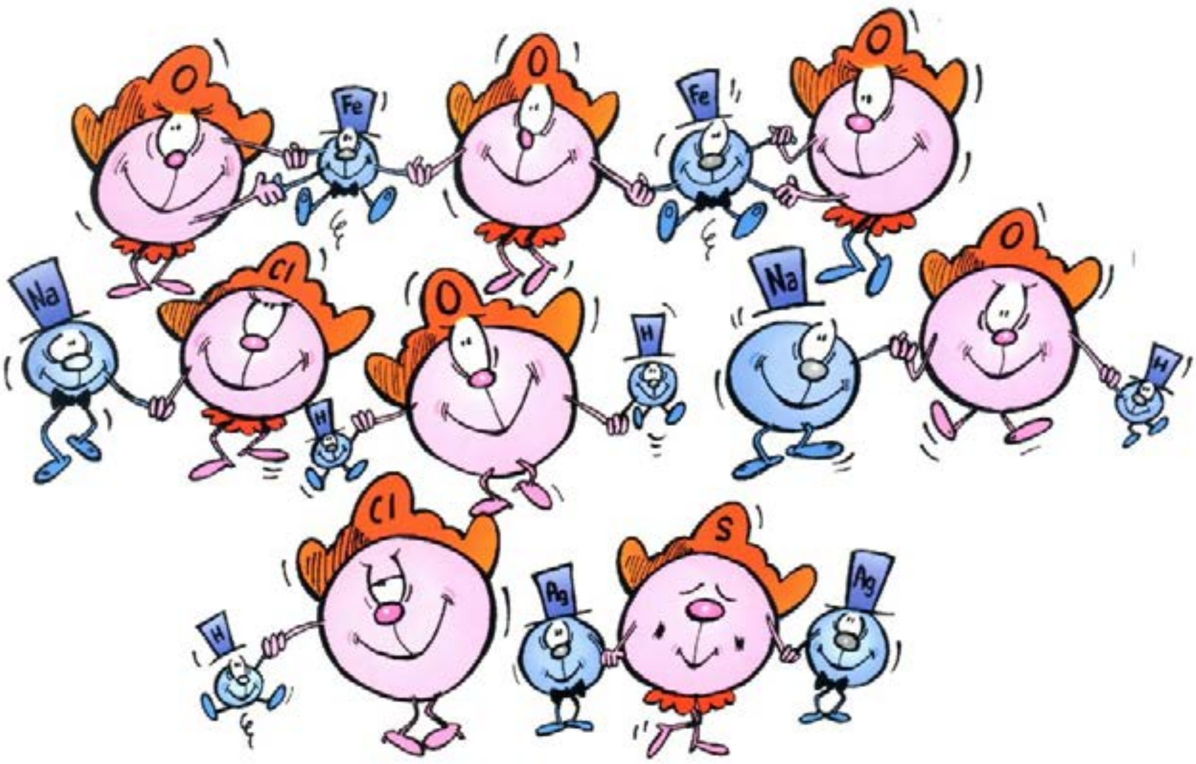
The Amazing World of Atoms

Words : Jacques Deferne

Drawings : Alain Gassener



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Warning

I ask the indulgence of chemists and physicist for the approach I have taken with this book. The simplifications and short cuts that I have taken with their subjects, the anecdotal nature of this book as well as its cartoons, all have one sole aim: to allow a reader, who has not done much chemistry, to learn about this subject, to understand chemical formulae, to have as idea of the composition of atoms and to gain familiarity with radioactive decay and nuclear fission.

This book started out as a short chemistry book intended for amateur mineralogists. However, I became fond of the characters in the World of Atoms, and expanded on their anatomy and genetic illnesses. This allows the reader to tackle as area of physics that is often talked about but poorly understood : the difference between radioactive decay and nuclear fission.

Experts in these fields may enjoy the human characteristics assigned to Niels Bohr's atom!

Teachers trying to instill chemistry into their pupils may find this book a useful mnemonic tool for this subject, which can become sterile if only presented in terms of formulae and chemical reactions!

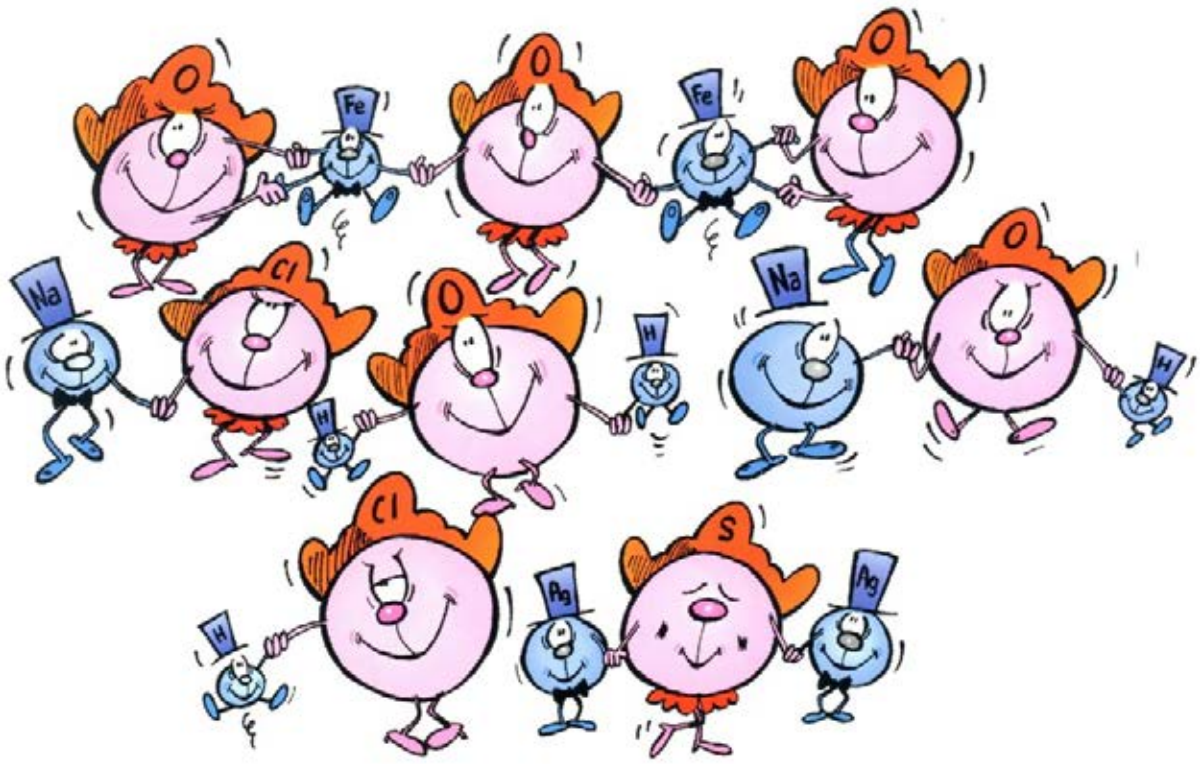
I hope that this book answers some of the questions asked by people curious about Nature's secrets, and distracts them from the banal world in which we live.

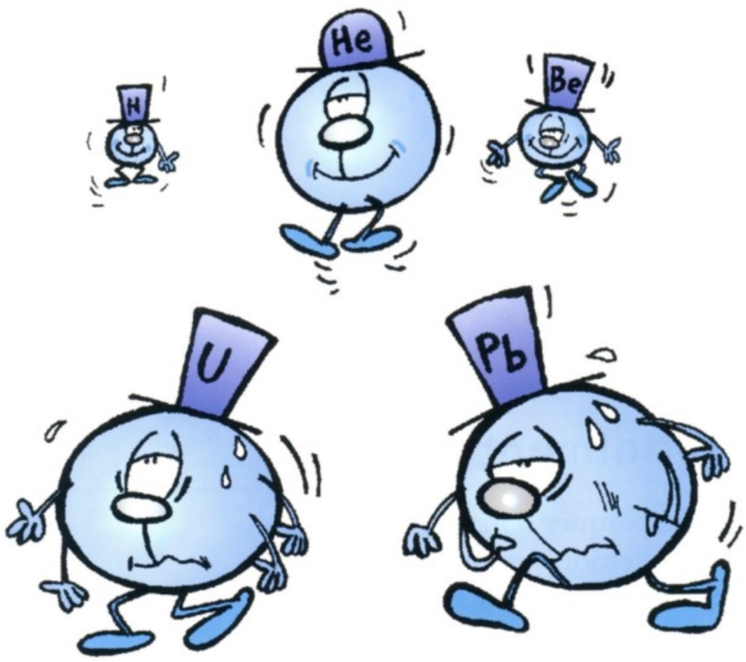
Jacques Deferne.

First contacts

A Journey into the Infinitesimal World of Atoms

Imagine we could follow in Gulliver's footsteps, and travel to the amazing, infinitesimal country of atoms. We would find ourselves in a world inhabited by tirelessly moving, colorful characters linked to form small and large groups. Each atom's head and torso is mixed to form a single, approximately spherical body with one or more arms





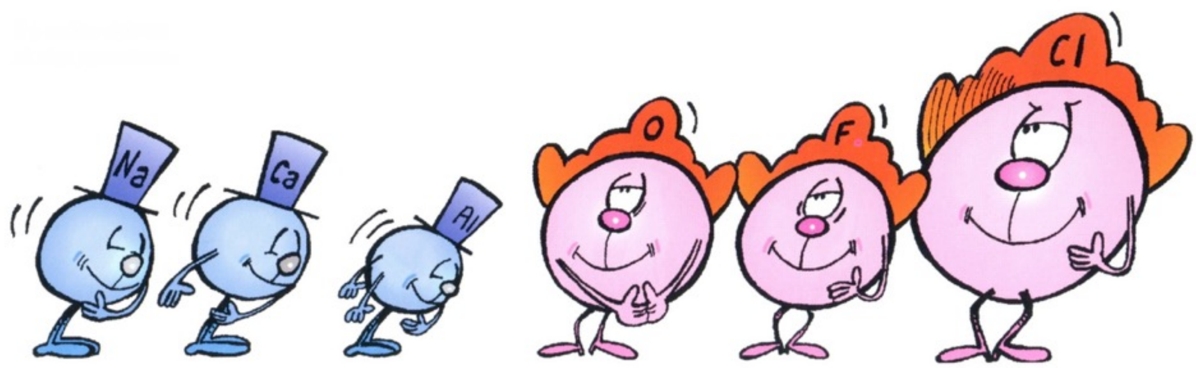
Some appear light, whilst others are so overwhelmed by their huge bulk that they have difficulty moving around.

Some of them are big, some small. There are some that seem to be very light and others are so overwhelmed by their huge bulk that they have difficulty moving.

As in our world, there are Ladies and Gentleman. They are easily distinguished as the Ladies are pink and wear lace bonnets. The Gentlemen are dressed in blue and sport top hats. We shall soon discover the anatomical factors that determine the sex of an atom.

Upon further examination of this small world, we notice that the individuals fall into different categories according to their size, mass , number of arms and the type of hat they wear.

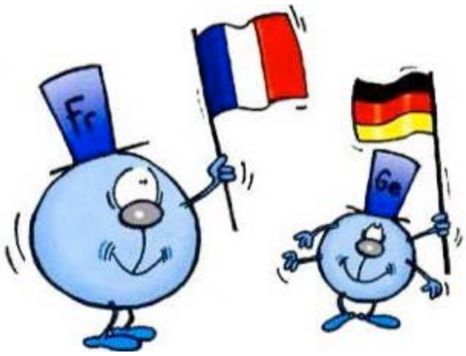
Each category has been given a name, a nickname (called a symbol) and a registration number.



There are Ladies and Gents.

The Naming of Atoms

Each atom has a patronymic name which identifies it as a member of a particular family. Atoms that have the same name have a similar appearance and similar habits. There are approximately 90 naturally occurring families of atoms. Their names have very different roots, such as:



Messrs. Francium and Germanium are nationalists

- Names derived from geographical regions :

  Europium, Francium, Germanium, Polonium,
  Hafnium (Latin for Copenhagen).
- Names from mythology :

  Cerium, Palladium(Pallas), Tantalum,
  Plutonium (Pluto), Thorium (Thor).
- Atoms named after materials :

  Carbon, Sulfur, Iron, Copper, Nickel,
  Lead, Zinc, Gold.
- Atoms named after famous people :

  Curium, Einsteinium,
  Mendelevium, Nobelium. [1]
- Names that indicate a physical characteristic :

  Phosphorus = light emitting
  Fluorine = melts easily
  Iodine = purple
  Bromine = foul smelling
  Dysprosium = difficult to find

Mr. Plutonium fright people

Mr. Phosphorus generates light.

Miss Fluorine easily melts

1 These are artificial families created by Man.

Chemical Symbols

Instead of using full names, Chemists (and crossword puzzle compilers) prefer to use abbreviations made up of one or two letters, known as chemical symbols. These symbols are marked on the atoms' hats.

Usually, the symbol is formed from the first, or the first two letters of the atom's name.

Crossword puzzle enthusiasts are good with symbols.

Aluminum	*Al*	*Iron*	*Fe*	*Carbon*	*C*
Sulfur	*S*	*Nickel*	*Ni*	*Hydrogen*	*H*

The first letter is always a capital, and the second a small letter. In some cases, the origin of the symbol is strange, and there does not appear to be any obvious connection to the atom's name. For example, there is:

Sodium	*Na (from Latin Natrium)*
Potassium	*K (from Latin Kalium)*
Gold	*Au (from Latin Aurum)*

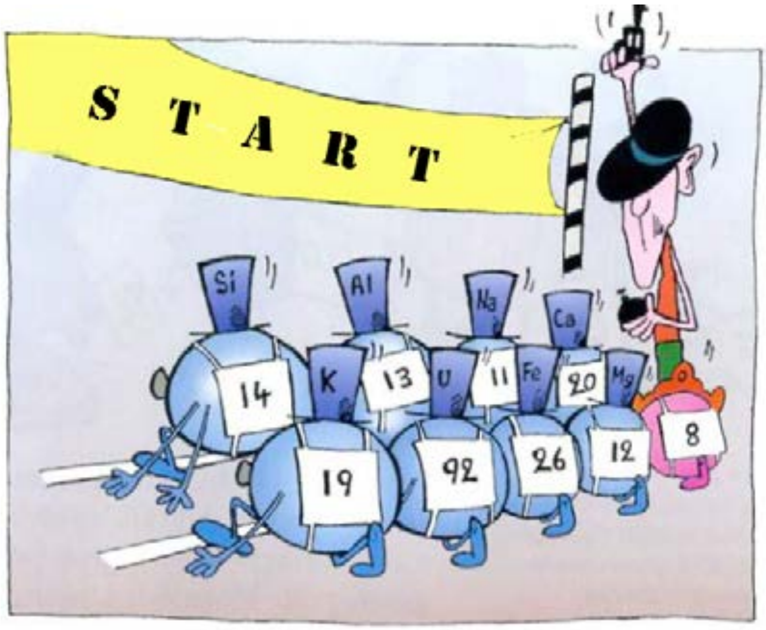
Registration Numbers

In the infinitesimal world, the atoms are organized with military precision. As well as having a name, each individual has a registration number between 1 and 92 which indicates the family it belongs to[1]. Chemists call this the atomic number.

1 Atoms with numbers 43 and 61, Messrs. Technetium and Promethium have disappeared from the world, victims of the congenital disease: virulent radioactive decay. Nowadays, Man can artificially make these atoms, but their life expectancy remains low!

All these numbers are designated by an official called Mendeleïev.[1] The numbering is carried out according to the following principles: the lightest atom, Mr. Hydrogen, has the number 1, and the heaviest, Mr. Uranium, has the number 92. Apart from a few exceptions, the atoms are numbered in order of increasing mass.

Nowadays, man's genius has enabled him to create new families of atoms. Thus, there have been some new additions to the world of natural atoms. The best known of these is Mr. Plutonium, who has been given the number 94.



Each atom also has a registration number.

The Masses of Atoms

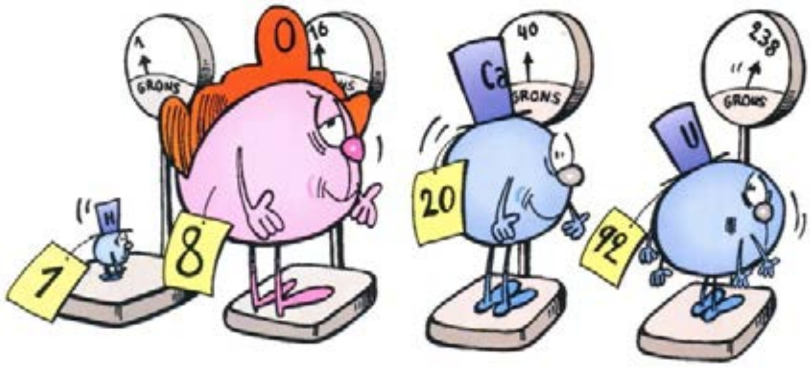
Apart from some exceptions, most of the members of a particular family of atoms have the same mass. On the other hand, different families have widely differing masses. Therefore, the atomic mass is one of the characteristics of each atomic family. If we were to weigh the lightest one, Hydrogen, we would find that it had a mass of 0.00000000000000000000000166 grams, which is not a lot! In order to avoid dealing with such cumbersome numbers, the Ministry of Weights and Measures in the World of Atoms has chosen the gron[2] to be the unit of mass, which is exactly equal to the mass of a hydrogen atom[3] .

---

1 Dmitri Ivanovitch Mendeleïev (1834-1907), a Russian chemist who invented of the periodic classification of chemical elements.

2 An imaginary unit only used in this book.

3 In fact, this is the mass in grams of 0.602488 billion billion hydrogen atoms. This large number is known as Avagadro's number (after the famous Italian chemist of that name, 1776-1856). In this way, atoms can be compared by expressing their mass in grams. Chemists have precisely defined an 'atomic mass unit' (a.m.u.) to be one twelfth of the mass of a carbon atom, which is equal to 1.66 x 10-24 grams.



The masses of the different atoms are spread between 1 gron for tiny Mr. Hydrogen and 238 grons for heavy Mr. Uranium.

If we now weigh all the other atoms, their masses are nearly always integer multiples of the mass of Mr. Hydrogen! For example, Mrs. Oxygen is 16 times heavier than Mr. Hydrogen, and Mr Calcium 40 times heavier. The masses of all the naturally occurring atoms are spread between 1 gron for hydrogen and 238 grons for uranium.

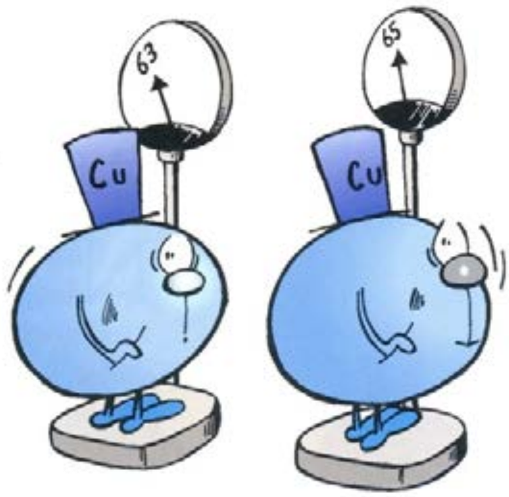
Some Family Members have Slightly Different Masses

Even in the World of Atoms nothing is perfect, and some members of a family can have different masses. Some members of the Uranium family only have a mass of 235 grons instead of the usual 238 grons. These individuals are few in number, and only make up 0.7% of the total number of family members. However, they are highly prized by man, who needs then for his nuclear reactors. The family members with slightly different masses are called isotopes.

Isotopes with masses slightly more or slightly less than average are found in many families. Generally they are present in tiny quantities, although there are some families in which they are plentiful.

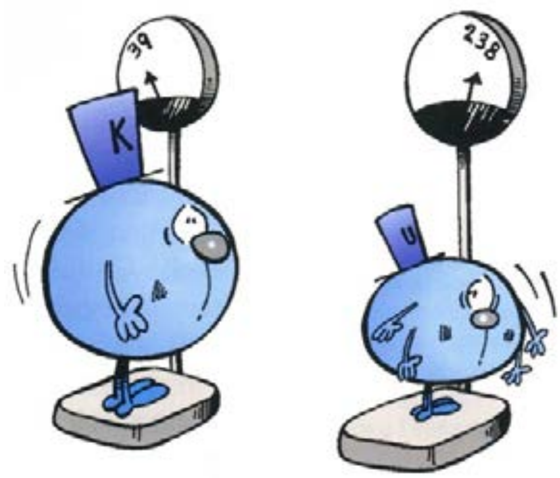
For example, 30% of the copper brothers have a mass of 65 grons whilst the others only have a mass of 63 grons. However, the behavior of all the isotopes in a single family is identical, inspite of the mass difference.

Atoms are approximately spherical. We could describe their size in terms of their waist measurement, but it is more usual to gauge their size by their atomic radius.



Some members of the Copper family have slightly different masses.

The Size of Atoms[1]



There is no explicit relation between the size and the mass of an atom.

A very small unit of distance is used, called an Ångström[2] (Å), which is one-tenth of a millionth of a millimeter.

There is no explicit relation between the size and the mass of an atom. Thus, Mr. Potassium whose mass is only 39 grons has an atomic radius of 1.33 Å, whilst heavy Mr. Uranium at 238 grons only has an atomic radius of 0.97 Å. The Lady atoms have a tendency to be stout, whilst the Gents generally remain thin. Later on we shall discover that the Gents shrink as they acquire more arms. The opposite is true for the Ladies.

The Number of Arms[3]

We have already said that atoms dislike being alone, and usually hold hands to form small groups[4]. Thus the arms are essential for forming groups.

Messrs. Iron and Manganese sometimes keep a hand in their pockets.
Curiously, once they take their hands out of their pockets they become thinner !

1 The author apologises to chemists for this short cut. The size is described in terms of the ionic radius, which plays an important role in the mineral world.

2 after Anders Jonas Ångström (1814-1874), a Swedish physicist famous for his work on the solar spectrum and on noble gases.

3 The number of arms and the level of excitation depend on the inner workings of the atom. This will be explained in the 'Anatomy of Atoms' chapter.

4 Chemists call these groups 'molecules'.

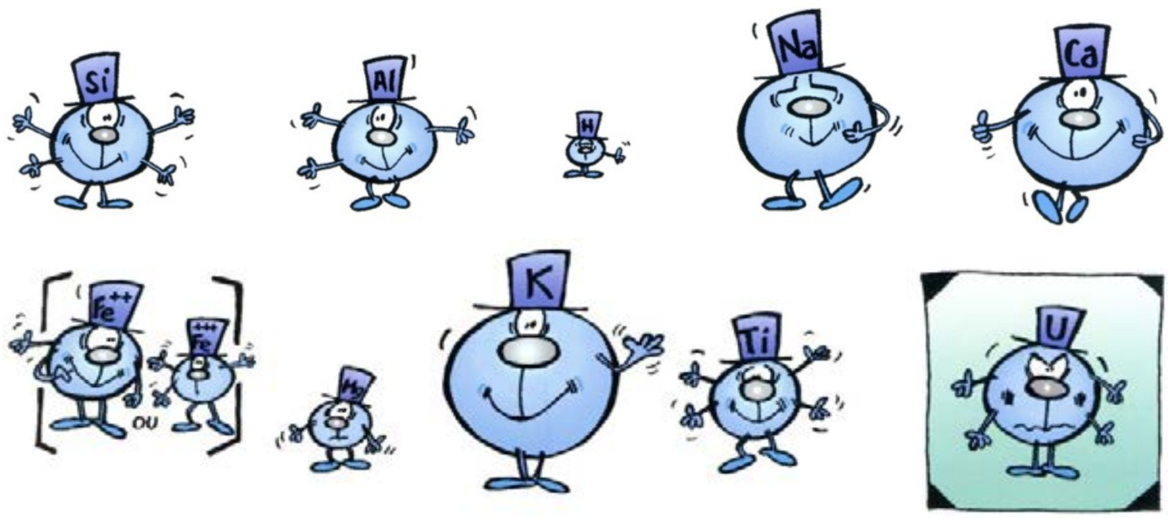
Different atoms have different numbers of arms. Messrs. Sodium and Potassium only have one arm each whilst Messrs. Calcium and Strontium have two. Mr. Aluminum has three and Mr. Silicon four.

Mr. Iron is a well known and slightly mischievous atom; he has two active hands and a third which he keeps in his pocket. He only takes his hand out of his pocket if he is a bit excited. What is remarkable is that he noticeably reduces in size as soon as he taken his third hand out of his pocket. His atomic radius is 0.76 Å then he has two arms, but with three arms it is only 0.64 Å!

Mr. Manganese is one of Mr. Iron's close friends, and they both behave in the same way. There are many other atoms whose number of arms changes depending on how excited they are. We shall return to this characteristic later on.

Ladies and Gents

There are only single sex families in the World of Atoms. There are many families of Gents, but barely half a dozen families of Ladies.



The most influential Gents : they are dressed in blue and sport top hats.
Bringing up the rear is the oafish and short-tempered Mr. Uranium

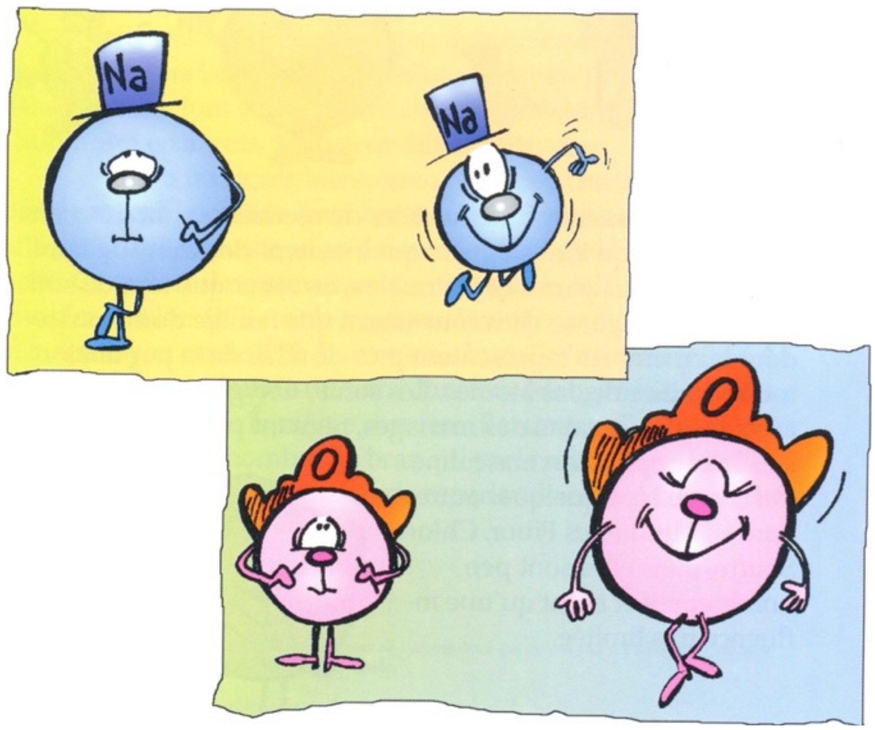
However, amongst the latter are the oxygen sisters. They form a powerful family whose members account for nearly 62% of the total atomic population. The oxygen sisters figure in practically all atomic marriages, having a nearly unshakeable hold over the male population. There are some other Ladies such as Mrs. Fluorine, Chlorine and Sulfur, but they are few in number and have limited influence.

The Ladies are dressed in pink and wear lace bonnets.
They are keen to marry and tend to be stout.

Atoms Grow or Shrink Depending on how Excited they are

We have seen that the Gents are generally thin whilst the Ladies have a strong tendency to be stout. When resting, the Gents have their hands in their pockets. When they get excited they take their hands out of their pockets and curiously grow thinner. The opposite is true for Ladies; Mrs. Oxygen nearly doubles in size when the excitement makes her take her hands out of her pockets.

Chemists (and crossword puzzle enthusiasts), who are always intrigued by the World of Atoms, nickname atoms in an excited state ions (or charge carriers), or more precisely anions if they are Ladies and cations if they are Gents.



The excitement causes Gents to become thinner...

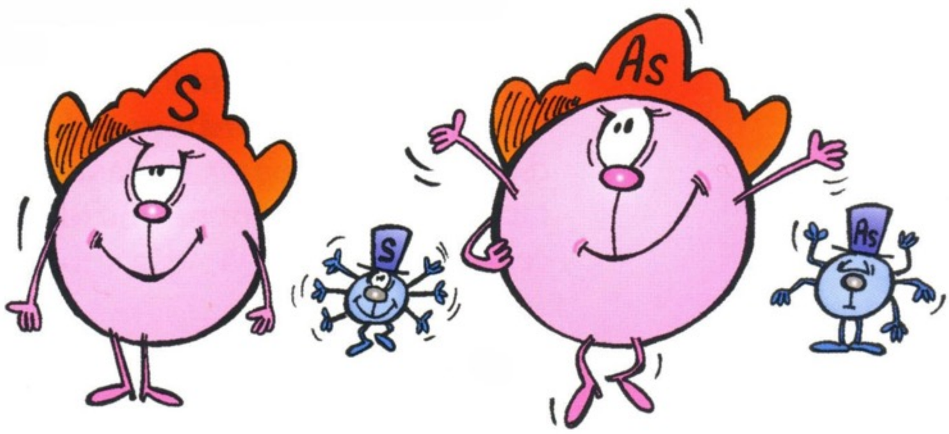
...Mrs. Oxygen nearly doubles in size when the excitement makes her take her hands out of her pockets.

Crossword puzzle enthusiasts also know about ions, cations and anions!

Androgynous Atoms

There are some families which do not have clear male or female characteristics, and which behave as Ladies in some situations and as Gents in others. In this category are the Sulfur, Arsenic, Tin families, and sometimes the Carbon family.

Chemists sometimes group all atoms which are definitely not Gents as non-metals. This group is made up of Ladies and androgynous atoms.



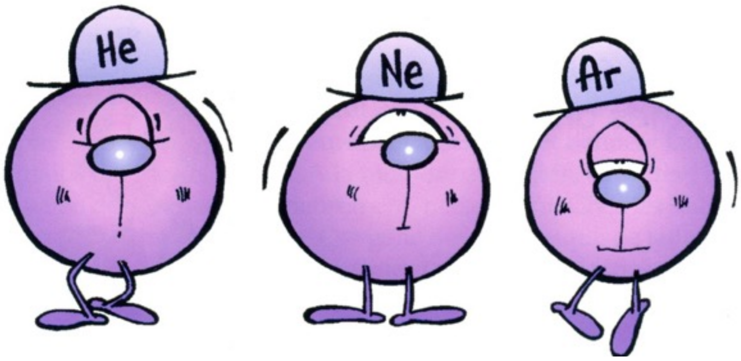
Sometimes Ladies and sometimes Gents, these atoms are androgynous

.

The Confirmed Bachelors

Although marriage is widespread in the World of Atoms, there are some families of confirmed bachelors : Messrs. Helium, Neon, Argon, Krypton, Xenon and Radon. They are dressed in purple and wear bowler hats. They don't have any arms. Their distant personalities and their scarcity give them the nickname of noble gases[1].

The confirmed bachelors have no arms. They are dressed in purple and wear bowler hats. Their scarcity and their aloof manner have given them the nickname "the noble gases".



Population Distribution

The population is very inhomogeneously distributed amongst the 90 naturally occurring families. A recent census[2] showed that ten families accounted for 99.3% of the population, whilst the remaining 80 families accounted for just 0.7%!

Amongst the ten largest families is one family of Ladies (the oxygen sisters) and nine families of Gents. The following table shows their relative importance:

Oxygen	61.5 %	Iron	1.8
Silicon	20	Magnesium	1.7
Aluminium	6	Potassium	1.2
Hydrogen	2.8	Titanium	0.2
Sodium	2.3	Other families	0.7
Calcium	1.8	Total	100

Latest Census of the World of Atoms
(percentage of the total population)

1 These elements are in the gaseous state at room temperature and pressure.

2 The census was made on the Earth's crust, which consists of the first 30 km of the Earth below our feet.

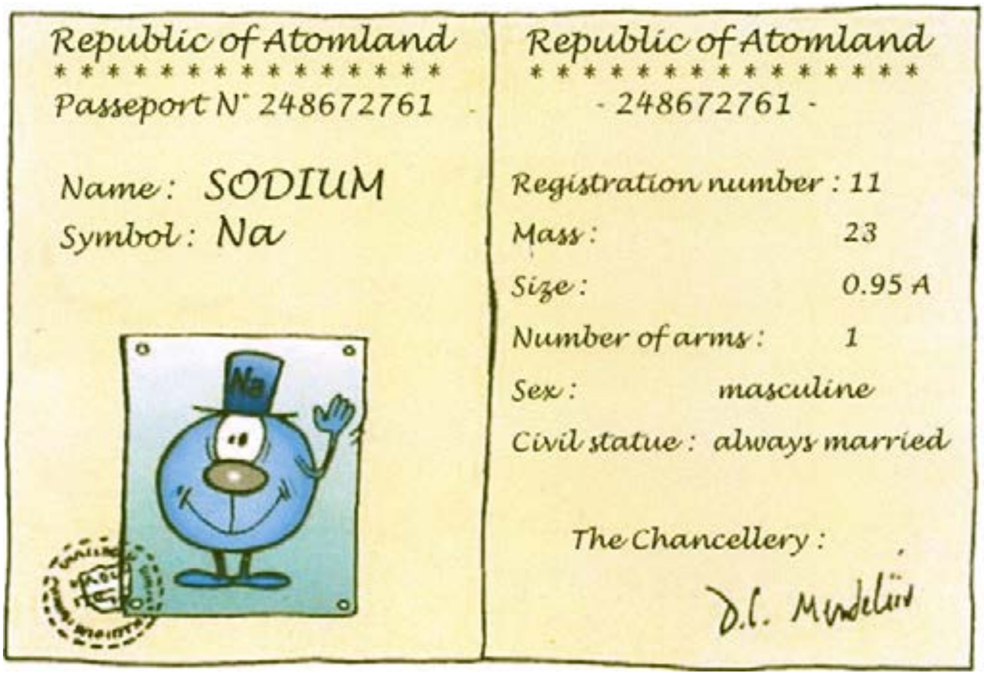
Man has many uses for Copper despite its rarity. Only two or three atoms in 100,000 are members of the Copper family! Likewise the carbon brothers, who play an important role in living beings, only make up 0.1% of the population. The aristocratic gold, silver and platinum are even rarer, constituting less than of a millionth of the total population!

Passports

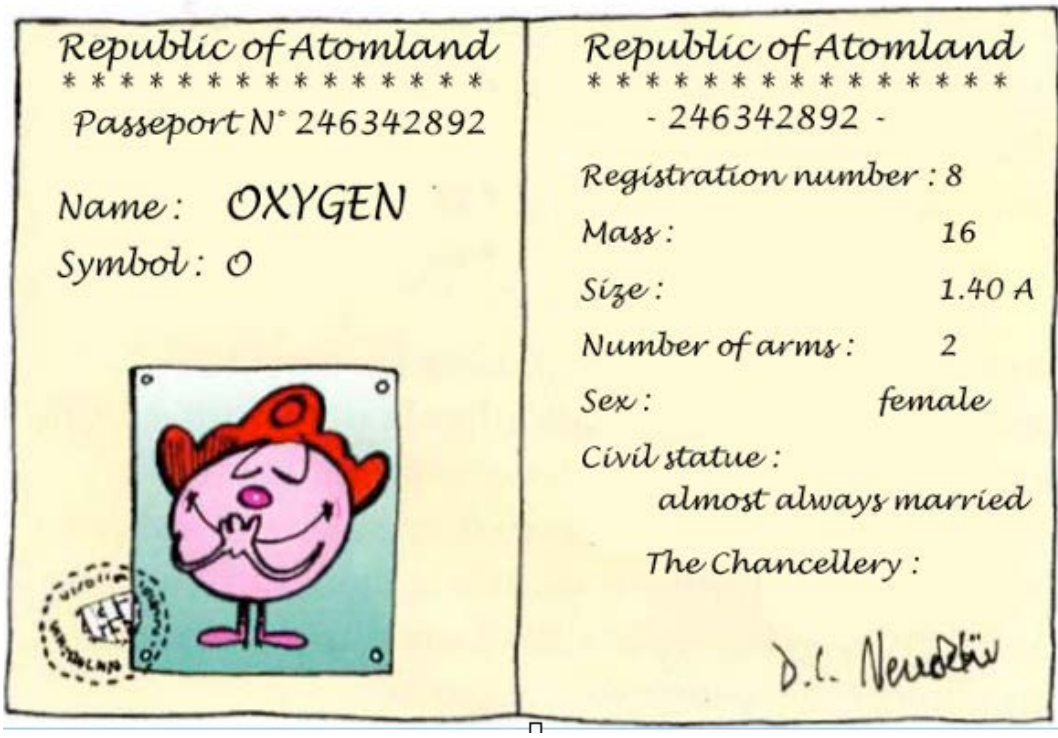
In order to identify the members of the population, the Passport Agency of the World of Atoms issues each family with its own passport containing the following particulars:

- *surname*
- *chemical symbol*
- *registration number*
- *mass*
- *size*
- *number of arms*
- *sex*
- *distinguishing features*

Each passport describes the average characteristics of a family of atoms. The recorded mass is an average of all the isotopes[1] masses, weighted by their individual abundance. This is why the recorded mass is not always a whole number. The individual isotopes of a family can be issued with separate passports on demand.



1 *See the paragraphs titled 'Some Family Members have Slightly Different Masses' on page 8, and 'Isotopes' on page 44.*


Republic of Atomland
* * * * * * * * * * * * * * *
Passeport N° 246342892
Name : OXYGEN
Symbol : O
Republic of Atomland
* * * * * * * * * * * * * * *
- 246342892 -
Registration number : 8
Mass : 16
Size : 1.40 A
Number of arms : 2
Sex : female
Civil statue :
almost always married
The Chancellery :

A Photograph of all the Atomic Families[1]

The Different Social Classes

The Atoms' social lives are very well organized in the World of Atoms. The social class is determined by the number of arms that the atom has. Some classes have high morals and strict protocols, others have slightly lax principles. It is generally found that atoms with fewer arms are more sectarian. During a thorough sociological study of the World of Atoms, Mendeleïev noticed that a periodicity emerged in the atoms' social classes when the atoms were arranged in order of ascending mass. Four special numbers govern this periodicity: 2, 8, 18, and 32.

The Local Authority thought it would be useful to take a photograph of all the atomic families, showing each individual's character and properties at a glance.

We have tried to find a photo showing a representative from each of the 90 naturally occurring families. However, we have only found a partial photo showing the lightest 18 atoms.

The following deductions can be made from the photo:

- *The atoms' masses increase with their atomic number.*
- *Individuals in the same column belong to the same social class, and have the same number of arms.*
- *Moving from left to right we successively find one-armed atoms, then two-armed atoms, then three-armed atoms, etc.*
- *The number of arms is equal to:*
    - *the column number for Gents*
    - *8 (special number) minus the column number for Ladies.*
- *The Gents are located on the left hand side of the photo, Ladies on the right hand side of the photo. The final column on the right is reserved for the confirmed bachelors.*
- *The atoms increase in size going down a column.*
- *Gents decrease in size along a row, but their number of arms increases along a row.*

In order to take the photograph of all the families, Mendeleïev placed the atoms in seven tiers, with the lightest atoms in the upper levels and the heavier ones in the lower levels as follows:

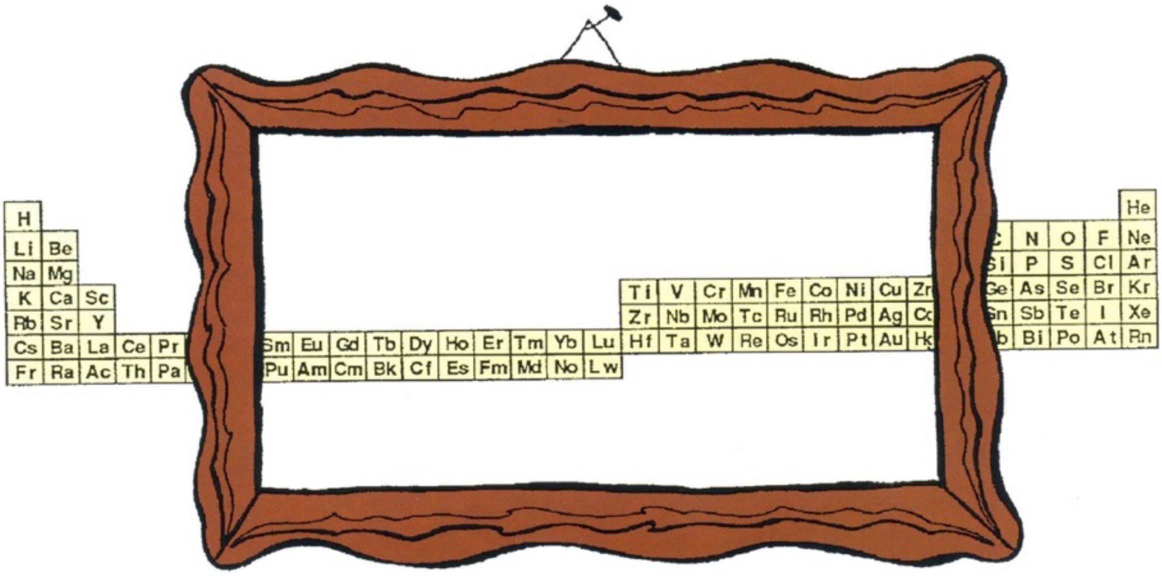
- *first level (top) : 2 people, Messrs. Hydrogen and Helium,*
- *second level : 8 people, from Lithium to Neon,*
- *third level : 8 people, from Sodium to Argon,*
- *fourth level : 18 people, from Potassium to Krypton,*
- *fifth level : 18 people[2] , from Rubidium to Xenon,*
- *sixth level : 32 people, from Caesium to Radon,*
- *seventh level (bottom) : 32 people[3] , from Francium to Lawrencium.*

---

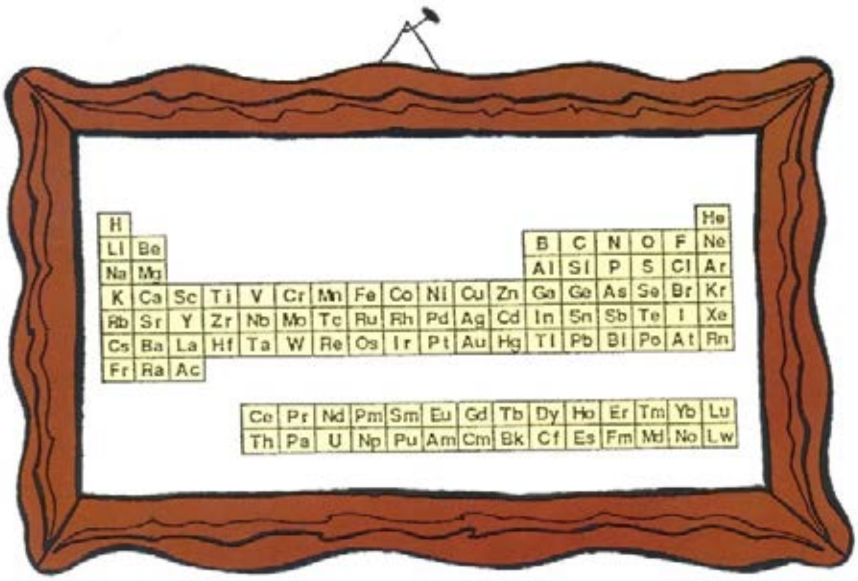
1 Chemists call this the Periodic Table of Atoms.

2 Rows 5 and 6 each have one empty space. These spaces were for Messrs. Technetium and Promethium, but they died prematurely of virulent radioactive decay.

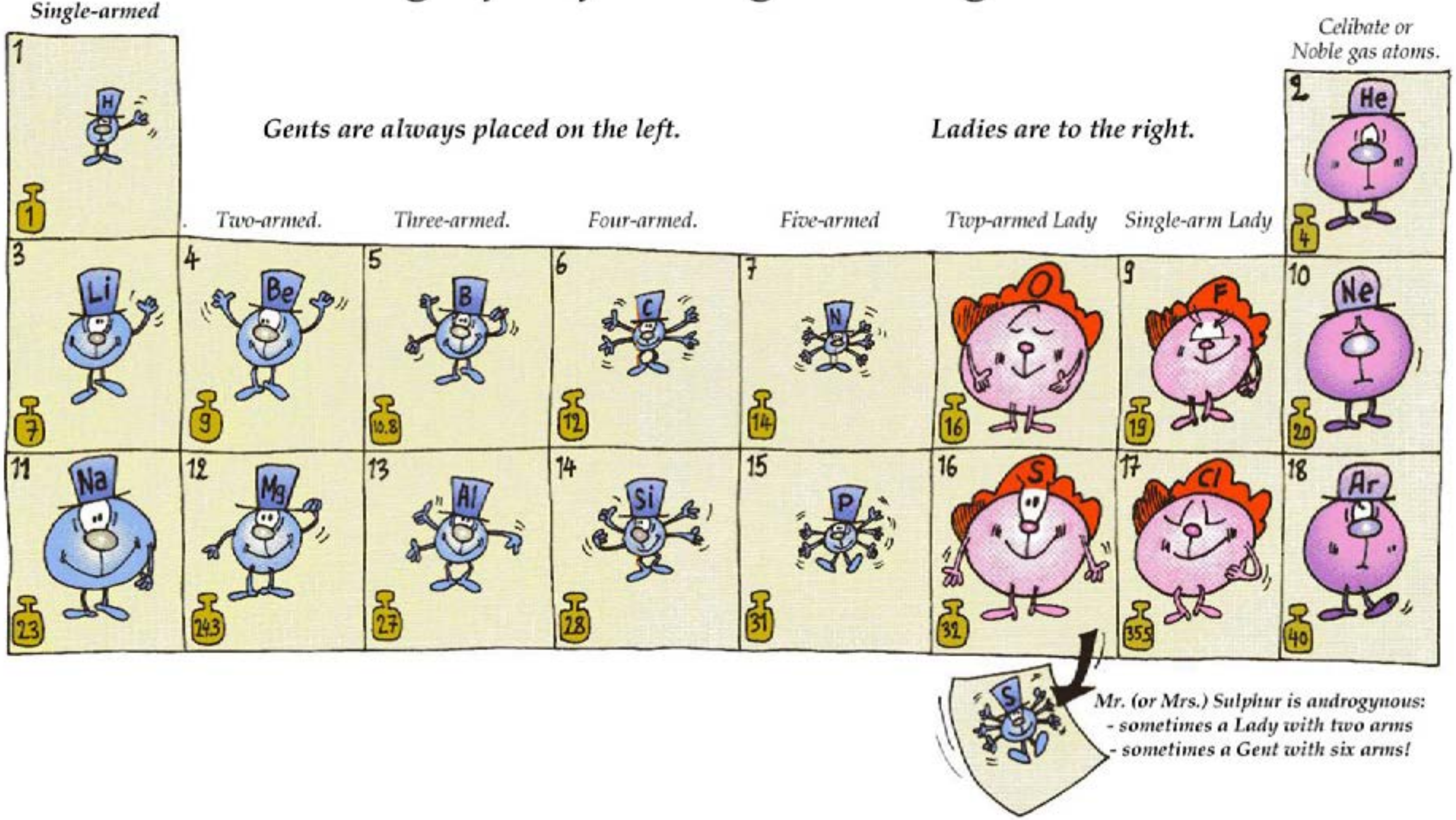
3 This lowest row should have 32 characters but not enough atoms have been found to fill it. Mendeleïev only found 6 individuals for this last row, Messrs. Francium, Radium, Actinium, Thorium, Protactinium, and Uranium. Today, Man has managed to create a dozen new families whose places are in this row. However, all of them are unstable, and have a low life-expectancy



Unfortunately, this arrangement is not particularly convenient as the upper rows are sparsely filled. This makes it difficult to find a suitable frame for the photograph. Mendeleïev's successors began the practice of regrouping 14 atoms from the longest two rows, and placing them in two separate rows at the bottom right of the photo. This photo is very important to Chemists who have named it the 'Periodic Table of Elements'. Each family of atoms is designated a compartment which displays the families details such as their name, symbol, atomic number, mass, number of arms (curiously called the "excitation state"), and size.

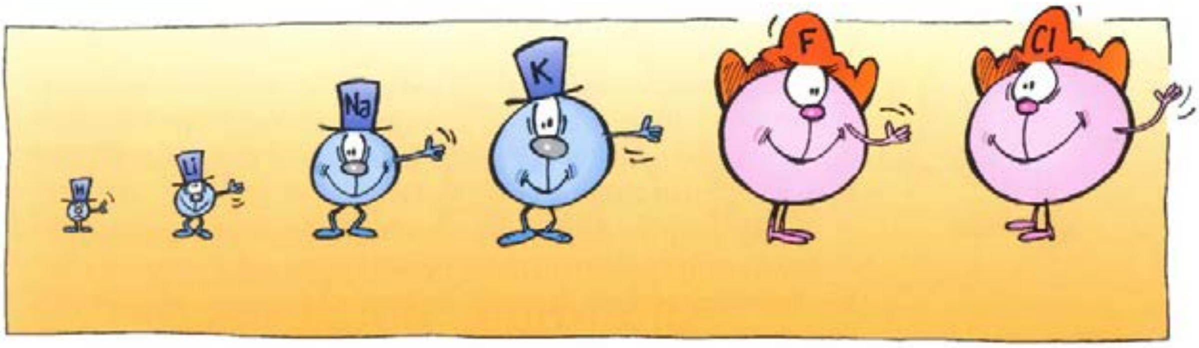


A Photograph of the Eighteen Lightest Atoms



The Class of Single-Armed Atoms

The members of the single arm class are fundamentalists. They have very similar characteristics and life styles, and follow strict traditions. Foremost members include Messrs. Lithium, Sodium, Potassium, and the Fluorine, Chlorine, Bromine and Iodine Ladies. With the exception of tiny Mr. Hydrogen, all the Gents are shiny metals which have low densities and quite low melting points.



Important characters belong to the one-armed class, in particular Messrs. Sodium and Potassium, as well as tiny Hydrogen. Seductive and corrosive, Messrs. Chlorine and Fluorine are never celibate.

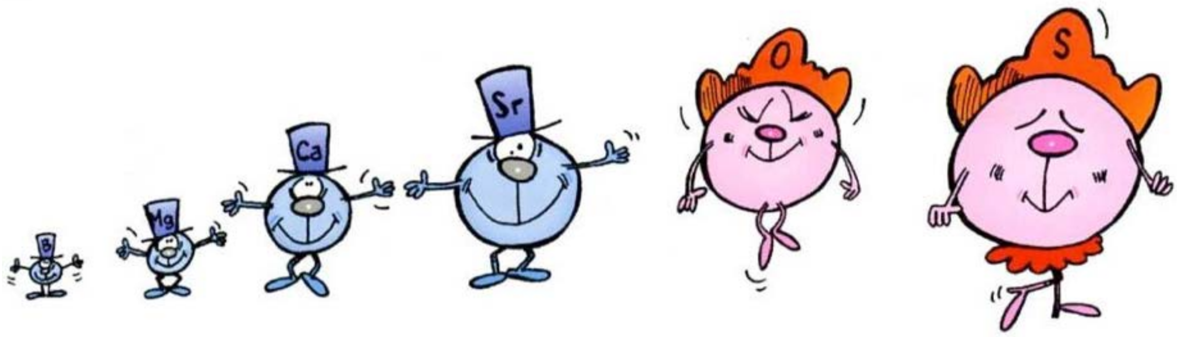
These Gents are all smitten by Ladies, and never remain single. They are often romantically linked to the Fluorine or Chlorine Ladies, who are influential members of the same social class. Together they form NaCl (rock salt) and KCl (sylvite), both well known to amateur mineralogists. They can also form dangerous HF (hydrofluoric acid). The two most influential Ladies in this social class are both quite stout and very volatile[1]. They are seductive and very aggressive, and are rarely single.

Hydrofluoric acid, a dangerous couple

1 They exist as gasses during their infrequent periods of celibacy.

The Class of Two-Armed Atoms

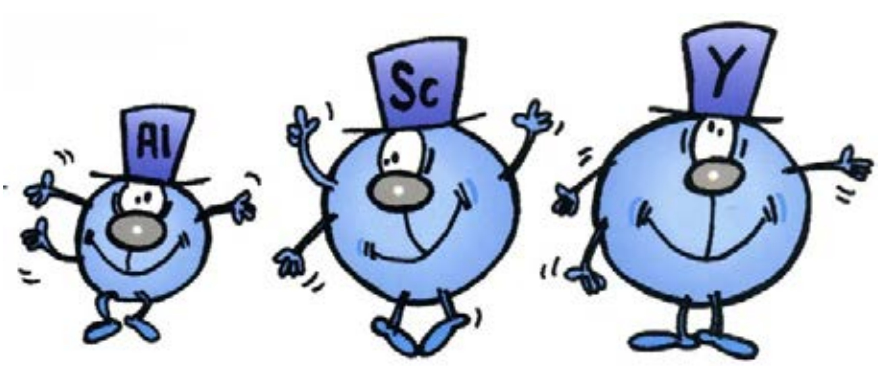
Although a lot less fundamentalist than the one-armed class, the two-armed class still form a clear group. The Gents have a metallic appearance and a fairly low density, but they have much higher melting points than their neighbors in the one-armed class. Mrs. Oxygen is a member of the two-armed class, and we shall soon discover that she figures in most of the atomic marriages. Slightly less enthusiastic about marriage is Mrs. Sulphur, who lives directly below Mrs. Oxygen, and sometimes has androgynous characteristics. All the same, she does have a soft spot for Messrs Iron, Lead Zinc and Copper, who are friends from a different social class. They form alliances that mineralogists call iron pyrite (FeS_2), galena (PbS), blende (ZnS) and chalcopyrite ($CuFeS_2$). Apart from the omnipresent Mrs. Oxygen, the class also boasts two characters who play a very important role in the Earth's crust, Messrs. Magnesium and Calcium. Light Beryllium and heavy Barium complete the class.



Two important ladies, Mss Oxygen and Sulfur belong to the two-armed atoms. However , Mrs Sulfur often shows her androgynous side and can then look just like a little six-armed man.

The Class of Three-Armed Atoms

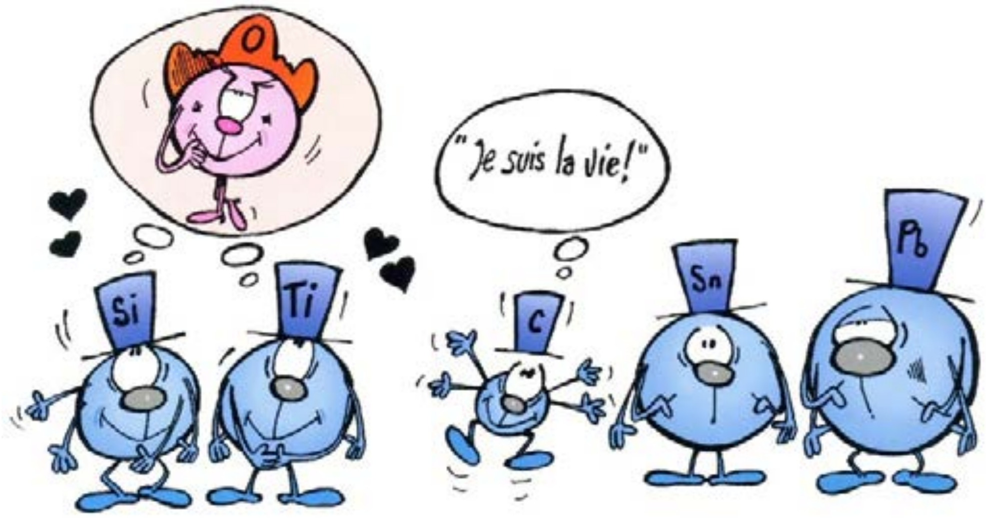
Only one member of this group is important. He is Mr. Aluminum, a lightly-built chap who often ties the knot with the Oxygen sisters. Indeed, we sometimes find communities made up of two Aluminum brothers and three Oxygen sisters, known by the acronym Al_2O_3. Mineralogists call this "corundum". The other members of the group are quite retiring and are few in number. There are no Ladies in these classes.



Mr. Aluminum is the only important member of the three-armed class.

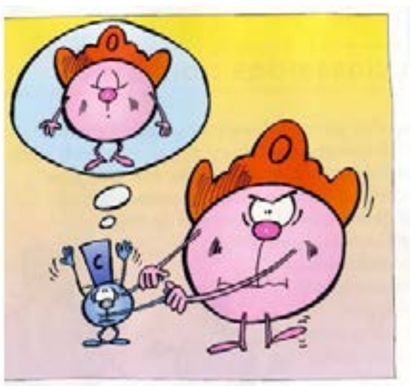
The Class of Four-Armed Atoms

This class boasts some very important characters such as Messrs. Silicon and Titanium. Both are extremely attracted to the Oxygen sisters forming triatomic SiO_2 (quartz) and TiO_2 (rutile).

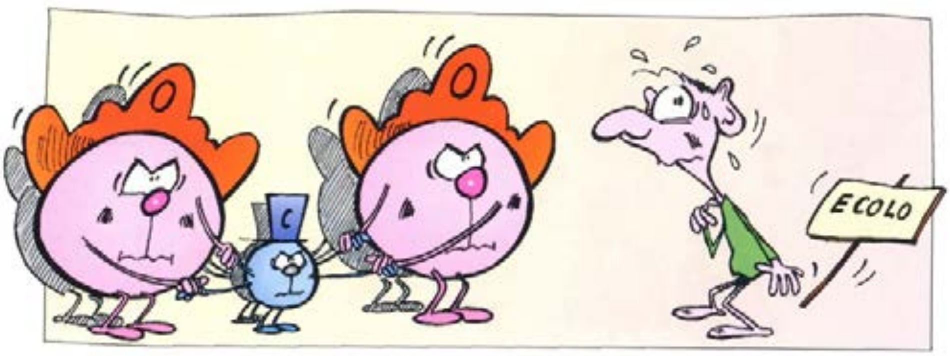


The four-armed class boasts several well known members.

There is one member of the class who is quite special: Mr. Carbon. He is very versatile, and can remain single or link up with Mrs Oxygen. They can form dangerous CO which will suffocate you if you don't watch out, or they can form triatomic CO_2, which is giving ecologists plenty of headaches at the moment.



The CO couple is very dangerous, and will suffocate you if you don't watch out. The Carbon atom dreams of seducing a second Miss. Oxygen...

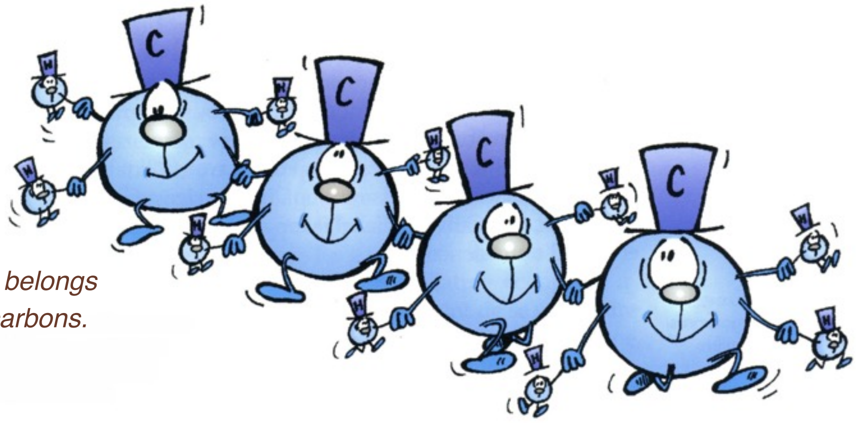


...to form triatomic CO_2, which causes ecologists plenty of headaches.

Father Carbon is the Source of Life!

Carbon is also a principal shareholder in hydrocarbon companies, and he is heavily involved in the structure of living beings!

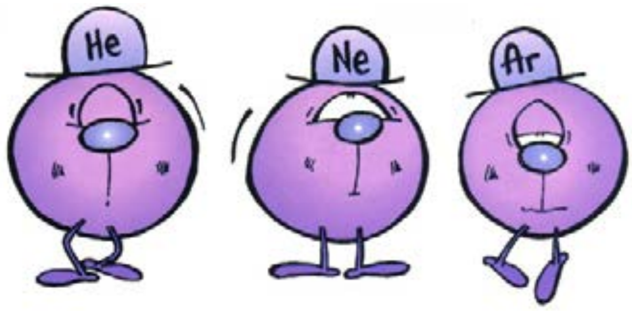
Father Carbon plays a very important role : he often frolics with hydrogen, forming either small groups, long chains or rings that make up the highly sought after hydrocarbon club. The club's ranks swell if new members are admitted, such as the Nitrogen brothers and the Oxygen sisters, and new important groups are formed known as organic molecules . These molecules are very important as they are the source of life.



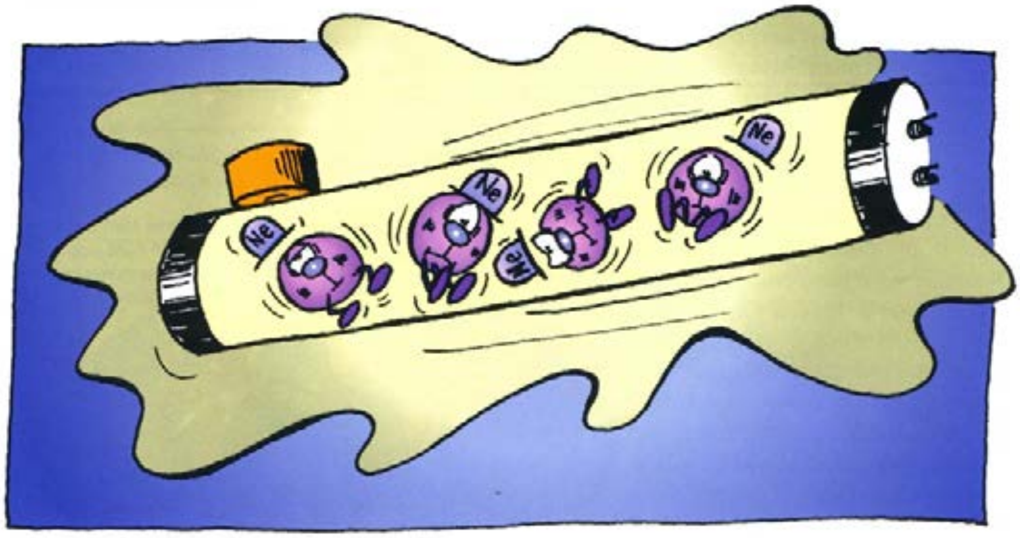
The butane farandole C_4H_{10} belongs to the great society of hydrocarbons.

Atoms with no Arms

This is a very sectarian class whose members always remain single. There are few of these confirmed bachelors, and they are all gases at room temperature. They are called noble gases. The most well known of them, Neon, can be excited by electrical discharges in a glass tube. A reddish light is given off by these luminescent tubes which are often used in advertisements.



Atoms with no arms are very sectarian. They are confirmed bachelors who never link up with anybody.



The noble gases emit light if they are subject to electrical discharges

Other Social Classes

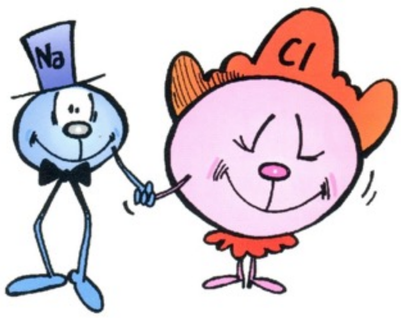
These classes are far less structured and strict than the preceding classes, and the individuals in them do not follow the traditional rules. All are high density metals that very often keep one or more of their hands in their pockets, and only take them out on special occasions. They are not keen on marriage, and can remain single for quite a long time. Man uses many of these atoms, examples being Messrs. Iron, Copper, Nickel, Manganese, Silver, Gold, and Platinum.

Marriage in the World of Atoms

Marriage is the norm in the World of Atoms. Nearly everyone is attached to one or more atoms, mostly mediated by the Oxygen sisters' dating agency which is the market leader in this field. Only confirmed bachelors such as the noble gases, and some aristocrats such as Messrs. Gold and Platinum, escape their clutches. There are those who try and shirk their responsibilities. Amongst them are Messrs. Sulphur, Carbon and Copper[1]. However, they never escape marriage for long, and nearly always end up following the customs of the World of Atoms[2].

The Vows

- *Marriages may by monogynous, polygynous or polyandrous. Communities are also allowed.*
- *There must be an equal number of masculine and feminine hands in each marriage.*
- *Only atoms of the opposite sex can hold hands.*
- *Couples or groups which take these vows are called molecules. They are identified by a list of their constituent atoms' symbols. The number of each type of atom in the marriage is written in subscript after its symbol. Molecules are often given patronymic names as well.*

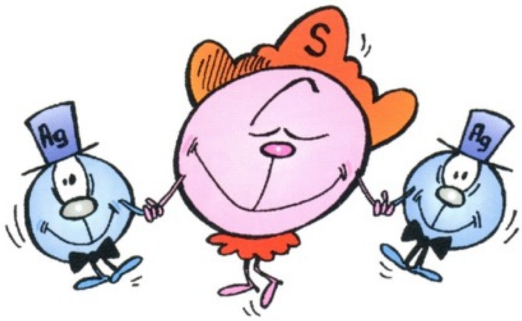


Mr. Sodium is monogamous. He keeps a firm grip on Mrs. Chlorine with his sole

1 Substances made up of a single element are called 'pure substances'. These include Gold, Platinum, Copper, Sulphur and Carbon (both diamond and graphite forms).

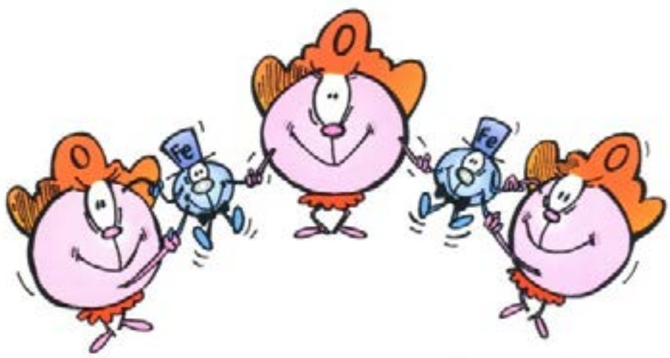
2 To satisfy his needs, Man has forced some atoms to divorce and become celibate. Thus he has enslaved the Iron, Copper, Lead and Zinc families. However, the Oxygen sisters are on the lookout, and they have deceitfully tried to undermine Man's work. They cause Iron to rust, change copper from grey to green, and oxidize Zinc and Lead.

Mr. Titanium is polygynous. He forms TiO_2 by being linked to two oxygen sisters. Mineralogists call this union rutile, anatase or brookit.



Polyandrous marriages also exist. Here, Miss Sulphur has trapped two Silver brothers. Chemists call this union silver sulphide. Mineralogists call it argentite.

In most cases, atoms live in small communities. Here, two Iron brothers have linked up with three oxygen sisters. This is Ferric Oxyde Fe_2O_3 to Chemists, hematite to mineralogists.



Certificates

There are only happy marriages in the World of Atoms. Each molecule's characteristics are recorded on its marriage certificate which is issued by the Registry Office. One of the molecule's main characteristics is its mass, which is called its molecular mass. This is easily found by adding up the masses of the atoms which constitute the molecule. Other information recorded in the marriage certificate includes the boiling point, melting point, density, refractive index, and distinguishing marks.

Marriage certificate

This certificate records the marriage between:

*Mr **Silicon** and two **Oxygen** sisters*

The community thus formed has the following names and symbols:

Patronymic name :	*Silicon Oxyde*
Symbol :	*SiO_2,*
Other names :	*Silica, quartz chalcedony, agate, amethyst...*

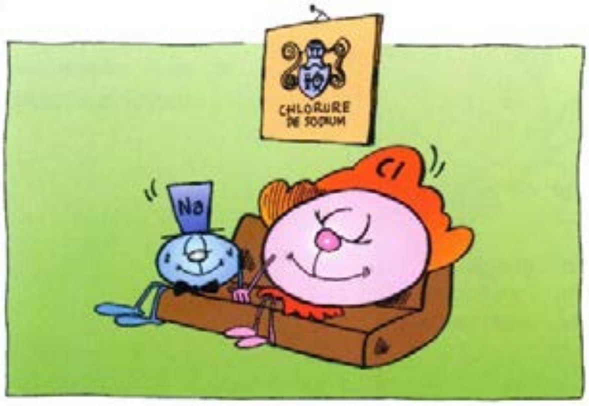
The community has the following properties:

Molecular mass :	*60.08 [grons]*	*Melting point :*	*1610° [C]*
Density :	*2.65 [gr/cm^3]*	*Boiling point :*	*≈ 2‘500° [C]*
Refractive index :	*1.54*	*Hardness :*	*7*

Distinguishing features :	*Very stable union, insoluble in acids, crystallizes in a rhombohedral structure.*
Origin :	*One of the constituents of granite and gneiss. The disintegration of these rocks produces the sand in our rivers, lakes and oceans. The sedimentation cycles transform them into sandstone and quartzite.*
Uses :	*The main material in the glass industry. Used for its piezoelectric properties in electronics. Is also used in concrete.*

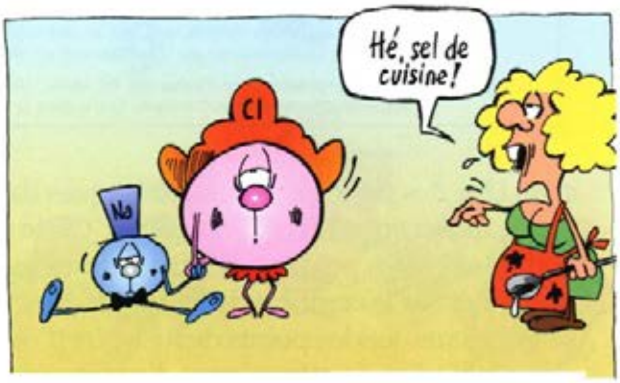
Patronymic Names of Molecules

Newly-wed NaCl is called sodium chloride. All the marriages in which Mrs. Chlorine figures prominently have names ending in "...chloride". However, a molecules are known by different names in different subjects. Chemists use the abbreviation NaCl and the name sodium chloride. Mineralogists give names to chemical substances that form beautiful crystals. They call the NaCl mineral "rock salt". Finally, greengrocers and chefs call the same substance table salt!



Mrs and Mr Chloride of Sodium
have an aristocratic name.

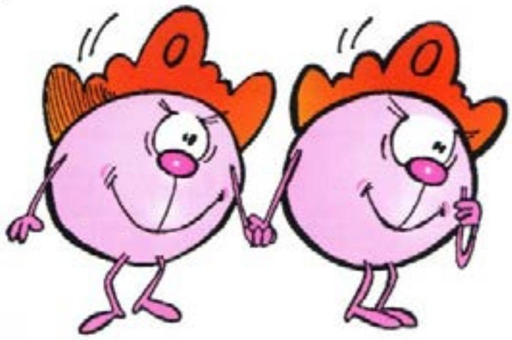
But mineralogists prefer to
call them halite...



...Whilst greengrocers and chefs
call them table salt!

Some Atoms can Sometimes Remain Celibate

Some atoms, such as the oxygen sisters or Mr. Hydrogen are usually very keen to marry, but they can remain single for a short while if they cannot find suitable partners. However, they hate solitude, and during their brief periods of celibacy they always hold hands and go about their day in twos. This is the case for the oxygen sisters in the atmosphere, where they are known by the symbol O_2.

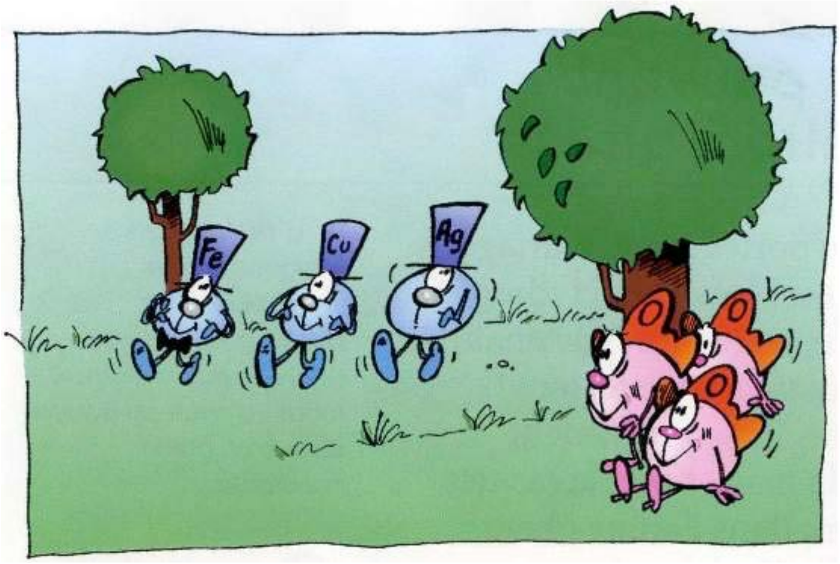


Here are two oxygen sisters, wandering around in the atmosphere. They hold hands, having not yet found suitable partners.

Less frequently, they go around in groups of three. These little groups, called ozone, are very effective in filtering out ultraviolet rays from the Sun. Their depletion in the upper atmosphere is a source of worry to ecologists.

Very infrequently, three oxygen sisters will link up to form O_3. This molecule is called Ozone, and its depletion in the upper atmosphere is a great source of worry to Man.

Other atoms still have fun whilst being single. Examples are Messrs. Copper, Iron, and Silver, who stroll around with their hands in their pockets.



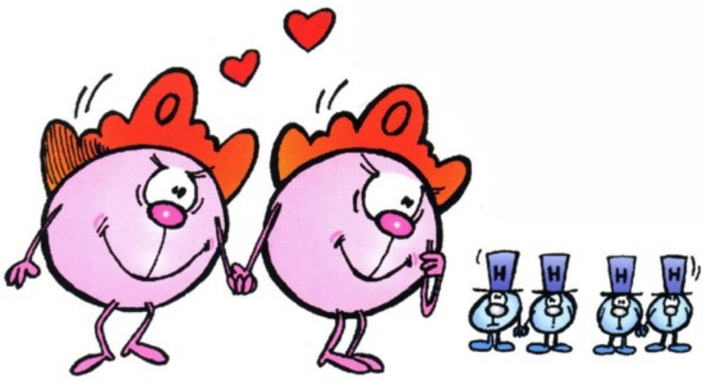
In fact, it is Man more than anybody else who induces these periods of celibacy as he has many uses for these atoms. However, the Oxygen sisters deceitfully keep an eye on these atoms, and are ready to pounce, oxidizing Silver and Copper and rusting Iron.

The Oxygen sisters deceitfully stalk celibate atoms.

An Explosive Encounter

Imagine that during the course of their travels, some single oxygen sisters run into some single oxygen brothers. If it is hot enough for them to shed their inhibitions, they fall into each others arms in an explosion of happiness. Each new molecule consists of an oxygen Lady attached to two hydrogen brothers, and is called H_2O or a water molecule. Chemists record this emotional moment in their usual poetic manner:

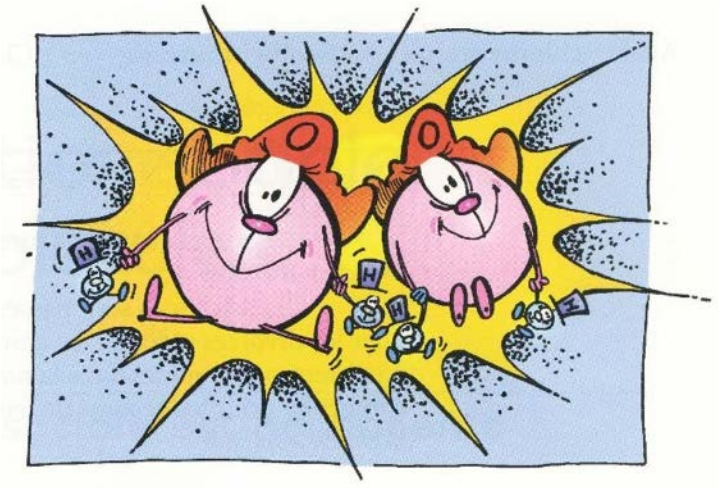
$$O_2 + 2H_2 = 2H_2O$$



This example demonstrates a curious point about marriage ceremonies. If the atmosphere is very friendly, there is an increase in the ambient temperature as some heat is generated.

Enough heat is given out during the marriage of an oxygen lady to a couple of hydrogen brothers to cause a powerful explosion.

During their travels, two oxygen sisters run into some hydrogen brothers...



Man can induce marriages like these in order to generate heat; this is done in metaloxy blow-torches! There are some instances in which the opposite happens. The atmosphere becomes glacial and everybody gets cold. Chemists show-off their Greek by calling the reactions which give out heat exothermic, and those which take heat endothermic.

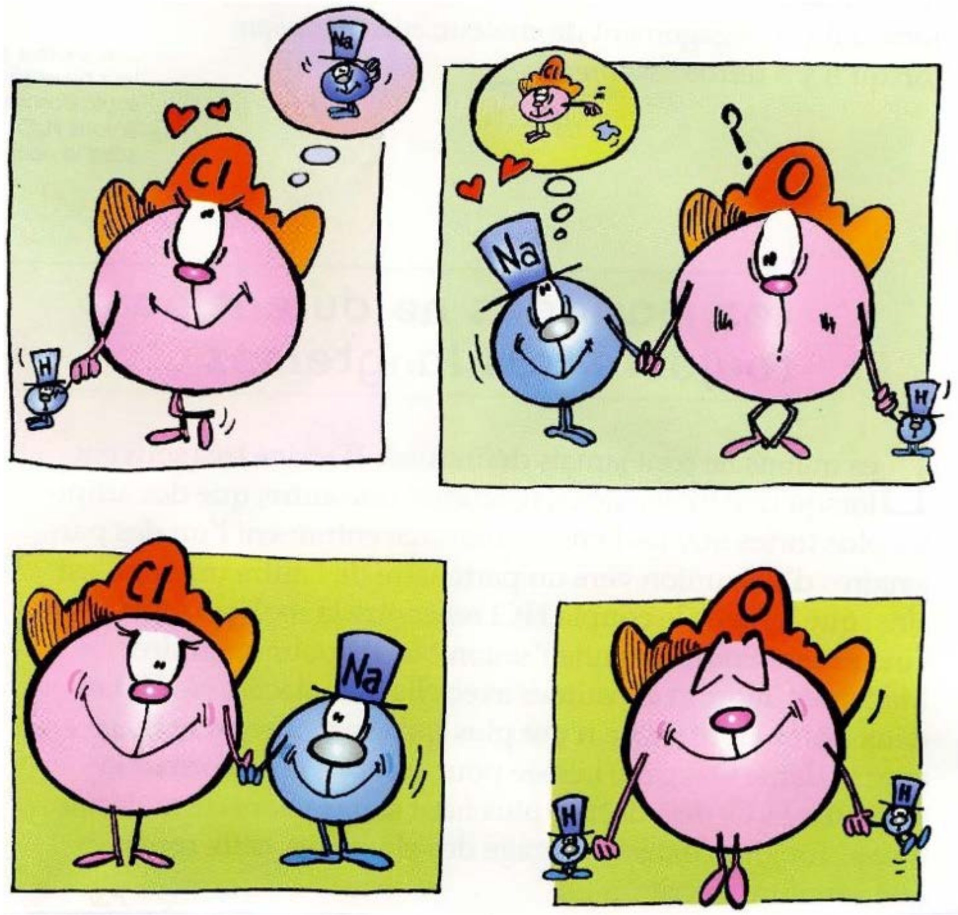
Marriage does not always last long

Some marriages don't last forever. Very often, two molecules will meet and one of the partners in one of the molecules will feel an overwhelming attraction for a partner in the other molecule. This happens when the HCl couple meet the NaOH molecule. Fickle Sodium leaves NaOH and runs off with Mrs. Chlorine to form an NaCl molecule. The two hydrogen brothers have no other option but to link up with Lady Oxygen, forming an H_2O or water molecule as described beforehand. Chemists write this romantic adventure as:

Hydrochloric acid + Sodium hydroxide = Sodium Chloride + Water

or in shorthand : $HCl + NaOH = NaCl + H_2O$.

*They call this type of adventure a **chemical reaction** !*



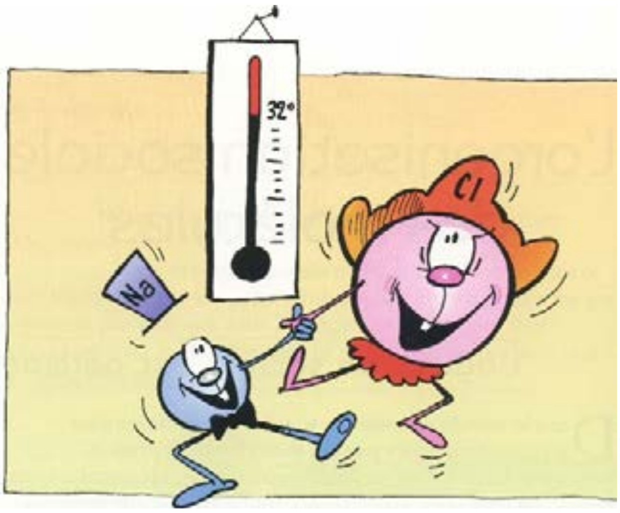
During a walk in the park, an HCl couple runs into an NaOH trio. Love is in the air... Mrs. Chlorine and Mr. Sodium get together, whilst Mrs Oxygen takes care of the two tiny Hydrogens - an arrangement that suits all !

*Man has become expert in inducing divorce and forcing atoms into new unions which haven't always naturally existed. All this is done for our comfort or for industry, and is called **applied chemistry**.*

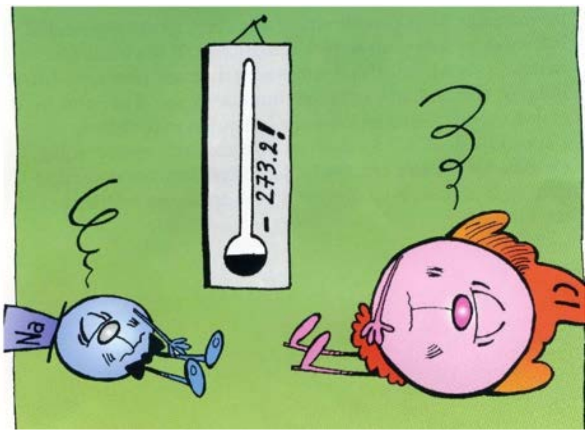
The Social Organization In the World of Atoms

Constant Hustle and Bustle

All the characters in the World of Atoms are happily bustling about. Some tirelessly move at great speeds and in all directions, bouncing off their fellow atoms or off obstacles in their path. This movement is incessant. However, in contrast to Man who, when it is cold, stamps his feet to get warm, the inhabitants of the World of Atoms become more agitated as it gets warmer. This agitation diminishes as it gets colder, and the atoms become lethargic as the temperature drops towards -273.2°C. This extremely low temperature is called absolute zero. Physicists have shown that it is not possible to obtain a lower temperature than absolute zero.



Atoms become more agitated the hotter it gets



They are paralyzed by the cold.
At about -273 °C, they become lethargic.

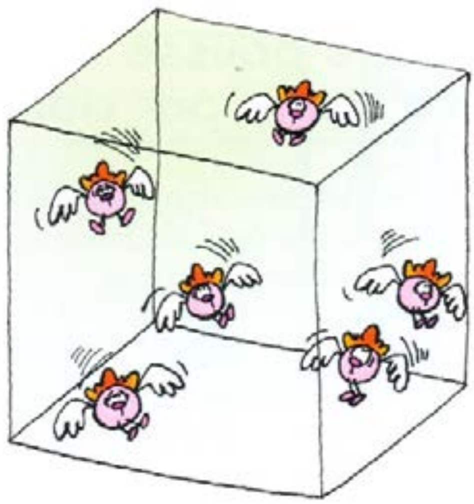
Molecules' Gregarious Nature causes them to form Clans

Similar molecules, as well as single atoms from the same family, have a strong tendency to group into separate clans. There is an attractive force which causes similar atoms and similar molecules to bunch up. These clans have a high population density if they are in solid or liquid form. The density is lower if the clan is a gas. For example, a 20 carat ruby[1] (4 grams in mass and 1 cm^3 in volume) is a clan of approximately 20,000 million billion Al_2O_3 molecules, all bunched together. One cubic centimeter of water holds 34,000 million billion water molecules, whilst a cubic centimeter of water vapor 'only' contains 28 million billion of the same water molecules, approximately 1200 times fewer.

Three Types of Clan[2]

Everybody knows that at room pressure, the H_2O (water) clan is in liquid form between 0°C and 100°C, in gas form above 100°C (water vapor) and in solid form below 0°C (ice). What is it that determines which state the clan is in? The answer lies in the social behavior of the atoms and molecules. Let us take the H_2O molecule as an example.

1. *Above 100°C, water molecules move about a lot and travel at great speed, bouncing off each other or off obstacles in their path. The attractive force between each molecule is far too weak to arrest this movement when they pass close to one other: this is the gaseous state.*



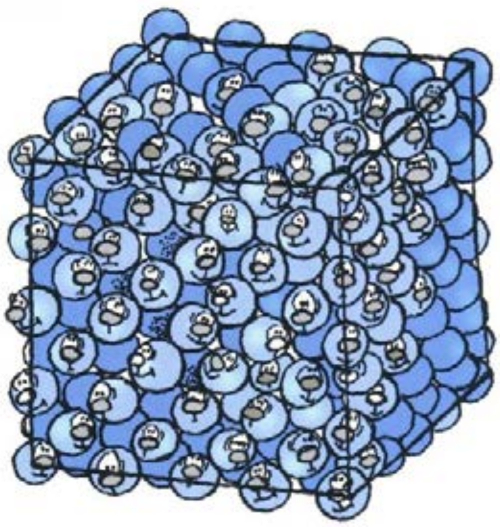
The gaseous state : the molecules travel at great speeds, bouncing off obstacles in their path.

1 A precious red type of corundum.

2 Physicists call this "three states of matter."

2. As the temperature drops, the molecules' speed decreases and the attractive force is now able to keep the molecules close to each other, but without forcing them to keep strict places: this is the liquid state. The molecules are constantly bustling about. They push and shove in a dense crowd of identical molecules, without trying too hard to escape. However, a container is needed to hold any reasonable volume as the force is only strong enough to hold small drops together.

The liquid state : the molecules a feebly attached to one another. A container is needed to hold the liquid.



Order is of paramount importance in the crystalline state.

3. As the temperature is further reduced, the molecules move around even less, and the attractive force is able to keep each molecule in a fixed place: this is the solid state. The molecules vibrate but cannot escape their designated places. The temperature must drop to nearly -273.2°C before they stop being agitated and become lethargic.

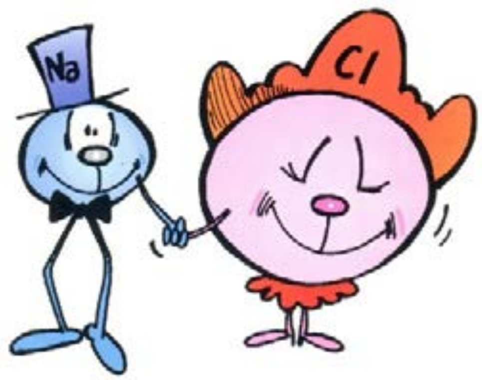
The Crystalline State

When atoms (or molecules) group together to form a solid, they do not park themselves in any old place but in very precise locations. These locations form a geometric configuration which repeats itself in all three directions. This ordered solid state is called the crystalline state.

Nearly all mineral substances are in the crystalline state. The only exceptions are glasses and plastics, neither of which have ordered atomic structures. These substances are said to be amorphous.

Upon examination of the NaCl couple, we notice that Mr. Sodium and Mrs. Chlorine are placed alternately along the edges of an imaginary cube. This structure is mirrored in the form of the NaCl (or table salt) crystals. You can check this by examining the crystals formed during the evaporation of salt water with a magnifying glass. The crystals formed are small cubes!

What is even more remarkable is that the very notion of marriage changes in the crystalline state. A super-community is formed from many identical marriages. The community is made up of billions and billions of atoms, with each type of atom in the same proportion as in the original molecule. Thus, one cm^3 of table salt contains 22,500 billion billion Chlorine atoms and an identical number of Sodium atoms.

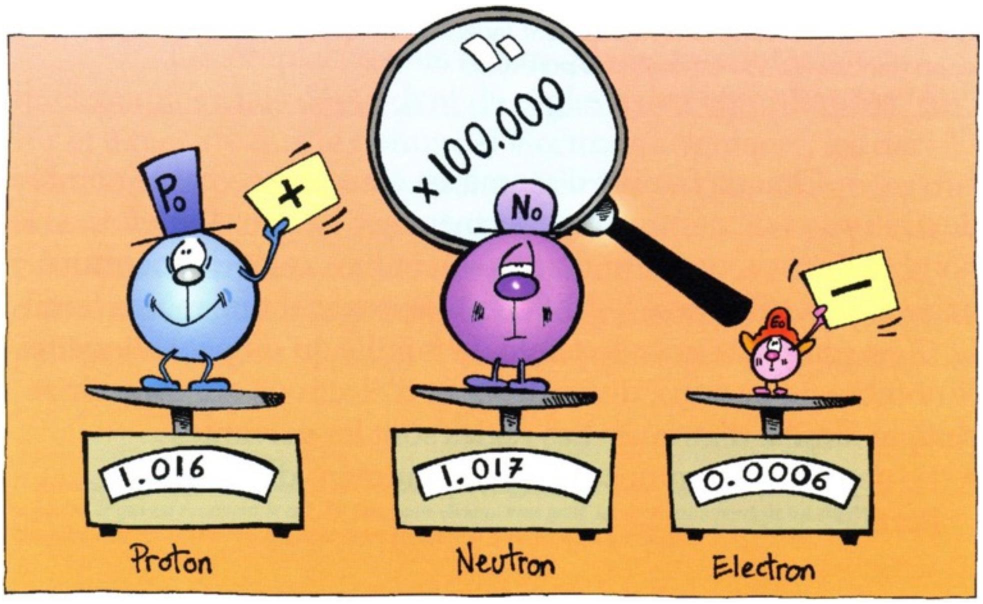


Halite (NaCl)

The Anatomy of Atoms

Various Organs in an Atom

Physicists have investigated the anatomy of atoms and have found that atoms are made up of electrons circling a nucleus. Electrons are small, extremely light particles with a mass of approximately 0.00054 grons. Each electron carries a negative electric charge. The electrons are very restless, and hurtle along a variety of orbits centered on a tiny nucleus, which is the heart of the atom. The electrons' orbits define the roughly spherical volume of the atom, and thus its size. The heart of the atom is made up of two types of particles, neutrons and protons. These particles are stuck together by a very powerful force to form a nucleus whose radius is approximately 100,000 times smaller than the atom's radius!



The main atomic organs.

The proton has masculine characteristics, the neutron is a confirmed bachelor and the tiny electron behaves like a Lady.

The fundamental constituents of an atom are thus:

- *The proton, which is a particle that carries a positive electric charge, and has a mass of approximately 1 gron. 602,200 million billion protons have a mass of 1 gram! This particle's mass is nearly equal to the mass of one hydrogen brother.*
- *The neutron, which is a particle with a mass approximately equal to a proton's, but does not carry an electric charge.*
- *The electron. This particle's mass is 1840 times less than that of a proton or neutron. An electron carries a negative charge. An unexcited atom has as many electrons as protons.*

Characteristics of Atoms's Constituents						
		Mass	Charge	State	Half-life	Decay products
Nucleus	Proton	1.016	+1	stable		
	Neutron	1.017	0	unstable[1]	18 min.	proton+electron[2]
Envelope	Electron	0.0006	-1	stable		

[1] Only unstable when 'free', i.e. not confined within a nucleus.

[2] A neutrino is also emitted. Neutrinos are nearly undetectable particles of much interest to astrophysicists. They belong to the strange world of particles.

Each family of atoms is characterized by the number of protons and neutrons in a member's nucleus. The number of protons is fixed but the number of neutrons varies slightly from isotope to isotope in the family. The photo of the atomic families can be used to find the number of protons, neutrons and electrons which characterize each family of atoms. The rules are:

- *The number of protons is equal to the family's registration number.*
- *The atomic mass is equal to the sum of the proton and neutron masses, which means that:*
- *The number of neutrons is equal to the atomic mass minus the registration number (atomic number).*

Thus, during Mr. Potassium's autopsy, we find 19 protons and 20 neutrons stuck together in the nucleus, and 19 electrons in the external envelope. These distinguishing marks are recorded in his passport!

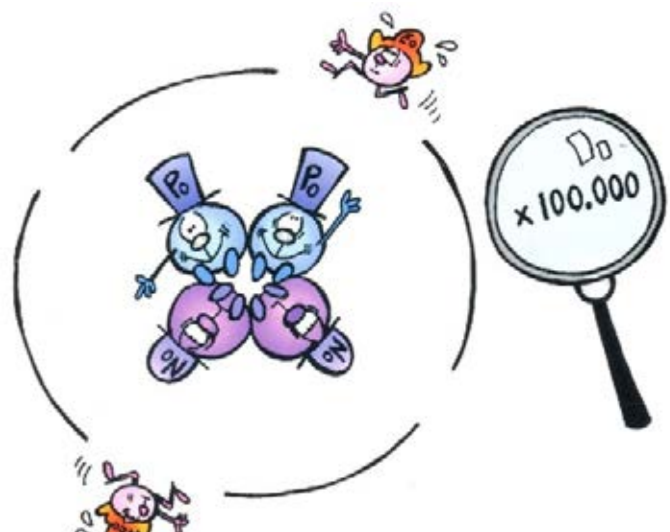
Mr. Potassium's autopsy reveals 19 protons, 20 neutrons and 19 electrons.

Electrons Determine the Social Behavior of Atoms

Electrons travel at breathtaking speed around many different orbits centered on the nucleus. There is equilibrium between the centrifugal force pushing electrons away from the nucleus, and the attractive force due to the protons.

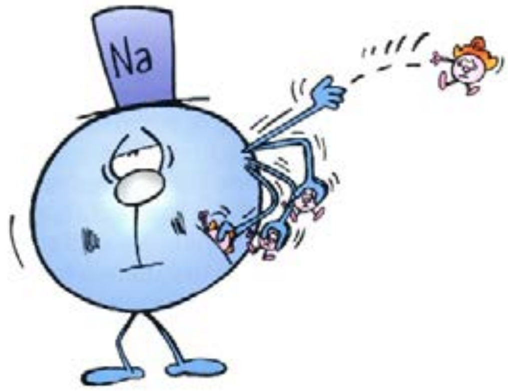
The orbits are arranged around the nucleus according to quite complicated rules. As more electrons are added, they occupy orbits that are further and further away from the nucleus. The outer electrons map out a sphere, which defines the atom's size.

We can group the various orbits according to their energy levels. Atoms apply the special number eight principle[1] to electrons in the outermost level. Atoms don't feel comfortable unless their outermost shell holds 8 electrons. Therefore, Mr. Sodium tries to rid himself of the one electron in his outer shell.



The structure of a Helium atom : The nucleus (magnified 100,000 times) is made up of two protons and two neutrons. Two electrons orbit the nucleus at great speed.

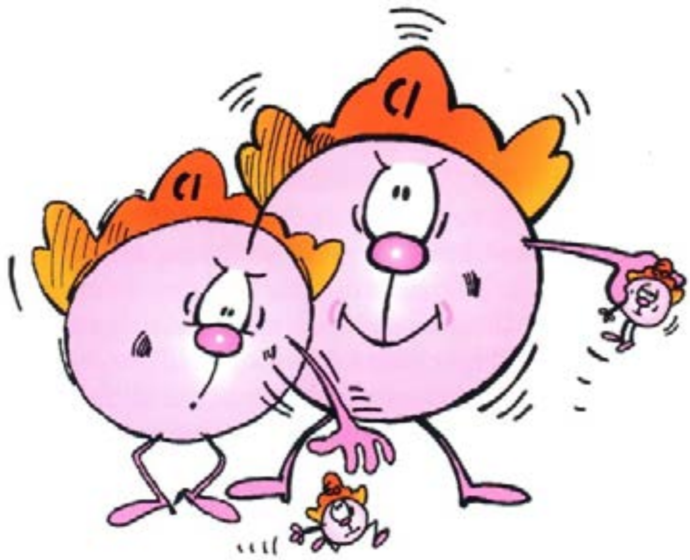
Disposing of this electron causes him to grow an arm and become a bit thinner! His colleague, Mr Silicon, wanders about with four arms because he has had to expel 4 electrons in order to adhere to the special eight principle. Mrs. Chlorine, who normally has seven in her outer shell, prefers to capture an extra electron to satisfy the number eight rule. As she does this she grows an arm. The oxygen sisters have to capture two electrons to add to the six in their outer shell, and grow two arms each. Mrs. Chlorine and Oxygen go up a few sizes[2] in the process!



Mr. Sodium expels an electron and takes a hand out of his pocket. He is a cation.

1 Messrs. Hydrogen and Helium are special cases; they worship the number 2!

2 Capturing electrons causes an atom to grow in size, expelling electrons causes an atom to decrease in size.



Atoms which capture electrons are Ladies. Chemists call them **anions.** They grow an arm for each electron captured, and go up a few sizes in the process.

Atoms which capture extra electrons have an excess negative charge equal to their number of arms. Chemists call them anions. They are the Ladies in the World of Atoms. Those which expel electrons gain an excess positive charge equal to their number of their number of arms. Chemists call them cations, and they are the Gents in the World of Atoms.

Therefore, it is the electrons which determine the atom's social behavior[1] , such as size, number of arms, sex, and interest in marriage.

Electrons are the 'particles' of electricity

Man always forces the copper brothers to remain celibate in an electric cable. They are forced to hold hands whilst the electrons flow freely amongst them. Man has invented many different types of electron pump such as the battery, dynamo and alternator, all of which force these free electrons to flow through the wire. This is electricity.

Therefore, an electric current is no more than the forced flow of electrons in a metallic conductor. It is a direct current if the flow is always in the same direction. An alternator causes the electrons to continually change direction giving rise to an alternating current! Thus, the electron can be considered to be the fundamental particle of electricity.

1 This includes all chemical properties as well as most of the physical properties.

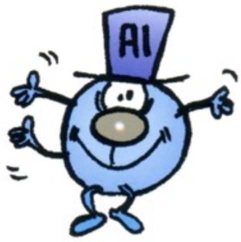
The nucleus, made up of protons and neutrons, is responsible for the atom's mass. It is also at the heart of two genetic illnesses which affect some atomic families.

Batteries are 'electron pumps'. They force the flow of free electrons in metals.

The Number 8, Ladies, Gents and the Rest

There is a close relationship between an atom's need to expel or capture electrons and its behavior. This relationship is summarized in the following rules:

1. *Atoms that expel electrons are Gents. They grow an arm for each electron expelled (chemists call them cations).*
2. *Atoms that capture electrons are Ladies. They have an arm for each electron captured (chemists call them anions).*
3. *Atoms which neither need to capture nor expel electrons to satisfy the number 8 rule are the confirmed bachelors. They are the noble gases, and they do not have any arms.*
4. *Some atoms are in two minds as to whether they should capture or expel electrons. Sometimes they are ladies, and sometimes they are gents, according to the situation they have adopted to satisfy the number 8 rule. These a toms are androgynous.*

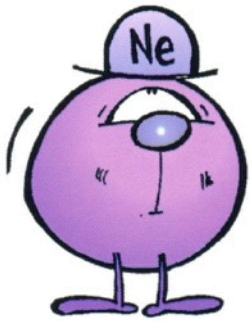


Mr. Aluminum
is a cation.

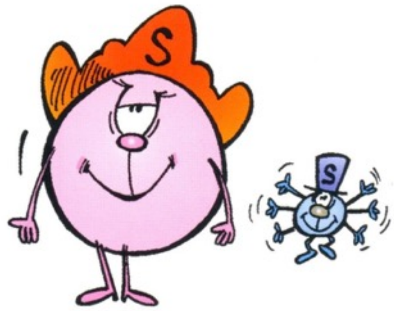
Mrs Oxygen is an anion

The Sulphur family falls into this last category. Each individual has 6 electrons in its outer shell when unexcited. The members of the family often hesitate between the following two options:

- either capture 2 extra electrons in order to satisfy the number 8 rule, and transform into large Ladies with two arms each.
- or expel 6 electrons, which transforms them into small Gents with 6 arms each.



Neither a cation nor an anion, Neon is a recluse.



Sometimes an anion, sometimes a cation, Mr. (or Mrs.) Sulphur is androgynous.

The mass of electrons in an atom never exceeds 0.05% of the atom's total mass. This means that virtually all the atom's mass comes from the protons and neutrons in the nucleus. This nucleus has a radius nearly 100,000 times smaller than the atom's.

Families of atoms are characterized by their number of protons. Each member of the Carbon family always has 6 protons, each member of the Copper family 29 protons, and each member of the Uranium family 92 protons. These numbers are the atoms' respective registration or atomic numbers.

Protons are always accompanied by neutrons except in the case of little Mr. Hydrogen, who has none. All the light families of atoms either have the same number or slightly more neutrons than protons. Heavier atoms can have up to one and a half times as many neutrons as protons.

There are some circumstances in which a neutron[1] can transform into a proton after having expelled an electron[2]. This is not one of the electrons circling the nucleus but a product of the decay of the neutron. We shall discuss this type of behavior later.

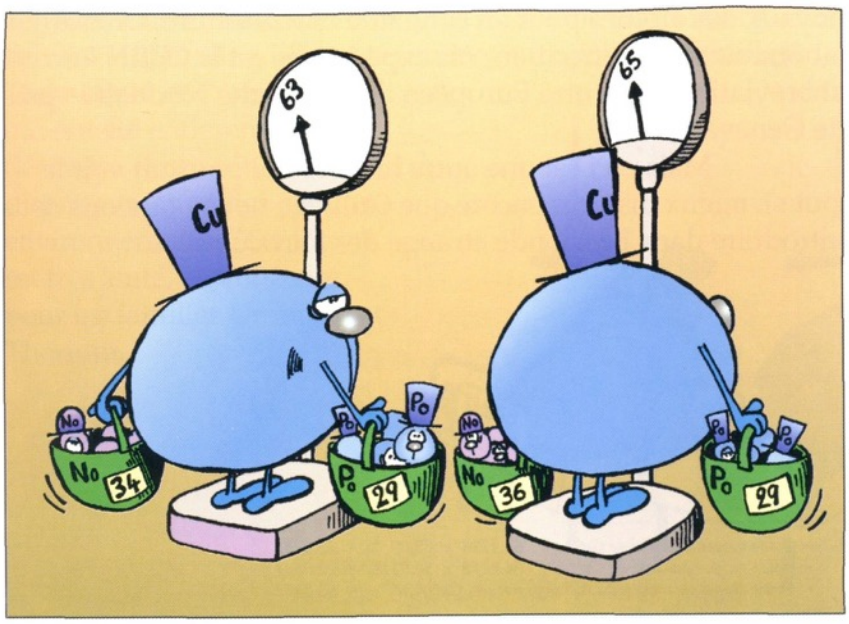
1 The neutron must be free, i.e. not confined within a nucleus.

2 A neutrino is also emitted. These nearly undetectable particles are of great interest to astrophysicists.

Isotopes

The number of neutrons can vary from individual to individual in some families. For example, all the members of the Copper family have 29 protons, but some possess 34 neutrons and others 36. As far as their chemical properties go, they are identical. What differs is their atomic mass. Some Copper atoms have an atomic mass of 63 grons and others 65 grons. These are the Copper family's two isotopes, and they are called Cu^{63} and Cu^{65}. The most well known isotopes are Carbon 14 (C^{14}), which is used to date some prehistoric objects, Cobalt 60 (Co^{60}), which is used for medical purposes, and Uranium 235 (U^{235}), which is used in conventional nuclear reactors.

Naturally occurring Copper is composed of 69% of the Cu^{63} isotope and 31% for the Cu^{65} isotope. Copper's atomic mass on the Periodic Table is the weighted average of the masses of Cu^{63} and Cu^{65}. This is why the atomic mass recorded in their passport is not a whole number but 63.54 grons[1] .



Some members of the Copper family have slightly different masses; they have a deficit of neutrons.

Isotopes are found in many families of atoms; but in most cases, there is one strongly dominant isotope, while the others are scarce, or very rare.

1 'Weighted' mass of Cu63 : 62.9298 grons x 69.09 % = 43.4781 grons
'Weighted' mass of Cu65 : 64.9278 grons x 30.91 % = 20.0691 grons
'Weighted' mass of naturally occurring Cu63/Cu65 = 63.5473 grons.

Further into the Nucleus

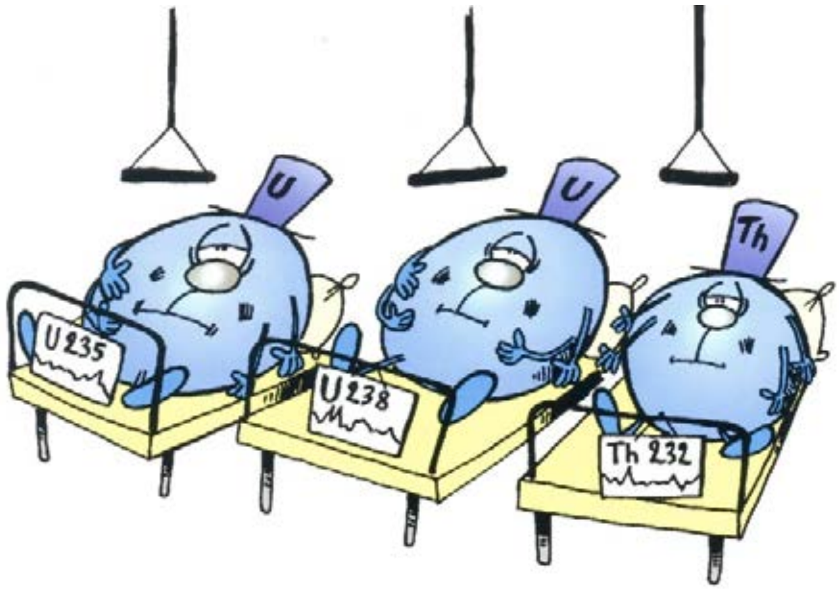
The anatomists in the Strange World of Atoms limit themselves to describing the electrons, protons and neutrons. However, Man's curiosity is driving him to discover the constituents of even these particles. Atomic nuclei are dissected in high energy experiments in order to elucidate their structure. One of the facilities where these experiments are performed is CERN, which stands for Centre European pour la Nuclear Research, and is situated near Geneva.

Perhaps if we become even more curious than Gulliver, this story may be told in the Strange World of Particles !

Radioactive Decay
A Genetic Illness of Atoms

Some atomic families suffer from a genetic illness which affects their nuclei (neutrons and protons). Physicists call this illness radioactive decay.

The Uranium and Thorium families in particular are prey to the disease, as well as some other families of lesser importance. A few rare isotopes from well known families are also infected. We shall discuss them later on in view of the interest Man has in them. The virulence of this disease varies from family to family. It was devastating for the Technetium and Promethium families, which were totally decimated and no trace of them remains today. The opposite is true for the Uranium and Thorium families, for whom the disease is much less virulent.



The Uranium and Thorium families in particular are prey to the disease.

The Sad Story of the Uranium Family

The Uranium family's plight is typical, and we shall discuss it at some length. Every member of this family has 92 protons. The majority of them (99.3%) have 146 neutrons: this is ^{238}U. The rest (0.7%) only have 143: this is ^{235}U. Both isotopes suffer from radioactive decay, but the virulence of the disease is different for each one.

Virulence of the Disease

It is not possible to predict how virulent the disease will be for a particular atom. On the other hand, it is statistically possible to predict the behavior of a population of atoms. Radioactive decay strikes randomly within the population. In the Strange World of Atoms, the half-life is the time it takes for half the atoms in the population to decay. We can diagnose this disease as responsible for the disappearance of:

- *half of the population of ^{238}U every 4.5 thousand million years,*
- *half of the population of ^{235}U every 710 million years[1] .*

The spread of the epidemic is interesting in itself. At any given moment, the members of the ^{238}U and ^{235}U populations know that half their number will suffer from the disease over the next 4.5 thousand million years and 710 million years respectively.

The Symptoms

Let us consider ^{238}U . The first signs are sudden convulsions followed by vomiting a variety of objects from the nucleus. These objects are the constituents of radioactivity, and are:

- *"alpha" [α] particles, composed of two protons and two neutrons[1] .*
- *"beta" [β] particles, which are electrons (from the decays of neutrons into protons).*
- *"Gamma" [γ] radiation, which are very energetic X-rays.*

These emissions[2] accompany the transformation of the poor ^{238}U into a marginal member of another family (a rare and unstable isotope). After two further crises and transformations into several other families, the atom finally transforms into ^{206}Pb, a stable isotope of the Lead family.

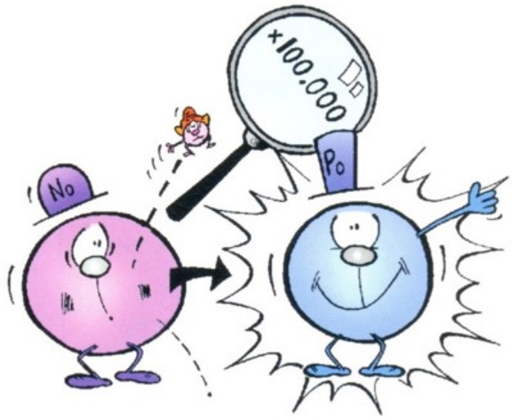
An α particle is made up of two protons and two neutrons. It is a Helium atom's nucleus.

1 ^{235}U disappears at a much faster rate than ^{238}U. Today, ^{235}U only accounts for 0.7% of natural Uranium. However, this proportion was 14% when the Solar System was formed, 4.6 thousand million years ago.

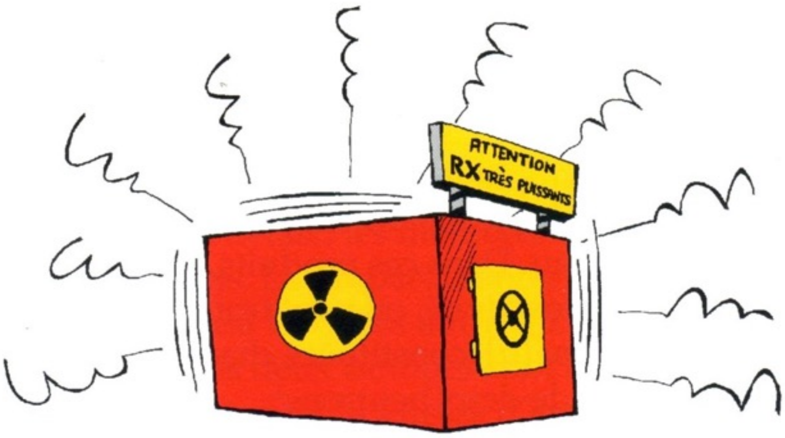
1 Note that an particle is a Helium (He4) nucleus.

3 The emission of these particles and the rays constitute 'radioactivity'. Living cells are very vulnerable to radioactivity which can cause a variety of illnesses, including cancer.

A particle α is an electron...
...from the decay of a neutron to a proton.



A neutrino is also emitted, which
is still a very mysterious particle.



γ rays are electromagnetic radiation of a very short wavelength. They are extremely penetrating X-rays.

Pathology of Radioactive Decay

The emission of a particle (2 protons and 2 neutrons) decreases the sick atom's mass by 4 atomic mass units, and reduces the atom's atomic number by two in the Periodic Table[1] .

The emission of a particle (an electron from the decay of a neutron into a proton) causes no detectable change in mass, but one of the neutrons changes into a proton. The sick atom increases its atomic number by one and moves forward one place in the Periodic Table.

The loss of a particle is accompanied by a nasty fever that leads to the emission of radiation and heat.

1 Or 'Photograph of Families'.

A high temperature and the expulsion of a particle are the first signs of the illness.

The first symptom of poor ^{238}U 's disease is the loss of an particle. He loses 4 atomic mass units and his mass drops to 234 grons. As there are two protons in an particle, his atomic number is reduced by two. This, he transforms into a member of the Thorium family (atomic number 90). However, he doesn't become a normal member of the Thorium family, but a rare and unstable isotope, ^{234}Th. This poor ^{234}Th very quickly loses two particles and transforms into Protactinium 234 (^{234}Th) for a few hours, and then into ^{234}U (an extremely rare isotope of the Uranium family. He will change into a dozen other families during the course of the disease. These are described in ^{238}U 's illness sheet.

Diagnose

Dr. Marie Sklodowska

Patient's name : Uranium

Symbol : ^{238}U

Number of protons : 92

Number of neutrons : 146

Symptoms : Indigestion, dizziness, nausea

Diagnosis : congenital radioactive decay with a long incubation period. (4.5 thousand million year)

Element	Symbol	Mass	Half-life	Radiation	Symptoms
Uranium	^{238}U	238		α	loses a He nucleus
Thorium	^{234}Th	234	24 d.	β	expels an electron
Protactinium	^{234}Pa	234	6 h. 45 m.	β	expels an electron
Uranium	^{234}U	234	250,000 y.	α	loses a He nucleus
Thorium	^{230}Th	230	80,000 y.	α	loses a He nucleus
Radium	^{226}Ra	226	1600 y.	α	loses a He nucleus
Radon	^{222}Rn	222	4 d.	α	loses a He nucleus
Polonium	^{218}Po	218	3 m.	α	loses a He nucleus
Lead	^{214}Pb	214	27 m.	β	loses a He nucleus
Bismuth	^{214}Bi	214	20 m.	β	expels an electron
Polonium	^{214}Po	214	1 second	α	loses a He nucleus
Lead	^{214}Pb	214	21 y.	β	expels an electron
Bismuth	^{210}Bi	210	5 d.	β	expels an electron
Polonium	^{210}Po	210	138 d.	α	loses a He nucleus
Lead	^{206}Pb	206	stable		

The final decay leads to an atom of the lead family: ^{206}Pb. This isotope is vaccinated against the disease, is stable and will not change with the passage of time. To recap: The disease causes Mr. ^{238}U to shed 8 particles and 6 particles, during which he temporarily assumes the identity of other elements, before he finally ends up as a stable state of Lead 206 (^{206}Pb).

Man has tried in vain to cure atoms of this disease. However, all research into the disease indicates that it is neither possible to lengthen nor shorten the disease's term. The two natural Uranium family isotopes will inescapably change into various isotopes of Lead:

- ^{238}U decays to ^{206}Pb with a half-life of 4.5 thousand million years,
- ^{235}U decays to ^{207}Pb with a half-life of 710 million years.

The Thorium family is another important family that suffers from the same sort of disease.

- ^{232}Th decays to ^{208}Pb with a half-life of 14 thousand million years.

After being ill for a long time, the members of the Uranium and Thorium families are changed into members of the Lead family.

Other Families are also Afflicted by the Disease

Some families that suffered from the disease have now disappeared. Let us consider the Technetium and Promethium families whom we mentioned earlier. They both existed when the Solar System was formed. However, the disease was particularly virulent, and Technetium had a half-life of 1.5 million years, Promethium a half-life of two and a half years.

- *^{98}Tc decays to ^{98}Ru with a half-life of 1.5 million years.*
- *^{147}Pm decays to ^{147}Sm with a half-life of 2.5 years.*

The Radium family is another interesting case. This family should have disappeared a long time ago as it suffers from a virulent strain of the disease:

- *^{226}Ra decays to ^{206}Pb with a half-life of 1600 years.*

However, members of this family survive as they are one of the products in the decay of ^{238}U! The decay of ^{238}U into members of the Radium family gives this family a fleeting presence in the World of Atoms, as those members that decay are replaced by new ones! There are other similar cases, but they shall not be discussed here.

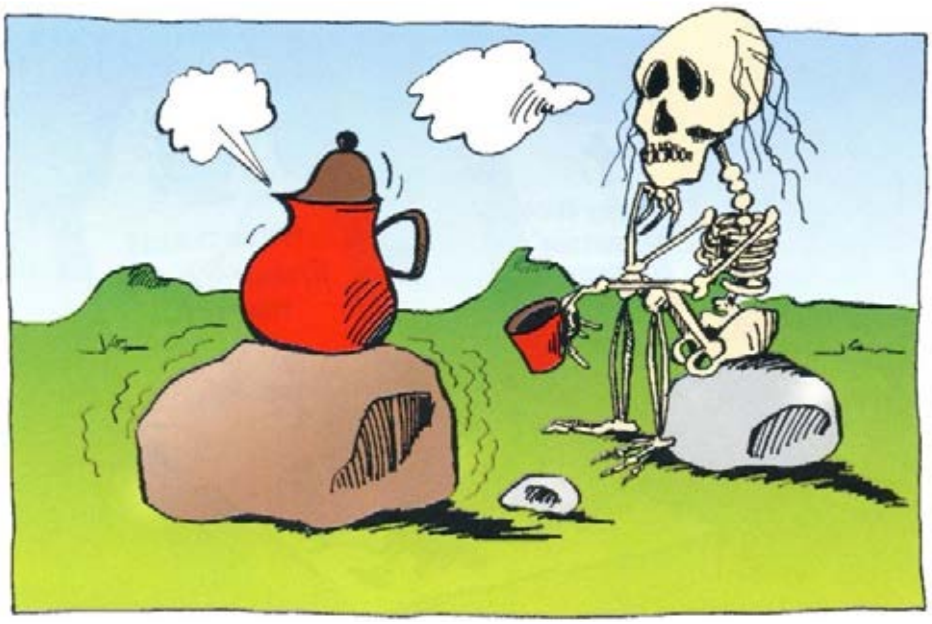
Virulent radioactive decay has caused two families to disappear prematurely.

Geologists make good use of this Disease

For a long time, Geologists have known that the temperature of rocks increases as you move deeper into the Earth. The average increase in temperature is 3°C every 100 meters. The temperature increases more rapidly in volcanic regions, and more slowly within very old rocks. These increases in temperature occur because there is a heat source at the centre of the Earth. Research has shown that much of this heat is due to the fever that accompanies the decay of Messrs. Uranium and Thorium, who are always present in small quantities in rocks made of granite.

Thus, a granite cube of side 30 cm gives out enough heat to brew 6000 liters of boiling tea...but you would have to wait one thousand million years!

This seems a long time, but Geologists are used to counting in thousands of millions of years and hundreds of cubic kilometers! On these scales, a cubic kilometer of granite gives out enough heat to boil 600 liters of water a day! This heat flux is responsible for volcanic activity, drives continental drift and the formation of mountain ranges, and indirectly causes the process of metamorphism in rocks.



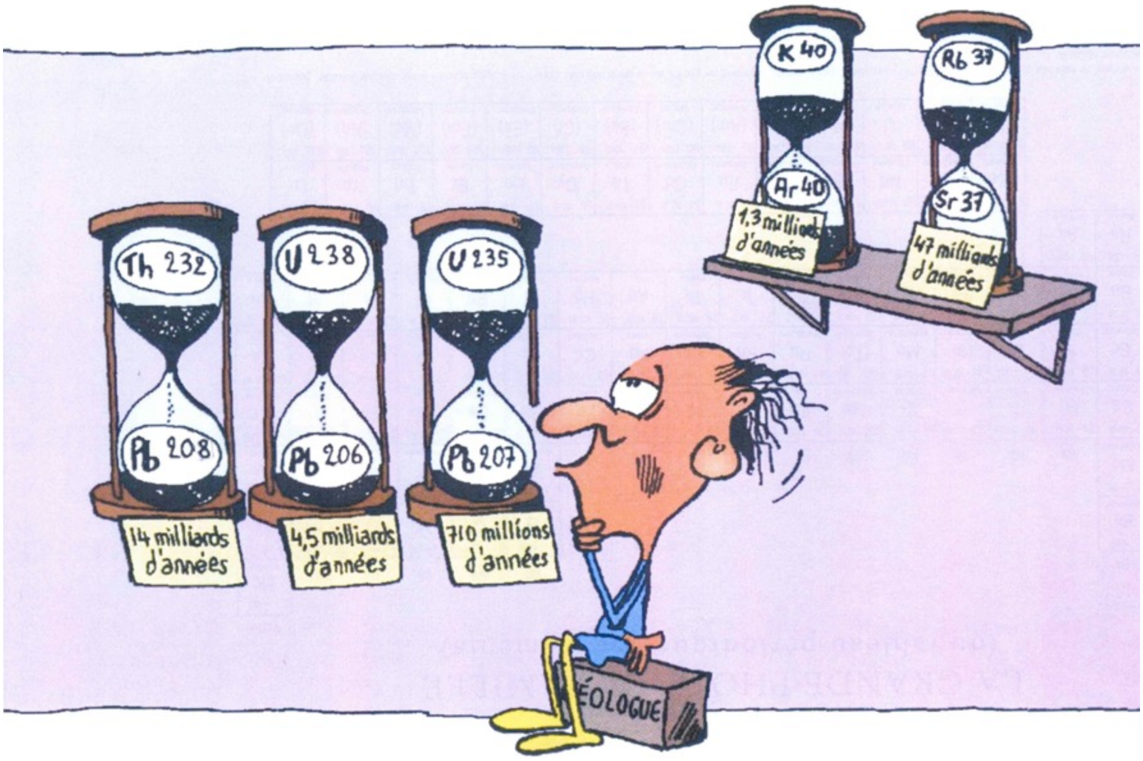
The intense fever caused by the disease generates heat. The level of radioactivity in a 100 kg block of granite is sufficient to boil a liter of water…

...if you wait 200,000 years!

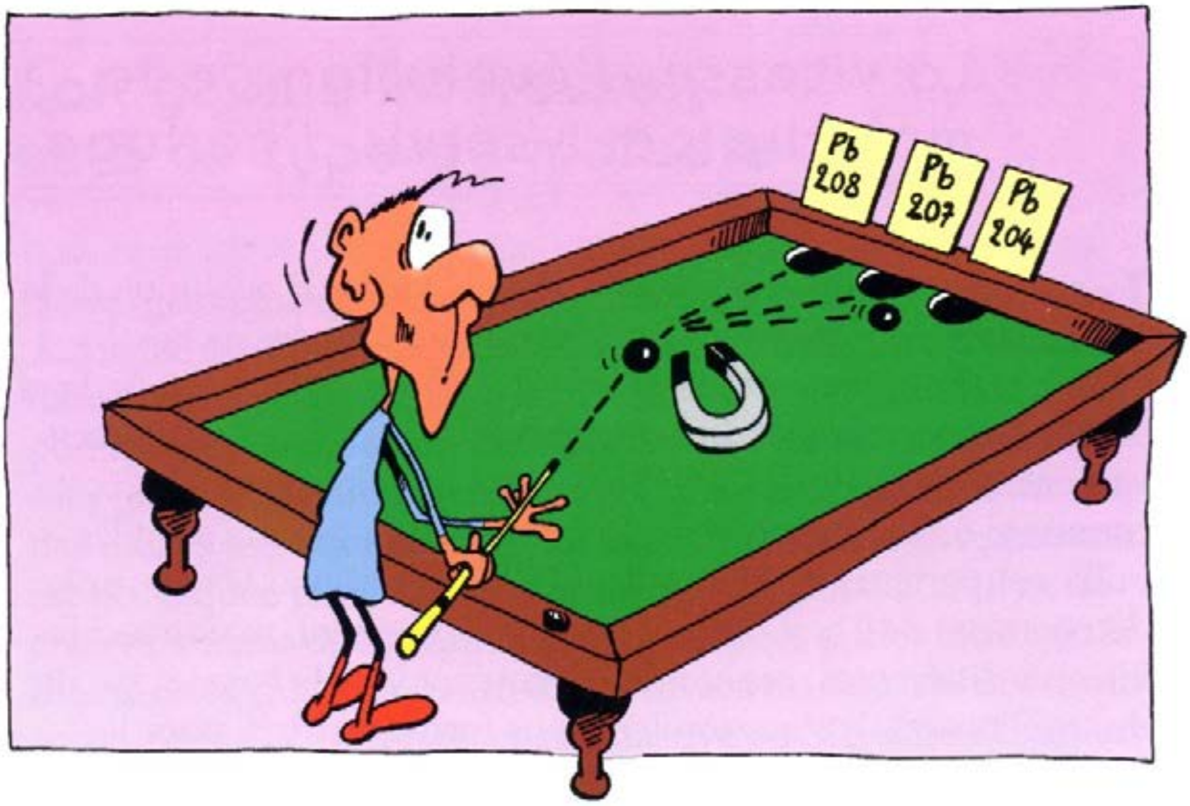
Radioactive Decay can be used as a Clock

Geologists have found that they can measure the age of minerals and rocks by measuring the speed of radioactive decay of some of the elements in the rocks. They note that the ^{238}U, ^{235}U and ^{232}Th that are locked in the rock when it is formed, decay to ^{206}Pb, ^{207}Pb and ^{208}Pb respectively, according to well known rules. It is as if the rock contains three hourglasses, the first filled with ^{238}U, the second with ^{235}U, and the third with ^{232}Th. The atoms flow through each hourglass at slow, but slightly different speeds, and accumulate in the bottom of each hourglass as ^{206}Pb, ^{207}Pb and ^{208}Pb respectively.

The rate of flow in each hourglass is known as it is just the atoms' decay time. Thus, it is possible to find the age of the rock if we can measure the relative quantities of these different isotopes in the rock.We can't use chemistry to distinguish between an element's different isotopes. We must use a physical method called mass spectroscopy. Atoms are accelerated inside the mass spectrometer and then deflected by a powerful magnet. The angle of deviation depends on each isotope. A detector counts the atoms of each isotope, and allows their relative quantities to be deduced.



The constant decay time of the disease can be used as a clock.



A mass spectrometer can separate the isotopes of a single family.

Unfortunately, there isn't always enough Uranium and Thorium in minerals and rocks for this method to work. So, geologists have investigated some marginal members of well known families (some of their rare isotopes), such as Messrs. Potassium 40 (^{40}K), Rubidium 87 (^{87}Rb) and Carbon 14 (^{14}C), which also suffer from radioactive decay as follows:

- *^{40}K decays to ^{40}Ca or ^{40}Ar (Argon[1]) with a half-life of 1.3 thousand million years,*
- *^{87}Rb decays to ^{87}Sr (Strontium) with a half-life of 47 thousand million years,*
- *^{14}C decays to ^{14}N (Nitrogen) with a half-life of 5600 years.*

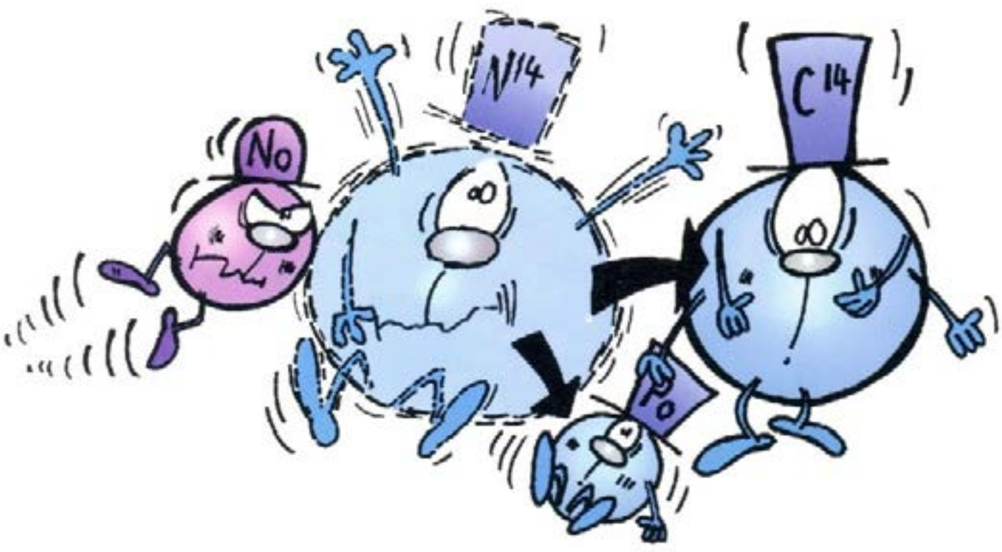
These elements are present in most rocks. Dating methods analogous to those described above have been applied to these isotopes.

1 *^{40}K mainly decays to ^{40}Ca, but it does sometimes decay to ^{40}Ar. The latter decay is of interest to geologists.*

Father Carbon

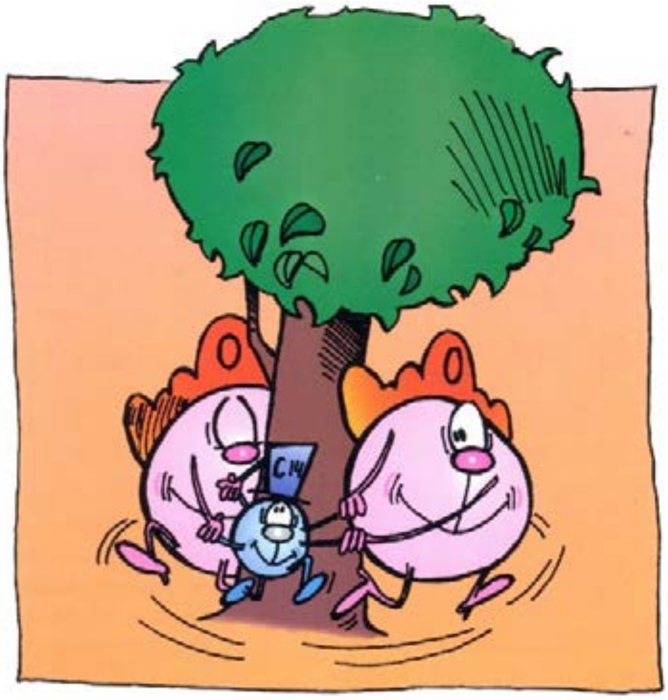
Everybody has heard of Father Carbon 14 (^{14}C). He actually seeks asylum in the Carbon family. Instead of being composed of 6 protons and 6 neutrons like all the members of the ^{12}C family, he has two extra neutrons that increase his mass from 12 to 14 grons. He is found in the upper atmosphere, where cosmic rays[1] are abundant. Cosmic rays are neutron generators, and sometimes one of these neutrons will collide with a Nitrogen nucleus, expel a proton and take its place. The poor Nitrogen transforms into a Carbon atom (^{14}C), without any change in mass. However, the ^{14}C atom is ill, and suffers from radioactive decay with a half life of 5600 years. He immediately marries two oxygen sisters in the upper atmosphere to form a CO_2 molecule.

The number of ^{14}C brothers that disappear from the atmosphere due to illness is compensated by new arrivals from the transformation of Nitrogen brothers. The proportion of ^{14}C in the atmosphere thus remains constant.



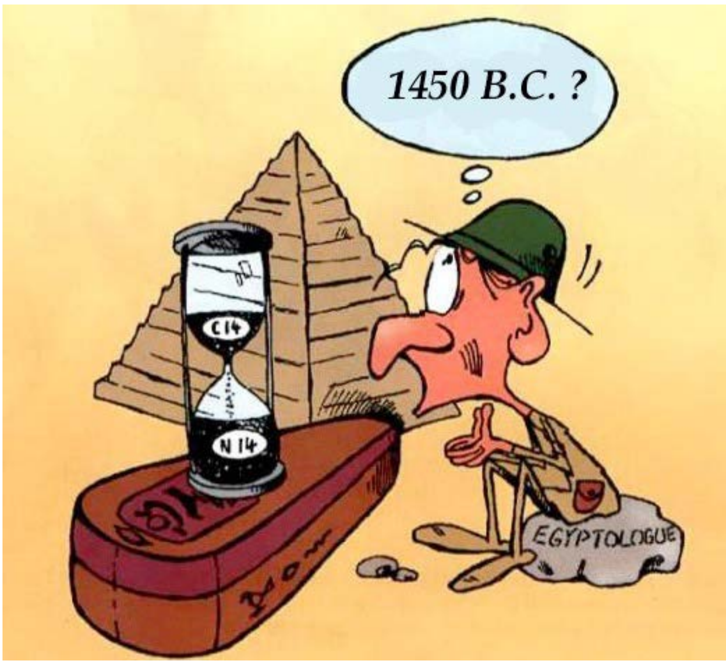
Carbon 14 is the product of the decay of a Nitrogen atom that has accidentally absorbed an errant neutron.

1 Cosmic rays are atomic nuclei, chiefly composed of protons, that arrive at Earth from interstellar space. 700,000 of these particles pass through every person every second. The interactions between these protons and atoms in the atmosphere produce 2.3 neutrons per second per cm^2.



He marries two Oxygen sisters and assumes the name carbon dioxide. This molecule can be absorbed by plants.

Vegetation absorbs CO_2, and the same $^{14}C/^{12}C$ proportion is found in wood as in the atmosphere. But, after a tree is felled it no longer absorbs CO_2 from the atmosphere. Inside the dead wood, the ^{14}C brothers slowly disappear, and are not replaced. So, a piece of wood from a Pharaoh's tomb contains a far lower $^{14}C/^{12}C$ proportion than a tree that has recently been felled. As the half life of the ^{14}C isotope is 5600 years, this type of clock is particularly useful to archaeologists, and allows them to date wood between 200 and 20,000 years old.



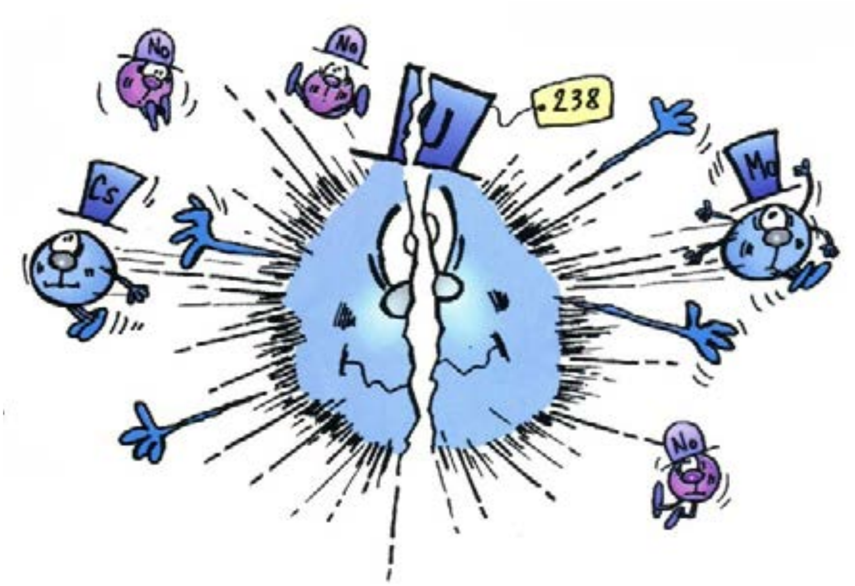
Carbon 14 is very useful to archaeologists

Another Genetic Illness : Spontaneous Fission of Atoms

Spontaneous Atomic Fission

The Uranium and Thorium families suffer from a second genetic illness called spontaneous fission. Fortunately, in general this disease is much rarer than radioactive decay. The disease causes the infected atom's nucleus to split violently apart, and is accompanied by a terrible fever. The two fragments are expelled at great speed away from one another, and finally form two smaller atoms.

Luckily for those afflicted by the disease, the incubation period is very long, running to thousands of billions of years. This means that the atoms are a million times more likely to disappear due to common radioactive decay than they are from spontaneous fission.



Uranium 238 can also suffer from spontaneous fission.
Fortunately, this disease is much rarer than radioactive decay.

Induced Atomic Fission

The virus is a neutron.

This type of fission is only well known because Man has found that it gives out an immense amount of energy and that it can be controlled. He has managed to infect some atomic families with this terrible disease, in particular the various members of the Uranium family.

The virus used is a neutron. The ^{235}U isotope can absorb a low speed neutron (a 'slow' or 'thermal' neutron).

Pathology of the Disease

Weighed down by a neutron, the victim becomes very unstable…

After the neutron has been injected, the poor ^{235}U increases in mass by 1 gron and transforms into a heavyweight of the Uranium family, ^{236}U. This atom cannot hold all the particles in its nucleus together. Just as a drop of water that has grown too large splits into two smaller drops, the poor ^{236}U bursts into two smaller atoms and expels two or three fast neutrons.

...and then splits into two smaller atoms, liberating several neutrons in the process. This brutal disease gives out lots of energy

An Incomprehensible Mass Deficit

If we were to weigh the two new atoms and the 2 or 3 neutrons, we would be surprised to find that their total mass does not add up to the 236 grons of the original ^{236}U. Therefore, during the course of the fission a small amount of matter has disappeared. Thanks to Einstein, we know that this matter has been transformed into energy according to the famous equation:

$$E = m \times c^2$$

This states that:

The energy [E] is equal to the mass loss [m]
multiplied by the speed of light squared [c^2].

This illness releases about 200 million times more energy per burst atom than can be produced in the most violent chemical reaction! Therefore, it is a good way of generating energy

A small mass deficit accompanies the disease

But What Becomes of the Neutrons?

By injecting a neutron into the nucleus of a poor ^{235}U, fission is induced, energy liberated, and 2 or 3 neutrons are created[1]. What happens to them? They are ejected from the material at high speed. As they are neutral, they are not affected by the electrons they might run into and they must collide head on with a ^{235}U nucleus to induce another fission. However, the target is very small and the probability of colliding with a Uranium nucleus to break it in two is very low. Furthermore, the neutrons themselves suffer from devastating radioactive decay that quickly transforms them into a proton and an electron[2] .

We can Turn the Odds in Our Favour

Man shrewdly knows how to change the probability of a neutron inducing the fission of a U^{235}, using a combination of two methods:

1. An increase in the concentration of ^{235}U atoms.

Natural uranium only contains 0.7% ^{235}U as opposed to 99.3% ^{238}U. So the ^{235}U proportion is enriched in expensive factories, which increases the number of targets per unit volume. For today's uses, the ^{235}U concentration is enriched to about 3%. This can be increased if so desired. However, only the military needs further enriched Uranium for some very special uses!

2. Slowing the neutrons down.

The neutrons produced by fission reactions travel too fast to latch onto a ^{235}U in their path. By using a moderator, the neutrons are slowed down and made more 'virulent'. By placing light atoms such as Messrs. Hydrogen, Beryllium or Carbon in the path of the neutrons, successive collisions with these light atoms increases their speed whilst slowing the neutrons down.

By combining these two methods the efficiency of the neutrons is increased. It is now possible to create and maintain a chain reaction, and if this can be controlled we can also make a nuclear reactor!

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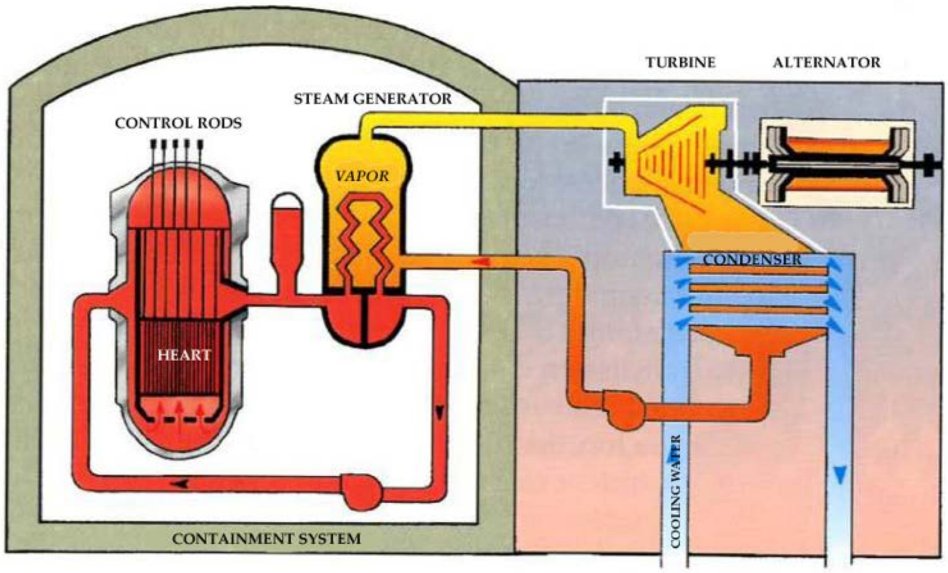
1 Physicists call them prompt neutrons.

2 One again we must also mention that a neutrino is emitted. This nearly undetectable particle carries away some of the energy liberated during the fission.



Simplified schematic of a nuclear reactor.

How does a Nuclear Reactor Work?

Nuclear reactors differ from one another in the type of fuel they burn, by the type of moderator they employ, and by the type of heat exchanger they use between the reactor and the turbines. However, the principle on which they work is much the same.

The fuel consists of Uranium rods enriched to about 3% ^{235}U. These rods are inserted into water which slows neutrons from the fission of ^{236}U atoms down (thanks to Mr. Hydrogen). These neutrons can now induce fission in other ^{235}U atoms. These fission reactions give out a gigantic amount of heat, which is used to generate steam to run the turbines which in turn generate electricity. In this set up, water plays the role of both the moderator and the coolant, transferring energy to the turbines.

The reaction is stopped by inserting Boron or Cadmium rods into the reactor that absorb neutrons and thus interrupt the reaction.

But where is the Nuclear Waste?

Going back to the poor ^{235}U's disease, we saw that after having absorbed a neutron and transforming into ^{236}U he split up into two lighter atoms. What are these atoms? Experiments show that each ^{236}U can split up differently, yielding two fission fragments whose masses are between 72 and 166 grons. These fragments consist of atoms from over 30 well known families in the World of Atoms.

However, they all have the unfortunate property of having far more neutrons than the normal members of their families; they are all heavy isotopes. They do not occur naturally, and are only produced during induced fission.

They are all unstable and suffer from radioactive decay[1]. It is these atoms that form the undesirable nuclear waste! The surplus neutrons quickly decay into protons and -particles (electrons), giving out heat and -rays in the process.

Some fission products decay to their stable states in minutes, some in hours and some in days. A few are highly radioactive but they do not suffer from the disease for a long time. Others take thousands of years before their activity diminishes appreciably. They are only weakly radioactive, but they remain that way for a very long time!

The pace of radioactive decay cannot be altered. Heat, which must be removed, continues to be released from the spent fuel for a long time after the reactor has been stopped. This is why the spent fuel is kept for several months or years in a water tank before it is reprocessed.

Nuclear waste is not only radioactive, it also gives out quite a lot of heat.

What if the Reaction gets out of Control?

Neutrons move at high speeds and, due to their lack of electric charge, pass unscathed through the clouds of electrons around nuclei. They must collide with a Uranium atom's nucleus in order to be absorbed. Now the nuclei are millions of times smaller than the whole atoms, so the neutrons can pass through a certain amount of Uranium without running into a nucleus, and escape from the material. To increase the probability of collisions, the concentration of ^{235}U in natural Uranium must be increased, or the neutrons slowed down, or a combination of both.

If we were able to assemble a large enough mass of ^{235}U, uncontaminated by its ^{238}U brothers (100% enrichment), we could start a chain reaction. As soon as one atom undergoes spontaneous fission the resultant neutrons will cause the neighboring atoms to undergo fission, which will liberate more neutrons to cause even more fission. The number of fission reactions increases at an incredible pace, giving out a gigantic amount of energy in a very short time: this is a nuclear explosion!

Luckily, these conditions are never fulfilled in a nuclear reactor so there is no chance of a nuclear explosion!

The minimum mass required to sustain a chain reaction is called the critical mass. This mass is about 20 kg for ^{235}U. We now have all the necessary pieces to make a nuclear bomb.

1 Some fission reactions give rise to delayed neutrons, such as Kr87 = Kr86 + n0. Although few in number, these neutrons are vital to the control of the chain reaction.

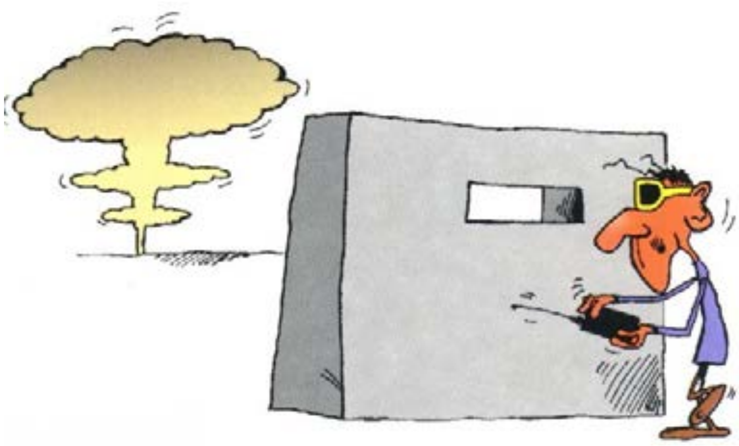
Recipe for making an Atomic Bomb

1. Take two pieces of ^{235}U whose masses add up to slightly more than one critical mass. Keep them well separated.
2. Place the two pieces of ^{235}U at opposite ends of a short cylinder.
3. Set up a remote control detonation system that forces the two pieces of ^{235}U rapidly together with the aid of a small explosive.
4. Retreat to a sensible distance.
5. Detonate!

Take two pieces of ^{235}U whose masses add up to slightly more than one critical mass. Keep them well separated.

Place the two pieces of ^{235}U at opposite ends of a short cylinder. Set up a remote control detonation system that forces the two pieces of ^{235}U rapidly together with the aid of a small explosive.

Retreat to a sensible distance



Detonate !

Fortunately it is not that easy

This recipe is very crude, and I advise you not to try it as things are (luckily) far more complicated in practice. Firstly, step [1] of the recipe is difficult to perform because it takes sophisticated technology, huge factories, and an enormous amount of energy to produce enough fissile material. Nobody can discretely produce highly enriched ^{235}U. The 3rd step is equally tricky to perform because a chain reaction will only occur if the two fragments of ^{235}U are brought together very quickly. Indeed, fission starts whilst the two ^{235}U fragments are being brought together, and enough heat is given out to melt and vaporize the explosive before a critical mass is achieved.

Conclusion

During the course of his experiments on induced fission, Man has managed to create new families of atoms. The best known of these is Plutonium (^{242}Pu) which has an atomic number of 94, and can be used to make atomic bombs. There are a further dozen or so families whose names can be found on the photograph of families (Periodic Table) under Uranium's position. However, all of them suffer from radioactive decay, with generally short incubation periods, and short life-expectancies.

All the methods described above generate a large number of unstable isotopes of well-known atomic families. We have already discussed them in the context of nuclear waste.

Although these isotopes have become cumbersome and we now need to find new solutions for their storage, some of them are used in a wide range of useful applications. The rays emitted by these isotopes are really extremely penetrating X-rays. They can be used to X-ray metallic structures to check for faults. They are also used to irradiate cancer tumors. In another medical application, a small amount of radioactive iodine is injected into a patient and its circulation within the body detected.

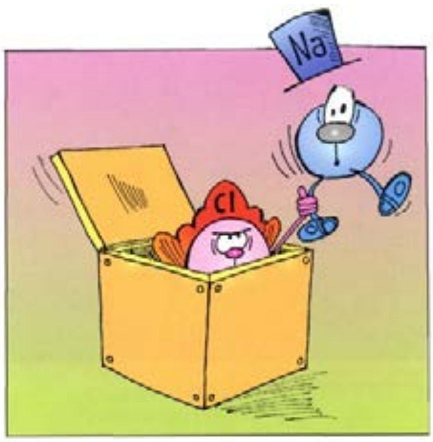
Thus, Man's exploration of the strange World of Atoms has lead to the development of chemistry, whose applications have become omnipresent in our environment. The same is true for nuclear physics and astrophysics, which give us a better and better understanding of the basic laws that govern the World of Atoms, and our Universe.

Glossary

Alpha Particle (α)	*A positively charged particle with a mass of 4 grons, made up of two protons and two neutrons. A product of some radioactive decays. An particle is a ^{4}He nucleus.*
Androgynous atom	*An atom that, depending on the particular circumstance, is either a Lady or a Gent (anion or cation)*
Ångström (Å)	*A measurement of length equal to one-tenth of a millionth of a millimeter.*
Anion	*A negatively charged ion, i.e. an atom that has acquired one or more extra electrons. In the Strange World of Atoms, it is a Lady.*
Arms	*These allow atoms to link together. The number of arms is a characteristic of an atomic family, and the social class to which it belongs. Chemists speak of the valency of the atom instead of its number of arms.*
Atomic Mass	*The mass, in grams, of 602,488 million billion identical molecules. In the Strange World of Atoms, this is measured in grons.*
Atomic Number	*A registration number given to each atomic family corresponding to its position in the Photograph of Atomic Families (Periodic Table). It is equal to the number of protons in the atom's nucleus.*
Atomic Radius	*The radius of an atom, measured in Ångströms. The radius varies with the level of atomic excitation. The radii quoted in this book correspond to atoms in their ground states.*
Avagadro	*A famous Italian chemist (1776-1856) who invented a scale for the masses of atoms and molecules.*
Avagadro Number	*The number of atoms that make up one gram of Hydrogen. The number is 602,588 million billion (6.022×10^{23}).*
Beta particle (β)	*A negatively charged particle that is the product of some radioactive decays. A particle is an electron from the decay of a neutron into a proton. Its mass is approximately 0.0005 grons.*
Bigamy	*A marriage between a Gent and two Ladies.*
Cation	*A positively charged ion, i.e. an atom that has lost one or more electrons. In the Strange World of Atoms, it is a Gent.*
Celibate	*Marital status of an atom with no arms. These atoms are Noble Gases.*
Chemistry	*Man's study of the habits and customs of the inhabitants of the Strange World of Atoms.*
Chemical Reaction	*A double divorce in which partners are swapped.*
Clan	*A gigantic gathering of identical atoms or molecules.*
Community	*A marriage that unites several Gents and several Ladies.*
Critical Mass	*The minimum mass of fissile material required for a spontaneous chain reaction to occur.*

Crystal	*A solid in which all the atoms are positioned in a periodic arrangement.*
Divorce	*The splitting up of a molecule whose constituent atoms then go on to form new molecules with other atoms.*
Einstein (Albert)	*(1879-1955). Born German, and successively took Swiss and American nationality. Won the Nobel prize in 1921. The author of Special Relativity in which the famous equation relating mass and energy ($E=mc^2$) appears.*
Electron	*An elementary particle 2000 times lighter than a proton or a neutron. The electron carries a negative charge, and is the 'particle' of electricity.*
Endothermic Reaction	*A reaction that absorbs heat from the surroundings.*
Exothermic Reaction	*A reaction that generates heat.*
Fission	*A reaction in which a heavy atom splits up into two or more smaller atoms.*
Gamma Ray (Y)	*A type of energetic X-ray, emitted by an atom suffering from radioactive decay.*
Gent	*An atom with male characteristics. The corresponding ion is called a cation.*
Gron	*An imaginary unit of mass used in the Strange World of Atoms. It is equivalent to the mass of a hydrogen atom.*
Half-life	*The time it takes for half of the members of a community to undergo radioactive decay.*
Induced Fission	*A recent, contagious, genetic illness in the Strange World of Atoms. This illness is provoked by Man.*
Ion	*An excited atom that has lost or gained one or more electrons. The ion has a charge equal to the excess number of electrons. Also known as 'charge carriers'.*
Isotope	*An atomic family member with a slightly different mass from the norm. This mass difference is due to a different number of neutrons.*
Lady	*An atom with female characteristics. The corresponding ion is called an anion.*
Marriage	*A union between atoms.*
Mass Deficit	*A mass deficit caused by the loss of some matter during a fission reaction. An incredible amount of energy is liberated.*
Mendeleïev	*Dmitri Ivanovitch, 1834-1907. A Russian chemist who invented the periodic classification of elements.*
Metal	*The name given by Chemists to the Gents of the Strange World of Atoms.*
Mineral	*A crystalline clan of atoms or molecules (see crystal).*
Neutrino	*A practically undetectable particle, produced from the decay of a neutron.*
Neutron	*A neutral particle of mass one gron. An isolated neutron is unstable, and decays to a proton, electron and neutrino.*

Noble Gas	*An atom with 8 electrons in its outer shell, and because of this neither captures nor expels electrons. In the Strange World of Atoms, these atoms have no arms, and are the confirmed bachelors.*
Non-metals	*The name given by Chemists to Ladies and androgynous atoms in the Strange World of Atoms.*
Nuclear	*To do with the nucleus.*
Nuclear Physics	*The science of the atomic anatomy, in particular the composition of the nucleus.*
Nucleus	*The heart of an atom, made up of neutrons and protons.*
Particle	*The name given to the constituents of atoms.*
Periodic Table	*See Photograph of all the Atomic Families.*
Photograph of all the Atomic Families.	*All the atomic families are arranged in this photograph according to the periodicity of the social classes to which they belong.*
Polygamy	*Marriage between a Gent and several Ladies.*
Polyandry	*Marriage between a Lady and several Gents.*
Proton	*A positively charged particle with a mass of 1 gron.*
Radioactive Atom	*An excited, unstable state of the nuclei of some atomic families. By emitting ionizing particles (,,), these atoms decay to other stable atoms.*
Radioactive Decay	*The regular decay of a community of atoms. Each particular family has its own decay rate.*
Radioactive Waste	*Unstable products from the fission of Uranium. They are all isotopes that suffer from radioactive decay, and emit dangerous, ionizing particles throughout the duration of their illness.*
Registration Number	*A number given to each atomic family; see Atomic Number.*
Social Agitation	*The level of atomic agitation depends on the temperature.*
Social Class	*A group of individuals with the same number of arms and similar characteristics. Each social class occupies a column in the Photograph of all the Atomic Families.*
Spontaneous fission	*A very rare genetic illness that can affect some heavy atoms (Uranium and Thorium).*
State of Matter	*There are three states : solid, liquid and gas.*
Symbol	*An acronym made up of one or two letters, identifying an atomic family.*



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