A little book about matter

> "If, in some cataclysm, all of scientific knowledge were to be destroyed, and only one sentence passed on to the next generation of creatures, what statement would contain the most information in the fewest words? I believe it is the atomic hypothesis (or the atomic fact, or whatever you wish to call it) that **all things are made of atoms - little particles that move around in perpetual motion, attracting each other when they are a little distance apart, but repelling upon being squeezed into one another**. In that sentence, you will see, there is an enormous amount of information about the world, if just a little imagination and thinking are applied."
>
> — Feynman, *Lectures on Physics*, Vol. I, p. 1-2

Lesson 1: An introduction to atoms

When introducing matter for the first time, there is no way of getting around **atoms**. It's an indisputable fact that atoms are real and that all matter surrounding us is made of atoms.[1] Your entire existence is directly connected to atoms: The table you are sitting at, your body, your blood, your brain, the air you breathe, planet Earth, and the Sun[2] – all these things are made of atoms. It is such an important observation that the great physicist Richard Feynman chose to start his monumental work on physics, *The Feynman Lectures on Physics*, with a first chapter devoted to exactly this topic.

What may surprise you is that the existence of atoms is a relatively new scientific fact. It was only in the beginning of the 1900s that most physicists accepted their existence. Other scientists and the general public got to know about them even later than that. The reason for the skepticism is that atoms are extremely tiny particles that you can't see with the naked eye or even with the best optical microscope[3] (we now have special, non-optical, microscopes that can make out individual atoms, see figure 1).

[1] We will, for the moment, totally ignore **dark matter** which is one of the great unsolved mysteries in modern physics. Our current understanding seems to suggest (emphasis on "seems to", we are really not certain about this) that 85% of all matter that interacts gravitationally in the universe isn't made of the type of atoms we are going to talk about here. Very strange indeed!

[2] Stars are actually the objects responsible for creating most atoms! Hence *you are literally made of stardust* :) More about *stellar nucleosynthesis* another time.

[3] This limitation is set by the wavelength of visible light which is around 500 nm. Hence you can't see objects smaller than that size.

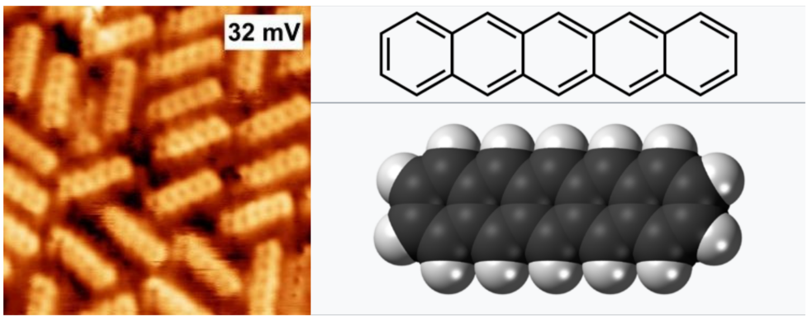


Figure 1: The left image from 2015, is a 5 x 5 nm scanning tunnelling microscope (STM) image of pentacene molecules. It's a picture of matter at the atomic/molecular scale. On the right you can see two different representations of a pentacene molecule: The molecule contains 22 carbon atoms (dark grey) and 14 hydrogen atoms (light grey) bonded together. (Image credits: here and Wikipedia)

Atoms are around a tenth of a billionth of a meter in size (n = nano = a billionth), a length also called one ångström (1 Å),

$$0.1\,\text{nm} = 0.1 \times 10^{-9}\,\text{m} = 10^{-10}\,\text{m} \equiv 1\,\text{Å (one ångström)}$$

and you can think of them as tiny, hard sticky balls. They can stick together (= bond) in many different ways to form collections of atoms called **molecules** and the study of molecules (and other types of **compounds** = substances made of more than one type of atom) is the subject we call **chemistry**.[4] The reason atoms interact with each other is because they contain positive and negative charges which can either attract or repel depending on the specific arrangement. An atom is the smallest "piece" of what we call an **element**. There are only around 100 different elements and everything in the universe is made up of these types of atoms - quite a remarkable fact![5] All elements (and therefore atoms) are neatly organised in the periodic table based on their chemical and physical properties. It was the Russian chemist Mendeleev who published the first recognisable periodic table in 1869 and since then a number of variations to his original table have been constructed.

[4] Very large macromolecules are the foundations of life as we know it. See for example this recent news.

[5] Everything is in fact made up of an even smaller number of elementary particles, something we will address when we cover particle physics.

Figure 2: The "most intelligent picture" ever taken. At the 1927 Solvay Conference in Brussels the world's most notable physicists met to discuss the new theory of quantum mechanics and the leading figures were Albert Einstein and Niels Bohr. 17 of the 29 attendees were or became Nobel Prize winners, including Marie Curie, who alone among them, had won Nobel Prizes in two separate scientific disciplines, physics and chemistry. (Wikipedia)

Despite their name ('atomos' is Greek for 'indivisible') atoms have internal structure and they consist of even smaller subatomic particles called electrons, protons and neutrons.[6] This was discovered in the beginning of the 1900s and it led to the development of **quantum mechanics**, from around 1897 to 1927 ("30 years that shook physics"), which is currently our most accurate theory of the atomic world. Quantum mechanics revolutionised physics because it is significantly different from the classical laws that had been developed earlier by great thinkers such as Newton, Maxwell and Einstein. To be honest, we haven't yet sorted out this confusion, and physicists today are still struggling with how to interpret quantum mechanics. Many physics students – as well as their teachers – consider quantum mechanics to be the most challenging conceptual hurdle to overcome in a modern physics education.

[6] Protons and neutrons have further internal structure, they are collections of quarks – more on this in the particle physics course.

After quantum mechanics was developed, new specialised fields of study such as **atomic physics**, **nuclear physics** and **particle physics** appeared up through the 20th century. All these fields are very much alive today and they are constantly changing our modern world without most people noticing it, e.g. World War II ended because of developments in nuclear physics, the engineering that goes into building a smartphone wouldn't exist without knowing how to apply quantum mechanics to the structure of solids[7], and the future of human civilisation will depend on whether or not we can build efficient and cheap solar panels or get fusion power working. Current theories about the nature of stars and the structure of the Universe are also all closely connected to these fields of study. Much of what makes the world go around today depends on using quantum mechanics to understand how matter behaves.

[7] Quantum mechanics explains how semiconducting materials work and that understanding led to the development of the transistor which revolutionised the field of electronics and paved the way for smaller and cheaper radios, calculators, and computers - the technology of our modern world.

Lesson 1: Exercises

1. The smallest atom that exists is the atom of the simplest and most abundant element in the Universe: Hydrogen. A hydrogen atom consists of one proton at the center of the atom (making up the entire nucleus in this case) and one electron surrounding it. These two particles are bound together by the electromagnetic attraction that oppositely charged particles experience. The charges they carry are of exactly the same size, but with an opposite sign. The proton is much more massive than the electron, so it's the electron that revolves around the proton (similar to how the Sun is at the center of the solar system due to its much larger mass than all the planets). The diameter of a hydrogen atom is around $0.1\,\text{nm} = 1\,\text{Å}$.

   (a) How many hydrogen atoms fit into 1 nm?

   (b) The left image in figure 1 is 5 nanometers by 5 nanometers. Use that information to estimate the size of the pentacene molecule in nanometers.

   (c) A human hair is around $70\,\mu$m wide. How many hydrogen atoms does that correspond to? (μ = micro = 10^{-6})

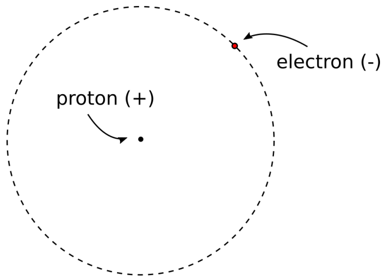


Figure 3: The simplest and most abundant element in the Universe, a hydrogen atom. The proton and electron are extremely small relative to the size of the atom (see exercise 3), which in itself is extremely small.

2. The 'size' of an atom is a somewhat fuzzy concept as you will find out when you study atoms in greater detail using quantum mechanics. This has to do with the fact that electrons don't follow well-defined circular orbits nor do they always have the same distance to the nucleus (and actually they aren't even considered particles!). But in most practical situations it still makes sense to talk about the 'size' of an atom and we have found empirically that atoms have sizes that fall within the range of 0.1 to 0.5 nm or 1 to 5 Å. Go to ptable.com, click on the properties tab, and click on the radius block on the left.

   (a) What is a picometer (pm)?

   (b) Which atom seems to be the largest atom? Write down its size in nanometers. Where have you also heard about this atom? (hint: one of the SI base units)

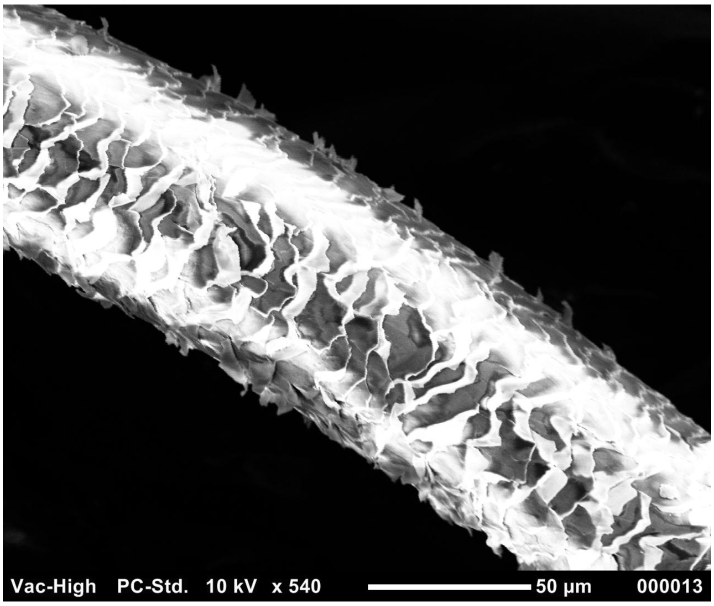


Figure 4: A picture of a human hair (source). Hair is made of human cells which are made of different molecules containing different types of atoms. It's an amazing fact that 99% of all atoms in the human body are either carbon (C), hydrogen (H), oxygen (O) or nitrogen (N)! The different ways in which these atoms combine and react are plentiful though - we are very complex biomolecular machines (which, by the way, doesn't make life less wonderful and awe-inspiring).

3. The atomic nucleus was discovered in 1909 and it turned out to be much smaller than the atom itself. The nucleus is around $10^5 = 100,000$ times smaller than the atom.

   (a) Hold out your fist and let it represent the diameter of the nucleus of the atom. How large is the diameter of the atom itself (express your answer in km)? This result always blows my mind!

   (b) As far as we know, the electron has no internal structure and it is extremely small. Furthermore, since the nucleus is only a tiny fraction of an atom, we can conclude that an atom is mostly empty space![8] Do a Google image search for the word 'atom' and discuss whether the images you see are good representations of what an atom really looks like.

4. The electron was the first subatomic particle to be discovered by J. J. Thomson in 1897. Protons and neutrons were discovered later, the proton in 1919 and the neutron in 1932.

   (a) What happens when two protons approach each other?

   (b) The neutron is a neutral particle (it doesn't carry any charge), hence its name. It was harder to discover than the electron and the proton because neutral particles don't experience electromagnetic forces so they don't interact a lot with other particles. What happens when a proton and a neutron approach each other?

   (c) Protons and neutrons are also referred to as **nucleons** – why do think that is?

   (d) In most nuclei, protons and neutrons stick together very tightly. Can this be explained by the electromagnetic force of attraction? Discuss.

[8] You could argue, however, that it consists of the quantum mechanical wavefunctions that define the electrons (if you have time, watch this until 52:48).

5. A neutral atom has an equal number of electrons and protons (all charges cancel out) and this number is also referred to as the **atomic number** since it is the number of the corresponding element in the periodic table.

   (a) Look up the following elements in the periodic table and write down their atomic number: Helium (He), Sodium (Na), Iron (Fe), Polonium (Po), Radium (Ra), Uranium (U). How many electrons and protons do their neutral atoms consist of?

   (b) The electrons in an atom arrange themselves in certain **orbitals** (or 'shells') as explained by the laws of quantum mechanics. In chemistry you will learn much more about how this works since the chemical properties of an element is directly related to how many electrons the atom has and how they are organised. Figure 5 is a representation of a neutral lithium atom (two electrons arrange themselves in the inner shell, one is left in the outer shell = a valence electron).

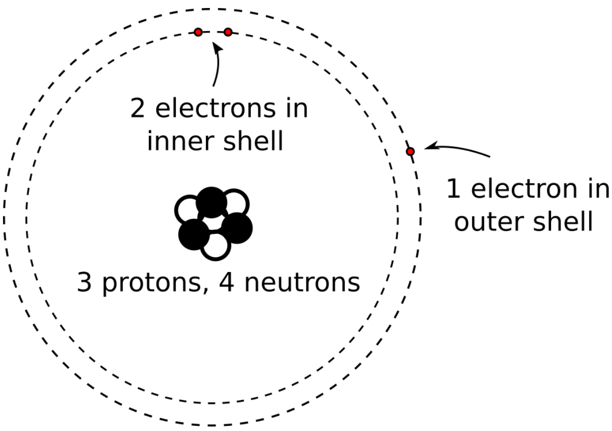


Figure 5: A neutral Li-7 atom.

   Atoms can relatively easily lose or gain electrons. When this happens an atom becomes charged (we now call it an **ion**) because the number of negative electrons and positive protons no longer balance out. For example, lithium's high chemical reactivity has to do with the fact that it only has one (valence) electron in the outer shell which it can easily lose and turn into the positive lithium ion, Li^{+}, seen on the right (which is much less reactive than the neutral element).

   If a magnesium atom loses two electrons, what ion does it become? If a fluorine atom gains an electron what ion does it become? (Fluorine ions - fluoride - are the actual particles in toothpaste.)

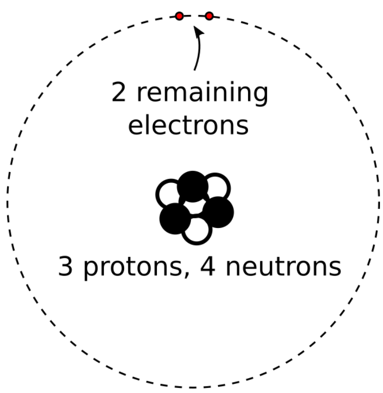
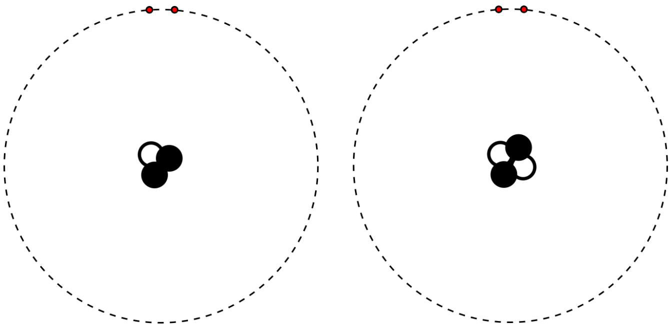


Figure 6: An ion (Li^{+}). Positive ions are called cations, negative ions are called anions.

   (c) When scientists learned how to carefully measure the mass of an atom (using **mass spectrometers**), they discovered that atoms of a given element typically have slightly different masses. E.g. most chlorine atoms seemed to come in a slightly lighter version and a slightly heavier version. This led to the discovery that atoms of the same element can have a different number of neutrons in their nucleus. Hence, the two different types of chlorine atoms have the same number of protons in their nuclei (both atoms are chlorine atoms), but a slightly different number of neutrons. We call these different atoms **isotopes**. Below is a representation of two common isotopes of helium (He is the second most abundant element in the Universe). On the left is helium-3 with 1 neutron + 2 protons (= 3 nucleons in total), and on the right is helium-4 with 2 neutrons + 2 protons (= 4 nucleons in total). The nucleus of a helium-4 atom is also called an **alpha particle**[9].

[9] Alpha particles were the first type of radioactivity discovered, more on that later.



The chemical properties of an element is directly related to how many electrons the atom has and how they arrange themselves into orbitals. Do you think isotopes of the same element have different chemical properties? (Isotopic labeling takes advantage of this).

6. We use the following convenient symbolism to represent a particular isotope:

$$^{A}_{Z}\mathrm{X}$$

Z is the atomic/proton number, A is the nucleon number, and X is the chemical symbol for the given element. We can find the number of neutrons, N, by calculating $N = A - Z$. For example,

$$^{238}_{92}\mathrm{U}$$

is the isotope of uranium (atomic/proton number 92) with 238 - 92 = 146 neutrons in its nucleus. We can write it even simpler as uranium-238 or U-238 (since we already know that uranium is element number 92). This neutral isotope would have 92 electrons in orbit around its nucleus.

Write down the number of all subatomic particles (electron, protons and neutrons) in the following isotopes:

$$^{2}_{1}\mathrm{H},\quad ^{12}_{6}\mathrm{C},\quad ^{14}_{6}\mathrm{C},\quad ^{56}_{26}\mathrm{Fe},\quad ^{235}_{92}\mathrm{U},\quad \text{plutonium-238}$$

7. Since atoms are so small, the everyday objects that surround us are composed of enormous numbers of them. Instead of trying to count every single one of them, we have defined a more practical unit of quantity called the **mole**, which is abbreviated "mol". One mole is now *defined as the following exact number*[10]:

[10] This definition is from November 2018 and it replaced the older definition that was "the number of neutral atoms in exactly 12 grams of carbon-12"

$$1\,\text{mol} \equiv 6.022\,140\,76 \times 10^{23}$$

This definition is put into action through Avogadro's constant,

$$N_A \equiv 6.022\,140\,76 \times 10^{23}\,\text{mol}^{-1}$$

which is simply the conversion factor that takes you from a quantity, n, expressed in moles to the actual number of particles, N. For example, if you have

$$n = 2.30\,\text{mol}$$

helium atoms, then that corresponds to the actual number

$$N = n \cdot N_A = 2.30\,\text{mol} \cdot 6.022\,140\,76 \times 10^{23}\,\text{mol}^{-1} \approx 1.39 \times 10^{24}$$

helium atoms. That's 1.39 million billion billion.

How many moles is 0.824×10^{21} particles? Express your answer in mmol (millimoles).

Figure 7: This is not a mole.

8. Atoms and molecules have tiny masses so it is inconvenient to express these in e.g. kilograms. Hence scientists have defined another unit of mass called the **unified atomic mass unit**, abbreviated "u", which is defined as *1/12 the mass of an unbound neutral carbon-12 atom in its electronic ground state and at rest*. In practice, this mass is approximately

$$1\,\text{u} \approx 1.66 \times 10^{-27}\,\text{kg}$$

(a) Nucleons (i.e. protons and neutrons) have roughly the same mass which is around 1800 times more massive than electrons, hence *most of the mass of an atom is due to its nucleus*. Since a carbon-12 atom has 12 nucleons (6 protons, 6 neutrons) and since "u" is defined as 1/12 of this mass, then it follows that the mass of a proton, m_p, and a neutron, m_n, is approximately 1 u. Here are the more accurate values (which one is heavier?):

$$m_p = 1.007\,276\,\text{u}, \quad m_n = 1.008\,665\,\text{u}$$

It therefore also makes sense to call the nucleon number, A, the **mass number**, since it represents an approximate value of the atom's mass expressed in the unified atomic mass unit. What is the mass, expressed in u to the nearest integer, of the following isotopes:

$${}^{2}_{1}\text{H}, \quad {}^{12}_{6}\text{C}, \quad {}^{14}_{6}\text{C}, \quad {}^{56}_{26}\text{Fe}, \quad {}^{235}_{92}\text{U}, \quad \text{plutonium-238}$$

(b) Since electrons have such small masses, the masses you wrote down in a) are also the approximate masses of the nucleus alone (= the atom minus the electrons). What is the mass (expressed in u and kg) of a uranium-238 nucleus?

(c) The **molar mass**, M, is per definition the amount of mass per mole:

$$M \equiv \frac{m}{n}$$

The unit of molar mass is often given as grams per mole (g/mol) because it turns out that the numerical value of the molar mass expressed in g/mol is very close to being equal to the mass of a single particle expressed in u. For example, the molar mass of hydrogen is around 1 g/mol (one mole of hydrogen atoms has a mass of 1 g) while its atomic mass is 1 u (the mass of one hydrogen atom, which is around the mass of one proton).

Molar mass is also defined for molecules and they are calculated by simply adding together molar masses for the individual types of atoms, e.g. the molar mass of water is:

$$M(\mathrm{H_2O}) = 2 \cdot M(\mathrm{H}) + 1 \cdot M(\mathrm{O}) = 18\,\mathrm{g/mol}$$

i. What is the mass of an individual water molecule expressed in u and kg?
ii. What is the total mass of $6.022\,140\,76 \times 10^{23}$ water molecules?
iii. How many moles of Fe-56 atoms are there in a 1.2 g lump of pure iron? How many individual atoms is this?

9. *Demonstration: How small are atoms?* Although atoms are extremely small, you can still estimate their size with a very simple experiment that never ceases to amaze me: Fill a large tray with still, shallow water and sprinkle Johnson's Baby Powder over the entire surface. Use a small syringe or a thin metal wire bent at an angle (or something similar) to make a small drop of oil and measure it's diameter using the magnifying glass (or your smartphone camera). We will be measuring quantities rather imprecisely here, as we are just looking for a rough estimate.

Gently put the oil drop onto the surface of the water and notice how the baby powder gets pushed outwards by the oil that spreads across the surface (all the oil molecules are tumbling out onto the water, they don't mix into it). Measure the diameter of the circular oil slick. With the above two measurements it is now possible to estimate (an upper boundary of) the size of an atom (or in this case, to be more accurate, a molecule of oil). The oil drop contains a very large number of oil molecules in a volume that is roughly spherical in shape with a radius, r, of around $r = 0.5\,\mathrm{mm}$:

$$V_{\mathrm{drop}} = \frac{4}{3}\pi r^3$$

When the drop is put into water all the molecules spread out into a cylindrical shape with a large radius of around $R = 0.25\,\mathrm{m}$ and a very small height, h:

$$V_{\mathrm{cylinder}} = h\pi R^2$$

We can assume that no oil molecules are lost in this process, so the volumes should be equal to each other

$$\frac{4}{3}\pi r^3 = h\pi R^2$$

and h can then be calculated:

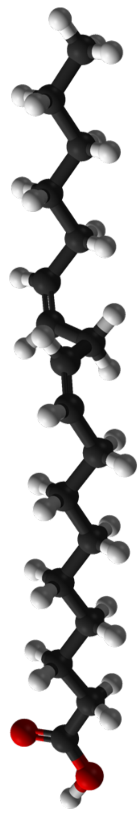
$$h = \frac{4}{3}\frac{r^3}{R^2} = \frac{4}{3}\frac{(0.5 \cdot 10^{-3}\,\mathrm{m})^{-3}}{(0.25\,\mathrm{m})^2} \approx 3\,\mathrm{nm}$$

This height represents *an upper bound* of the size of an oil molecule because we don't know how many oil molecules have piled on top of each other to form the slick[11], so our conclusion is that a sesame oil molecule is no more than 3 nm large.[12] Not bad for a simple tabletop experiment!

[11] We also don't really know whether it truly is a perfect cylinder - it could be more of a pyramid shape with more molecules piling up in the middle.

[12] This is obviously a very imprecise results because we haven't taken the large uncertainties into account. If we assume the uncertainty of the sphere radius is 0.1 mm (20 %) and the cylinder radius is 0.01 m (4 %), then we get an uncertainty of 68 %. The overall magnitude, however, is still in the nanometers.

Sesame oil is mainly composed of two types of molecules, oleic acid and linoleic acid. These are long molecules containing each 18 carbon atoms, 2 oxygen atoms and a larger number of hydrogen atoms. The picture on the right is a linoleic acid molecule (oleic acid looks very similar - it's just bent at the middle). These oil molecules have a hydrophilic end (the end with the two red oxygen atoms) which is strongly attracted to water, and a hydrophobic end which is repelled by water. If the slick really was only one molecule thick, these molecules would most likely stack up as shown on the right like small pieces of grass on the surface of the water and h would indeed be a good measure of the length of such a molecule. Looking up the atomic radius of a carbon atom in ptable.com, we would expect such a molecule to have a length of around



$$18 \times (2 \times 0.077\,\mathrm{nm}) \approx 3\,\mathrm{nm}$$

Answers to all the exercises.