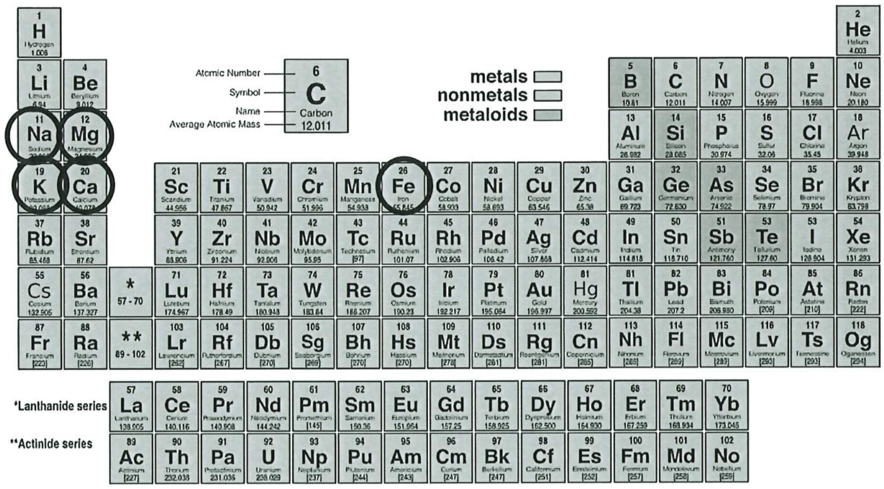
Magnesium – more than a silver ribbon

Among the elements most abundant in organic life, non-metals dominate, especially carbon, hydrogen, oxygen and nitrogen. Metallic elements do, however, play a key role in biological systems, including the human body, with sodium (Na^+), potassium (K^+), calcium (Ca^{2+}), magnesium (Mg^{2+}) and iron (Fe^{3+}/Fe^{2+}) ions being the most abundant. Of these metals, however, only magnesium and iron find common use in other areas of chemistry as actual metals. You will probably be aware of iron's importance in steel – which holds up both our skyscrapers and our teabags on the end of a teaspoon. You may also be aware of the key role of iron ions at the centre of haemoglobin, which carries oxygen to cells around the body, and carbon dioxide back to the lungs. Magnesium may not be as famous as iron, but the variety of its roles in both organic and inorganic chemistry is impressive – and much of this relies on the principles you will cover in your study of group 2 at A Level.



The location of some metals in the periodic table which have important ions in the body

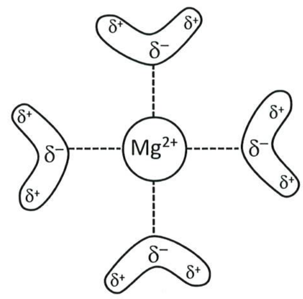
Magnesium and life

Magnesium is the eighth most abundant element in Earth's crust, being slightly less abundant than potassium, sodium and calcium, and less than half as abundant as iron and aluminium. Despite this, magnesium is the most abundant metal across all cellular life. The reason for this is linked to the origin of life, where magnesium ions clearly had properties that made magnesium suited for incorporation into cells.

Staying in solution

Magnesium ions have a stronger electrostatic attraction to water molecules (and hydroxide ions) than the elements of group 2 below magnesium, which means they are more soluble. This is because magnesium ions are smaller, and can be thought of as having a 'more concentrated' 2+ charge, which attracts the partial negative charge (δ^-) on oxygen in water molecules more strongly.

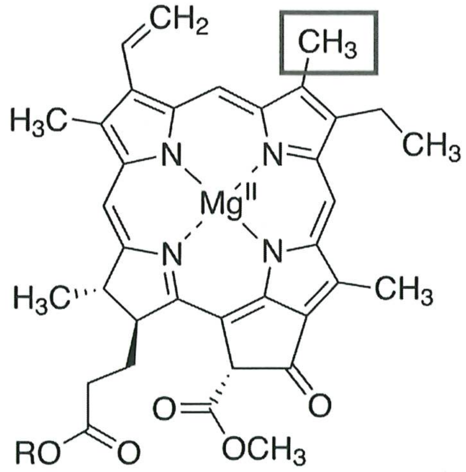
Because calcium ions are less soluble than magnesium ions, they are more likely to form solid precipitates with other ions found in water, such as sulfate ions and carbonate ions. This explains why magnesium sulfate is soluble whereas the sulfates of group 2 below it are much less soluble, and why calcium has a common role in living organisms as part of solids such as calcium carbonate (which makes up shells, coral and eggs) and a form of calcium phosphate which makes up bones.



Mg^{2+} interacting with δ- O atoms in water molecules

Sodium ions and potassium ions are soluble, like magnesium ions, but form much weaker attractions to water molecules due to their 1+ charge. The reason they are soluble in water, despite forming much weaker attractions than the 2+ ions in group 2, is that the group 1 ions do not form comparably strong electrostatic attractions to other ions or molecules either, and, therefore, remain dissolved in water instead of forming precipitates.

Transport



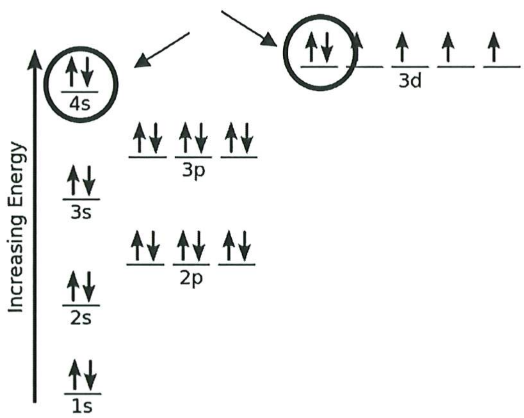
The structure of chlorophyll-a. Most of it is made of carbon and hydrogen (the parts without letters) but in the middle is an Mg^{2+} ion electrostatically attracted to four δ- nitrogen atoms.

The ability of magnesium to bind well to water molecules means it has the potential to be transported across membranes, a key trait in early cellular life. Sodium and potassium ions most commonly pass in and out of cells without contributing to any structures once inside the cell – they just pass out again (movement that is key to nerve transmissions). However, because magnesium can form stronger electrostatic attractions, magnesium ions can then bind to other substances containing electronegative oxygen or nitrogen atoms. This means transported magnesium ions can be incorporated into important structures inside the cells, such as chlorophyll in plants, or bind to substances to allow them to carry out their role; for example, binding to ATP (our 'energy currency') in many organisms.

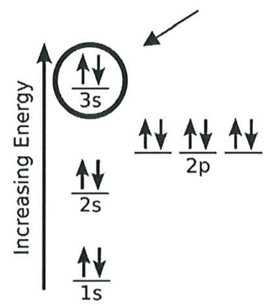
Fe vs Mg

Iron 2+ ions (Fe^{2+}) behave in a similar way to magnesium ions – they form relatively strong bonds with water, and can then also form new electrostatic attractions with other molecules containing nitrogen or oxygen atoms inside a cell. Both Fe and Mg are essential in many forms of life. Two key differences between the two are:

1) their size – magnesium's outer electrons are in a 2p subshell, whereas
2) and iron's ability to be oxidised into other ions, mainly Fe^{3+}. This change involves Fe^{2+} losing an electron to form Fe^{3+}, which it often regains to form Fe^{2+}.



Iron electronic structure – the 4s electrons are lost easily, but a 3d electron may also be lost and regained, meaning iron forms both Fe^{3+} and Fe^{2+} commonly



Magnesium electronic structure – the 3s electrons are lost easily, but after that the 2p electrons are held much more strongly

The extra electron that Fe^{2+} loses when it forms Fe^{3+} can allow other chemical reactions to occur, often more quickly than they would have done otherwise, meaning that Fe^{2+} ions can play a role as a catalyst for reactions involving oxidation and reduction. Mg^{2+} does not lose or gain electrons easily – the 3s electrons in Mg atoms are easily lost to form Mg^{2+} as they are further away and not held strongly, but losing subsequent 2p electrons from Mg^{2+} ions is very difficult due to their proximity to the nucleus. This means that Mg^{2+} ions are chemically quite stable (whereas magnesium metal is very reactive). There are many examples of biological molecules that must not change chemically if they are to perform their function (e.g. the backbone of DNA and the molecules in cell membranes), and, therefore, Mg^{2+} is much more suited in these situations than Fe^{2+}.

Magnesium as a metal

Most people associate magnesium metal with the strips that get burned in Chemistry class and produce a bright white light (while the teacher tells the class not to look directly at it!). It also gets remembered for being put in test tubes of hydrochloric acid, watching it bubble and lighting the gas to produce a squeaky pop – showing it to be hydrogen. Not many people think of magnesium as being a metal that is useful in real life, and this is an injustice to a metal that has a very important set of properties.

Density

The metals in the top left of the periodic table have in common a high reactivity, but also a low density due to their low molecular weight. Magnesium is the least reactive of the metals in groups 1 and 2 (with the exception of beryllium, which is quite different from the other elements), and is by far the most commonly used as a metal in alloys, partly due to its lower reactivity. Only iron and aluminium are more commonly used to make metal objects and structures, and magnesium is normally used to form an alloy with these metals. The advantage of using magnesium with these metals is that its low density allows for lower-density alloys to be made, which is important in construction, transport, electronics and many other areas of technology where a light weight is important.

Elektron

The risk with using magnesium in alloys is that the metal itself is very reactive, burning in a very exothermic, vigorous reaction. This is very rarely a problem in alloys, as shown by the fact that 'Elektron' – an alloy containing magnesium – has been used to make engines for the aerospace and car industry, with the Magnesium Elektron Ltd company having produced the alloy in Manchester since 1936.

On two occasions, however, the flammability of the magnesium has meant that Elektron has hit the headlines. Firstly, in World War II, when the low-density Elektron was used to make bomb casings. The lighter-weight bombs could be transported and dropped in higher numbers, and when they exploded on landing the burning magnesium burned through metal, reacted with any water poured on it, and continued to react for over 15 minutes. In the 1955 Le Mans race the same effect was observed with horrifying consequences when a car with an Elektron engine crashed and its fuel tank exploded, causing the Elektron engine to subsequently explode and shower the crowd in burning magnesium. Unwitting stewards attempted to put out the fires with water, making them much worse and creating flames which burned for several hours. Sadly 85 spectators were killed, as well as the driver of the car.

Parts of a car which can be made from magnesium alloys include the steering wheel, inner door frame and seat frame.

Modern research continues to work on developing magnesium alloys that are resistant to the heat of engines and safe to use by varying the amount of magnesium in the alloy, and including other metals which reduce the likelihood that magnesium will react with oxygen.

Comprehension questions

1. Explain what the following terms mean:
   a) Electronegative
   b) Partial charge
   c) Precipitate
   d) Molecular weight
   e) Alloy
2. Why are barium ions (Ba^{2+}) less soluble in water than the ions of the elements above barium in group 2?
3. Summarise the key properties of a) Mg^{2+} ions and b) Magnesium metal mentioned in the article.
4. Summarise the key reasons why Mg^{2+} ions are the most common metal ion in cellular life, despite magnesium not being the most common metal on Earth.

Application questions

5. Enthalpy of hydration is the energy released when one mole of a gaseous metal ion binds to water. The enthalpies of hydration of K^+, Mg^{2+} and Na^+ are, from largest to smallest:

   $$-1926 \text{ kJ mol}^{-1}, -406 \text{ kJ mol}^{-1}, -320 \text{ kJ mol}^{-1}$$

   Match the values to the metal ions, explaining your reasoning.
6. Suggest the benefits and risks of using lithium in alloys compared to magnesium.
7. Suggest the main environmental advantage of using magnesium in engines as opposed to transition metals from the centre of the periodic table.
8. Mg^{2+} ions can act as catalysts, but often in a different way to Fe^{2+}/Fe^{3+} ions. Often this involves magnesium ions acting as a **cofactor**. Find out what this means, and write an explanation of this using a diagram, and find out a biological example of when this is important.
9. Magnesium ions can act as **Lewis acids**, which allow pH to be lowered in a gentle fashion that is suitable in cells, rather than by releasing lots of H^+ ions like Bronsted–Lowry acids which can be too strong. Find out what a Lewis acid is, and explain why a Lewis acid (such as Mg^{2+}) would slightly lower the pH of water.

Taking it further

10. Copper ions are also important to life. Research some of the key roles that copper plays, and explain what the key properties of copper ions are that allow it to perform its role well in living systems.

