BIOL 157 – BIOLOGICAL CHEMISTRY I
Lecture 1
Elemental Composition of Cells

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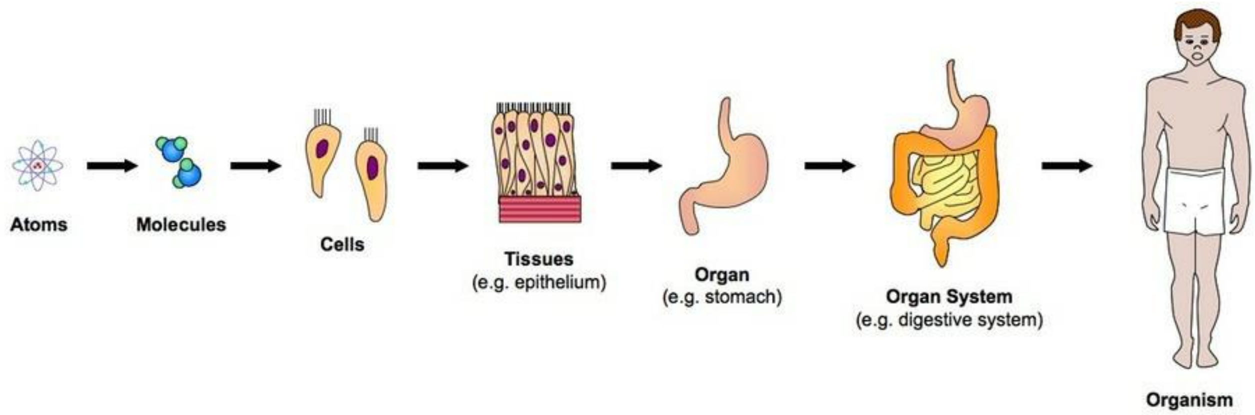
Introduction

All living cells and organisms are made up of elements which are intricately organized to form recognizable structures characteristic of the cells or organisms. Therefore, our journey to finding how the various elements are organized to give rise to a functional cell or organism will start from the basic units of matter, which are the atoms of the various elements.



Study Objectives

In this lecture we will go through:

1. How elements were formed: the origin of elements
2. The list of elements that make up living cells
3. Why some elements were incorporated in cells while others were excluded
4. Why carbon forms so many compounds.

Origin of Elements

Elements are believed to have been formed through the following processes

i. Big bang
ii. Fusion reactions in the stars
iii. Artificial synthesis

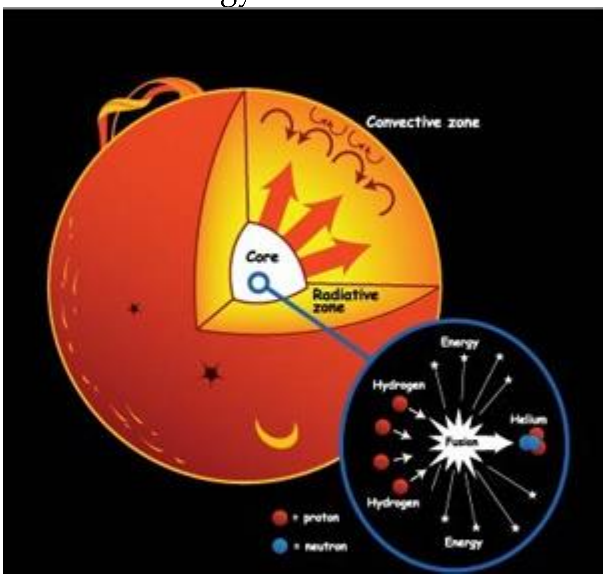
The naturally occurring elements are presumed to have been formed through the first two processes.

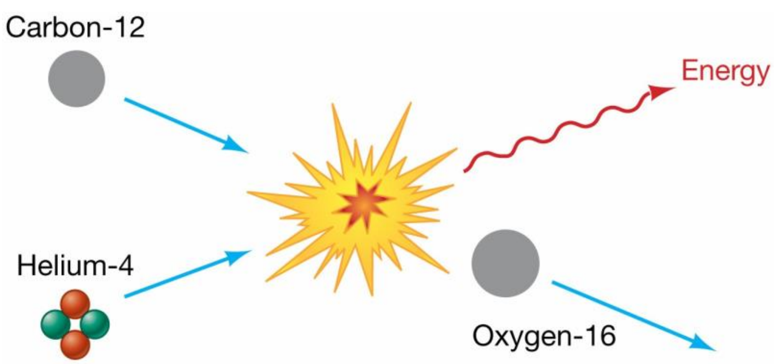
The Big bang theory

The 'big hang theory' has been used by some scientists to explain the origin of the uninverse. According to this theory, some billions of years ago, there was an explosion of an infinitely hot and dense ball of primordial matter. Immediately after the explosion, only two elements, hydrogen and helium were formed. At this point in time, there were no stars, no light. Gravitational forces brought together clouds of gas that eventually collapsed into vast galaxies made up of billions of stars. All the elements other than hydrogen and helium were formed in the centre of these stars, and these elements were released upon the explosion of some of these stars.

Fusion reactions in the stars

There is the **stellar hypothesis** for the formation of elements beyond hydrogen and helium. This hypothesis argues that the very high temperatures and concentrations of reactants required for the formation of other elements can be achieved in the core of stars. The very high temperatures are required to overcome the electrostatic repulsion that exists between the positively charged nuclei, which must fuse. The fusion reactions radiate heat and light, so that a star is formed from the cloud of gas. At some point an enormous amount of energy is released that leads to the explosion of the star.





Most visible stars emit light created by the burning of hydrogen to form helium. The hydrogen that fuels most stars is eventually used up. In larger stars, the hydrogen gets exhausted much more rapidly in large stars like the sun. Upon the exhaustion of hydrogen, the core temperature of the star reduces, and the star begins to collapse. The heat released by the collapse causes the core temperature to rise to new levels until the ignition temperature for helium is reached. For a fusion reaction involving helium nuclei, which has twice the positive charge of hydrogen, much higher temperatures are required in the order of 20×10^6 K.

Two helium nuclei fuse to form beryllium (^{8}Be) nucleus which is unstable, and so does not survive for any length of time. Another helium nucleus can fuse with Be to form Carbon (^{12}C). Another fusion with helium forms oxygen (^{16}O). The largest atom that can form from the nuclear fusion reactions is iron (^{56}Fe). Those atoms that are larger than Fe are formed when the neutrons resulting from the explosion of a star are captured by the nuclei of Fe atoms. The even-numbered elements are far more abundant than those with odd number mass numbers. The former are formed through mainstream fusion reactions whereas the latter are formed through side reactions. The relative abundance of the elements is dependent on the mechanism of formation and the stability of the nuclei formed.

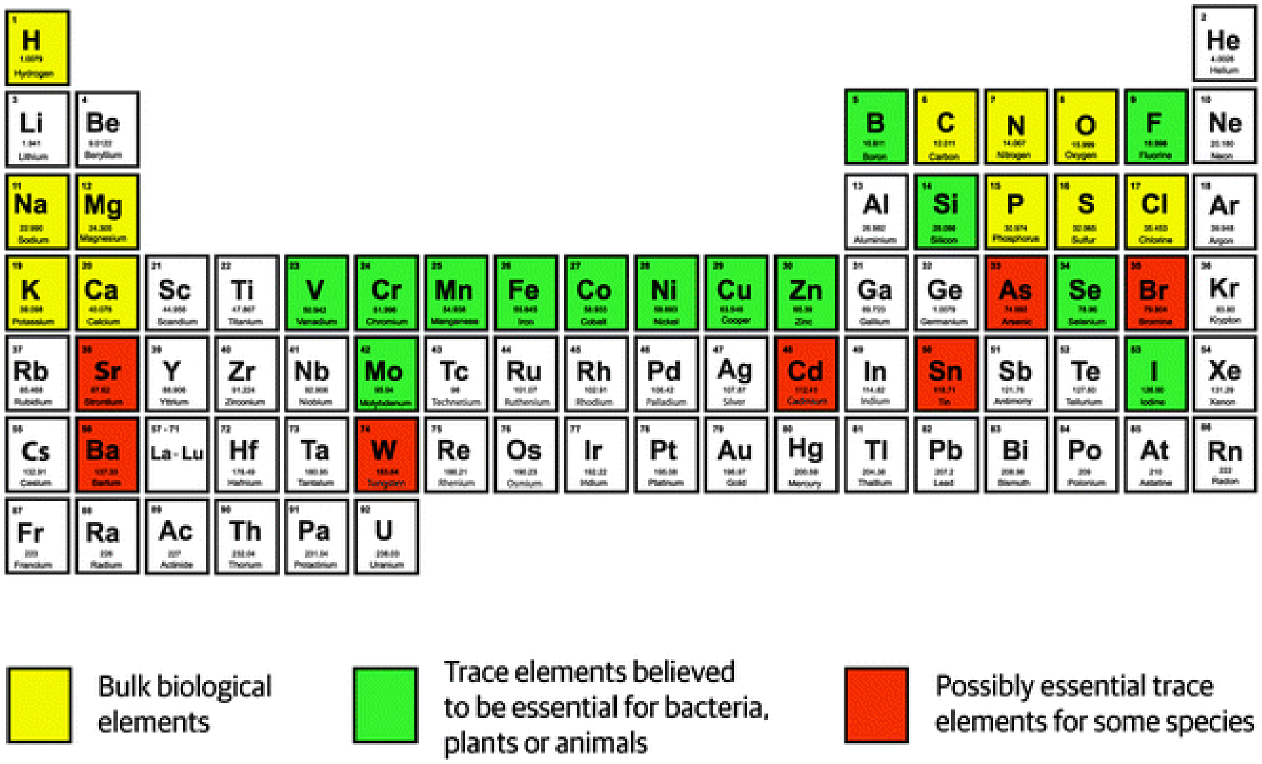
Laboratory synthesis of elements

Various fusion reactions can be used to synthesise elements. New elements with atomic number beyond 92 (the transuranium elements) have been synthesized this way. In the process, high energy particles are required to fuse with target nuclei. Such high-energy particles can be produced in cyclotrons, which provide accelerators that use electric fields to accelerate particles to high speed. For example, Seaborg formed the synthetic element, Californium, by using a cyclotron to accelerate the nuclei of C-12 to fuse with U-238.

Elements utilized to form cells

The phenomenon of natural selection appears to have operated in the choice of elements as cellular components. At present, there are over 117 elements, but less than a third of these elements are found in cells. Indeed, about thirty elements are recognized as being essential and hence indispensable to various living cells. Definitely, there should be some features of these elements that might have enhanced their incorporation in cells, while there should be other features that preclude the use of others. The properties of the biosphere also played a part in the selection of the elements.

One important factor which immediately comes to mind is the composition of earth and its atmosphere. The composition of the human body (which can be taken as a fair representative of living organisms) is very close to that of the earth crust, yet there are significant differences in relative amounts of the different elements. The percentage of atoms in the earth show in decreasing order; oxygen (48.86%), iron (18.84%), silicon (13.96%) and magnesium (12.42%). The percentage of carbon is just about 0.10. Furthermore, there is similarity in the concentration of the main ions in sea water and that of blood plasma: such ions like Cu^{2+}, Mg^{2+}, Ca^{2+}, Na^{+}, K^{+} etc. This implies that man has his ancestry in the sea. Another point worth noting is that despite the fact that less than a third of the elements are used, almost every group on the periodic table has its representative in living cells (chemical democracy?) As shown in the table below, elements from 15 out of the 18 groups on the periodic table are found in cells. In addition, apart from the f-block elements (lanthanides and actinides), all the other blocks; s- p- and d-blocks have their representatives.



From basic chemistry, we know that elements in a group show similar physical and chemical properties, and such properties enable them perform specific or general functions. It is therefore reasonable to suggest that fifteen different groups are used in order to optimize all possible functional values. Over 99% of the mass of most cells is made up of six elements, which are thus called the major or bulk elements. These are carbon, hydrogen, oxygen, nitrogen, phosphorus and sulphur (CNONPS). All life require these elements, together with the other elements, Na, K, Mg, Ca, B, V, Mn, Fe, Co, Ni, Cu, Zn, Si, Se, Cl, Br and Cr. The others are F and I; these are the trace or minor elements. The six major elements are found in the organic compounds of the cell. The trace elements are usually inorganic constituents, found primarily in the fluids that bathe the cell.

Striking features of the major elements

1. Majority are p-block elements
2. They are able to form covalent bonds
3. They are non-metals
4. They have smaller atomic sizes/numbers
5. They are neither too reactive nor inert.

Looking at the major elements, their atomic numbers are low, and their atomic sizes, small. Given the background that the major compounds formed by these elements are organic, the elements used should be such that the compounds formed would be stable. The intramolecular bonds in organic compounds are covalent. Strong covalent bonds are formed from atoms with small atomic orbitals which are able to make more effective overlap to form such covalent bonds. Of particular interest is carbon, which is the most versatile of the major elements, and is the most predominant in organic compounds. Why is carbon so unique in its ability to form many compounds?

1. First of all, carbon has got an ideal size, neither too small nor too big. As a result, it is able to form stable covalent bonds through effective overlap of its atomic orbitals with those of other atoms as it forms compounds. If carbon were to be too small, it could not have been surrounded by several atoms. On the other hand, if carbon were to be too big, the bond that it forms with other atoms would be long and weak.
2. The tetravalency of carbon is also important; it is able to form four covalent bonds.
3. Another feature shown by carbon is its power of catenation. This is the ability of carbon to form bonds with itself, in straight chains, branches or rings. This is possible because of the stability of C-C bonds.
4. Carbon is also able to form multiple bonds, either with itself or with other atoms. The multiple bonds could be a double or triple bond. Examples of the multiple bonds are C=C and C≡C. Multiple bonds with other atoms include C=O, C≡N and C=S. All these provide variety in organic compounds. Note that such multiple bonds are formed between small atoms. A condition that must be satisfied before a multiple bond is formed is that the first sigma covalent bond should be strong. It is only after the formation of a strong sigma covalent bond that there can be effective sideways overlap of orbitals to form pi-bonds. Where the sigma is long, as expected for big atoms, there cannot be effective overlap to form pi-bonds.

Let us now focus attention on three other elements which have the capacity to make three or more bonds, and so appear to have the potential to form chains of covalently bonded compounds.

Silicon

Silicon is a congener of carbon; it is immediately below carbon in group IVA. Thus Si is tetravalent, but because of its larger atomic size, two silicon atoms cannot approach enough to allow effective overlap. Therefore, silicon-silicon bonds are weak. Compounds in which there occur chains of Si-Si bonds are rare. In contrast, Si-O bonds are so stable chains of alternating Si and O atoms are essentially inert. Even though silicon is far abundant in the earth crust than carbon, it is carbon, which has been preferentially incorporated in living cells. In fact, silicon is about 140 items more abundant than carbon in the earth crust.

Nitrogen

In the case of nitrogen, because it has five valence electrons when it forms N-N bond, the bond energy will be low relative to that of C-C. When the N-N bond is formed, there remains a lone pair of electrons on the atoms. The repulsion between the lone pairs on the bonded nitrogen atoms will markedly reduce the bond energy of N-N bond. Therefore, we expect extended chains of nitrogen atoms to be very unstable.

Boron

Turning to boron, it has three valence electrons. Unlike nitrogen, it will form electron deficient compounds: this will tend to limit the stability of boron compounds.

Reasons why other elements were not incorporated

1. Artificial nature of some elements: All those elements with atomic number above 92 (the transuranium elements) and three below, Technetium (Tc), Astatine (At) and Francium (Fr) are artificially made.
2. Inert nature of some elements: Some of the elements are inert. For example, the rare gases could not have been used. Some of the elements are scarce or unavailable, like the actinides and lanthanides.
3. Toxic nature of some elements: Some elements are toxic; for example, lead, mercury and beryllium. Mercury can cause liver, brain and kidney damage; Pb^{2+} can cause anaemia by inhibiting haem synthesis; Be^{2+} can interfere with many functions of Mg^{2+}.
4. Radioactivity of some elements: Some elements are radioactive, so they are unstable. Apart from their instability, as they disintegrate, they may give off particles or radiations that could cause harm to the cell.

Note that even though some elements are non-essential to life, they may be valuable with regard to the quality of life: they can be used as drugs for the treatment of various disease conditions. Lithium compounds like Li_2CO_3 is for the treatment of schizophrenic conditions. Platinum and gold complexes are anticancer and anti-arthritis preparations respectively. Kaolin which contains aluminium has anti-diarrhoeal properties.

