

# Elements of Life and Death



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By

Lars Olof Björn

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## INTRODUCTION

Ninety-eight percent of the mass of the human body is made up of six elements: oxygen, carbon, hydrogen, nitrogen, sulfur, and phosphorus. The present book will be concerned with the importance of more than 40 other elements for the human body and for animals, plants, fungi, and bacteria. Hydrogen and oxygen are the elements of water, without which life is hard to imagine. They, and also carbon, nitrogen, sulfur, and phosphorus are necessary for proteins and nucleic acids, which are also components required by all life on our planet.

Some other elements are also required for all life forms – humans, animals, plants, fungi, bacteria, and archaea. They are K, Ca, Mg, Fe, Zn, Mo, Cu, Mn, and Ni. Well, not quite true. There are actually bacteria which do not need Fe (iron), and Ni (nickel) is probably not universally required either. And we and other animals need Na. We shall return to these elements later.

But some organisms require other elements, or their essentiality is controversial. This will be the elements that we shall focus on in this book, such as As, B, V, Cr, Cd, Si, Co, I, F, Br, Sb, Se, Te, La, Ce, Pr, Nd, Gd. We shall also have something to say about biological uses of some other elements, as Cl and Fe, which are extremely important in some ways that most people are unaware of. And we cannot abstain from Agatha Christies favourite poison, thallium (see [https://en.wikipedia.org/wiki/Thallium\\_poisoning](https://en.wikipedia.org/wiki/Thallium_poisoning), <https://www.nytimes.com/1977/06/24/archives/agatha-christie-booksaves-an-infants-life.html> “The pale horse”, [https://en.wikipedia.org/wiki/The\\_Pale\\_Horse](https://en.wikipedia.org/wiki/The_Pale_Horse), and <https://www.imdb.com/title/tt10485750/>).

We shall also include in our account several other elements which are not necessary for any organisms, but anyway are of biological interest.

1																		18
H																		He
2	Li	Be																
	Na	Mg	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18
	K	Ca	Sc	Ti	V	Cr	Mn	Fe	Co	Ni	Cu	Zn	Al	Si	P	S	Cl	Ar
	Rb	Sr	Y	Zr	Nb	Mo	Tc	Ru	Rh	Pd	Ag	Cd	In	Sn	Sb	Te	I	Xe
	Cs	Ba	57-71 lantha- noids	Hf	Ta	W	Re	Os	Ir	Pt	Au	Hg	Tl	Pb	Bi	Po	At	Rn
	Fr	Ra	89-103 acti- noids	Rf	Db	Sg	Bh	Hs	Mt	Ds	Rg	Cn	Nh	Fl	Mc	Lv	Ts	Og

Overview of the periodic system of elements. Those with green background are major constituents of all organisms, and are not treated in this book. Those on grey background are of no known direct biological use, and are not treated here either. The elements on red background are required by at least some organisms, or are parts of known enzymes. The status of elements on white background, chromium and aluminium is disputed, and will be discussed. Note the numbers on top of the columns, which are used for numbering the following chapters (except that there is no chapter 18).

At the beginning of each chapter the periodic system is shown as above, but with the symbols for elements treated in the chapter surrounded by a light blue frame.

# CHAPTER ONE

## ALKALI METALS

1																	18	
H																	He	
2	Li	Be											B	C	N	O	F	Ne
3	Na	Mg	3	4	5	6	7	8	9	10	11	12	Al	Si	P	S	Cl	Ar
4	K	Ca	Sc	Ti	V	Cr	Mn	Fe	Co	Ni	Cu	Zn	Ga	Ge	As	Se	Br	Kr
5	Rb	Sr	Y	Zr	Nb	Mo	Tc	Ru	Rh	Pd	Ag	Cd	In	Sn	Sb	Te	I	Xe
6	Cs	Ba	57-71 lantha- noids	Hf	Ta	W	Re	Os	Ir	Pt	Au	Hg	Tl	Pb	Bi	Po	At	Rn
7	Fr	Ra	89-103 acti- noids	Rf	Db	Sg	Bh	Hs	Mt	Ds	Rg	Cn	Nh	Fl	Mc	Lv	Ts	Og

### 1.1 Lithium – the metal that was “in the beginning”

In the beginning was the Big Bang. The first elements that followed were hydrogen, helium and lithium ( $^7\text{Li}$ ). Here we shall concentrate on biological aspects of this, the first metal to come into being. Present-day natural lithium also consists of a small amount of  $^6\text{Li}$ . For further information about creation and destruction of lithium, see Lodders (2020).

Some plants are considered to be lithium hyperaccumulators (Jiang et al. 2014, Elektorowicz & Keropian 2015, Kawanagh et al. 2018, Qiao et al. 2018, Anguliano et al. 2022). Even closely related plants may show great differences in their accumulation ability. For instance, for plants grown in a soil amended with 20 mg Li/kg, the Li concentration in leaves of *Brassica napus* amounted to 7.8 mg per kg dry matter; for *Brassica oleracea* it was 1423 mg per kg dry matter (Kawanagh et al. 2018). There are lithium accumulators in several plant families: *Brassica oleracea*, *Brassica juncea* and *Cardamine hirsuta* in Brassicaceae, *Helianthus annuus* in Asteraceae (Elektorowicz & Keropian 2015, Kavanagh et al. 2018), *Apocynum venetum* in Apocynaceae (Jiang et al. 2014, Qiao et al. 2018), and *Agrostis tenuis* in Poaceae (Anguliano et al. 2022). At least in *Apocynum venetum* the lithium is deposited mostly in the vacuoles (Qiao et al. 2018). Since high amounts

of lithium is a poison for many organisms, one can assume that lithium accumulation is a way for plants to protect themselves from herbivores and parasites, corresponding to what has been demonstrated for nickel accumulating plants.

Also some bacteria are able to accumulate high amounts of lithium. Of 70 organisms (bacteria, fungi, and actinomycetes) the most efficient accumulators (from a solution containing  $72.0 \mu\text{M Li}^+$ ) are the bacteria *Arthrobacter nicotianae* (Micrococcaceae)  $125.8 \mu\text{mol}/(\text{g dry weight})$  and *Brevibacterium helovolum* (Brevibacteriaceae)  $98.1 \mu\text{mol}/(\text{g dry weight})$ , both in the order Micrococcales (Tsuruta 2005). In the cyanobacterium *Arthrospira platensis* the concentration of lithium after three days reached  $2500 \mu\text{g}/(\text{g d.w.})$ , i.e.  $360 \mu\text{mol}/\text{g d.w.}$  at a concentration of  $500 \text{ mg}/\text{L}$  ( $72 \text{ mM}$ ) (Cepoi et al. 2021). Bruna et al. (2022) studied bacterial strains from the Atacama desert that grew well at  $\text{Li}^+$  concentrations up to  $700 \text{ mM}$  (*Pseudomonas rhodesiae*, *Planomicrobium koreense*, and *Pseudomonas sp.*). They seemed to protect themselves from lithium by precipitating it as lithium sulfide.

Also some fungi accumulate lithium; one species that has been studied is *Lentinus crinitus*, Polyporaceae (Faria et al. 2019, 2022). These authors also list data for a number of other fungi.

Lithium has been used as medicine for a number of medical problems. Most importantly, it has been used for a long time (Cade 1949, Ferensztajn-Rochowiak et al. 2021) for alleviating the symptoms of bipolar disorder, but, depending on genetic constitution, is effective only for about half of the patients, and only 20–30% are “excellent responders” (Papiol et al. 2022). The specific neurobiological mechanisms through which lithium exerts its effects on brain function are not fully understood; current knowledge is reviewed by Bergamelli et al. (2021). Bipolar disorder patients exhibit abnormally high cytosolic  $\text{Ca}^{2+}$  levels and protein kinase C hyperactivity that can be downregulated by long-term  $\text{Li}^+$  treatment. Protein kinase C is a protein with three calcium ions in the molecule, and calculations show that lithium ions can displace one of the calcium ions, and thereby inhibit the enzymatic activity, in agreement with experiments (Grauffel et al. 2021). Rubidium and cesium ions do not have this effect on protein kinase C, and do not have the same effect on bipolar disorder as lithium ions have. It should be pointed out that several other explanations for the lithium effect on bipolar disorder have been proposed. For instance, Espanhol & Vieira-Coelho (2022) report that lithium medication has a positive effect on the brain’s white matter. Different explanations may not be mutually exclusive. Rybakowski & Ferensztajn-Rochowiak (2022) are of the opinion that

lithium is underused for treatment of bipolar disorder considering the good results obtained with it.

A question that has been very hotly debated is whether lithium medication lowers the risk of suicide or not, and there have been several suggestions that lithium should be added to drinking water in order to protect people from suicide (see Araya et al. 2022).

Lithium has occasionally been used or suggested for treating a number of other medical problems: Cancer (Ge & Jakobsson 2019), sepsis-induced skeletal muscle atrophy (Lee et al. 2021), glaucoma (Vallée et al. 2021), osteoarthritis (Todd et al. 2018), psoriasis (Grzelj & Sollner Dolenc 2020), Alzheimer's disease (Wallace 2014, Ishii et al. 2021), and pulmonary injury caused by *Actinobacillus pleuropneumoniae* (Zhang et al. 2022). Presently we do not have data for verification of these claims. An inverse relation between lithium in drinking water and incidence of Alzheimer's disease is very weak, and can be shown only for men (Muronaga et al. 2022).

Lithium medication also has unwanted effects, such as kidney damage (Hayes et al. 2021) and endocrine dysfunction (Lerena et al. 2022) and must therefore be used with caution. In some places in Afghanistan the lithium content is high, and in vitro experiments point to a risk that this may induce malignant transformation of human cells (Sudo et al. 2020). In vitro experiments with cell cultures indicate that lithium ions at a concentration of more than 100 mg/L are toxic to neurons and may generate fibrils of amyloid-beta peptide, reminiscent of Alzheimer's disease (Wang et al. 2014).

Lithium ions affect the activities of a number of magnesium-dependent enzymes, including some in the respiratory chain. They also have an influence on the transcription of certain genes (reviewed by Roux & Dosseto 2017).

The total human mobilization of Li from the Earth's crust,  $>1,000 \times 10^9$  g/year, is much larger than Li mobilized by the natural processes of chemical and mechanical weathering, 94 and  $132 \times 10^9$  g/year, respectively (Schlesinger et al. 2021). This means that there is a great risk for contamination of the environment.

Natural lithium consists of two isotopes whose natural relative abundance is 7.59% for  ${}^6\text{Li}$  and 92.41% for  ${}^7\text{Li}$ . It has been suggested that tritium ( ${}^3\text{H}$ ) fusion should be used for future environment-friendly energy production, and that the tritium, which is rare in nature, should be synthesized using  ${}^6\text{Li} + \text{neutron} \rightarrow {}^3\text{H} + {}^4\text{He}$ . Thus there is need for fractionation of lithium to get  ${}^6\text{Li}$ , and this one should use its enrichment by certain algae (López-Rodas et al. 2021). Also the  ${}^7\text{Li}$  would find use in the nuclear energy industry.

## 1.2 Sodium and potassium

### 1.2.1 Roles in enzyme function

Many enzymes are activated by potassium ions, fewer by sodium ions, and some are less selective, and can be more or less activated by sodium, potassium, or other similar ions. Already long ago it was noticed that some enzymatic processes are stimulated by potassium ions. An example is the study by Boyer et al. (1942) of phosphorylations in muscle (Fig. 1.2.1). Kachmar and Boyer (1953) discovered that an enzyme, pyruvate kinase, required potassium for activity (although not all pyruvate kinases require potassium ions; Ramírez-Silva et al. 2022). Pyruvate kinase is a crucial enzyme of the glycolytic pathway that catalyzes production of the second of two ATP molecules by converting phosphoenolpyruvate and ADP to pyruvate and ATP. With a saturating concentration of pyruvate, the reaction rate is 400 times as high with (90 mM) as without potassium ions; further information on the activation of this enzyme by potassium is provided by Oriá-Hernández et al. (2005).

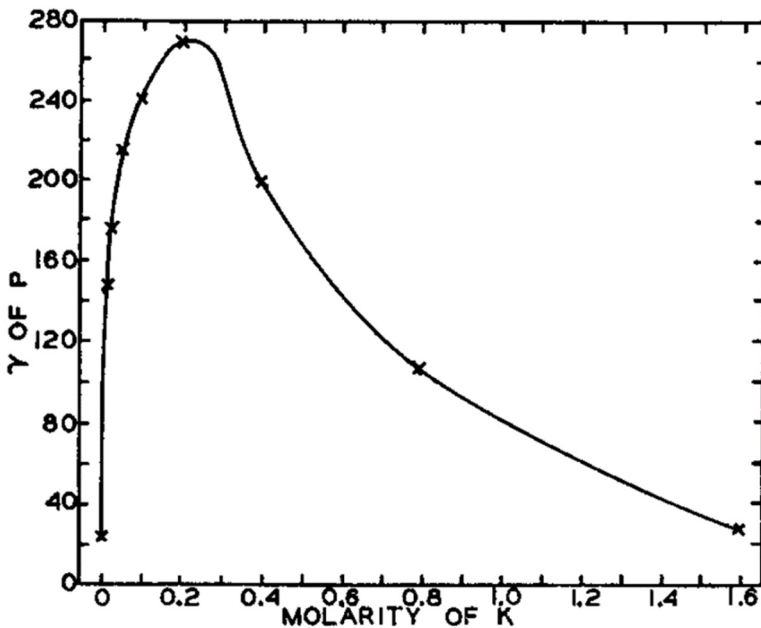


Fig. 1.2.1. The effect, of potassium ion concentration on the transfer of phosphate from 3-phosphoglycerate to creatine in rat muscle (Boyer et al. 1942). Reproduced under CC by 4.0 (<https://creativecommons.org/licenses/by/4.0/>) license.

Page & Di Cera (2006) give a comprehensive list of enzymes activated by potassium or sodium ions. They classify pyruvate kinase as a type I  $K^+$ -activated enzyme, and list nine more enzymes of this type. Type I  $K^+$ -activated enzymes require, in addition to  $K^+$ , a divalent cation, such as  $Mg^{2+}$  or  $Mn^{2+}$ , for activity, and the phosphate group is only 3.3 Å away from  $K^+$ . In Type II  $K^+$ -activated enzymes the potassium ion activates the enzyme allosterically. The phosphate group does not come close to  $K^+$ . Page & Di Cera (2006) list seven enzymes of this type. In general, enzymes requiring  $K^+$ , such as kinases, are also activated by  $NH_4^+$  and  $Rb^+$ , but not as well, or not at all by the larger cation  $Cs^+$  or the smaller  $Na^+$  and  $Li^+$ .

Also the  $Na^+$ -activated enzymes are classified by Page & Di Cera (2006) as type I or type II. The first one, a type I enzyme, that was discovered was  $\beta$ -galactosidase (Cohn & Monod 1951). In type I the substrate is complexed by a  $Na^+$ - $Zn^{2+}$  combination. In addition to  $\beta$ -galactosidase Cohn & Monod (1951) refer fructose 1,6-bisphosphate aldolase to this category. Type II requires only one metal ion, and in some cases it can be either  $Na^+$  or  $K^+$ ; sometimes, as for the very important the serine protease thrombin involved in blood clotting, it must be  $Na^+$ . In addition there are several other  $Na^+$ -activated proteolytic enzymes, as chymotrypsin and related enzymes (Krem & Di Cera 2001).

The function of thrombin is delicate, as blood clotting is vitally important for stopping loss of blood and blood pressure as a consequence of injury, but internal clotting of blood is life-threatening. In line with this, regulation of blood clotting is complicated (Dang et al. 1995, Di Cera 2008), and we shall here limit ourselves to the role of sodium ions.  $Na^+$  activation of thrombin is specific and allosteric (Wells and Di Cera 1992) and is required for optimal cleavage of fibrinogen (Dang et al. 1995). That the activation by  $Na^+$  is allosteric means that the regulator  $Na^+$  binds to another site on the protein than the site that binds the substrate, fibrinogen. The form of thrombin that is active in converting fibrinogen to the clot-forming protein, fibrin, is called the “fast form”. The “slow form” has the opposite effect, i.e., prevents clotting.

### 1.2.2. Roles in nerve signal transmission

Another very important biological function of potassium and sodium ions is in neural signal transmission. When a nerve cell is in a resting state, an ATP-driven ion pump protein (sodium-potassium  $Na^+/K^+$  pump) is active in maintaining an ionic disequilibrium. The energy stored in ATP is used for moving  $K^+$  into, and  $Na^+$  out of, the cell. As one molecule of ATP is hydrolyzed, two  $K^+$  ions move into the cell, and three  $Na^+$  ions out of it.

Because potassium channels in the plasma membrane, with the cell in the resting state, are open, potassium ions can diffuse in both directions, and a steady state develops, with the inside 70 mV negative compared to the outside. The cell membrane also contains sodium channels, but in the resting state of the cell these are closed.

When the nerve cell is stimulated in some way (by a signal from a neighbouring nerve cell, or by something else), some sodium channels open, and an “action potential” is triggered. As sodium ions flow into the cell, the potential on the inside changes from -70 mV to -55 mV. This causes the rest of the sodium channels to open and the potassium channels to close, and the inside potential to change from -55 to +30 mV (Fig. 1.2.2). As this potential is reached the sodium channels close, and the potassium channels open again, which causes a return to the resting potential.

The process just described takes place at one point of the long extension, the axon, of a nerve cell. But seen in a larger perspective, a pulse of positive inside potential moves away from the point where the process started, i.e., the nerve impulse is transmitted along the axon.

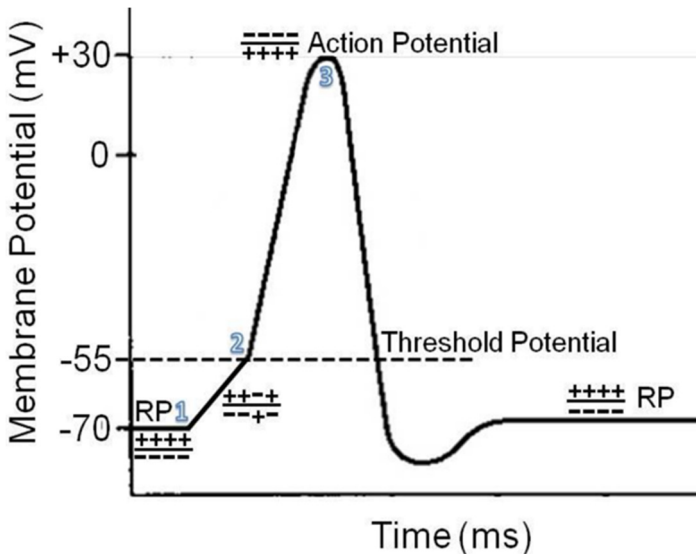


Fig. 1.2.2. The potential changes at one point of a nerve cell extension. 1 resting potential, 2 potential for triggering of mass opening of sodium channels, 3 maximum potential. Reproduced from the Vancouver Community College Learning Centre (<https://learningcentre.vcc.ca/media/vcc-library/content-assets/learning-centre/worksheets/by-coursex2fprogram/life-sciences/NerveSignalTransmission.pdf>) under a CC by 4.0 (<https://creativecommons.org/licenses/by-nc-sa/4.0/>) license.



Nerve cells have extensions of two kinds, shorter dendrites, and very long axons. In vertebrates the axons are equipped with myelin sheaths of lipid material (except at places called nodes of Ranvier) which isolate them from the surroundings. This speeds up signal transmission, since signals “jump” across the isolated segments, from one node to another node. Invertebrate axons generally lack myelin sheaths, which results in slower signal transmission.

### 1.2.3 Role of potassium ions in stomatal regulation

Regulation of the stomatal aperture in plants is very complicated, and not exactly the same in all plants. It has evolved to let carbon dioxide in to enable photosynthesis without losing too much water by transpiration – in many cases a precarious balance. With some exceptions stomata are closed in the dark, when no photosynthesis can take place anyway (but some plants keep stomata open at night to absorb carbon dioxide in an unreduced form for later use). The guard cells surrounding the stomatal apertures are so constructed that the stomata open when their inner pressure increases due to increased osmotically active substances. One of the most important of these substances is potassium ion (Sawhney & Zelitch 1969, Humble & Raschke 1971, Andrés et al. 2014). Because plants differ in the details, it would carry too far here to describe all the intricacies of stomatal regulation, in which red and blue light as well as carbon dioxide concentration and water status all play different important roles.

The uptake of potassium ions into the guard cells is electrically driven, and takes place if the inside of the cell has a negative potential of ca 70 mV in relation to the outside (Roelfsema et al. 2001); see also Roux & Leonhardt 2008).

Sodium is not required by all plants, but in case of insufficient potassium sodium can to some extent serve instead, but not completely replace it (seemingly *Salicornia bigelovii* Torr. is an exception; see below (Wakeel et al. 2011, Erel et al. 2020)). Some plants need sodium as a micronutrient, such as several species having the C<sub>4</sub> photosynthetic pathway (Brownell & Crossland 1972). Sodium chloride has been shown to alleviate drought stress in several species (He et al. 2019, Guo et al. 2020, Huihui et al. 2021).

According to Yamada et al. (2016) *Salicornia bigelovii* Torr. grows best with Na<sup>+</sup> but no K<sup>+</sup> in the root medium (Fig. 1.2.3). However, if the plants, before being transferred to the test medium, were pre-grown in a solution containing, in addition to other nutrients, 10 mM NaCl, the plants contained some sodium ions at the start of the treatment.

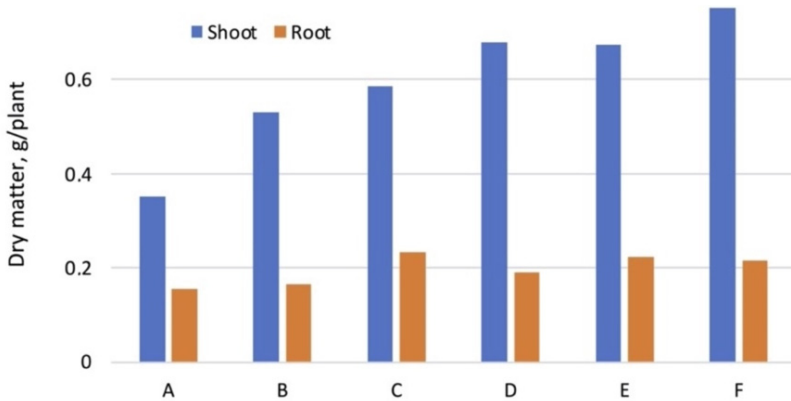


Fig. 1.2.3. Effect of shifting  $\text{Na}^+/\text{K}^+$  ratio on growth of dwarf glasswort (*Salicornia bigelovii* Torr.) after growing for 1 week in nutrient solutions with the sum of sodium and potassium ion concentration 100 mM, but with varying concentrations of each of these ions: In A  $\text{Na}^+$  0,  $\text{K}^+$  100; in B  $\text{Na}^+$  20,  $\text{K}^+$  80; in C  $\text{Na}^+$  40,  $\text{K}^+$  60; in D  $\text{Na}^+$  40,  $\text{K}^+$  40; in E  $\text{Na}^+$  80,  $\text{K}^+$  20, and in F  $\text{Na}^+$  100,  $\text{K}^+$  0 mM. Because the plants contained Na and K before the start of the differential treatment, the final amounts of the elements, in mol per kg dry matter were as follows: A 1.60 Na, 2.09 K; B 1.88 Na, 2.04 K; C 2.14 Na, 1.80 K; D 2.62 Na, 1.61 K; E 2.96 Na, 1.10 K; F 3.38 Na, 0.52 K. Data from Yamada et al. (2016).

As one moves upwards in the food chain, the concentration of sodium in organisms increases. Kaspari (2020) found the concentration to mostly range 10–100 ppm in forbs, grasses (and nectar as well), 100–1000 ppm in invertebrate herbivores, and it was above 3000 ppm in all of 33 invertebrate predators tested.

Some plants living under conditions with high sodium chloride are able to rid themselves of salt by salt glands on the leaves. Examples are *Atriplex canescens* (Guo et al. 2022), *Tamarix* species (Wei et al. 2020, Duan et al. 2022, Hussain et al. 2022), *Limonium bicolor* (Zhao et al. 2023), and some mangrove trees, e.g., *Avicennia* species (Tan et al. 2013).

### 1.3 Rubidium

According to Osretkar & Krauss (1965) *Chlorella pyrenoidosa* Chick can be grown in a medium with rubidium instead of potassium, although the growth rate was lower than with potassium. Baum (1965) tested several algae for their ability to use rubidium instead of potassium. Most species could not, but six species could. One of them, *Chlamydomonas reinhardtii*, showed the most pronounced response. With a contaminant level of 5.48 mg

K per liter, it initially grew equally well with 160.5 mg/L of KCl, and with the corresponding amount of RbCl, but reached a higher maximum cell density with KCl. MacLeod & Snell (1948) found that rubidium ion replaced  $K^+$  completely for growth of *Lactobacillus casei* and *Streptococcus faecalis*, partially for *L. mesenteroides* 9135 and *L. arabinosus*, and not at all for *Leuconostoc mesenteroides* 8042.

## 1.4 Cesium

Cesium has in many cases a negative effect on organisms. For instance, it inhibits the growth of a mutant of *Arabidopsis thaliana* by reducing the uptake of potassium (Adams et al. 2019). It decreases the growth of *Chlorella emersonii* when the alga is grown photoautotrophically, but not when it is grown chemoheterotrophically, also by interfering with potassium (Avery et al. 1992). Also the growth of a *Streptomyces* species was inhibited by cesium, because it competitively inhibited potassium uptake (Kuwahara et al. 2011). But in many potassium-deficient microorganisms cesium can promote growth by partly replacing the functions of potassium. In the absence of potassium, Kup-mediated  $Cs^+$  uptake partially supported cell growth of *Escherichia coli*, however, at a much lower rate than with sufficient  $K^+$ . In  $K^+$ -limited medium (0.1 mM), the presence of  $Cs^+$  (up to 25 mM) in the medium enhanced growth as much as control medium containing 1 mM  $K^+$  (Tanudjaja et al. 2017). Kato et al. (2017) observed a positive correlation between intracellular  $Cs^+$  concentrations and growth yields under  $K^+$ -deficient conditions by constructing an *Escherichia coli* strain that can be induced to express a  $Cs^+$ -transport system.

## References

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recretohalophyte *Limonium bicolor*: Distribution, morphology, and induction. J. Integr. Plant Biol. 00: 17 pp. (early access).  
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# CHAPTER TWO

## ALKALINE EARTHS

1																	18
H																	He
2											13	14	15	16	17	18	
Li	Be											B	C	N	O	F	Ne
Na	Mg	3	4	5	6	7	8	9	10	11	12	Al	Si	P	S	Cl	Ar
K	Ca	Sc	Ti	V	Cr	Mn	Fe	Co	Ni	Cu	Zn	Ga	Ge	As	Se	Br	Kr
Rb	Sr	Y	Zr	Nb	Mo	Tc	Ru	Rh	Pd	Ag	Cd	In	Sn	Sb	Te	I	Xe
Cs	Ba	57-71 lantha- noids	Hf	Ta	W	Re	Os	Ir	Pt	Au	Hg	Tl	Pb	Bi	Po	At	Rn
Fr	Ra	89-103 acti- noids	Rf	Db	Sg	Bh	Hs	Mt	Ds	Rg	Cn	Nh	Fl	Mc	Lv	Ts	Og

### 2.1 Beryllium

Beryllium is an element that is toxic to plants (Ali et al. 2018, Sheteiwiy et al. 2022) as well as animals including humans. The initiation and progress of chronic beryllium disease are described by MacMurdo et al. (2020). Between 134,000 and 800,000 workers are exposed to beryllium in the workplace within the United States (beryllium ceramics, machining, rod and wire production, production of computers and other electronic devices), and more than one million people are exposed to beryllium dust in the United States annually (Infante et al. 2004), with 2–20% of them developing beryllium sensitization. But there are also other sources of beryllium poisoning. Many coals contain considerable amounts of beryllium, and burning such coal can result in health risk (Petanová & Bencko 2020). The beryllium in coal is to a small extent due to beryllium-uptake in the coal-forming plants, but most of the beryllium is derived from volcanic ash (Yang 2007). Concrete dust may sensitize people against beryllium (MacMurdo et al. 2021). Beryllium does not enter the body only through mouth and nose: Also uptake through the skin by contact with metallic objects has been documented (Magnano et al. 2022).

Twelve isotopes ( $^5\text{Be}$  to  $^{16}\text{Be}$ ) of beryllium are known, most of them radioactive, with half-lives from  $5 \times 10^{-21}$  s ( $^6\text{Be}$ ) to  $1.39 \times 10^6$  years ( $^{10}\text{Be}$ );

only  $^9\text{Be}$  is stable. An important radioactive isotope is  $^7\text{Be}$  (Fig. 2.1.1), with a half-life of about 53.22 days (but somewhat dependent on the environment). Despite its short life, it is important because it is continuously formed by reaction between cosmic rays and nuclei of oxygen and nitrogen in the Earth's atmosphere. Arnold & Al-Salih (1955) predicted that this would happen, and found  $^7\text{Be}$  in rainwater and snow.

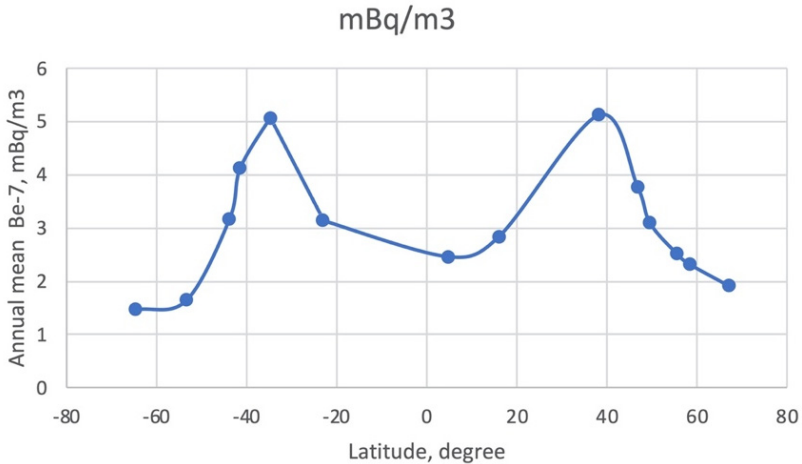


Fig. 2.1.1. The average distribution of  $^7\text{Be}$  radioactivity in air (one outlying value deleted). The combined effect of production rate and air currents cause the  $^7\text{Be}$  maxima to be located at ca 35°S and 35°N. Redrawn from data of Villarreal et al. (2022).

$^7\text{Be}$  has been useful for studying air currents in the atmosphere, surface soil particle migration, and interception of particles in the air by plant canopies.

$^7\text{Be}$  decays through electron capture (i.e., electron transferred to the atom's electron cloud to the nucleus, mainly from the K shell, and to a few percent from the L shell), a process whose rate to a slight extent depends on the atom's environment, e.g., whether it occurs as pure beryllium metal, in an alloy, or in an organic compound (Gholamian et al. 2021, Ray et al. 2020, Tkalya et al. 2021). Inside a C36 fullerene cage the half-life is about 2.5% larger than outside. The capture rate also to some extent depends on electrical field and pressure. A gamma photon is emitted when an electron falls from an outer orbital to the empty place in the K (or L) shell.

Chronic beryllium disease is associated with DNA methylation and gene expression changes (Yang et al. 2019). It is often mistaken for beryllium-unrelated sarcoidosis (Müller-Quernheim 2006).

## 2.2 Magnesium

Magnesium, as free  $Mg^{2+}$  ions, or bound to organic compounds, are essential for all organisms. We shall start by mentioning its presence in all forms of chlorophyll, since without chlorophylls and photosynthesis in which they play a crucial role, this planet would be very different, and not inhabited by us. Magnesium is inserted into the chlorophyll precursor protoporphyrin IX by the enzyme magnesium chelatase with the help of ATP (Fig. 2.2.1). Further steps leading to chlorophylls (including bacteriochlorophyll) are described by Willows (2019).

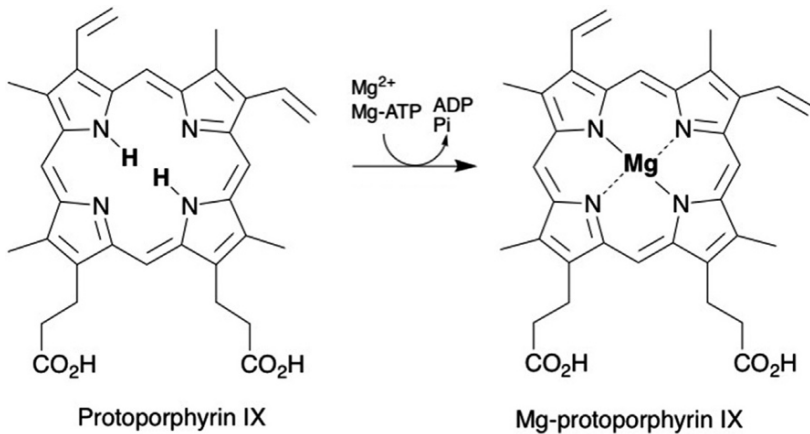


Fig. 2.2.1. The insertion of magnesium into protoporphyrin IX.

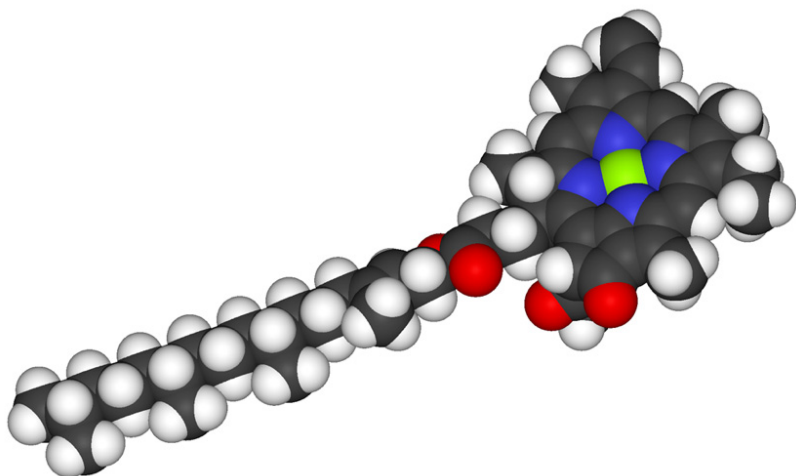


Fig. 2.2.2. Model of a chlorophyll *a* molecule. Carbon black, hydrogen light grey, nitrogen blue, oxygen red, magnesium green. The long extension to the left is the alcohol phytol, forming an ester with the acid chlorophyllide *a*, to the right. Wikipedia (<https://upload.wikimedia.org/wikipedia/commons/9/92/Chlorophyll-a-3D-vdW.png>).

What is commonly referred to as ATP, is, in most cases, a complex between ATP and a magnesium ion (Fig. 2.2.3). The magnesium ion can be coordinated either with two or three of the phosphate groups. Buelens et al. (2021) found some preference for two groups, although according to Dudev et al. (2017)  $Mg^{2+}$  prefers to bind ATP tridentately to each of the three phosphate groups, and Liao et al. (2004) found both arrangements equally probable. However, in free solution with  $pH < 6$ , magnesium ions are displaced by hydrogen ions, with far-reaching effects (Wolf & Cittadini 2003).