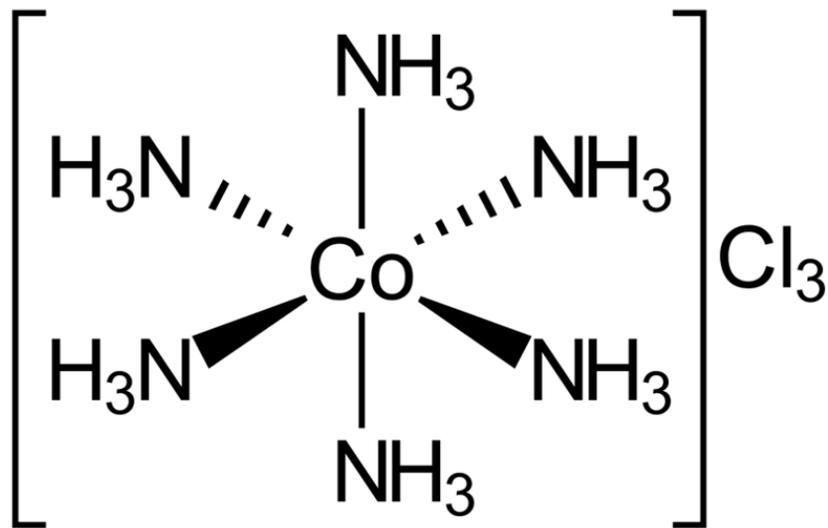
Ligands: 4NH_3 molecules, 2Cl^- ions

Charge on a central metal ion



Complex ion	Ligands	Central metal ion	Oxidation state
$[\text{Fe}(\text{OH})_2 (\text{H}_2\text{O})_4]^+$	$4\text{H}_2\text{O} \quad 2\text{OH}^-$	Fe^{3+}	+3
$[\text{Cr}(\text{NH}_3)_4 \text{Cl}_2]^+$	$4\text{NH}_3 \quad 2\text{Cl}^-$	Cr^{3+}	+3
$[\text{Ni}(\text{CN})_4]^{2-}$	4CN^-	Ni^{2+}	+2

Charge on a central metal ion



Coordination compound	Complex ion / counter ions	Ligands	Central metal ion	Oxidation state
$[\text{Co}(\text{NH}_3)_6]\text{Cl}_3$	$[\text{Co}(\text{NH}_3)_6]^{3+}$ 3Cl^-	6NH_3	Co^{3+}	+3
$\text{K}_3[\text{Fe}(\text{CN})_6]$	$[\text{Fe}(\text{CN})_6]^{3-}$ 3K^+	6CN^-	Fe^{3+}	+3

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**Oxidation states of the
transition elements**

Oxidation states

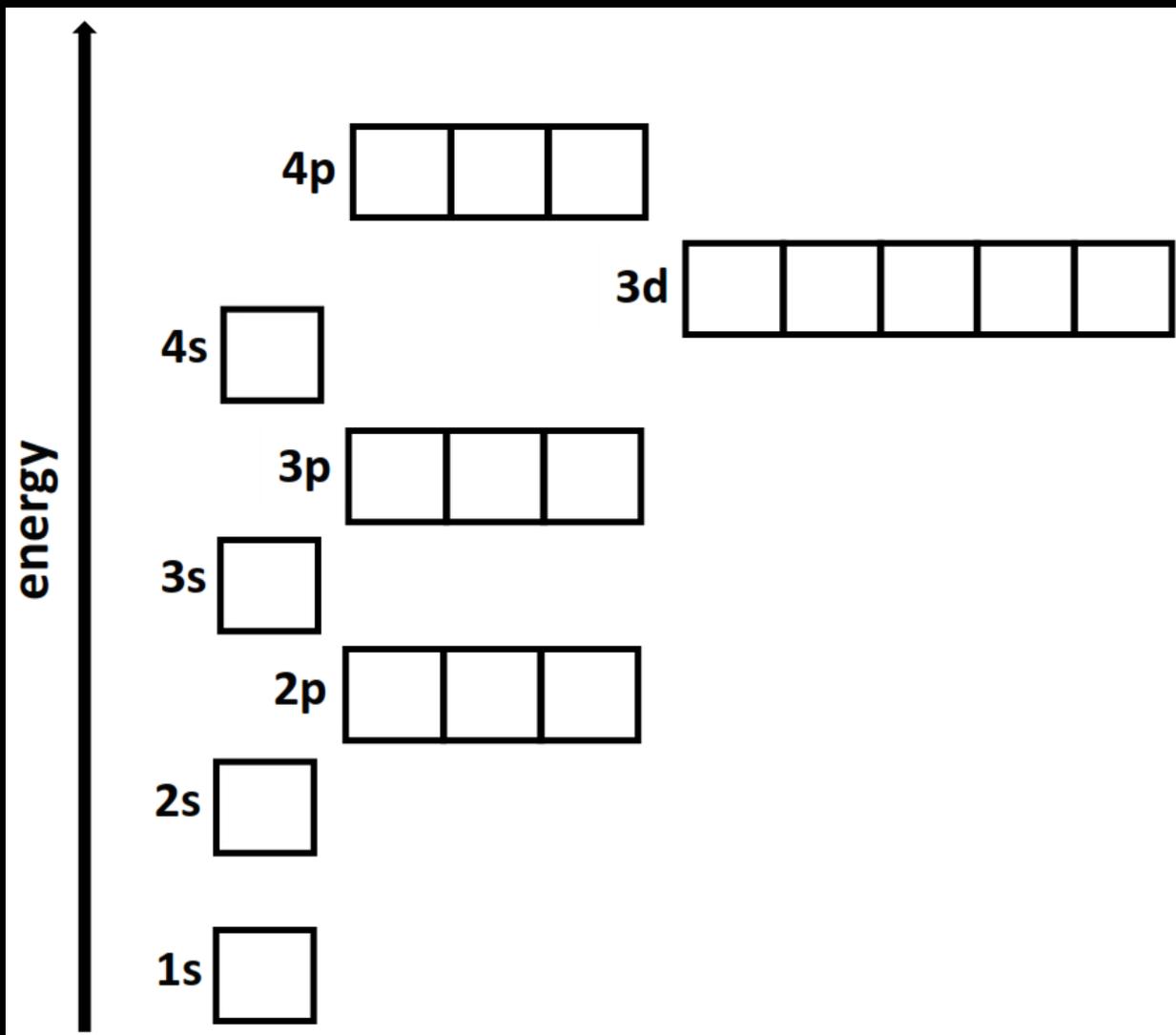
Transition elements show variable oxidation states in compounds.

Sc	Ti	V	Cr	Mn	Fe	Co	Ni	Cu	Zn
								+1	
	+2	+2	+2	+2	+2	+2	+2	+2	+2
+3	+3	+3	+3	+3	+3	+3			
	+4	+4		+4					
		+5							
			+6	+6					
				+7					

All transition elements (except Sc) can have an oxidation state of +2.

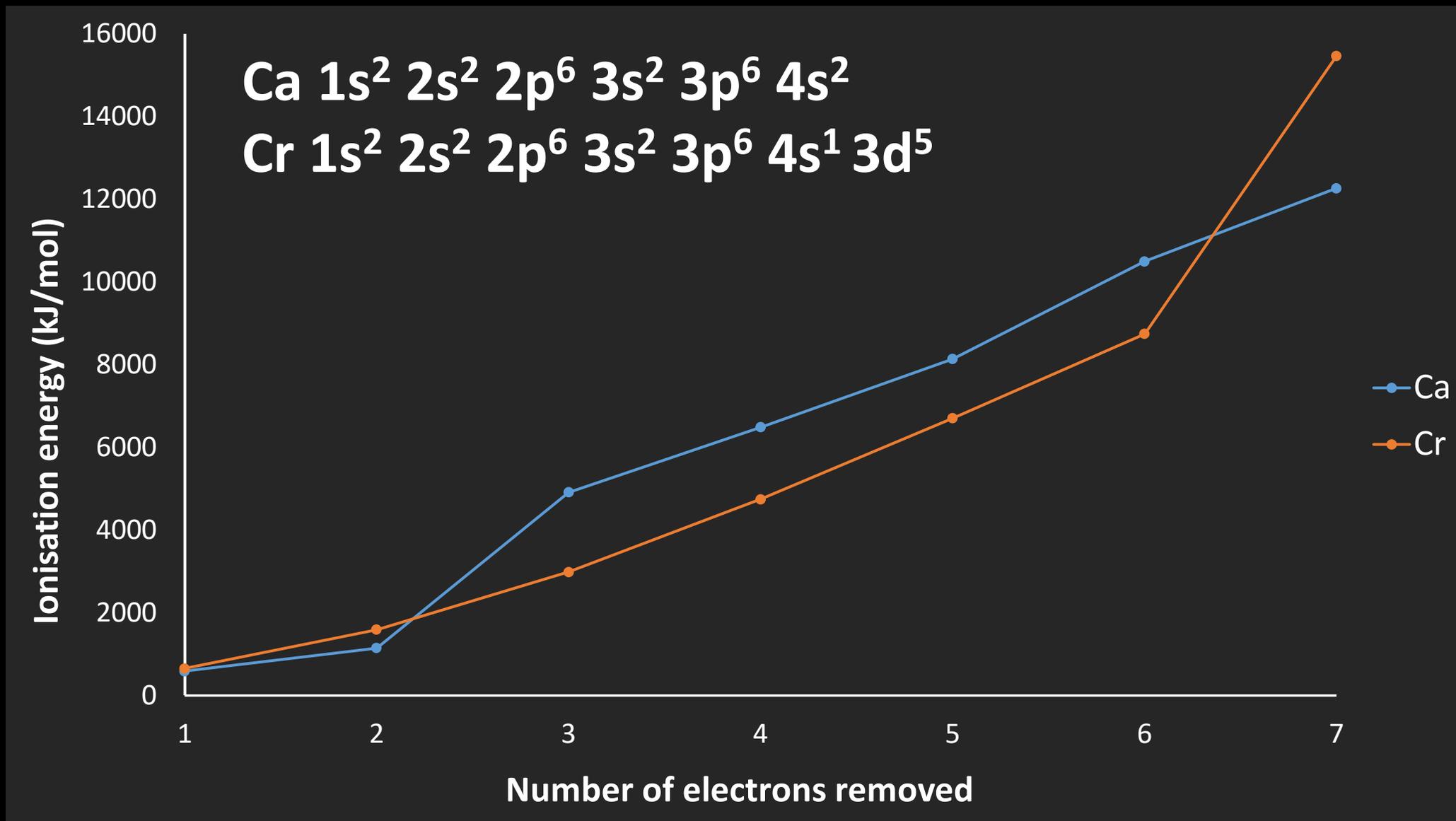
Transition element	Known oxidation states	Electron configuration	Orbital diagram (4s and 3d sub-levels only)	
Sc	<u>+3</u>	[Ar] 4s ² 3d ¹	4s $\boxed{\uparrow\downarrow}$	3d $\boxed{\uparrow} \boxed{} \boxed{} \boxed{} \boxed{}$
Ti	<u>+2</u> <u>+3</u> <u>+4</u>	[Ar] 4s ² 3d ²	4s $\boxed{\uparrow\downarrow}$	3d $\boxed{\uparrow} \boxed{\uparrow} \boxed{} \boxed{} \boxed{}$
V	<u>+1</u> <u>+2</u> <u>+3</u> <u>+4</u> <u>+5</u>	[Ar] 4s ² 3d ³	4s $\boxed{\uparrow\downarrow}$	3d $\boxed{\uparrow} \boxed{\uparrow} \boxed{\uparrow} \boxed{} \boxed{}$
Cr	<u>+1</u> <u>+2</u> <u>+3</u> <u>+4</u> <u>+5</u> <u>+6</u>	[Ar] 4s ¹ 3d ⁵	4s $\boxed{\uparrow}$	3d $\boxed{\uparrow} \boxed{\uparrow} \boxed{\uparrow} \boxed{\uparrow} \boxed{\uparrow}$
Mn	<u>+1</u> <u>+2</u> <u>+3</u> <u>+4</u> <u>+5</u> <u>+6</u> <u>+7</u>	[Ar] 4s ² 3d ⁵	4s $\boxed{\uparrow\downarrow}$	3d $\boxed{\uparrow} \boxed{\uparrow} \boxed{\uparrow} \boxed{\uparrow} \boxed{\uparrow}$
Fe	<u>+1</u> <u>+2</u> <u>+3</u> <u>+4</u> <u>+5</u> <u>+6</u>	[Ar] 4s ² 3d ⁶	4s $\boxed{\uparrow\downarrow}$	3d $\boxed{\uparrow\downarrow} \boxed{\uparrow} \boxed{\uparrow} \boxed{\uparrow} \boxed{\uparrow}$
Co	<u>+1</u> <u>+2</u> <u>+3</u> <u>+4</u> <u>+5</u>	[Ar] 4s ² 3d ⁷	4s $\boxed{\uparrow\downarrow}$	3d $\boxed{\uparrow\downarrow} \boxed{\uparrow\downarrow} \boxed{\uparrow} \boxed{\uparrow} \boxed{\uparrow}$
Ni	<u>+1</u> <u>+2</u> <u>+3</u> <u>+4</u>	[Ar] 4s ² 3d ⁸	4s $\boxed{\uparrow\downarrow}$	3d $\boxed{\uparrow\downarrow} \boxed{\uparrow\downarrow} \boxed{\uparrow\downarrow} \boxed{\uparrow} \boxed{\uparrow}$
Cu	<u>+1</u> <u>+2</u> <u>+3</u>	[Ar] 4s ¹ 3d ¹⁰	4s $\boxed{\uparrow}$	3d $\boxed{\uparrow\downarrow} \boxed{\uparrow\downarrow} \boxed{\uparrow\downarrow} \boxed{\uparrow\downarrow} \boxed{\uparrow\downarrow}$

Oxidation states



Transition elements lose their 4s and 3d electrons when they form ions. The 3d and 4s orbitals are close in energy. Successive ionisation energies of the transition elements show a gradual increase.

Oxidation states



Oxidation states

Transition elements have variable oxidation states.

Almost all transition elements have a +2 oxidation state because they lose their 4s electrons first.

The 4s and 3d orbitals are close in energy which results in a gradual increase in successive ionisation energies.

Group 1 and 2 elements only have one oxidation state (+1 and +2) because of the large increase in IE after the valence electrons are removed.

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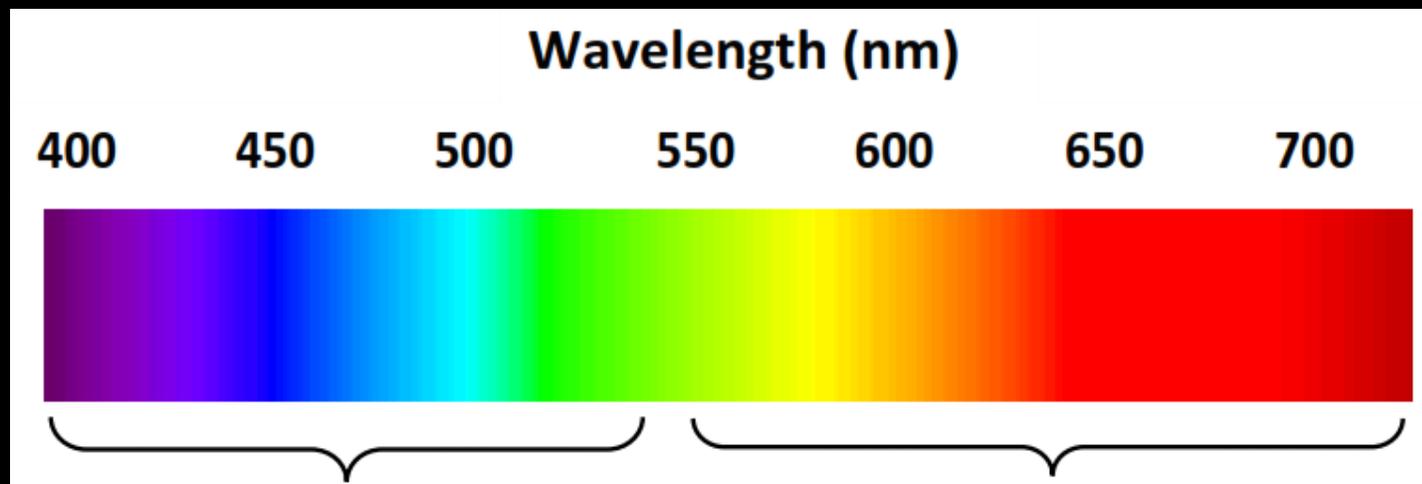
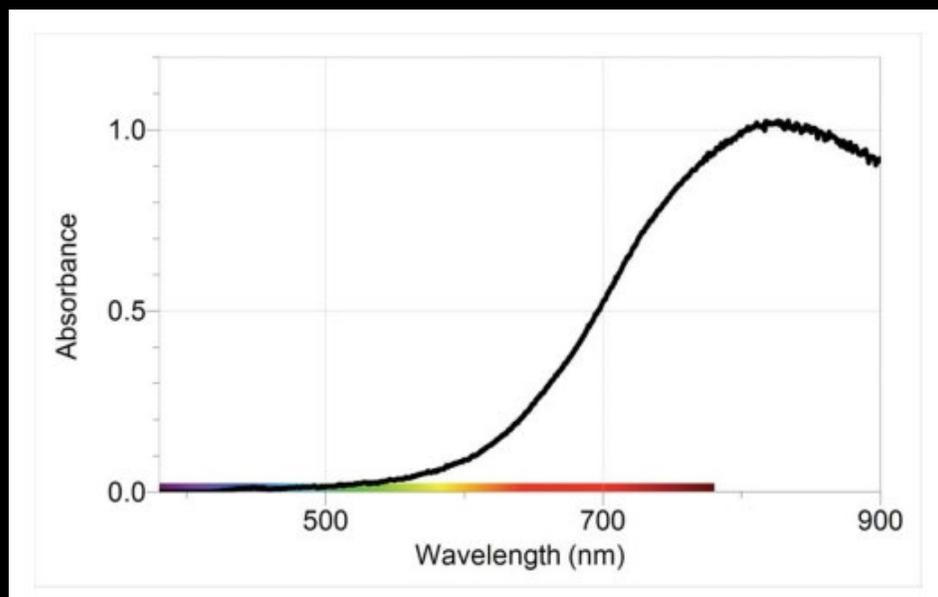
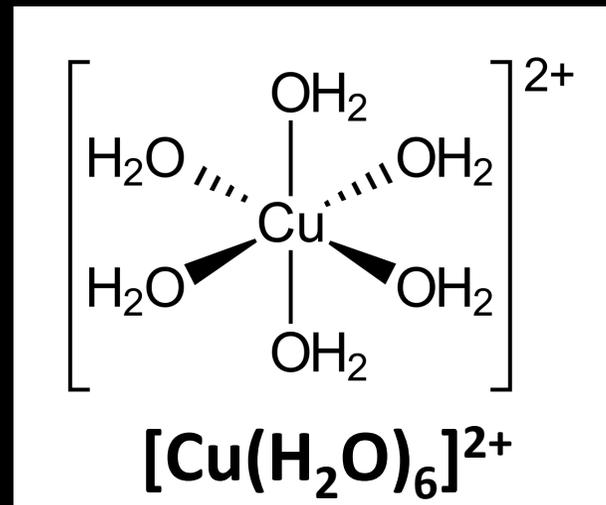
**Colour of
complex ions**

Colour of complex ions

Transition elements form coloured compounds.



Colour of complex ions



These wavelengths
are transmitted

These wavelengths
are absorbed

Colour of complex ions

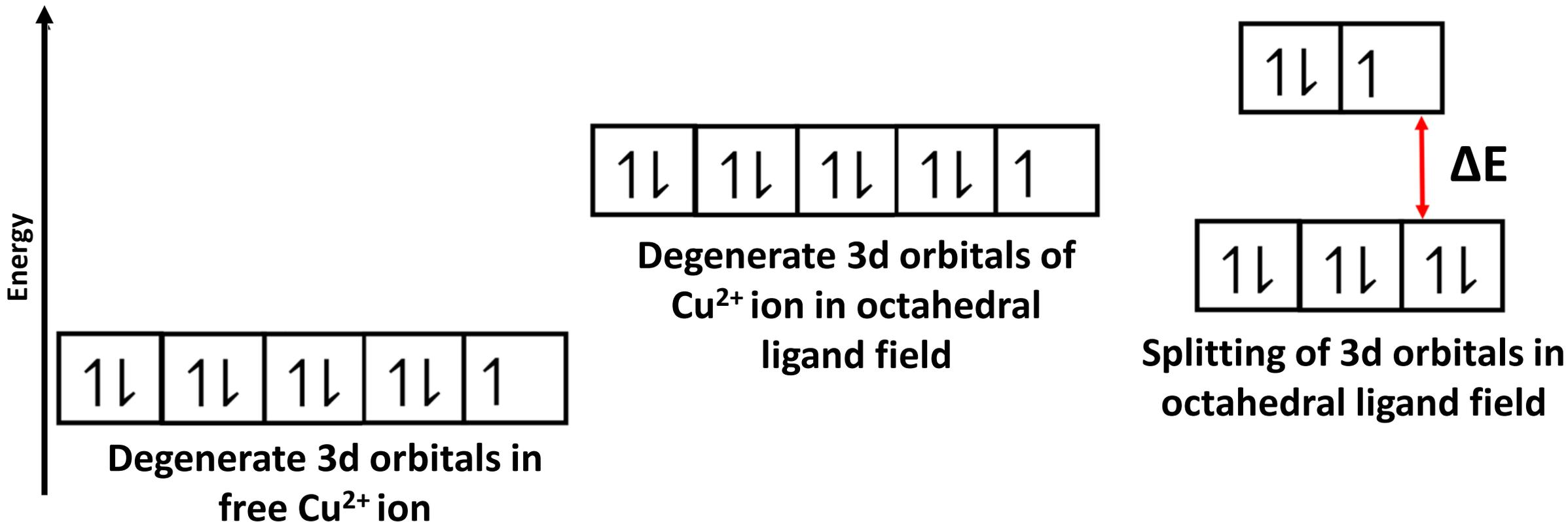
Crystal field theory states that the properties of complex ions are caused by the splitting of the d orbitals into two sets of different energies.

The splitting occurs when ligands approach the central metal ion; this causes repulsion between the lone pairs of electrons on the ligands and the electrons in the five d orbitals of the central metal ion.

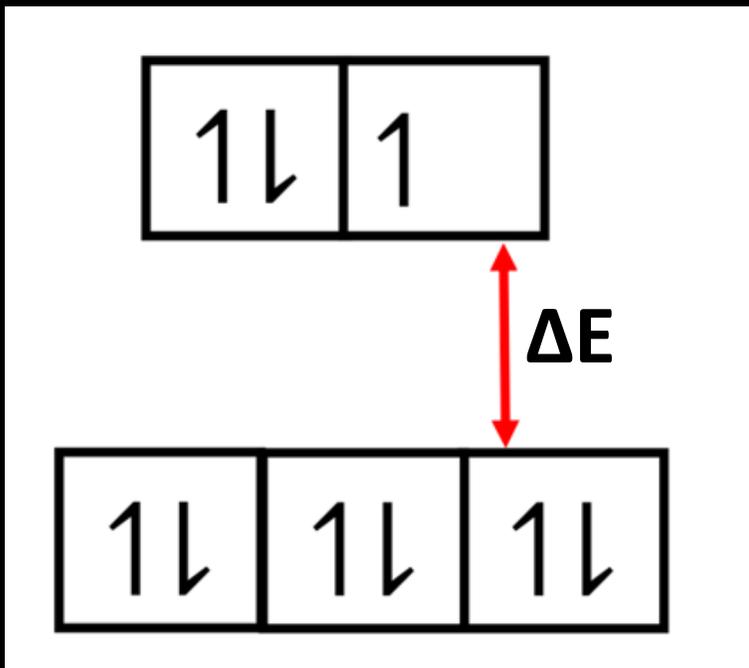
The d electrons are repelled unequally which causes splitting, with two d orbitals of higher energy and three d orbitals of lower energy.

Colour of complex ions

Crystal field splitting in an octahedral field of ligands

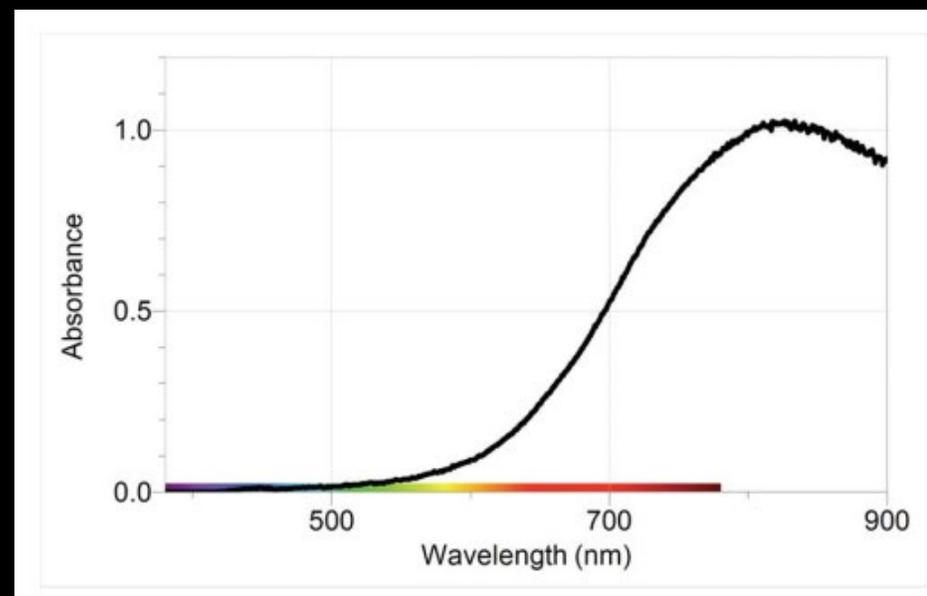


Colour of complex ions

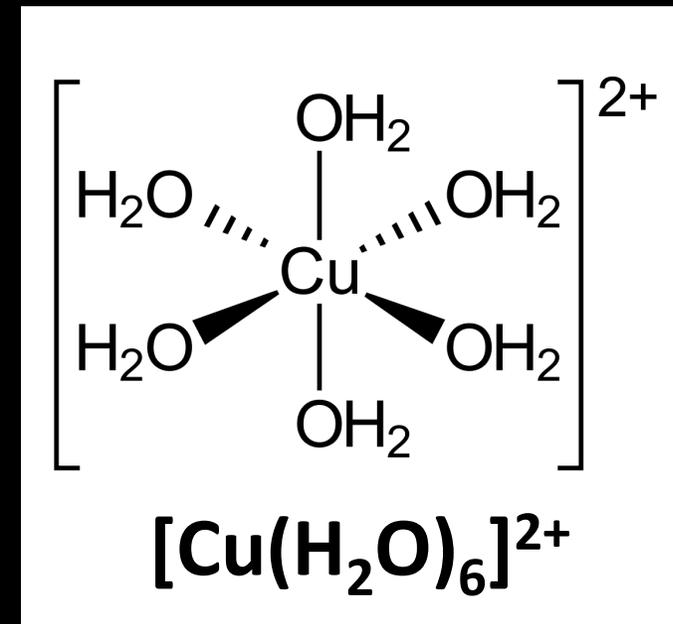
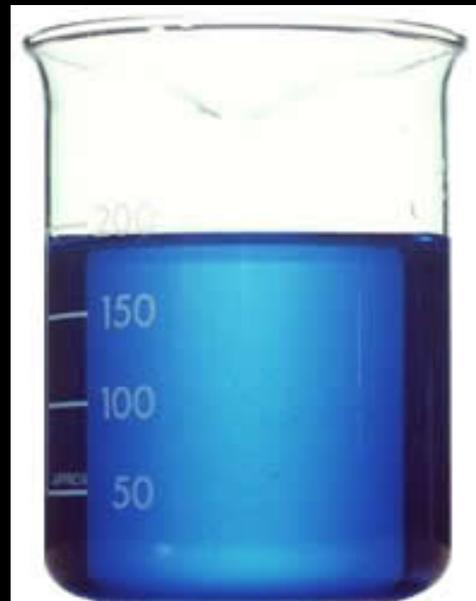
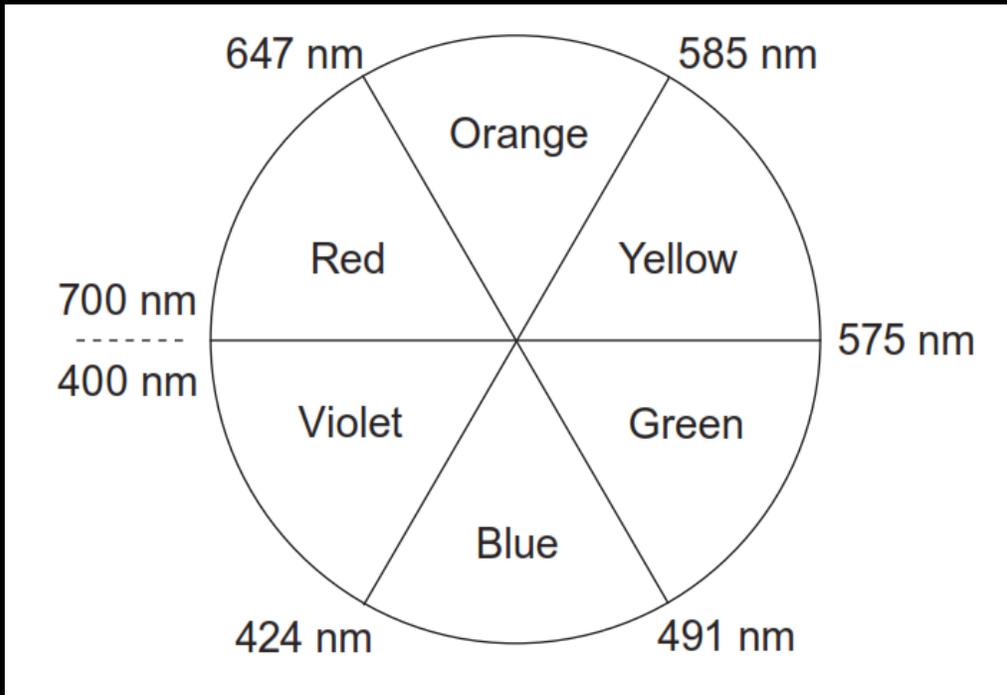


An electron from the lower set of d orbitals can transition to the higher set of d orbitals by absorbing energy (d-d transitions).

The energy absorbed by the electron corresponds to the wavelengths of visible light.



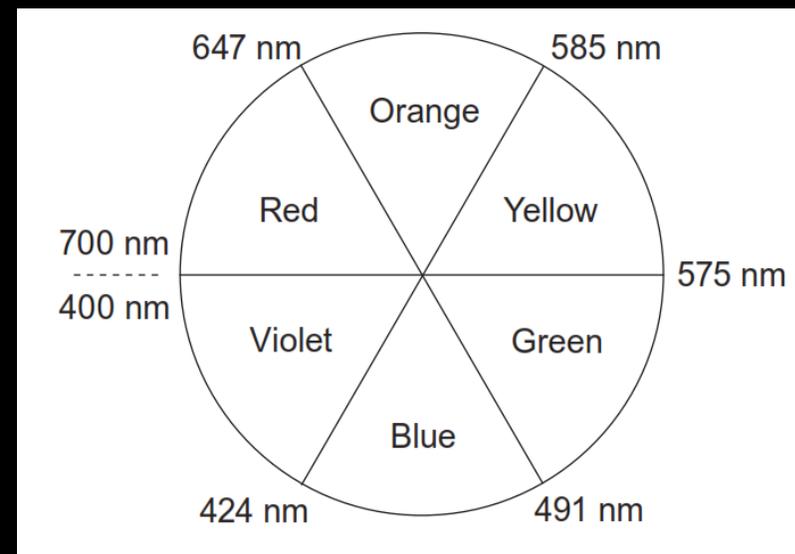
Colour of complex ions



The hexaaquacopper(II) ion appears blue because it absorbs orange light and transmits blue light.

The colour observed is complementary to the colour that is absorbed.

Colour of complex ions



Complex ion	Colour observed	Colour absorbed
$[\text{Cr}(\text{H}_2\text{O})_6]^{3+}$	Green	Red
$[\text{Co}(\text{H}_2\text{O})_6]^{2+}$	Red	Green

Colour of complex ions

Transition elements have incomplete d orbitals.

The d orbitals split into two sets of higher and lower energy when the ligands bond to the central metal ion.

The energy gap between the two sets of d orbitals corresponds to the wavelengths of visible light.

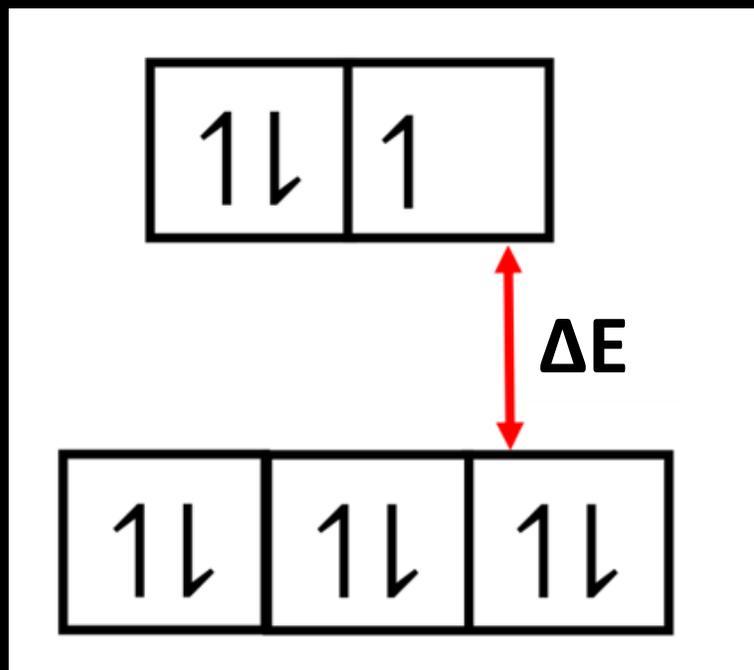
Electrons can transition from the lower to higher set of d orbitals by absorbing certain wavelengths of visible light.

The colour observed is complementary to the colour that is absorbed.

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**Factors that affect the
colour of complex ions**



Any factor that changes the difference in energy (ΔE) between the two sets of d orbitals will change the wavelength of light that is absorbed when electrons transition from the lower set to higher set, and therefore the colour of the complex ion.

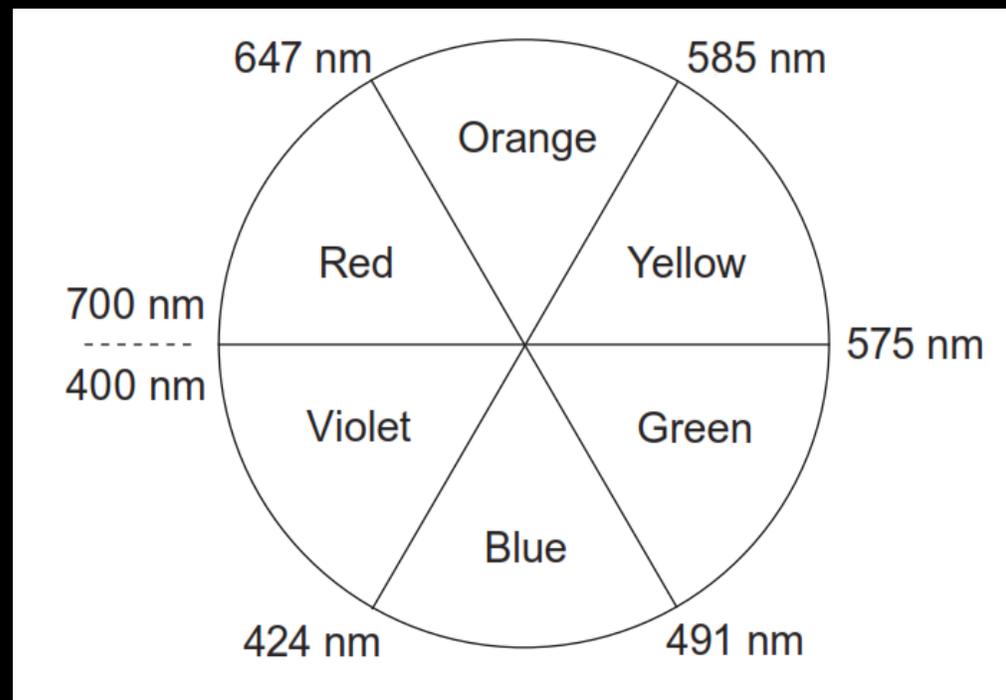
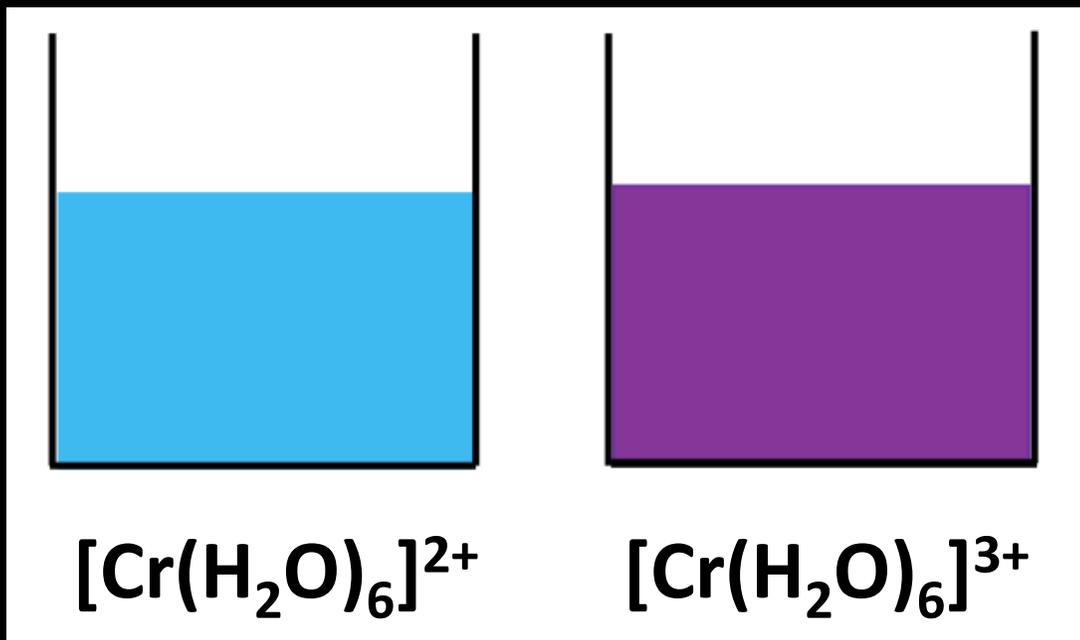
Identity of the central metal ion

Oxidation state of the central metal ion

Geometry of the complex ion

Identity of the ligands (spectrochemical series)

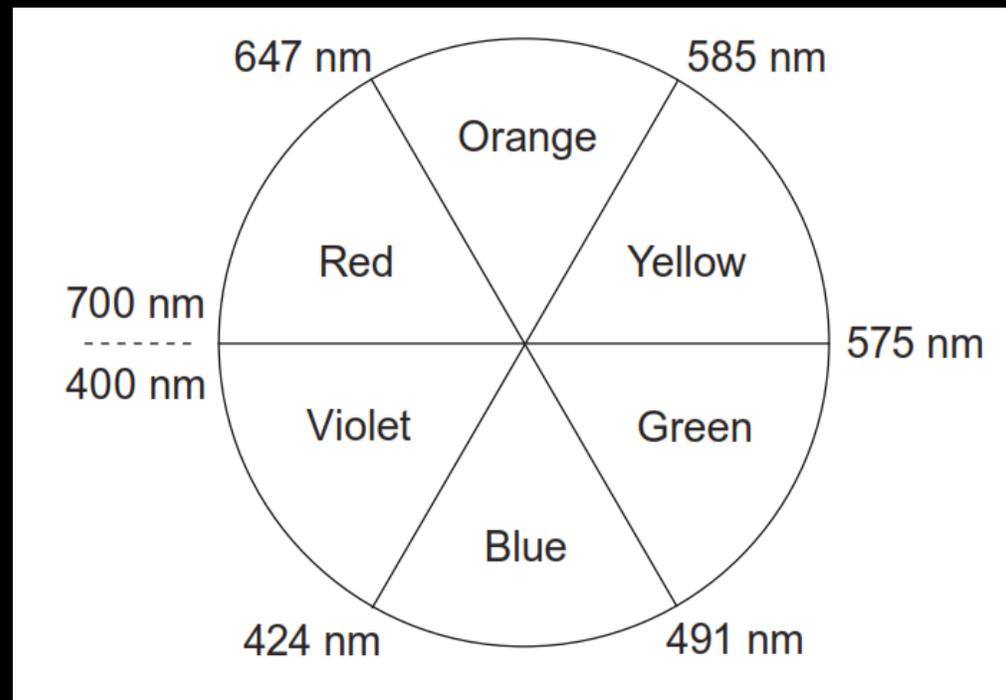
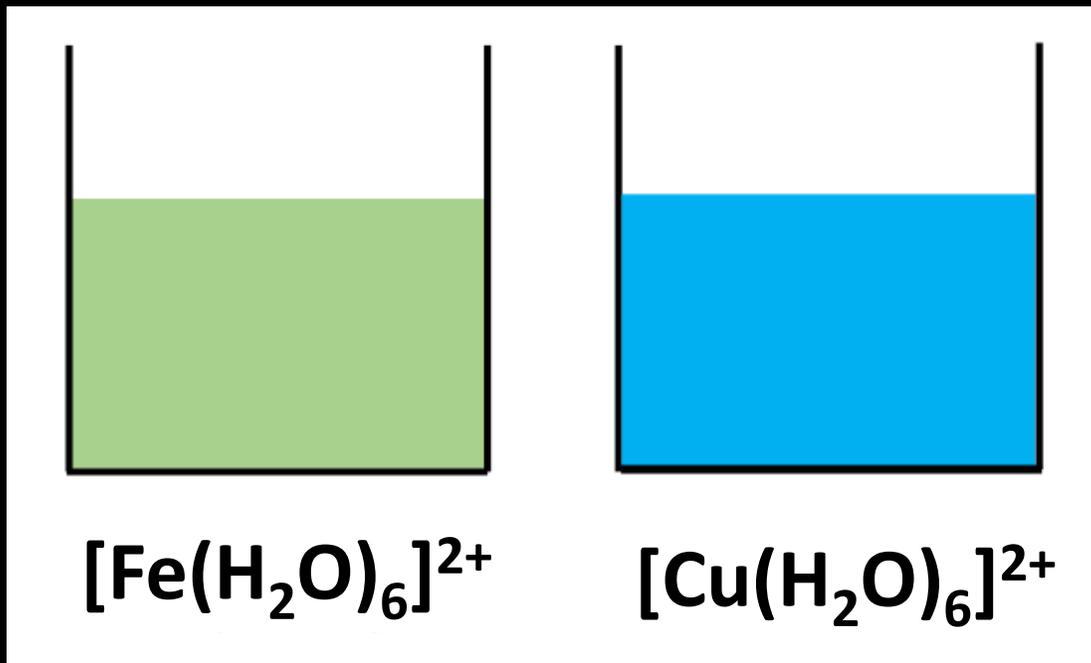
Factors that affect the colour of complex ions



An increase in the oxidation state of the central metal ion increases the energy difference between the two sets of d orbitals.

The wavelength of the light absorbed decreases.

Factors that affect the colour of complex ions



The change in the identity of the central metal ion causes a difference in the wavelength of light absorbed. The Cu^{2+} ion causes a larger energy gap and a shorter wavelength of light to be absorbed.

Identity of the central metal ion

Oxidation state of the central metal ion

Geometry of the complex ion

Identity of the ligands (spectrochemical series)



The spectrochemical series arranges ligands in order of their ability to split d-orbitals in an octahedral complex ion.

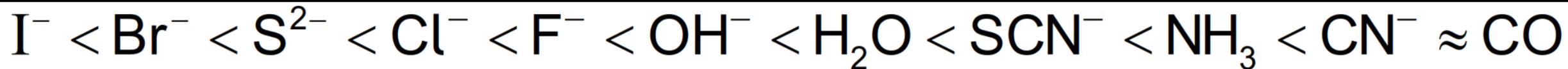
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Tutorials for IB Chemistry

**The spectrochemical
series**

The spectrochemical series

The spectrochemical series arranges ligands in order of their ability to split d orbitals in an octahedral complex ion.

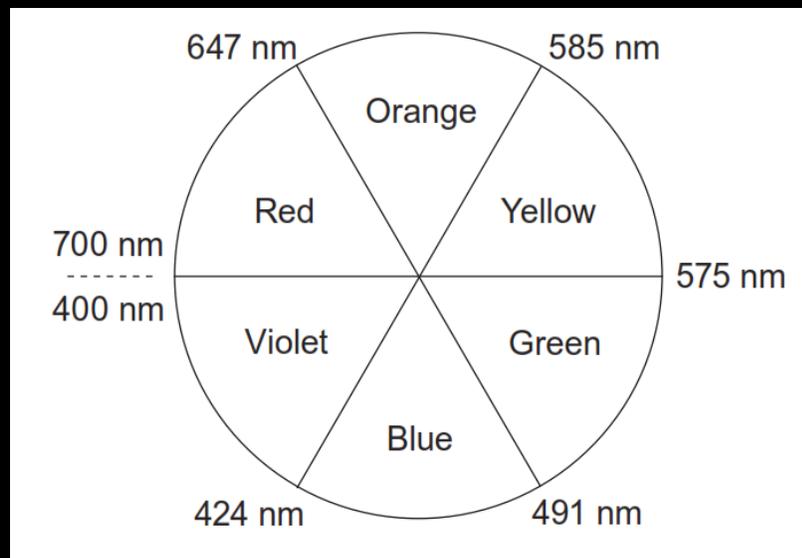


Increasing splitting of d orbitals

Weaker field
ligands

Smaller ΔE

Longer λ

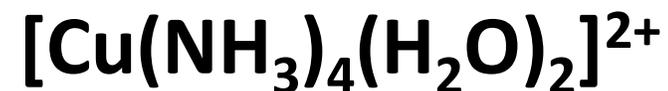
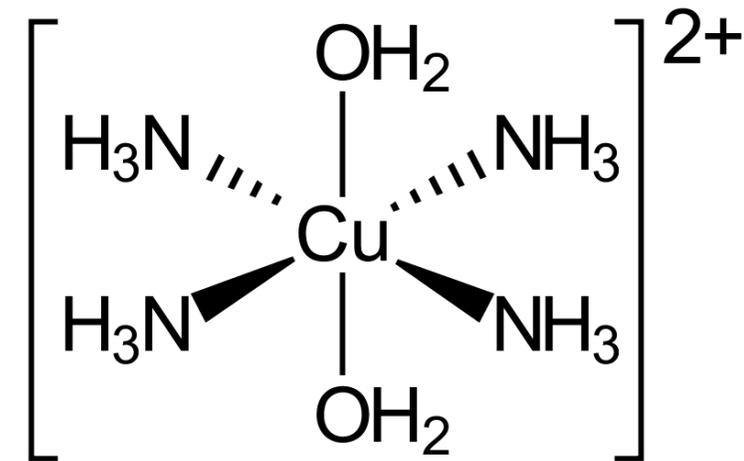
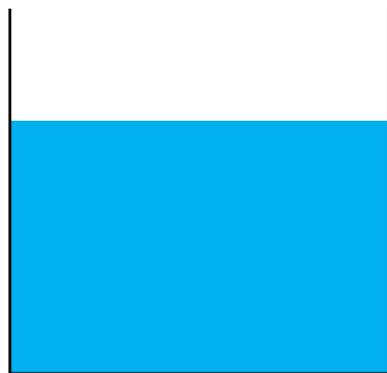
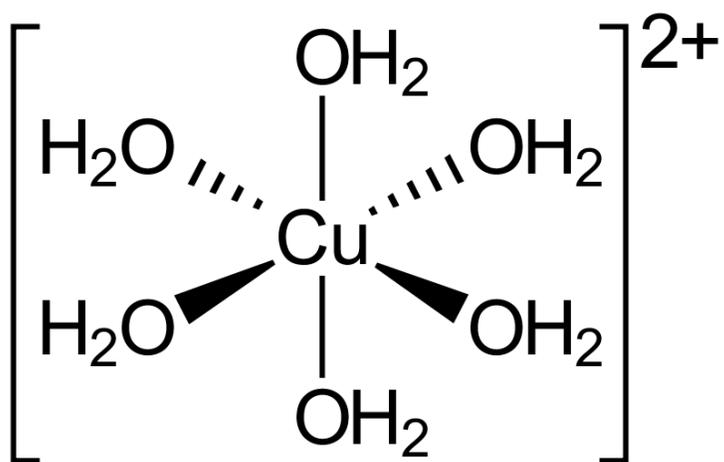


Stronger field
ligands

Larger ΔE

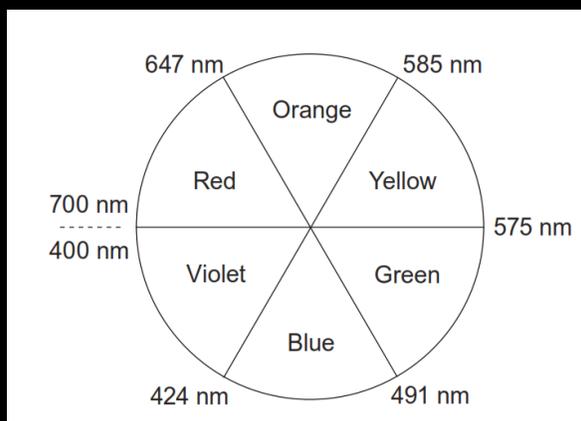
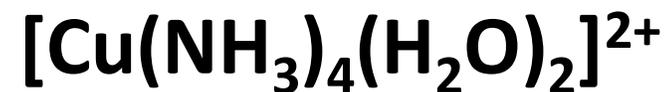
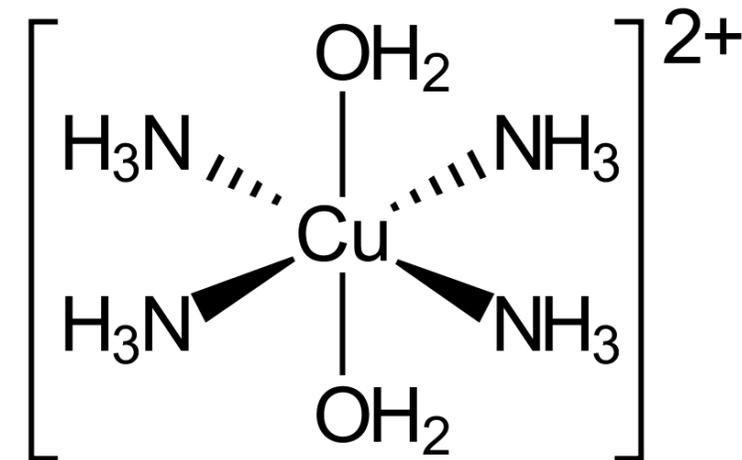
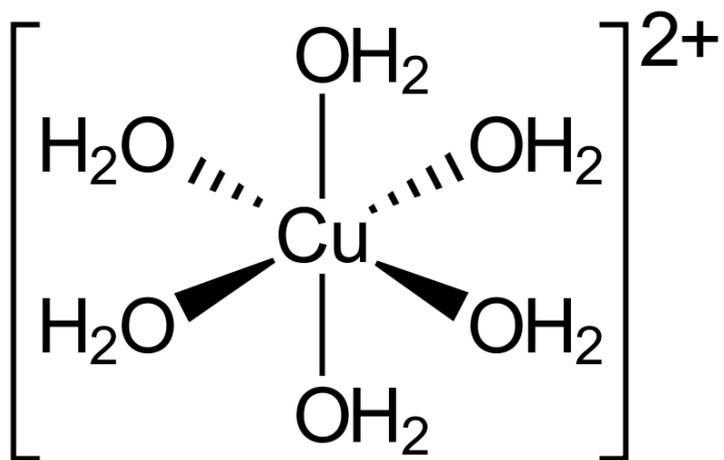
Shorter λ

The spectrochemical series

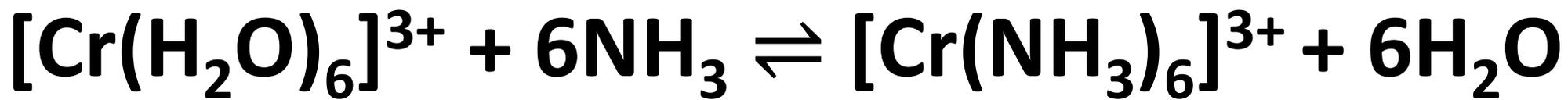
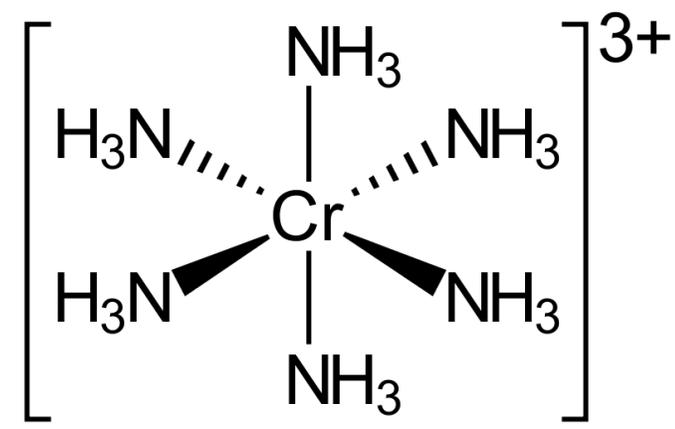
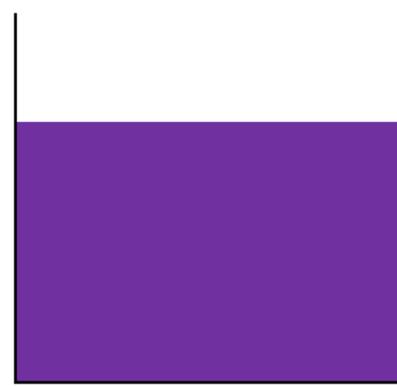
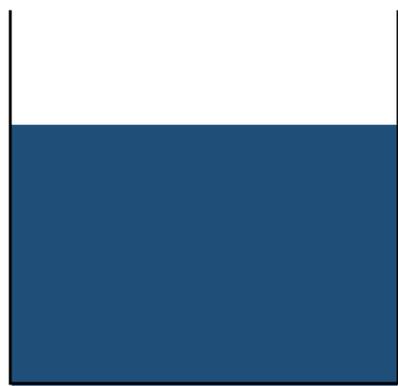
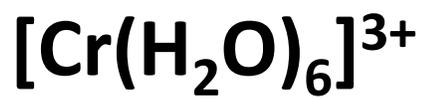
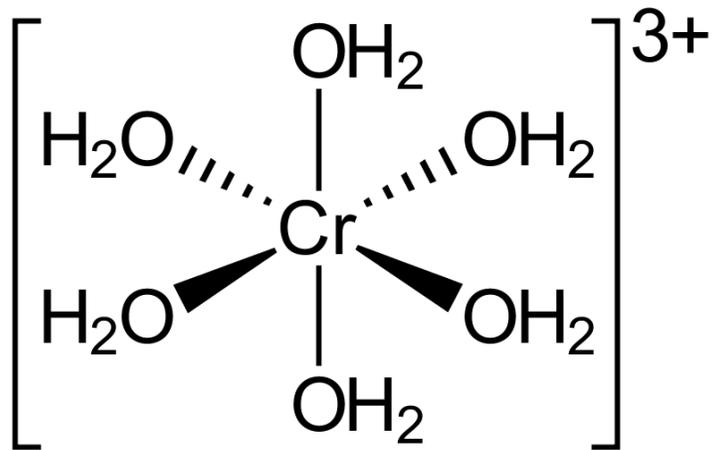


NH₃ is a stronger field ligand; it produces a larger ΔE which means a shorter wavelength of light is absorbed.

The spectrochemical series



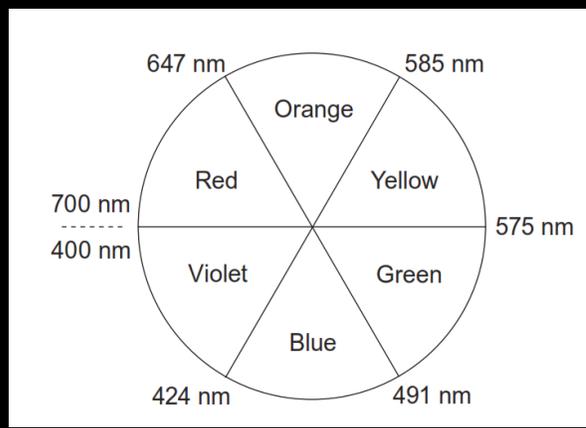
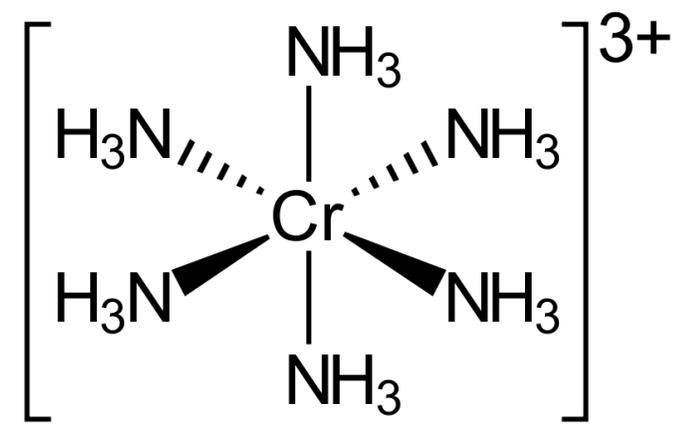
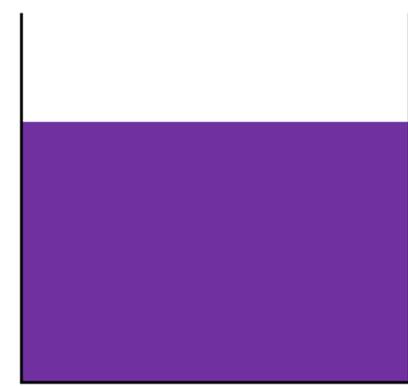
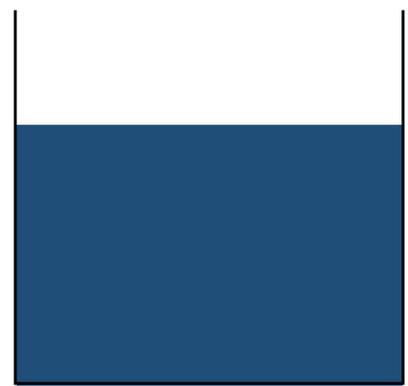
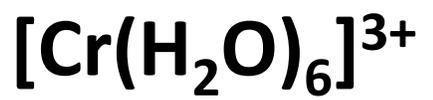
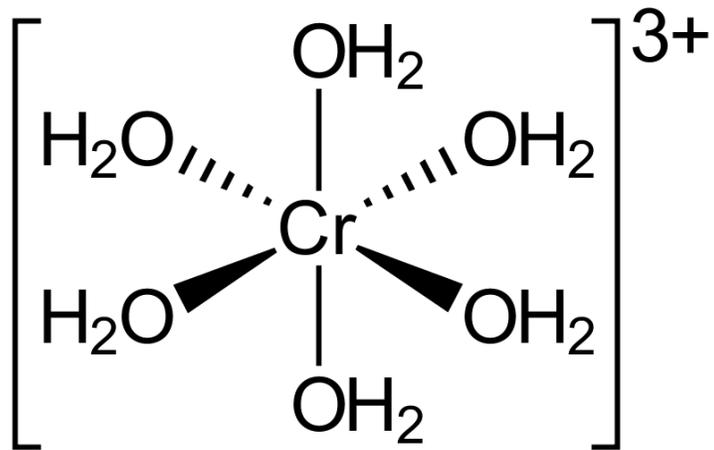
The spectrochemical series



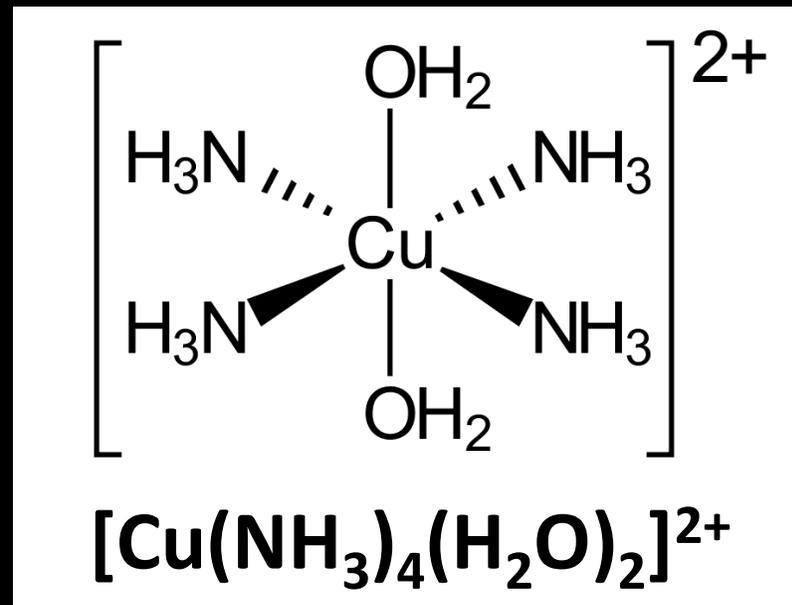
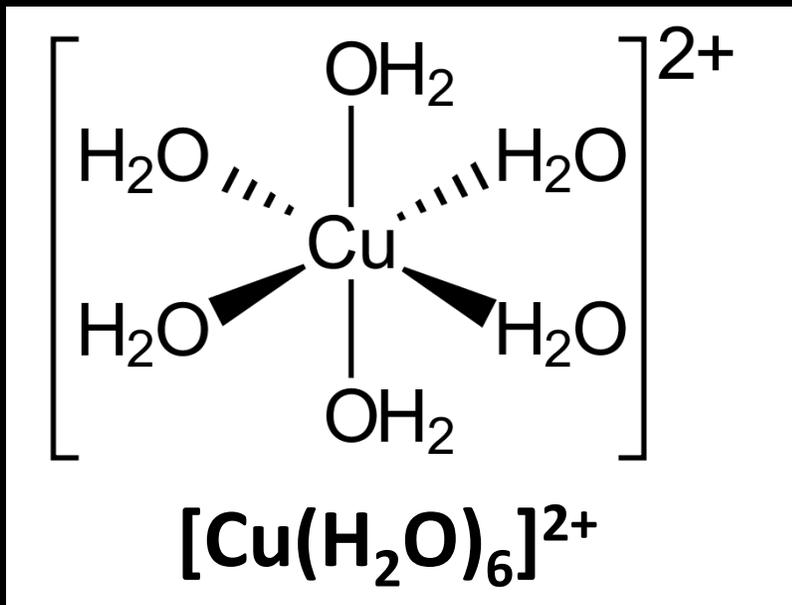
$\text{I}^- < \text{Br}^- < \text{S}^{2-} < \text{Cl}^- < \text{F}^- < \text{OH}^- < \text{H}_2\text{O} < \text{SCN}^- < \text{NH}_3 < \text{CN}^- \approx \text{CO}$

NH₃ is a stronger field ligand; it produces a larger ΔE which means a shorter wavelength of light is absorbed.

The spectrochemical series

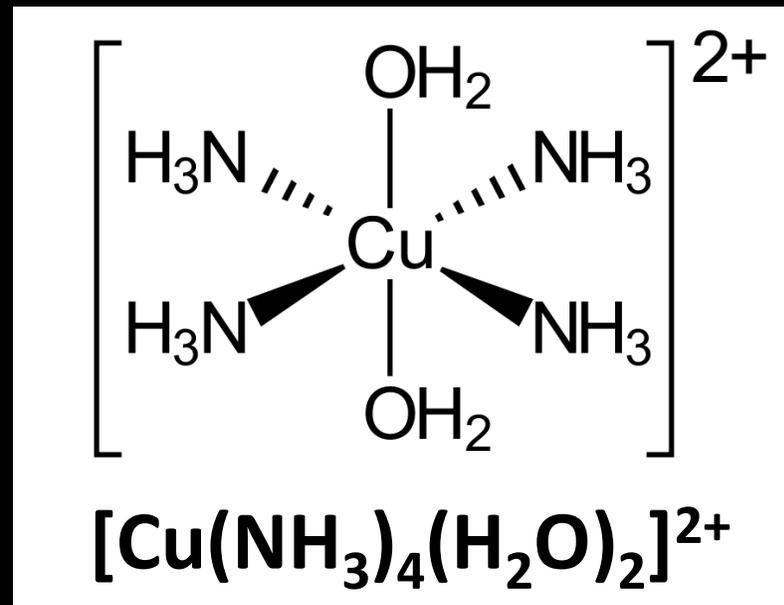
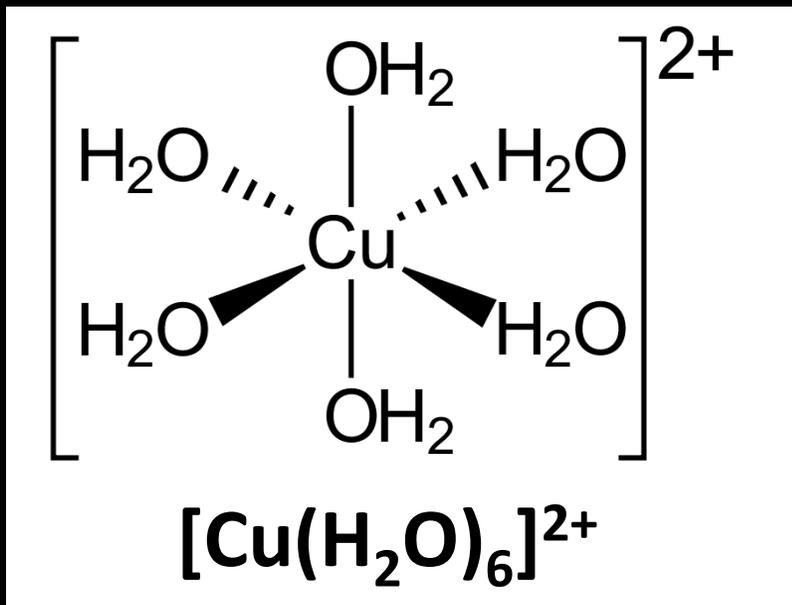


The spectrochemical series



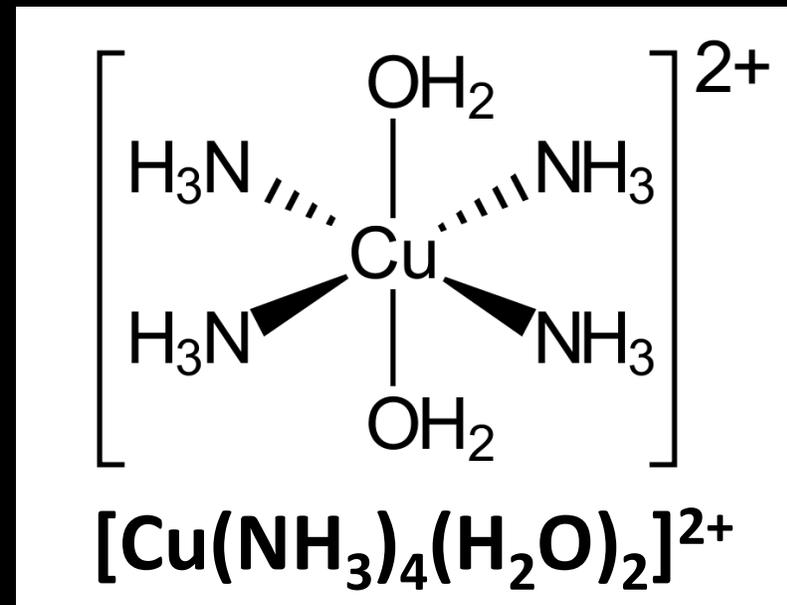
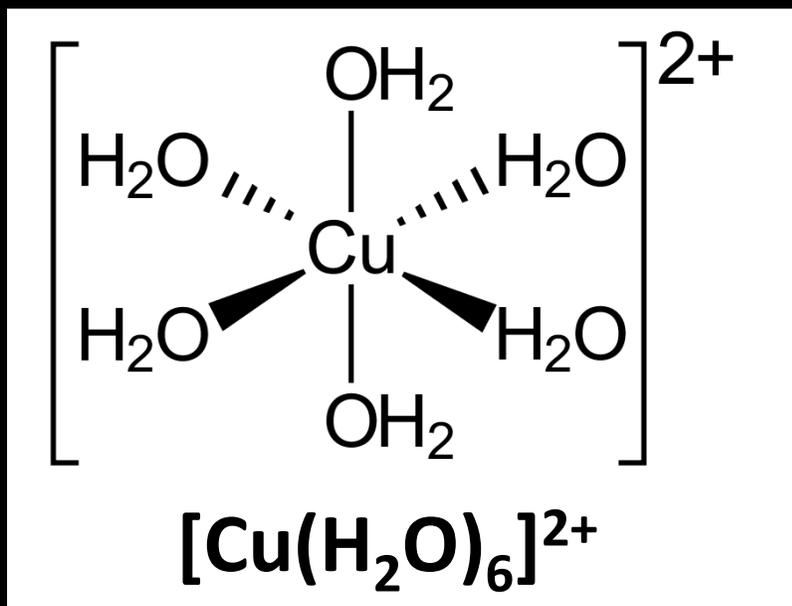
NH₃ is a stronger field ligand, therefore, it produces a larger difference in energy between the two sets of d-orbitals. The wavelength of light absorbed decreases.

The spectrochemical series



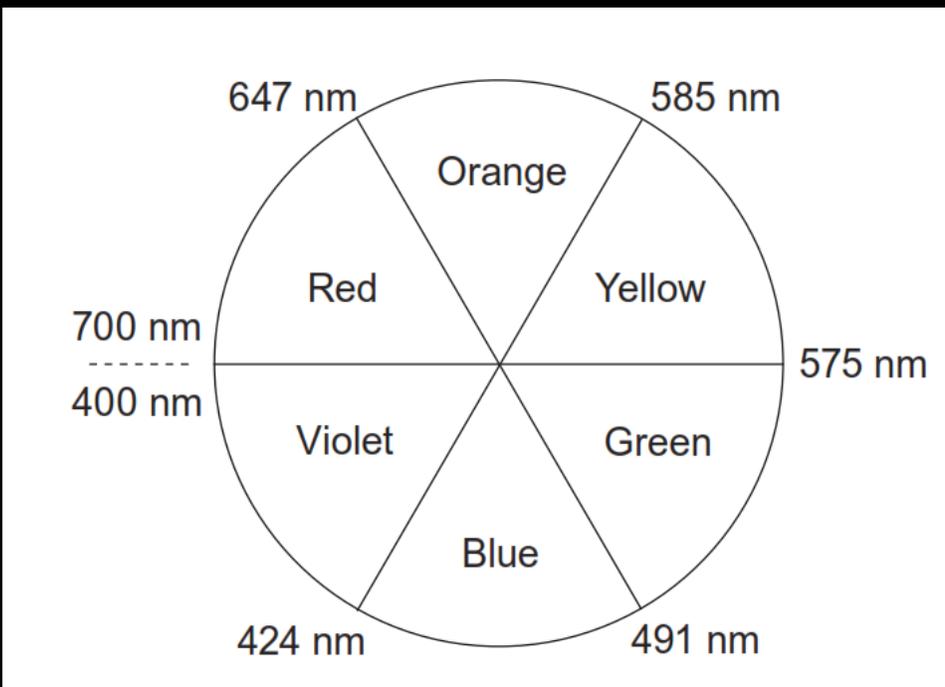
Ligand replacement – a stronger field ligand replaces a weaker field ligand.

The spectrochemical series



NH_3 is a stronger field ligand, therefore, it produces a larger difference in energy between the two sets of d-orbitals. A larger amount of energy is absorbed by the electron transitions from the lower to the upper set of d-orbitals, therefore, the wavelength of light absorbed decreases.

The spectrochemical series



$[\text{Cu}(\text{H}_2\text{O})_6]^{2+}$ - orange light is absorbed and blue light is transmitted.

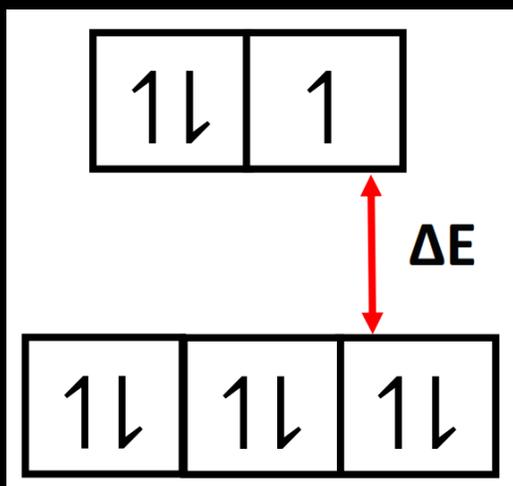
$[\text{Cu}(\text{NH}_3)_4(\text{H}_2\text{O})_2]^{2+}$ - yellow light is absorbed and violet light is transmitted.

The spectrochemical series

The spectrochemical series arranges ligands in order of their ability to split d-orbitals in an octahedral complex ion.



Increasing splitting of d-orbitals



The greater the splitting, the greater the energy difference (ΔE) between the two sets of d-orbitals.

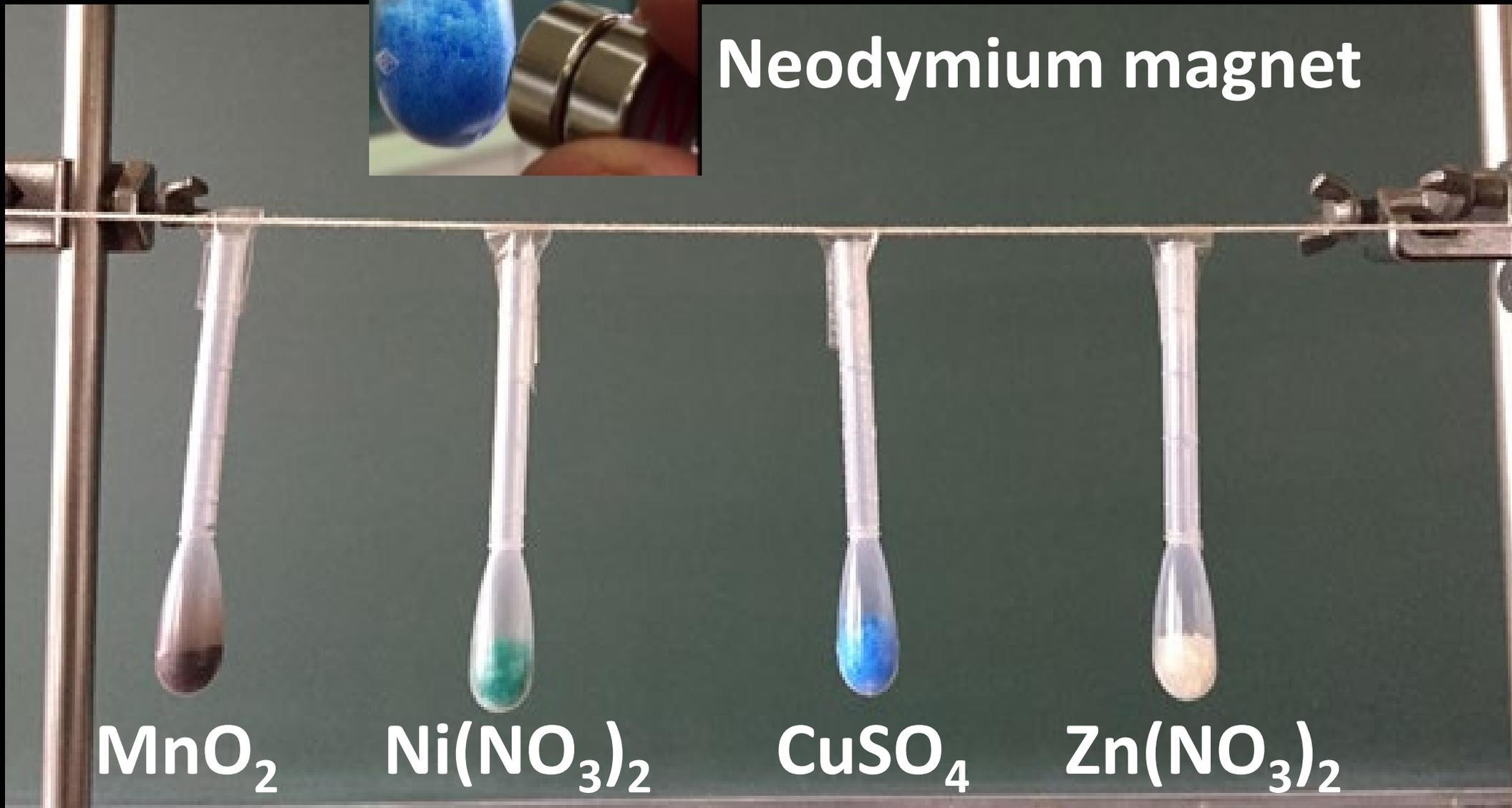
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**Magnetism in
transition elements**



Neodymium magnet



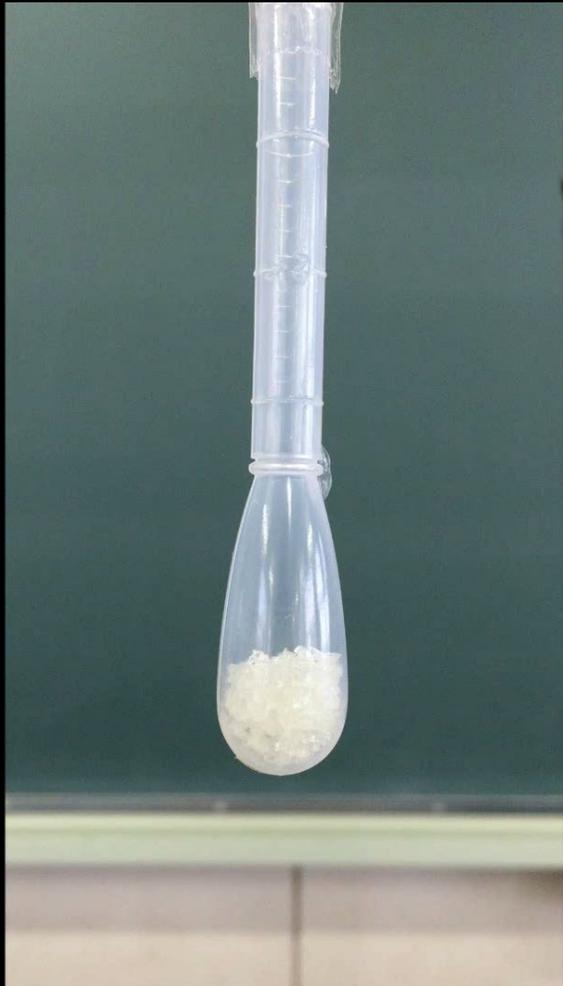
MnO_2

$\text{Ni}(\text{NO}_3)_2$

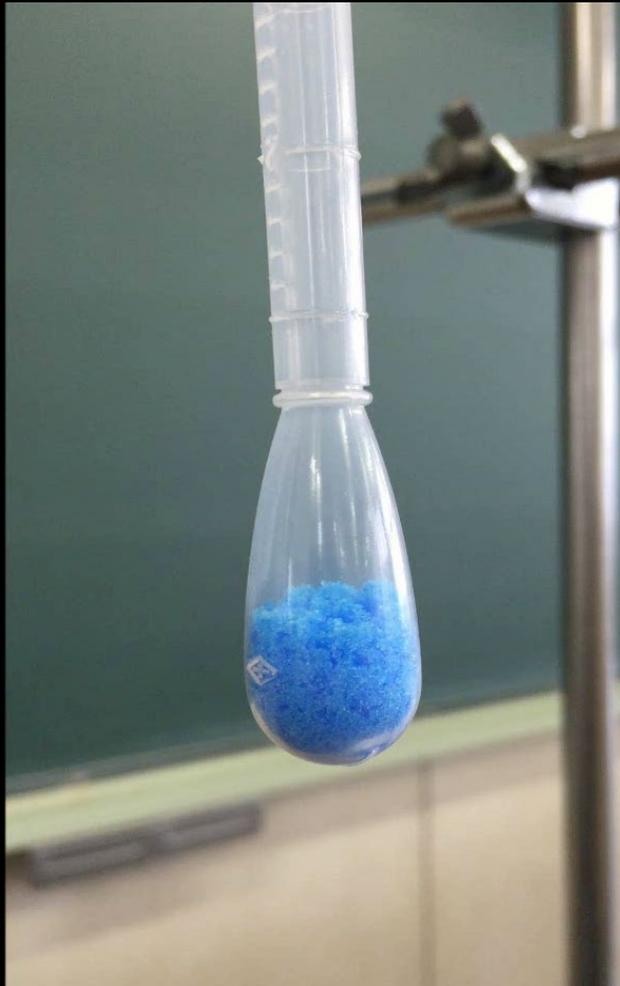
CuSO_4

$\text{Zn}(\text{NO}_3)_2$

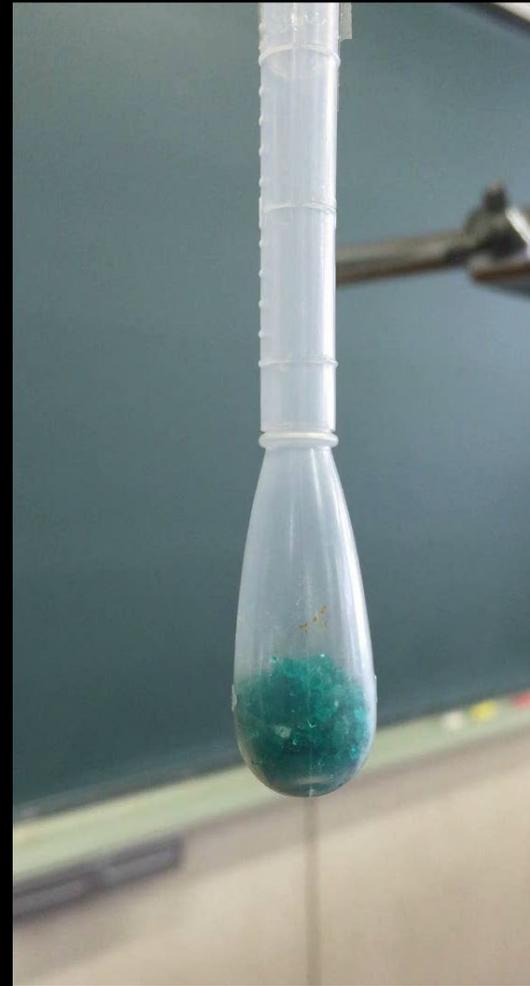
Magnetism of the transition elements



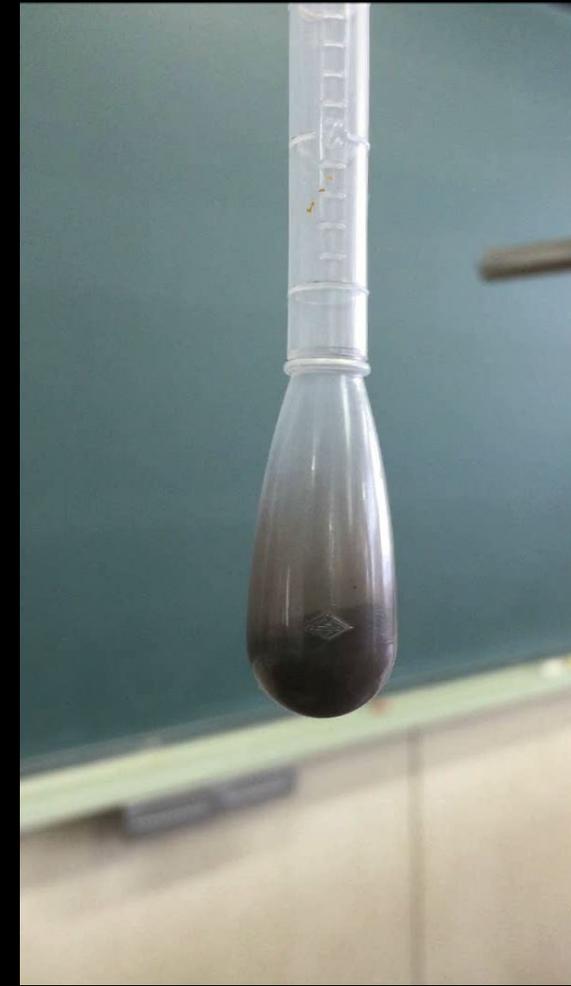
$\text{Zn}(\text{NO}_3)_2$



CuSO_4



$\text{Ni}(\text{NO}_3)_2$



MnO_2



Zn²⁺ ion

Electron configuration of Zn²⁺ 1s²
2s² 2p⁶ 3s² 3p⁶ 3d¹⁰

3d				
↑↓	↑↓	↑↓	↑↓	↑↓

No unpaired 3d electrons



Cu^{2+} ion

Electron configuration of Cu^{2+}



3d				
1↓	1↓	1↓	1↓	1

One unpaired 3d electron

Ni²⁺ ion

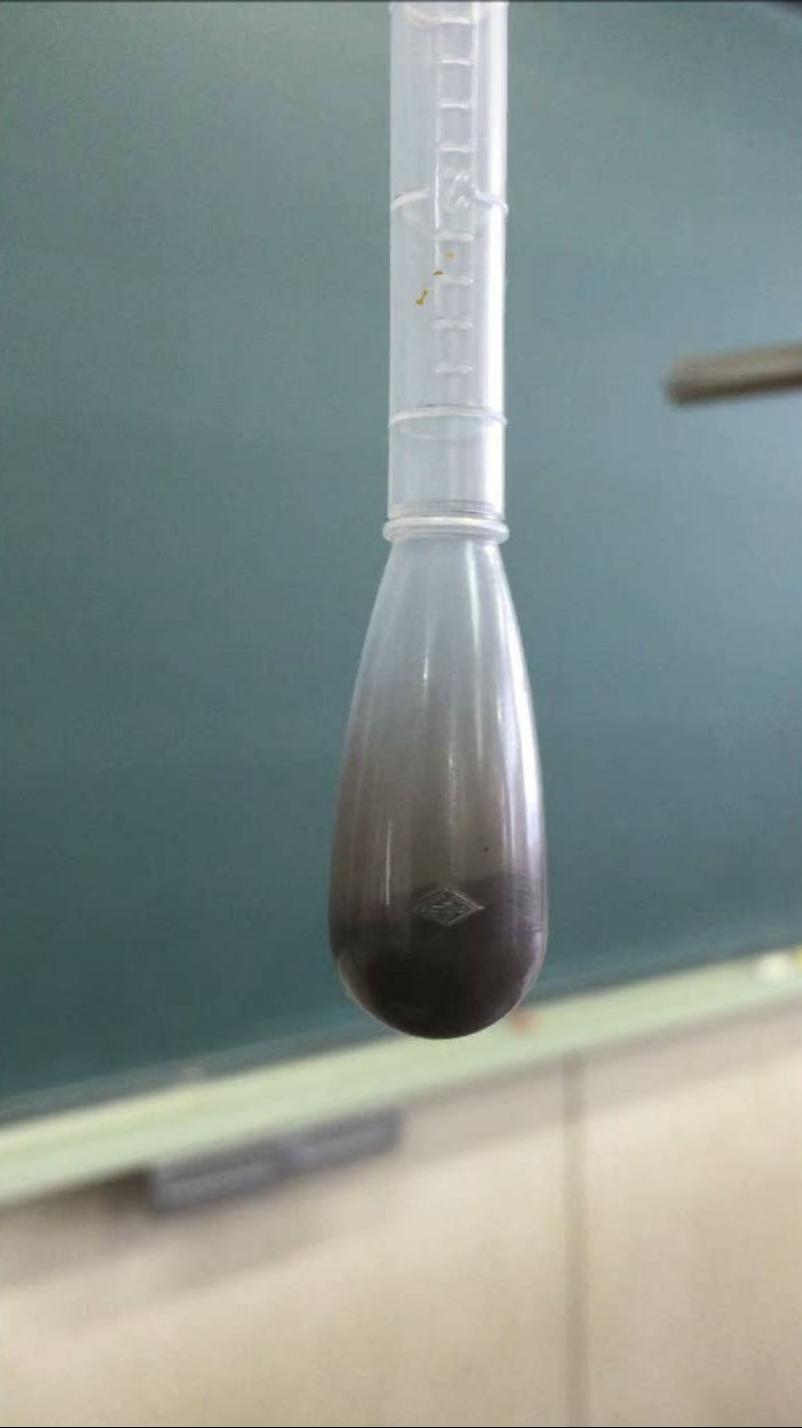
Electron configuration of Ni²⁺



3d				
↑↓	↑↓	↑↓	↑	↑

Two unpaired 3d electrons





Mn⁴⁺ ion

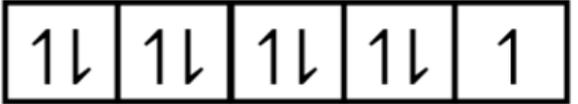
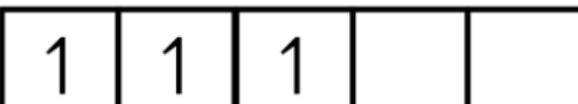
Electron configuration of Mn⁴⁺



3d				
1	1	1		

Three unpaired 3d electrons

Summary

Ion	Effect in external magnetic field	Unpaired 3d electrons
Zn^{2+}	No effect*	<div style="text-align: center;">3d</div> 
Cu^{2+}	Weak effect	<div style="text-align: center;">3d</div> 
Ni^{2+}	Stronger effect	<div style="text-align: center;">3d</div> 
Mn^{4+}	Strongest effect	<div style="text-align: center;">3d</div> 

Increasing effect in magnetic field as number of unpaired 3d electrons increases.

Diamagnetism

No unpaired electrons.

Weakly repelled in an external magnetic field.



Zn²⁺ ion

Electronic configuration of Zn²⁺



3d				
↑↓	↑↓	↑↓	↑↓	↑↓

No unpaired d electrons

Paramagnetism

One or more unpaired d electrons.

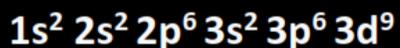
Attracted by an external magnetic field.

Paramagnetism increases with the number of unpaired electrons.



Cu²⁺ ion

Electronic configuration of Cu²⁺



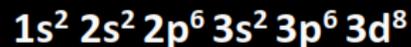
3d				
↑↓	↑↓	↑↓	↑↓	↑

One unpaired d electron



Ni²⁺ ion

Electronic configuration of Ni²⁺



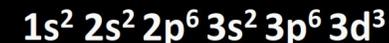
3d				
↑↓	↑↓	↑↓	↑	↑

Two unpaired d electrons



Mn⁴⁺ ion

Electronic configuration of Mn⁴⁺



3d				
↑	↑	↑		

Three unpaired d electrons

Increasing number of unpaired d electrons = increasing paramagnetic effect

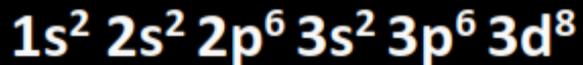
Ferromagnetism

Iron, nickel and cobalt are ferromagnetic – they remain magnetised after the external magnetic field is removed forming permanent magnets.



Ni^{2+} ion

Electronic configuration of Ni^{2+}



3d				
↑↓	↑↓	↑↓	↑	↑

Two unpaired d electrons

Unpaired electrons align parallel in domains

