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Amazing Water – A Physicist’s View

Water is everywhere, familiar and necessary to life. My special interest in water began in 1985, when I started to write computer programs to simulate the appearance of water in ponds and streams to create animation. In 1999, with a group of students, I completed a five-year project to make a short movie¹ which featured a waterfall, splashes, and the textures formed by sunlight in a shallow pool. The more I studied the behaviour of water, the more I came to realise that this most ordinary of materials, has the most extraordinary properties among liquids. To understand this idea properly, we must delve into a little atomic physics. This essay is based on a talk given to the Art+Water Project introductory meeting for scientists and artists, early in 2019.

UNDERLYING ATOMIC PHYSICS

Only too often, popular ‘science’ texts tell us that atoms are made of protons and neutrons surrounded by a cloud of negatively charged electrons. The protons are positively charged and the neutrons are not charged. This is a useful description because it accounts for many of the observable properties of atoms and gives us a mechanism to explain a lot of chemistry too. This description is sometimes called “the Rutherford atom”, and my purpose in including a little history is to persuade you that these theories are based on mechanical experiments that have been repeated thousands of times. We can be as certain of the structure of the atom as we are that water flows downwards, or that the cycle of seasons will continue with periods of longer days alternating with periods of longer nights.

Between 1908 and 1913, at The University of Manchester, Hans Geiger and Ernest Marsden, under the direction of Ernest Rutherford, demonstrated that the mass of an atom is concentrated at a central point, which Rutherford called the nucleus. The key experiment was to detect the alpha particles emitted by the radio-active element radium. These particles were deflected as they passed through a thinly beaten sheet of gold, and the way they were scattered agrees with a mathematical formula devised by Rutherford. There is a detailed, but readable, explanation of this freely available on Wikipedia.²

In 1869, the Russian chemistry professor, Dimitri Mendeleev, published the first version of his periodic table. The idea that chemical properties of elements repeated themselves in cycles, as the weight of the atoms increased, had been growing for about one hundred years. Mendeleev made better sense of the idea and predicted the existence of several undiscovered elements that were needed to complete the pattern. As these were discovered and fitted into the table, the idea that chemical properties repeated in cycles as the weight of the atoms increased became accepted by the scientific community.³

But it was the Rutherford atom that made sense of it all. The key was understanding that it was not the weight of the atom that mattered but the number of protons in the atomic nucleus. We call this the atomic number. The corresponding number of electrons around the nucleus arrange themselves in “shells”. As each shell fills, any extra electrons have to have wider orbits, and the number of electrons in the outermost shell starts again at one. The chemical properties depend more than anything else on the number of electrons in the outermost shell because these are the electrons that interact with adjacent atoms. This is why the properties repeat.

Group	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	
1	1 H																		2 He
2	3 Li	4 Be											5 B	6 C	7 N	8 O	9 F	10 Ne	
3	11 Na	12 Mg											13 Al	14 Si	15 P	16 S	17 Cl	18 Ar	
4	19 K	20 Ca	21 Sc	22 Ti	23 V	24 Cr	25 Mn	26 Fe	27 Co	28 Ni	29 Cu	30 Zn	31 Ga	32 Ge	33 As	34 Se	35 Br	36 Kr	
5	37 Rb	38 Sr	39 Y	40 Zr	41 Nb	42 Mo	43 Tc	44 Ru	45 Rh	46 Pd	47 Ag	48 Cd	49 In	50 Sn	51 Sb	52 Te	53 I	54 Xe	
6	55 Cs	56 Ba	57 La	* 72 Hf	73 Ta	74 W	75 Re	76 Os	77 Ir	78 Pt	79 Au	80 Hg	81 Tl	82 Pb	83 Bi	84 Po	85 At	86 Rn	
7	87 Fr	88 Ra	89 Ac	* 104 Rf	105 Db	106 Sg	107 Bh	108 Hs	109 Mt	110 Ds	111 Rg	112 Cn	113 Nh	114 Fl	115 Mc	116 Lv	117 Ts	118 Og	
				* 58 Ce	59 Pr	60 Nd	61 Pm	62 Sm	63 Eu	64 Gd	65 Tb	66 Dy	67 Ho	68 Er	69 Tm	70 Yb	71 Lu		
				* 90 Th	91 Pa	92 U	93 Np	94 Pu	95 Am	96 Cm	97 Bk	98 Cf	99 Es	100 Fm	101 Md	102 No	103 Lr		

Figure 1. Periodic Table.

A modern version of the periodic table of the elements is shown in Figure 1. The elements are ordered in rows and the columns show groups of elements with similar properties. Within one column, elements with heavier atoms have higher melting and boiling points. The lighter ones are gases at ordinary temperatures and the heaviest are solid. In group 16, we have, oxygen (O), sulphur (S), selenium (Se), tellurium (Te), and polonium (Po). Oxygen is a gas, the others are all solids whose melting points get progressively higher as the atomic number increases. When these elements combine with hydrogen, we get the compounds in Figure 2. As the elements get heavier, the compounds with hydrogen get denser, with higher boiling points, except for water. The lightest molecule in the list belongs to the densest material. Why?

Formula	Name	State at 20 °C	Boiling point °C
H ₂ O	Water	Liquid	100
H ₂ S	Hydrogen sulphide	Gas	-60
H ₂ Se	Selenium Hydride	Gas	-41.25
H ₂ Te	Tellurium Hydride	Gas	-2.2
H ₂ Po	Polonium Hydride	Liquid	36.1

Figure 2. Hydrides of the Group 16 elements.

The Rutherford model of the atom is not good enough to explain this. We have to abandon the idea that the electrons are like little planets orbiting around the nucleus. Instead, we use the description of quantum mechanics, where we dispense with the physical metaphor, and simply use mathematics as the description. We still have heavy particles in the nucleus surrounded by much lighter electrons, but the new mathematics represents each particle as a sort of cloud of probability values. Every point in space has a probability that a certain electron is there, and the tiny region where this probability is high tells us the approximate position of the electron. The notion of electrons in particular places gives us a clue to the cause of crystal structure and much more.

When there are exactly eight electrons in the outermost shell they make a particularly stable, symmetrical structure. Electrons have another quality that we call “spin”. We label the two possible spin values “up” and “down” and two electrons with opposite spin form a close pair, where possible. Four pairs tend to occupy the four corners of a regular tetrahedron (a triangular pyramid). The atoms of elements in group 18 of the periodic table all have this structure and they are chemically inert. They do not join with other elements to make chemical compounds.

The elements of group 16 all have six electrons in the outermost shell. When they combine with hydrogen, the single electrons of two hydrogen atoms join these six electrons to make a stable eight. This structure has a negative charge because of the two extra electrons, and the positively charged hydrogen nuclei stay attached.

In the case of water, these hydrogen nuclei are fairly close to the oxygen nucleus because of the small size of the oxygen atom. The electron of each hydrogen atom forms a pair with one of the oxygen electrons. The four pairs form a tetrahedron, and the two hydrogen nuclei sit at two of the corners, creating an asymmetric molecule (Figure 3). The positively charged hydrogen nuclei are attracted to the negative end of adjacent molecules, forming chains and clusters that behave like large molecules, which explains the unusual density and high boiling point. Because water molecules effectively have a positive electric charge on one side and a negative charge on the other, we say water molecules are “polar”.

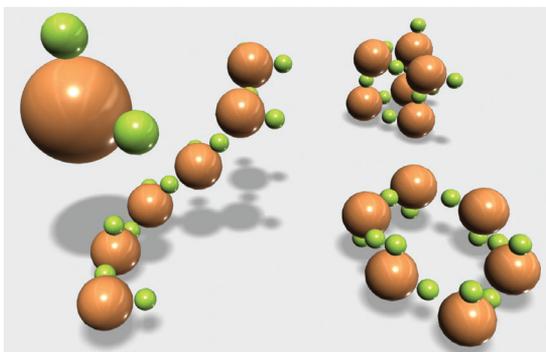


Figure 3. Polar water molecule, chain, prism and ring structures.

The unusual physical and chemical properties of water all result from this asymmetric polar molecule. These properties are responsible for such diverse things as the underlying chemistry of life and the stability of the surface temperature of the earth.

WATER CHEMISTRY

The atoms of common salt or sodium chloride (NaCl) each contain one atom of sodium and one of chlorine. The sodium atom has one electron in its outer shell, while chlorine has seven. The single electron makes a stable eight with the chlorine atom, and we are left with a positively charged sodium atom (known as a sodium ion) and a negatively charged chlorine ion. In the solid form, these are tightly bound by electrostatic attraction and form the well-known cubic crystal structure. In water, these ions readily separate, attaching themselves to the charged ends of water molecules. Many similar substances separate into ions in water, and this enables many chemical reactions that will not happen in the absence of water. This includes many of the chemical processes essential to life.

WATER MOVEMENT: SURFACE TENSION AND VISCOSITY

Because the water molecules attract each other, energy is needed to separate them. Within the volume of water, all the molecules are surrounded by others. But on the surface, some the molecules have no surrounding molecules on one side. So, a body of water tries to minimise its surface area as surface molecules try to get inside. This is why raindrops are spherical. We call this effect surface tension the water behaves as if it had a surface skin. You can float a steel sewing needle on this skin if you put it there carefully enough. Larger bodies of water are less obviously affected by surface tension, because the effect of gravity and inertia become more important. It is the intriguing shapes of splashes caused by water droplets that inspired Heramaahina Eketone's work, *Kōpata*, in the exhibition.⁴ To see these at their best in nature, you need a camera capable of high-speed video, recording at rather a small scale. However, there are many short movies accessible through the internet. Search the web for "slow motion splashes."

Water has low viscosity. That means it does not offer the resistance to motion that is characteristic of treacle. This is related to the very flexible nature of the bonds between water molecules. The rings and chains split and rebuild very fast. Low viscosity encourages turbulent behaviour and is responsible for eddies, whirlpools and splashing behaviour.

At a very large scale, water motion is affected mostly by gravity and inertial forces. Waves in water have the intriguing property that large ones move faster than smaller ones. So waves in the ocean or on rivers often appear to be covered by a texture of smaller waves. The gravitational attraction of the moon drives tides in the oceans. But the tides don't really follow the moon as we might expect. The motion lags behind the driving force because the water takes time to accelerate. Land masses can reflect waves both large and small, and some shapes cause resonant effects where the cycle time of wave motion is close to a day or several whole days. This can cause an amplification of the tides. In New Zealand we have some curious resonance; for example, high tide in Nelson generally coincides with low tide in Port Chalmers.

WATER AND TEMPERATURE

There are eighteen types of ice known to science. This includes sixteen crystalline forms that depend on temperature and pressure in various ways, amorphous ice, and the recently discovered square ice that can be formed between graphite sheets.⁵ But even common hexagonal crystalline ice, which is all of the ice that most of us ever see, has a vast diversity of appearance and nature. We can commonly observe snowflakes, ice sheets on ponds and lakes, icicles, hoar frost and hail. There are also forms peculiar to glaciers and numerous variations within these categories.

John Tyndall's 1873 classical text on the forms of water describes many of these and it is still in print. It is a delight to read and a wonderful example of clarity in scientific writing. Among many examples, he describes his experiment with "ice flowers", which was the inspiration for Pam McKinlay's work titled *Ice is Cool*.⁶ A 1931 recreation of Tyndall's original experiment is available on The Royal Institution of London's YouTube Channel.⁷

Liquid water is denser than ice. The solid hexagonal crystal structure packs the molecules less closely than the liquid with its molecular rings and chains. In the ocean, this results in an amazingly stable temperature in the bulk of the deep water. Water is most dense at about 4°C. Any that approaches the freezing point becomes less dense and slowly rises. Any warmer water also rises. The result is that most of the ocean's water remains at this temperature. Three fifths of the deep oceanic water create a thick constant temperature blanket that absorbs much of the effect of rapid changes on the surface. The dinosaurs may have been destroyed by a long period of cold following a collision with a comet. But in the deep ocean, the temperature remained at 4°C.

Geoff Wyvill is an emeritus professor of computer science at The University of Otago. He studied physics at Oxford and computer science later at the University of Bradford. He is best known for his work in computer graphics where he has published over one hundred technical articles. He has produced or directed five short animated movies, three of which have been shown in international festivals. He is a director of the Dunedin company, Animation Research Limited, which he co-founded in 1991.

1. SIGGRAPH '99, "ACM SIGGRAPH 99 Electronic art and animation catalog," (July 1999), also at: <https://www.youtube.com/watch?v=YmZVUqaZ4Ng&t=118s>
2. https://en.wikipedia.org/wiki/Geiger-Marsden_experiment
3. https://en.wikipedia.org/wiki/Periodic_table#Mendeleev's_table
4. Heramaahina Eketone, "Kōpata", *Junctures, The Journal of Thematic Dialogue*, 21, 65.
5. <https://en.wikipedia.org/wiki/Ice>
6. Pam Mckinlay, "Ice Is Cool – Artist's response to John Tyndall's Ice Flowers," *Junctures, The Journal of Thematic Dialogue*, 21, 73.
7. Royal Institution Archives, "Tyndall's Ice Flowers," <https://www.youtube.com/watch?v=gmmnQ3x21q8&list=PLal2DqO6taLYOSyIC7zf938wHLQpgRCFj>