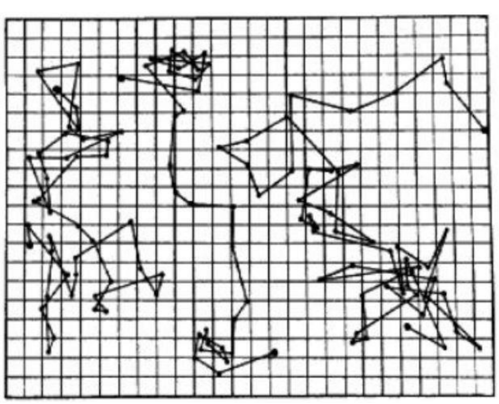
From Atom to Nucleus

The idea that matter may be made of tiny elementary blocks – atoms – dates back to Antiquity, yet it was not until the turn of the 20th century that this hypothesis took precedence, confirmed by experiment. The exploration still goes on today, as the atom, then the nucleus have revealed their internal structures.

The Brownian Motion as observed by Jean Perrin

Diagram adapted from Jean Perrin, Les Atomes*. It displays the course of three colloidal particles with a radius of 0.53 micrometres (µm) observed under a microscope. Their successive positions are recorded every 30 seconds and connected by straight lines – the grid spacing is 3.2 µm. The trajectories are erratic and subject to random changes of direction.*

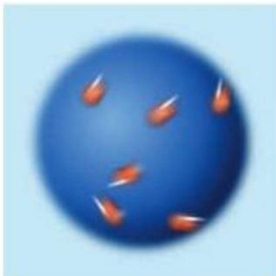


Credit: J.-B. Perrin

The idea of matter as an assembly of tiny elementary constituents dates back to Antiquity. In the 5th century B.C. the philosopher Anaxagoras spoke of indivisible seeds, which Democritus later called atoms ('unbreakable' in Greek). This theory held that everything, including the soul, is made up of different kinds of atoms which determine their properties. When the balance is disrupted – a living being dies, an object breaks apart – atoms are released and form new structures. Such materialistic perspective came into conflict with Christianity and sank into oblivion.

The situation changed in the 17th and 18th centuries with the development of a more scientific approach. Dogma was replaced by theories based on observation and whose predictions could be tested. The first chemical elements were discovered. For example, oxygen and hydrogen were used to synthesise water; conversely, water could be separated into these two elements. In both reactions, the ingredients and products exist in precise and invariable proportions ($H_2 + 1/2\ O_2 = H_2O$). In the early 1900s, after a century of controversy, these phenomena were explained by the concept of molecules, assemblies of chemical elements. Within a few years, the theory was confirmed experimentally.

Pollen grains suspended in a liquid follow erratic trajectories. Einstein took an interest in this 'Brownian motion' (named after the botanist Robert Brown, who first described the phenomenon) and showed in 1905



Thomson's atom

Rutherford's atom

Bohr's atom

'Modern' atom

Credit: B. Mazoyer

that it was caused by collisions between the pollen and the molecules in the liquid. A few years later, Von Laue illuminated crystals with X-rays that revealed their structure, an assembly of tiny atoms.

The atom is in fact misnamed, as it can be split into pieces. This even broke with everything that had been observed up to then: breaking a piece of matter had always given pieces of matter, just smaller ones. That law was no longer true on the scale of the atom, whose constituents are of a different nature. On closer inspection, the atom is actually 'mostly empty space', as demonstrated by Rutherford in 1911. In the centre the positively charged nucleus is very small but concentrates all the atom's mass. Around it orbit negatively charged electrons – hence the atom's neutrality – which are responsible for chemical reactions. The electron, discovered by Thomson in 1897, is still considered elementary today, unlike the nucleus, which has a complex internal structure. The latter contains nucleons (protons and neutrons) which are themselves made up of more fundamental particles called quarks. What happens next? Well, we don't know. Nothing indicates that our current vision of a point-like electron and of quarks as the ultimate nucleus constituents is right. No doubt, Nature still has many more surprises in store for us!

Evolution of the vision of the atom in the 20th century

Thomson saw the atom as a 'pudding' (1903, 1906), a positively charged sphere in which electrons are embedded. In 1911 Rutherford discovered the (tiny) nucleus and positioned the electrons as orbiting around it. But his model had a major flaw: by orbiting so, electrons would lose energy and 'fall' towards the nucleus under the influence of the electromagnetic force. Thus, in 1913 Bohr postulated that electrons were constrained to remain on well-defined trajectories, called energy levels. This idea still underlies today's representation of the atom, although we now imagine electrons as 'diffuse clouds' rather than material points. These four models are illustrated here by artistic and non-scientific representations.

Characteristics of the atom constituents: the electron (elementary particle) and the nucleons (the proton and the neutron, made up of quarks)

Masses are expressed in kg and in MeV/c^2. MeV is an energy unit well suited to the study of particles and, through the $E = Mc^2$ formula, the quantity MeV/c^2 does correspond to a mass unit. The electric charges of these constituents are multiples of the elementary charge.

	Electron	Proton	Neutron
Mass	$9.11 \cdot 10^{-31}$ kg 0.511 MeV/c^2	$1.67 \cdot 10^{-27}$ kg 938 MeV/c^2	$1.68 \cdot 10^{-27}$ kg 940 MeV/c^2
Electric charge	–1	+1	0

***Translated from 'De l'atome au noyau'*, Passeport pour les deux infinis, *IN2P3/Dunod*, https://pass2i.ijclab.in2p3.fr/ (French); updated with ICHEP2024 conference (https://ichep2024.org) for IPPOG**