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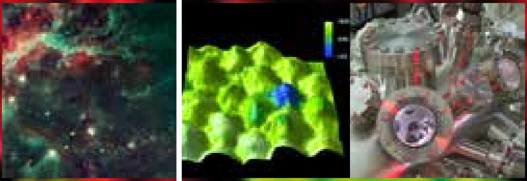
1 → The atom

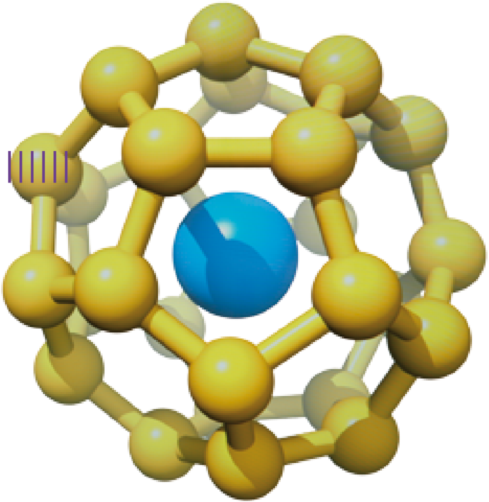


ATOMS: AT THE HEART OF THE MATTER

PHYSICAL-CHEMICAL PROPERTIES OF MATTER

THE ATOMIC NUCLEUS, A WHOLE NEW WORLD, A WHOLE NEW PHYSICS

The atom



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Theoretical chemistry modelling.

Production: Agence Gimmik - Illustrations: Yuvanoe - In collaboration with F. Saint-Jalm, physics-chemistry teacher
Cover photo: ©F. Charra/CEA - Nanoscopic sieve formed by ordered molecular assembly on an atomically flat graphite surface - 07/2017

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From left to right:
John Dalton,
Ernest Rutherford
and James Chadwick.

The idea that matter is composed of indivisible units called "atoms" has traversed the centuries, sometimes refuted, sometimes embraced.

The advent of quantitative chemistry, in the early nineteenth century, brought the concept back to the fore, sparking a century-long battle between opponents and proponents of the "atomic hypothesis".

In the twentieth century, the weight of compelling left physicists and chemists forced to accept the microscopic structure underpinning all matter in the Universe. They set about studying these immensely complex objects called atoms.

TIMELINE

- **The theory that matter is composed of indivisible elements stretches back to the fifth century BC.**
- **From 1600 to 1800, early philosophizing of extremely small entities (molecules or atoms) to describe matter emerges in treatises by renowned thinkers: Galileo in Il Saggiatore (The Assayer) or Descartes in Le Monde (The World)**
- **In 1808, John Dalton borrows the concept of atoms to explain the laws of chemistry. In his atomic theory, Dalton posits that the ultimate particles of a homogeneous body are perfectly alike, but different from body to body. By extension, any and every chemical reaction had to be identifiable as a new arrangement of atoms which cannot, themselves, be changed.**
- **In 1897, Joseph John Thomson shows that cathode rays are composed of massive and negatively-charged particles, i.e. electrons. He thus theorizes atoms as composed of a positively-charged matter, as well as being full of electrons.**
- **In 1908, Jean Perrin definitively demonstrates that matter is composed of atoms.**
- **In 1911, Ernest Rutherford discovers, by shooting particles at a gold foil, that most of the mass of an atom is concentrated in a tiny-volume nucleus surrounded by electrons, although how they behave remains a mystery. In 1918, the same Rutherford conceptualizes the idea that each atomic nucleus is composed of protons-particles that are far more massive than electrons, and positively-charged. However, later mass and charge measurements of atomic nuclei demonstrate the existence of neutral protons, which were dubbed neutrons in 1920 and which James Chadwick finally discovered in 1932.**
- **In 1913, Niels Bohr introduced the first model describing electron energy levels.**
- **In 1964, Murray Gell-Mann and Georg Zweig sketched out an early theory of quarks, which were proven to exist later in 1968.**

AN ATOM IS MADE UP OF A NUCLEUS OF PROTONS AND NEUTRONS, AND AN ELECTRON CLOUD.

Atoms: at the heart of the matter

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Simulation of a galaxy formation.

ORIGIN AND FATE OF ATOMIC NUCLEI

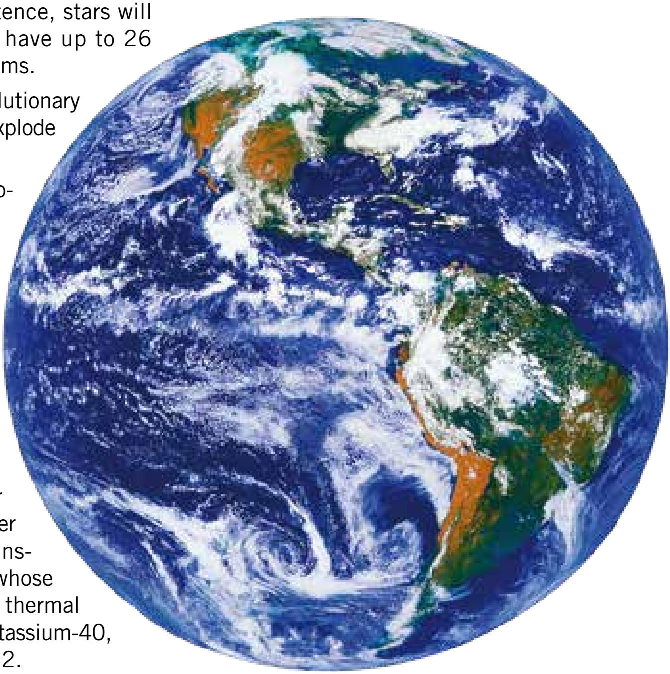
Matter as we know it constitutes 5% of everything in the universe. Most of the atoms the universe that compose it (hydrogen, helium, and some lithium) were formed in the very first moments after the Big Bang, in what is called primordial nucleosynthesis. All its stable atomic nuclei were formed in the cores of stars by nuclear fusion reactions causing lighter nuclei to fuse and form heavier nuclei.

Over the course of their existence, stars will thus create nuclei that can have up to 26 protons, i.e. nuclei of iron atoms.

When they reach their last evolutionary stage, the most massive stars explode into a supernova.

The titanic energy of this explosion serves to synthesize many even heavier atomic nuclei. Those that are stable, or that have a very long half-lives, get ejected into the clouds of gas and cosmic dust from which new stars are formed.

Earth is thus composed of 32.1% iron, 30.1% oxygen, 15.1% silicon, 13.9% magnesium, and all the other chemical elements in far smaller proportions. It also harbors unstable (radioactive) isotopes, whose steady decay has dictated the thermal state of Earth's core: mainly potassium-40, uranium-238 and thorium-232.



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All material bodies are made up of an assembly of atoms. From left to right: metal - crystal or polymer.

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WHAT IS AN ATOM?

Although a large proportion of the mass of the universe is probably of unknown nature (dark matter), the ordinary matter that we do know is composed of atoms.

The myriad modes of atoms assembly yield an immense diversity of molecules, macromolecules, polymers, crystals, metals, nanomaterials, and more.

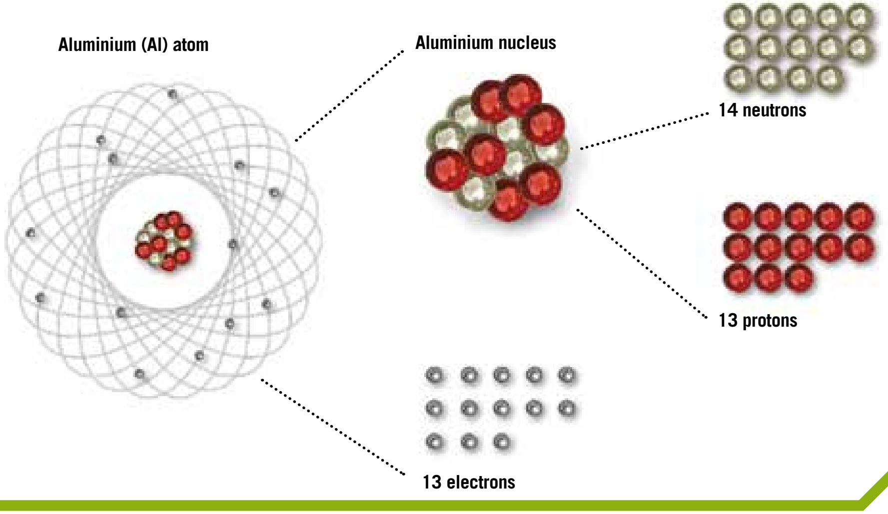
Atoms are built from three building blocks; protons, neutrons, and electrons.

The atomic nucleus is an assembly of **protons** and **neutrons**. The protons and neutrons are the nucleons (from the Latin word nucleus, meaning kernel).

The **electrons**, which are negatively charged (and classed as fermions), orbit close around the nucleus, which is positively charged. Taken individually, electrons are not really particles as such, but together they form an **electron cloud** where their different levels of energy lend them different degrees of excitation.

It is like they are unbound in space, but we can calculate the probability of finding them in a given position.

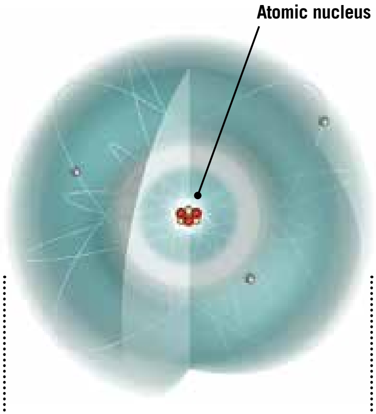
Symbolic representation of the components of an atom



REPRESENTATION OF THE ELECTRON CLOUD OF A LITHIUM ATOM

The lithium atom shown has three protons, four neutrons and three electrons.

We cannot give the exact position of the three electrons in the lithium atom's electron cloud. In this representation, the electrons are most likely to be found in the darker areas. This image was produced using mathematical formulae.



DIAMETERS OF ATOMS AND NUCLEI

The diameter of an electron cloud runs from 0.5×10^{-10} m (hydrogen) up to 4.3×10^{-10} m (radium). This is incredibly small—you would have to 'stack' 1,000,000 hydrogen atoms just to reach the diameter of a hair! Long considered inexistent as they are impossible to see, the invention of scanning probe microscopy now brings tangible proof that they are real. The atomic nucleus is much smaller still.

The diameter of the nucleus of a hydrogen atom (a single proton) is 2×10^{-15} m, and that of a uranium atom is 2×10^{-14} m. **The nucleus has a diameter that is about 100,000 times smaller than the atom itself**.

VOLUME, MASS, AND DENSITY

The bodies that make up our everyday environment (metals, crystals, polymers) are made up of atoms that are attached to other atoms by bonds that hold them together. The density of these atoms is therefore much the same as the density of these solid bodies.

Atoms are incredibly small, and so their mass and volume are tiny. For example, take a pinhead of iron of 1 mm^3 in volume. It is made up of 60 million billion iron atoms!

A proton and a neutron share roughly the same mass, which is 1840 times greater than that of an electron, which means **practically all an atom's mass is concentrated in the nucleus.** Take an iron atom. Its nucleus has a diameter of around 10^{-14} m, for a mass of 9.3×10^{-26} kg, so the density of the nucleus comes to 1.4×10^{17} $kg.m^{-3}$, which equates to just over a hundred billion kilograms per centimeter cubed. So if the pinhead was made up exclusively of nuclei of iron atoms, its mass would equal 1.4×10^{8} kg, or 140,000 tons!

To estimate the mass of a nucleus, you simply have to know how many nucleons it has. Given that the mass of a nucleon is approximately 1.67×10^{-27} kg, it is easy to calculate the approximate mass of an atom. However, the result of the calculation is still just an estimate.

But scientists can measure the mass of an atom directly, using a mass spectrometer. The atoms are introduced in vapor phase into an ionization chamber, then accelerated through a tunnel by an electrical field. They then reach a magnetic field which causes to curve their trajectories. The point where they hit the detector characterizes their mass, which can thus be measured with precision.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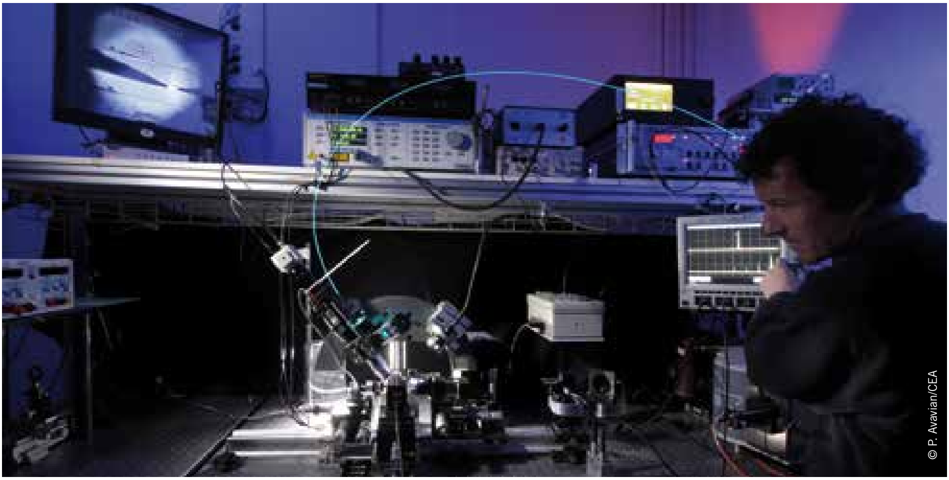
Mass spectrometry enables fast isotopic measurement on a sample.

ELECTRIC CHARGE

The positive electric charge of the proton is exactly the opposite of the negative charge of the electron. The neutron has no electric charge and is neutral. Any atom that counts as many protons in its nucleus as electrons in its electron cloud therefore has a net neutral electric charge.

However, in certain conditions (typically chemical reactions), the atom can lose or gain one or more electrons, and thus become positively or negatively charged, **in which case it is called an ion.**

Optical scanning probe microscope.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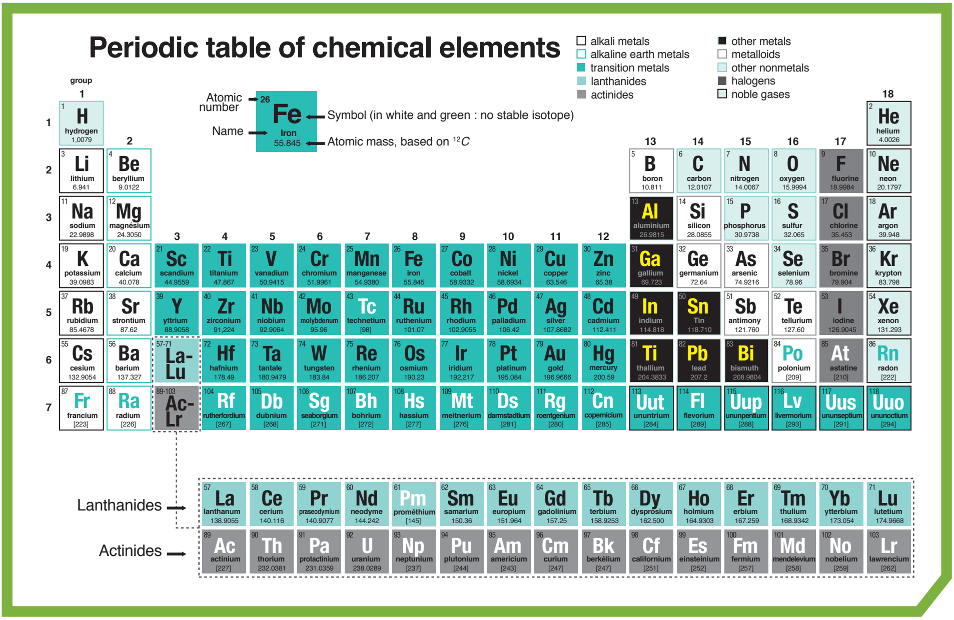
CHEMICAL ELEMENTS AND ISOTOPES

For a given atom, the number of protons Z, which is also the number of electrons, is its atomic number. The number of neutrons is N. The simple calculation $N + Z = A$ thus sums its number of nucleons, called the mass number. These are the numbers that define the chemical elements. Each element is denoted by a symbol and its atomic number (e.g. $_1$H for hydrogen, which has just one proton, or ^{26}Fe for iron which has 26). The original periodic table devised in 1869 by Dmitri Mendeleev to classify the atoms according to their mass and chemical properties has progressively grown into today's version.

On Earth, there are 94 chemical elements.



Periodic table of chemical elements

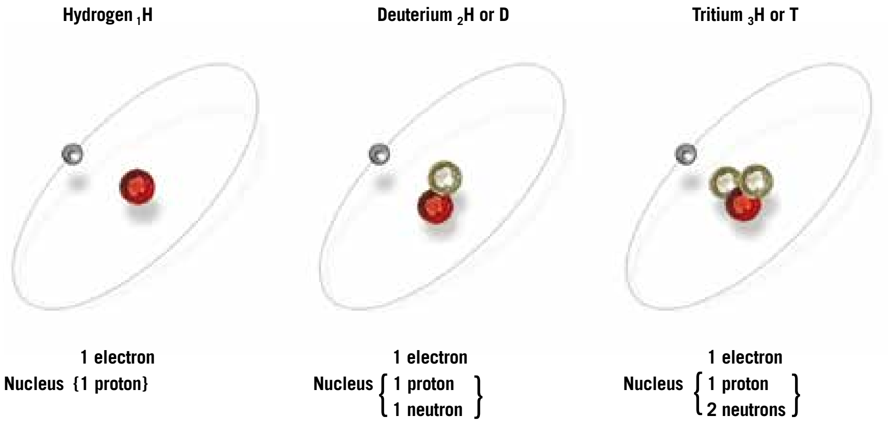
- ☐ alkali metals
- ☐ alkaline earth metals
- ■ transition metals
- ■ lanthanides
- ■ actinides
- ■ other metals
- ☐ metalloids
- ☐ other nonmetals
- ■ halogens
- ☐ noble gases

Atomic number → 26
Fe ← Symbol (in white and green : no stable isotope)
Name → Iron
55.845 ← Atomic mass, based on ^{12}C

group	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18
1	1 H hydrogen 1,0079																	2 He helium 4.0026
2	3 Li lithium 6.941	4 Be beryllium 9.0122											5 B boron 10.811	6 C carbon 12.0107	7 N nitrogen 14.0067	8 O oxygen 15.9994	9 F fluorine 18.9984	10 Ne neon 20.1797
3	11 Na sodium 22.9898	12 Mg magnésium 24.3050											13 Al aluminium 26.9815	14 Si silicon 28.0855	15 P phosphorus 30.9738	16 S sulfur 32.065	17 Cl chlorine 35.453	18 Ar argon 39.948
4	19 K potassium 39.0983	20 Ca calcium 40.078	21 Sc scandium 44.9559	22 Ti titanium 47.867	23 V vanadium 50.9415	24 Cr chromium 51.9961	25 Mn manganese 54.9380	26 Fe iron 55.845	27 Co cobalt 58.9332	28 Ni nickel 58.6934	29 Cu copper 63.546	30 Zn zinc 65.38	31 Ga gallium 69.723	32 Ge germanium 72.64	33 As arsenic 74.9216	34 Se selenium 78.96	35 Br bromine 79.904	36 Kr krypton 83.798
5	37 Rb rubidium 85.4678	38 Sr strontium 87.62	39 Y yttrium 88,9058	40 Zr zirconium 91,224	41 Nb niobium 92.9064	42 Mo molybdenum 95.96	43 Tc technetium [98]	44 Ru ruthenium 101.07	45 Rh rhodium 102,9055	46 Pd palladium 106.42	47 Ag silver 107.8682	48 Cd cadmium 112.411	49 In indium 114.818	50 Sn Tin 118.710	51 Sb antimony 121.760	52 Te tellurium 127.60	53 I iodine 126.9045	54 Xe xenon 131.293
6	55 Cs cesium 132.9054	56 Ba barium 137.327	57-71 La-Lu	72 Hf hafnium 178.49	73 Ta tantale 180.9479	74 W tungsten 183.84	75 Re rhenium 186.207	76 Os osmium 190.23	77 Ir iridium 192,217	78 Pt platinum 195.084	79 Au gold 196.9666	80 Hg mercury 200.59	81 Ti thallium 204.3833	82 Pb lead 207.2	83 Bi bismuth 208.9804	84 Po polonium [209]	85 At astatine [210]	86 Rn radon [222]
7	87 Fr francium [223]	88 Ra radium [226]	89-103 Ac-Lr	104 Rf rutherfordium [267]	105 Db dubnium [268]	106 Sg seaborgium [271]	107 Bh bohrium [272]	108 Hs hassium [277]	109 Mt meitnerium [276]	110 Ds darmstadtium [281]	111 Rg roentgenium [280]	112 Cn copernicium [285]	113 Uut ununtrium [284]	114 Fl flevorium [289]	115 Uup ununpentium [288]	116 Lv livermorium [293]	117 Uus ununseptium [291]	118 Uuo ununoctium [294]

Lanthanides	57 La lanthanum 138.9055	58 Ce cerium 140.116	59 Pr praseodymium 140.9077	60 Nd neodyme 144.242	61 Pm prométhium [145]	62 Sm samarium 150.36	63 Eu europium 151.964	64 Gd gadolinium 157.25	65 Tb terbium 158.9253	66 Dy dysprosium 162.500	67 Ho holmium 164.9303	68 Er erbium 167.259	69 Tm thulium 168.9342	70 Yb ytterbium 173.054	71 Lu lutetium 174.9668
Actinides	89 Ac actinium [227]	90 Th thorium 232.0381	91 Pa protactinium 231.0359	92 U uranium 238.0289	93 Np neptunium [237]	94 Pu plutonium [244]	95 Am americium [243]	96 Cm curium [247]	97 Bk berkélium [247]	98 Cf californium [251]	99 Es einsteinium [252]	100 Fm fermium [257]	101 Md mendelevium [258]	102 No nobelium [259]	103 Lr lawrencium [262]

Symbolic representation of the isotopes of hydrogen



All the atoms of a given chemical element will have the same number of protons (which, again, is a number that defines the chemical element) but they may not all have the same number of neutrons. Two atoms sharing the same number of protons but a different number of neutrons are **isotopes** of that element.

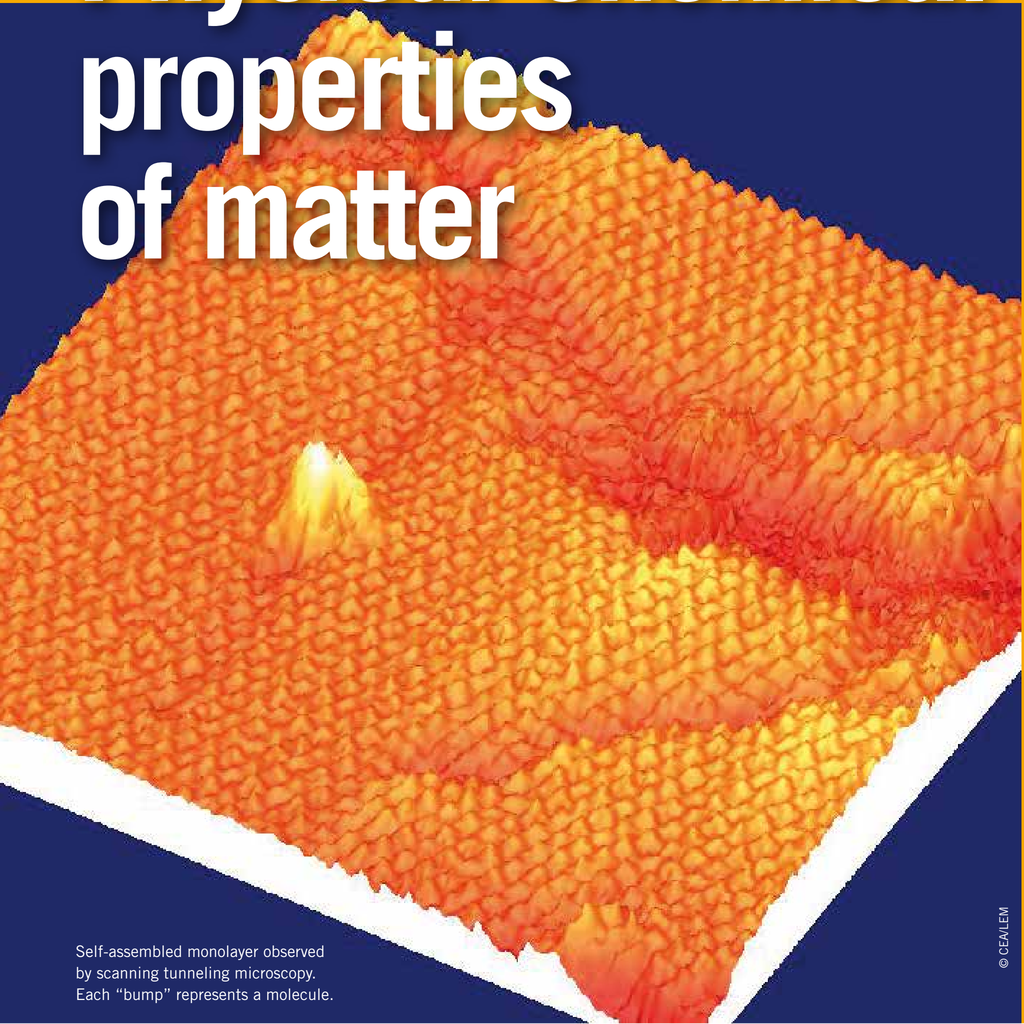
For example:

- All the isotopes of hydrogen have just one proton but can have zero, one or two neutrons. They are hydrogen (the most ubiquitous form), deuterium and tritium.
- All the isotopes of carbon have 6 protons. The most abundant have 6, 7 or 8 neutrons.
- All uranium atoms have 92 protons. There are two isotopes in natural uranium: uranium-235 which has 143 neutrons (235 = 92+143) and uranium-238 which has 146 neutrons (238 = 92 + 146).

An isotope takes the name of its chemical element associated with its total nucleon number, which, taking carbon as an example, gives: ^{12}C, ^{13}C and ^{14}C.

THE ELECTRON CLOUD DICTATES ALL MATERIAL DIVERSITY.

Physical-chemical properties of matter



Self-assembled monolayer observed by scanning tunneling microscopy. Each “bump” represents a molecule.

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Chemical manipulations on a vacuum gas manifold.

The chemical properties of an atom depend only on the number and arrangement of the electrons in its electron cloud; all isotopes of the same element thus share the same chemical properties. However, the slight difference in the mass of their nucleus means that their physical properties are also slightly different.

CHEMICAL PROPERTIES OF THE ATOM

The electrons in an atom's electron cloud have to be orbiting in allowed states. We cannot assign them clearly defined trajectories, but we can describe the state each electron occupies.

This is done based on four properties of electrons: their energy level, their angular momentum, the projection of this angular momentum on a given direction, and their spin.

angular momentum: A property that describes their kinetic potential in orbital motion.

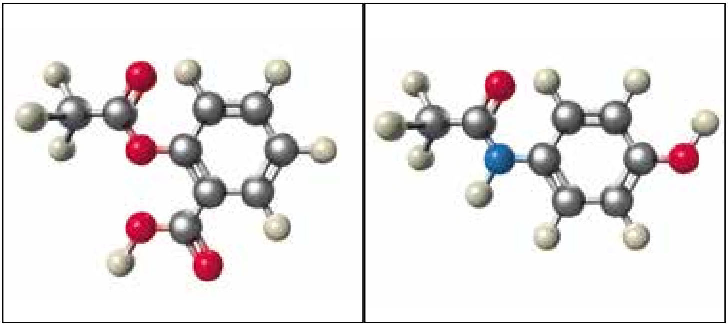
spin: An intrinsic property of the electron, analogous to rotation.

The structure of the electron cloud that results from the distribution of these properties has two consequences. The first is that it dictates how chemical symbols are laid out in Mendeleev's periodic table. The second is that it dictates the type of chemical properties of the different elements.

Certain electron cloud configurations are particularly stable. Atoms configured like this are not chemically reactive - they are inert. They are the atoms of noble gases, whose symbols are written in the column farthest to the right in Mendeleev's periodic table.

Atoms near the noble gases tend to realign their electron cloud to make it resemble a noble gas. They can do this by ionizing, by gaining or losing one or more electrons, or by establishing a covalent bond with other atoms. They thus share the property of certain electrons.

covalent: Where each of the bonded atoms shares an electron in one of its outer shells to form an electron pair binding the two atoms.



The aspirin molecule (at left) and paracetamol molecule (right) look much the same. Both are composed of carbon atoms (in grey), hydrogen atoms (in white) and oxygen atoms (in red). A nitrogen atom is shown in blue.

Matter that we call “organic”, i.e. built around the covalence of atoms of carbon, oxygen, nitrogen and hydrogen, offers an inexhaustible source of molecules.

The other atoms in the periodic table have more complex electronic structures. They attract together and coalesce by metallic bonding. The metal obtained is solid at normal temperature, and conducts electricity.

Where the atoms share one or more free electrons, called delocalized electrons.

PHYSICAL PROPERTIES OF MATTER

All of the physical properties of matter: hardness, malleability, ductility, transparency, color, phase transition temperatures, electrical conductor or insulator, etc... like all of its chemical properties: acid or base, oxidizer or reducer, solvent or solute, etc... are entirely due to the different behaviors adopted by the electrons in the electron clouds.

We now know how to organize these atoms to get new properties, such as high-temperature superconductivity, to get supermagnetic properties, to get miniature electrical circuits or use them to store data.

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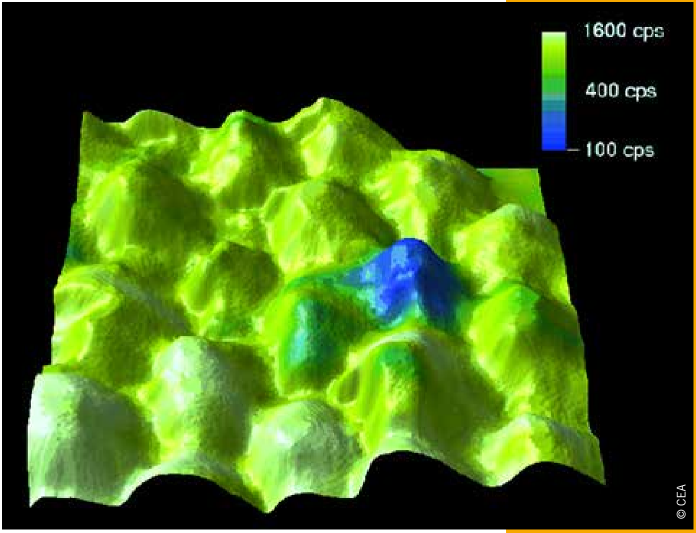
The MesoXcope is a photoelectron emission microscope that serves to study the chemical and electronic structure of surfaces, at simultaneously high spatial (50 nm) and spectroscopic (50 meV) resolution.

Luminescent effect of silver nanoparticles produced by an electrical current locally injected by the tip of a scanning tunneling microscope.



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SEEING AND PROBING ATOMS

From macroscopic scale down to micrometric scale, it is possible to form images based on light waves, using optical microscopy.

To form images of smaller objects, it becomes necessary to use particles, like electrons, which have a sub-micrometer wavelength. Electron microscopes work as the same principle as optical microscopes (such as scanning electron microscopes, or SEM for short). By pushing their performances to the extreme, scientists have managed to get down to atomic scale (0.1 nm).

Scanning probe microscopes broke onto the scene in the early 1980s. They work to the principle of examining a relatively flat surface with an extremely fine probe that interacts with the atoms. Landmark types since include the scanning tunneling microscope (STM) that uses a weak electric current travelling between the sample and a conducting tip, the atomic force microscope (AFM) that uses the mechanical interaction between the sample and a tip mounted on a flexible cantilever, and the near-field scanning optical microscope that, with an extremely fine optical fiber, exploits the properties of evanescent waves in the near-field sample surface.

The latest type to emerge is the scanning tunneling-induced luminescence microscope (STL). The common denominator to all these microscopes is that they enable atomic-scale studies of various molecules and their behavior on different substrates.

It remains impossible to form images of atomic nuclei, but it is possible to generate images by calculating the distribution of masses and charges inside the nuclei and mapping these calculations against measurements of certain of their properties.

THE FOUR FUNDAMENTAL INTERACTIONS

Physicists manage to explain all observable physical phenomena in the universe with a set of just four forces, or interactions, considered as “fundamental”. What are they?

- Gravitation - a classic discovered by Isaac Newton over three centuries ago;
- Electromagnetic interaction, identified as such by James Clerk Maxwell in the second half of the nineteenth century, and which explains the binding of everyday matter;
- Weak interaction, discovered in the 1930s, responsible for certain radioactive processes, including beta decay;
- Strong interaction, discovered around about the same time as weak interaction, which very solidly binds together the constituents of atomic nuclei.

Gravitation governs a vast array of phenomena, from why objects fall to the movement of the planets. Gravitation is also what makes stars form from primordial gaseous matter, which it forces to contract. Gravitation is also why stars, once they have formed, attract and coalesce together and form galaxies.

Gravitation interaction is an attractive force with infinite range (which means the force between two masses is null only if the distance separating them is infinite). Gravitation cannot be shielded against, so any attempt to weaken or abolish its influence is destined to fail. However, it is by far the weakest of the four interactions, so much so that its effects at particle scale can be considered negligible, especially as particles are subjected to far stronger forces...

Electromagnetic interaction is far stronger than gravitation. Its effects are manifest in everyday life, as it is electromagnetic force that makes household appliances work. However, on a more fundamental level, it is electromagnetic interaction that holds atoms and molecules together, that governs all chemical reactions, and that explains macroscopic optical phenomena (since light is formed of electromagnetic waves, which are made of photons). Electromagnetic interaction, like gravitation, has infinite range, but since it can be attractive or repulsive (depending on the sign of the electric charges involved), its combined cumulative effects get cancelled out over large distance due to the net neutrality of matter.

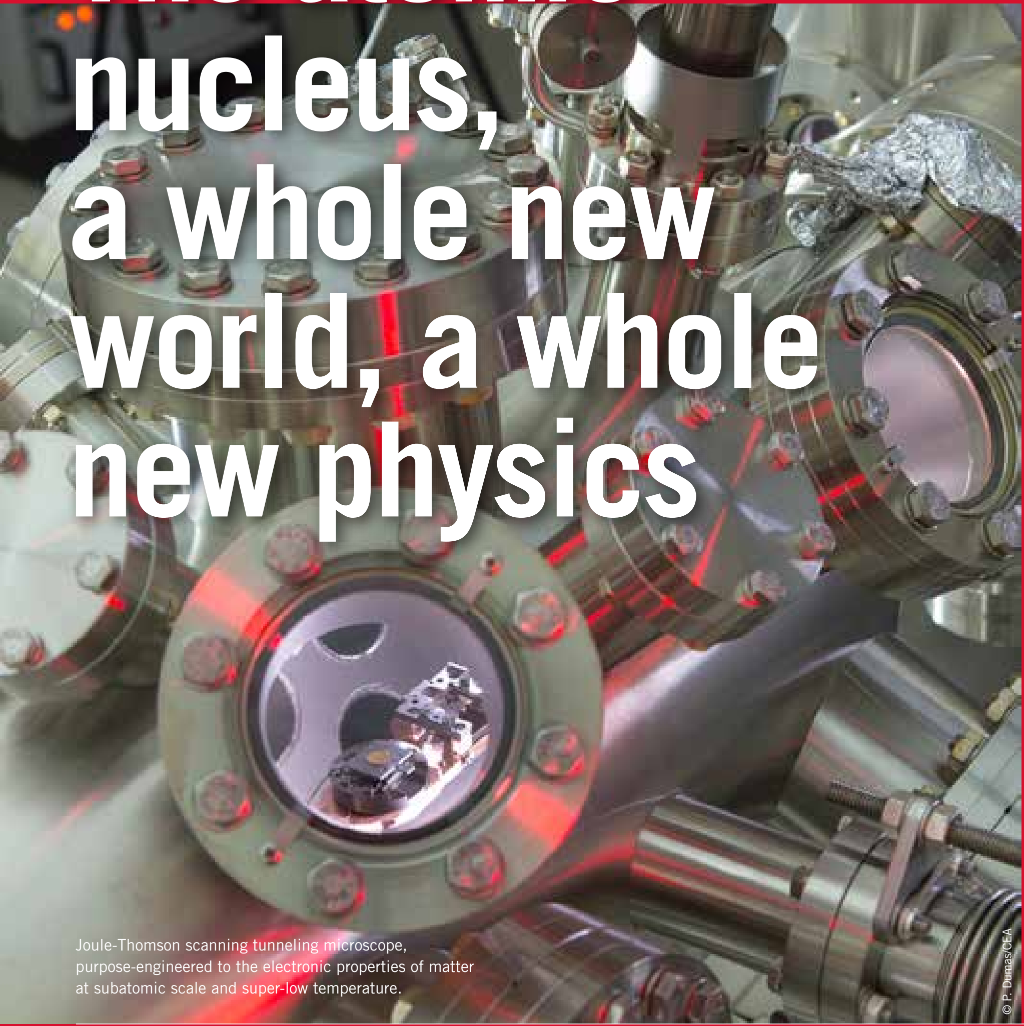
Weak interaction has an extremely short range, of the order of a billionth of a billionth of a meter. This makes it basically, like glue, a contact interaction: two particles can only interact by weak force if they are practically touching. It is weak interaction that is responsible for beta decay, the process by which a neutron decays into a proton and an electron. Weak interaction, as its name suggests, is a very weak force, which is what makes it so difficult to observe. Even so, weak interaction still plays an absolutely capital role, crucially in the nuclear reactions that fuse hydrogen to power the sun. If it were to disappear from the universe, our Earth's star would cease to shine...

Strong interaction is by far the strongest of the four fundamental interactions, yet for a long time it remained in the dark. Physicists deduced its existence in the 1930s, when they realized that there was something amazing about the stability of atomic nuclei. As they carry same-sign electrical charges, the protons in the nucleus should repel one another due to the electrical force that tends to separate them. And yet, they appear to be very solidly bound together. So what could be counter-dominating their electrical repulsion? As no force in classical theory could explain this nuclear binding energy, the hypothesis was postulated, and has since been experimentally confirmed, that inside atomic nuclei there must be a hugely intense force - strong nuclear interaction - with an extremely short range, of the order of a millionth of a billionth of a meter...

This force acts like a kind of glue cementing two nucleons (proton or neutron) that are in contact but that very quickly loses weakens the instant that they are even slightly apart. Even so, strong interaction is still incredibly powerful - it can stop a proton launched at a hundred thousand kilometers per second, and stop it within a few millionths of billionths of meters...

IN NUCLEAR PHYSICS, PRACTICALLY EVERYTHING IS WAITING TO BE DISCOVERED.

The atomic nucleus, a whole new world, a whole new physics



Joule-Thomson scanning tunneling microscope, purpose-engineered to the electronic properties of matter at subatomic scale and super-low temperature.

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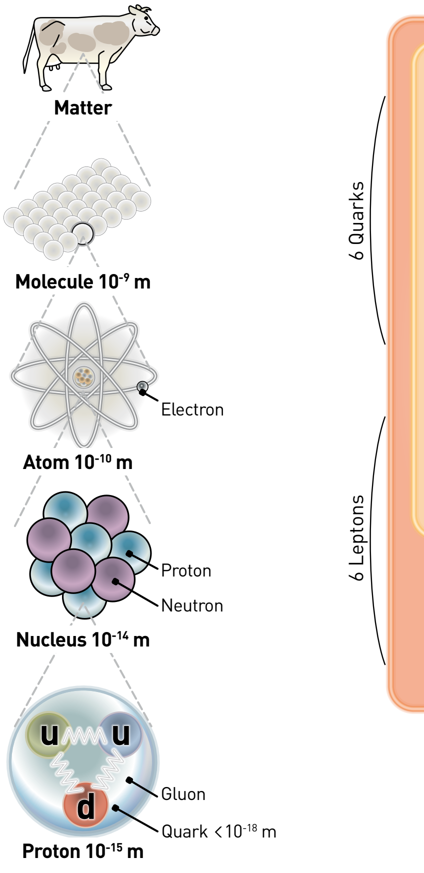
DRILLING DOWN TO THE ELEMENTARY

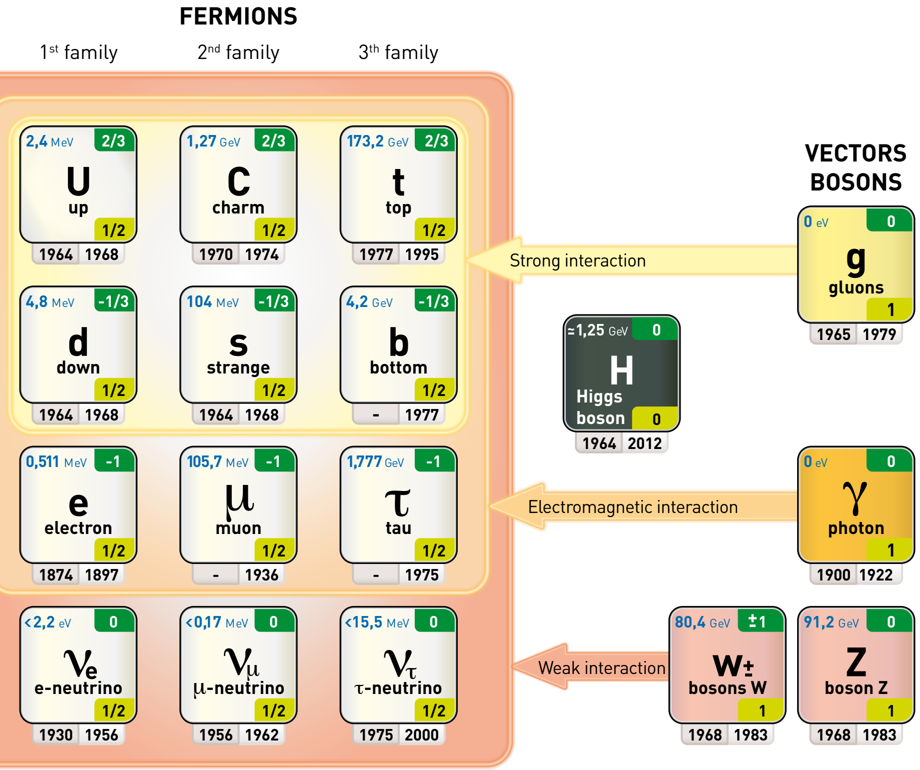
While the size-scale of atoms and their electron clouds is the nanometer (10^{-9}), the size-scale of atomic nuclei and nucleons is the femtometer (10^{-15}). The size of the particles that are considered with today's science as elementary is of the order of 10^{-18} meters.

The nucleus is an extremely dense and complex ultrasmall object. It is like a Russian doll, with nested layers that get increasingly small. It was long thought that protons and neutrons were elementary particles i.e. ultimate constituents without any substructure. But observations in experiments performed in the 1950s and 1960s with steadily-improving bigger and more powerful particle accelerators showed that large numbers of particles are produced after the collisions.

This diversity was interpreted by assuming that they were composed of even smaller constituents, dubbed quarks. The nucleons contain up quarks and down quarks that assemble in triplets by strong interaction.
Quarks like electrons are fermions. The quark model today counts six types of quarks, grouped into three generations. Quarks interact through attraction by exchanging gluons that are not fermions but bosons. As well as an electric charge equal to -1/3e or⅔2/3e, they also carry another charge called color, labeled blue, green or red nothing to do with real perceived colors, but a code borrowing the same three-valued logic as strong interaction.



Mass: expressed, at this scale, as energy, and thus in electronvolts, due to the mass–energy equivalence $E=mc^2$.
Electric charge: positive or negative.
Spin : operates many magnetic properties at subatomic scale, and differentiates fermions (1/2-integer spin) from bosons (integer-spin).



THE STANDARD MODEL OF PARTICLE PHYSICS

This standard model is the theory describing the elementary particles of matter and the particles that mediate the fundamental interaction forces between them all at scales down below 10^{-15} m.

Some of these particles have been observed and studied for decades. Others, like the Higgs boson predicted in 1964 but not discovered until 2012 at the CERN (see page 23), are only beginning to be studied.

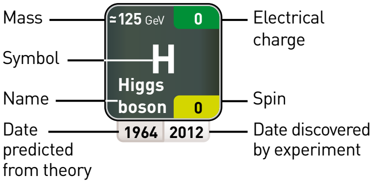
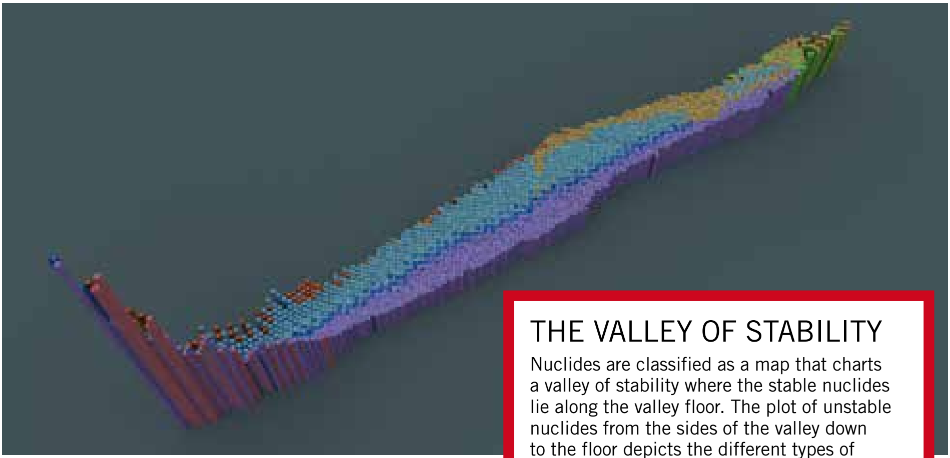


Illustration: Fabrice Mathé



THE VALLEY OF STABILITY

Nuclides are classified as a map that charts a valley of stability where the stable nuclides lie along the valley floor. The plot of unstable nuclides from the sides of the valley down to the floor depicts the different types of radioactivity.

See the animated version at http://irfu.cea.fr/la-vallee-de-stabilite/index.php

Produced by Frédéric Durillon – Animea 02-2012

STABILITY OF ATOMIC NUCLEI

Atomic nuclei composed of Z protons and N neutrons are only bound together by strong interaction, which manifests as the exchange of π mesons between nucleons, just as Hideki Yukawa had predicted back in 1935 (a prediction that made him the first Japanese physicist to receive the Nobel Prize in Physics in 1949). We would later learn that the π mesons are composed of one quark and one antiquark of the same particle family. Neutrons and protons share out the energy of the nucleus and thus get propelled with extremely rapid motion.

The nucleon assembly can be stable (there are 256 stable nuclei for 80 elements) or, more often, unstable (approaching 3,000 nuclei). For each of the unstable nuclei, we define a radioactive period or half-life T, the time after which half of its radioactive nuclei have decayed. Unstable nuclei want to get back to a stable state, via a decay chain. Cesium (half-life 1.2 s), for instance, becomes stable neodymium by changing into barium (half-life 14.5 s), lanthanum (half-life 14.2 min), cerium (half-life 33 h) and praseodymium (half-life 13.5 d).

RADIOACTIVE DECAY

A specimen's radioactive activity (expressed in units called becquerels) decreases over time as its unstable nuclei progressively decay. For each radioactive isotope, and for each of decay mode it undergoes, we define a half-life, or radioactive period, as the time after which half of the radioactive atoms initially present have spontaneously reacted. For different radioactive nuclides, this half-life period varies wildly over orders of magnitude ranging from a few milliseconds up to several billion years!

NUCLEAR PHYSICS

Nuclear physics is the study of the atomic nucleus and the interactions involded between its constituents.

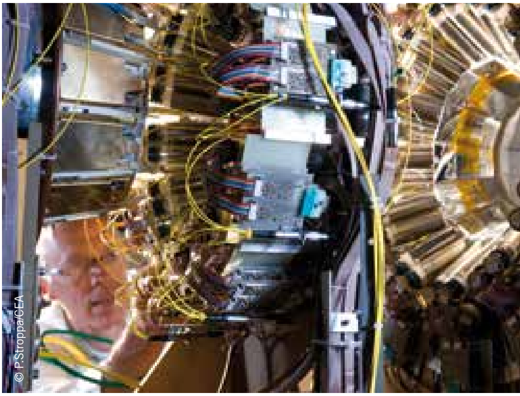
It studies the nucleus as a collection of nucleons that move with attraction, the mechanisms underpinning their attraction forces and the influence of quarks on their properties and behaviors. Its method of inquiry is to probe nuclei with an atom-scale-adapted ‘micro-scalpel’ a beam of accelerated particles that is used to see what proportions of the particles are deflected or absorbed. It also lets us see how the nuclei react by ejecting nucleons, producing other particles, and so on.

Over the past few decades, as technology has moved forward, bringing increasingly sharp and wide-ranging observations, so has the nuclear modeling developed to explain them, bringing increasingly complex explanations.
The models themselves have also evolved, spurred by the power of computer simulation. They have moved on to complex structures where the nucleons form stable aggregates inside the nucleus or, in other cases, make up a diffuse halo surrounding a denser core. A revolution opening up a whole new world of nuclear physics.

NEW NUCLEI TO SYNTHESIZE AND STUDY

Frédéric Joliot and Irène Joliot-Curie made the discovery of artificial discovery back in 1933, and a host of atomic nuclei have been synthesized since. While nuclear physics centers at Dubna in Russia, Darmstadt in Germany and Berkeley in the USA focus on synthesizing high-atomic-number nuclei, here in France the CEA/CNRS center of Ganil, National Large Heavy Ion Accelerator (Grand accélérateur national d’ions lourds) in Caen is a facility that investigates the stability of the nuclei produced in an effort to better understand how strong interaction holds nucleons glued together.
The Ganil explores two lines of inquiry: studying stable nuclei in various states of excitation, and producing and studying exotic nuclei. The Ganil went live in 1983 and its extension, Spiral2, started up in February 2012, will soon be operational.

Which are nuclei characterized by their unusual neutron-proton ratios and extremely short-lived lifespans before decaying.


© P.Stroppa/CEA

The charged particle multidetector array Indra, a facility for studying heavy-ion collision.


© P. Stroppa/CEA

Quadrupoles of the Spiral2 linear accelerator.

SPIRAL (in-line-beam radioactive ion production system) is a Ganil facility built in 2001 and used to produce and accelerate exotic nuclei. Exotic nuclei are characterized by their very unusual neutron–proton ratios and extremely short-lived lifespans before decaying. Exotic nuclei are a vital focus of study in many subfields of nuclear physics, but also astrophysics, chiefly to understand how atomic nuclei are formed in stars and supernovas. Although physicists already know how to synthesize exotic nuclei in the laboratory, the Spiral facility means they can now produce exotic nuclei in large quantities, accelerate them, observe their collisions with other nuclei and thereby understand their structure.

To explore the boundaries even further, the second-generation Spiral2 facility will be able to produce exotic nuclei a thousand times more powerfully than previously possible.

The objective is to continue producing these synthetic nuclei in order to discover the nature of these particles and understand the laws governing how they behave. But this time, in contrast to the first-generation accelerator, it will also allow to produce and study heavier exotic nuclei, and maybe, for the first time ever, even “super-heavy” nuclei.


© P. Stroppa/CEA

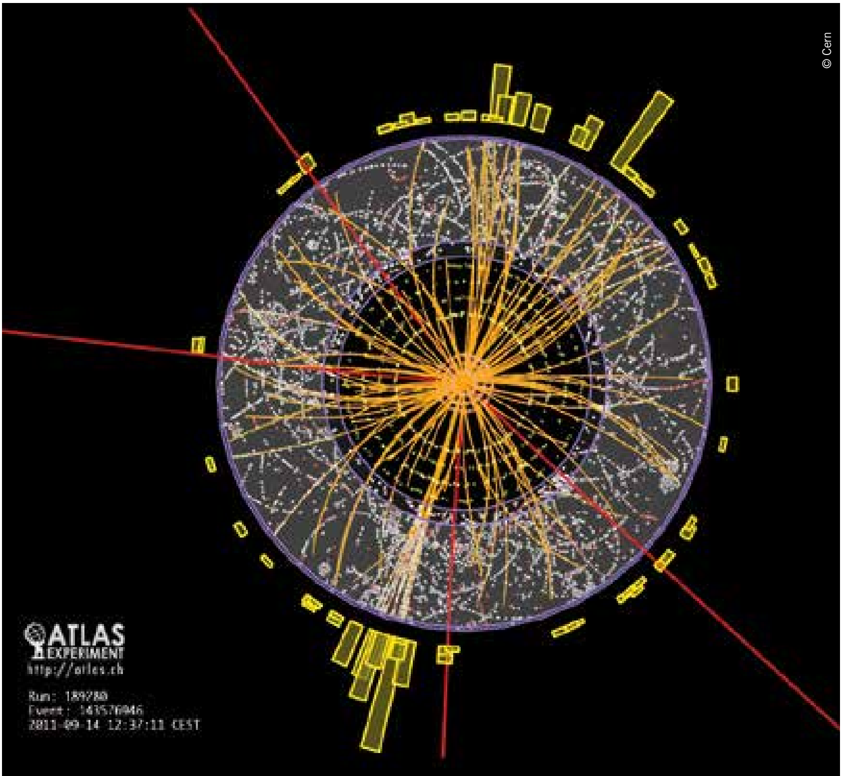
The Alice experiment, hosted at CERN, is focused on studying the physics of matter in its extreme states of temperature and density.

NUCLEAR MATTER

Strong interaction can form atomic nuclei up to a mass number (number of nucleons) of up to 300. However, it is possible to force the nucleons temporarily into higher-number assemblies by accelerating heavy ions (like lead ions) with colossal energy densities (several TeV).

When two heavy nuclei collide, their nucleons meld during the split second of the impact, and the conditions prevailing inside quark-gluon plasma formed resemble the temperature and pressure conditions marking the state of the universe milliseconds after the Big Bang (the Big Bang nucleosynthesis scenario). The plasma that forms is unstable, and the vast majority of the energy injected to form it transforms into a huge array of all kinds of particles that are instantaneously detected. Proton–lead collisions help distinguish what happens in a cold plasma compared to a hot plasma with lead-lead collisions. What makes these collisions so interesting for research is that they test out the mechanisms of primordial nucleosynthesis by comparing today’s measurements against the result of what happened 13.7 billion years ago. This is what is done at the LHC since 2012 with heavy ion collisions.

THE HIGGS BOSON



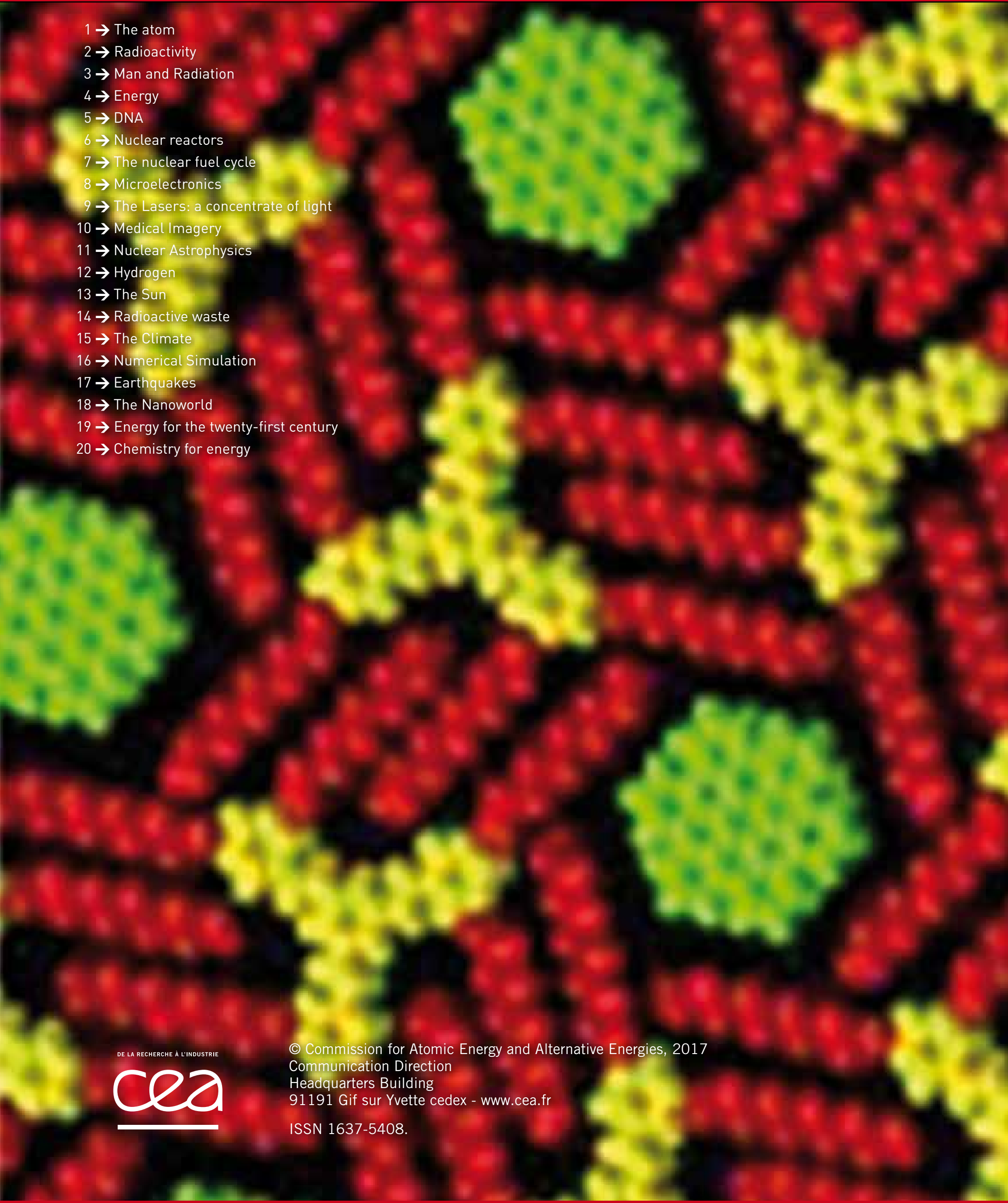
© Cern

Event display of a proton proton collision in a transverse view of the Atlas detector.

At the **Large Hadron Collider (LHC)**, it is sometimes protons, hydrogen nuclei, that circulate in densely-packed bunches, with 100 billion protons in each bunch! The collider is a 27 km circumference circular tunnel embedded 100 m underground beneath the France-Switzerland border. These proton bunches travel at 11,000 revolutions per second. Two beams travel in opposite directions and collide every 25 ns at four locations around the accelerator ring, corresponding to the positions of four particle detectors. The beam energy deliverable, at 7 to 8 TeV, recreates temperature and pressure conditions similar to those prevailing in the universe shortly after the Big Bang.

Of the 6 million billion LHC proton–proton collisions produced from 2010 to 2012, the Atlas and CMS experiments each recorded around 10 billion interesting collisions. Thanks to this colossal accumulation of data, isolated events stack up and emerge the signal from the background noise. In July 2012, around 400 collisions signatured events signaling a particle consistent with the Higgs boson. The Higgs boson was predicted back in 1964 by theoretical physicists François Englert, Robert Brout and Peter Higgs, and its discovery earned them the 2013 Nobel Prize in Physics.

THE COLLECTION



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ISSN 1637-5408.