Parity violation in weak interactions: A broken mirror that is the physicists' good luck

Measurement of parity violation in weak interactions, a process discovered just fifty years ago, achieved a very high degree of precision in two experiments in which CEA research workers have been participants. This quirk of nature is now being used as a new probe for the subatomic world, making use of the tiny contribution of the weak force to the interaction of electrons and matter.

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Hall A at the CEBAF accelerator, accommodating the HAPPEx experiment.

From Mme Wu's experiment to Yang and Lee's Nobel Prize

On 9 January 1957, 1949-vintage Château Lafite-Rothschild was served to Mme Chien-Shiung Wu's team, to toast the downfall of **parity symmetry**. That symmetry is indeed violated in the **β decay** of cobalt-60 **atoms**! The finding was published the following week, along with that from Léon Lederman's group, who had also just failed parity symmetry, independently, in a measurement of π **meson**(1) decay. These findings, bringing about an upheaval in particle physics, were the outcome of experiments then-current technology made it possible to set up rapidly. Mme Wu's experiment was the more difficult of the two, owing to the need to cool the cobalt to very low temperatures; Lederman's, on the other hand, was carried out in 36 hours! What had been lacking was the sheer nerve to go out and check on what had thus far seemed "self-evident." Since Wigner's work, in 1927, parity indeed stood as one of the fundamental symmetries of **electromagnetism**. It is often referred to as left–right symmetry, or mirror-symmetry, since it entails that every physical process is equivalent to its own mirror image. Parity predicts, for instance, that a **molecule** and its mirror image have an equal probability of being synthesized in a chemical reaction, a phenomenon that was observed as early as 1848 by Pasteur. Parity likewise underlies the selection rules for **atomic transitions**. Going beyond electromagnetic processes, parity further stands as an exact symmetry for the **strong nuclear** and **gravitational forces**, thus extending its reach from the atomic nucleus to the galaxies! (See Box B, ***Fundamental interactions and elementary particles.***)

(1) A meson is a particle made up of one quark and one antiquark.

The intuitive, empirical character of parity symmetry had thus placed it close to the hearts of physicists. When two young theorists, Chen Ning Yang from Princeton University and Tsung Dao Lee from Columbia University, questioned, in their October 1956 paper, the conservation of parity in interactions governed by the weak force, few of their colleagues were prepared to accept this notion… Lee and Yang had the merit of carrying through a detailed, critical analysis of a troubling experimental finding, the *θ–τ puzzle* (see Box 1), which resists any theoretical interpretation, unless parity violation by the **weak interaction** be adduced. At the time, the only description of this interaction was the theory propounded by Enrico Fermi in 1934, to account for the β decay of the **neutron** into a **proton**, **electron**, and **antineutrino**. Taking its cue from the electromagnetic model, this theory "naturally" included parity. Lee and Yang's suspicions, regarding this natural assumption, deepened, however, when they realized that, counter to what holds for the other interactions, no measurement warranted the claim, or its confutation, of a conservation of parity in weak processes. Their 1956 paper went on to suggest a series of experiments where one such process is compared with its mirror image, as an unambiguous test of parity conservation. Thus it was that, contacted by T. D. Lee, Mme Wu was the first to carry out one of the suggested measurements, going on to prove parity violation a few months later. Lee and Yang were awarded the Nobel Prize the very year the findings were published, in 1957.

The θ - τ puzzle

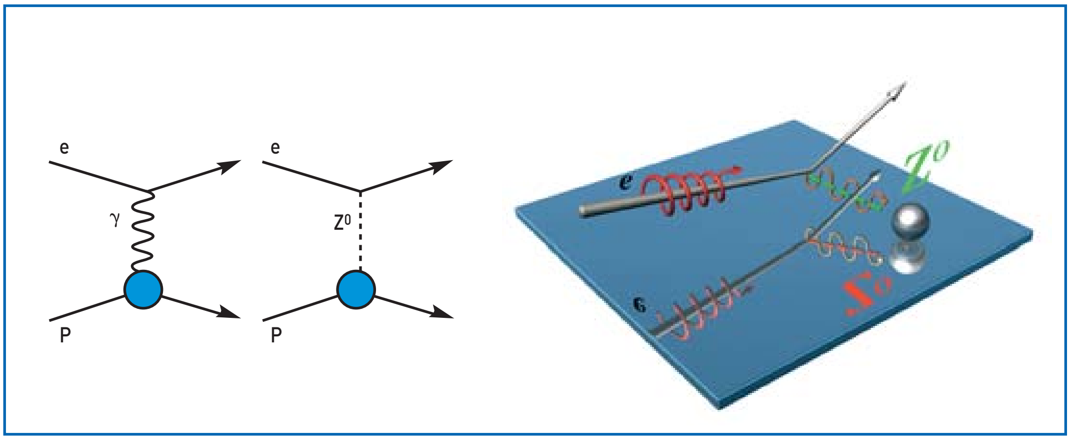
1

Before the first large **accelerators** were built, discovering new, unstable particles relied on observation of **cosmic rays** in *cloud chambers*, i.e. containers holding supersaturated gas where charged particles leave a path materialized by a string of microscopic droplets. Owing to their high energy, cosmic rays reaching the Earth may produce all kind of secondary particles as they interact with the detector. To increase the number of events, laboratories would be set up in high places, where such rays are less attenuated. This was the case, e.g., on the ridge coming down from the Aiguille du Midi, a peak above Chamonix (in the Mont-Blanc range in the French Alps), a ridge known ever since as "Cosmic Ridge" (*"arête des cosmiques"*).
In a similar laboratory in the Andes, C. F. Powell identified, in 1949, a new particle he dubbed the **τ** (tau) **meson**. This particle leaves a signature of its presence in detectors, in that it decays into 3 π (pi) **mesons**, lighter particles he had discovered two years earlier. A further meson, dubbed the **θ** (theta) **meson**, manifests itself through decay into 2 π mesons. Analysis of the events observed showed the masses and lifetimes exhibited by the τ and the θ to be identical, within experimental uncertainties. Such very strong similarities led physicists, logically, to interpret these two objects as being one and the same particle.
The "theta–tau (θ–τ) puzzle" emerged as a result of the paper published by R. H. Dalitz, in 1953, showing that the 2-π and 3-π states exhibit opposite parities. This entails that, if the θ and τ mesons are indeed one and the same object, then their decay mechanism, assigned as it is to the **weak interaction**, violates parity.
This troubling experimental finding is what gave rise to parity symmetry coming under scrutiny, with respect to the weak interaction. Through their survey of then-available measurements, Lee and Yang showed that this "unreasonable" issue did nevertheless remain open, going on to suggest a range of new experiments, which proved decisive. Nowadays, the θ and τ are recognized as forming one and the same particle, known as the kaon.

The electroweak standard model

Fifty years on, physicists still have no idea as to the causes of parity violation, however its manifestations are subject to precise description, and measurement. In the years from 1961 to 1967, Sheldon Glashow, Abdus Salam and Steven Weinberg built up a unified theory of electromagnetic and weak forces, now known as the *electroweak standard model*. One major prediction from that model is the existence of three messenger particles for the weak interaction: two charged particles, the $\mathbf{W^-}$ and $\mathbf{W^+}$, responsible for β^- and β^+ decay, and one neutral particle, $\mathbf{Z^0}$, which does not alter the nature of the particles involved in the reaction. Electroweak unification resides in the fact that the Z^0, the neutral messenger for the weak force, and the **photon**, the neutral messenger for electromagnetism, are "comparable," inasmuch as whenever one of the two is involved in a physical process, then so is the other: there is interference between the weak process, and the electromagnetic process. This may be seen with the example of the **elastic scattering** of an electron on a target proton (see Figure 1). The final state of that reaction, a *scattered* electron and a *recoiling* proton, provides no way of ascertaining which particle was exchanged; a measurement necessarily covers the sum of both contributions.

Does this entail that all so-called electromagnetic processes necessarily include a weak, parity-violating component? In theory, yes indeed. In practice, one fundamental difference sets apart the photon from the Z^0: mass. The photon exhibits zero mass, which endows electromagnetism with an infinite range, whereas the Z^0 is extremely massive – as much as five molecules of water – this resulting in restricting the range of the weak interaction to some 10^{-18} m! This distance being 10 million times smaller than the typical size of an



CEA/DR

Figure 1.
Photon–Z^0 interference in the elastic scattering of an electron on a proton target. The two reaction diagrams yield precisely the same final state, both contributing to the overall number of events measured. The artist's impression, with a photon exchange shown in yellow, and that of a Z^0 shown in green (pink in the mirror image), clearly shows how the process and its "reflection" are not symmetrical.

atom, it may be understood why parity holds as a good selection rule for atomic transitions…

A new instrument to investigate matter

It is nonetheless this tiny contribution from the weak force to the interaction of electrons with matter that recent experiments have been using, as a new research tool. This approach is analogous to the rise of **infra-red**, **X** or **gamma** astronomy (see *Infrared, X- and gamma radiation: nonvisible wavelengths to probe the Universe*). Just as viewing an object at nonvisible wavelengths enriches its description, and our understanding of it, likewise the Z^0 provides a new probe to investigate matter and its interactions, to complement the photon used in most current experiments.

The HAPPEx (Hall A Proton Parity Experiment) experiment, conducted in 2004–5 at the **CEBAF** accelerator at the Jefferson Laboratory (Virginia), in the United States, takes up this approach. Its purpose is to investigate the proton, one constituent in the atomic nucleus. The process used to that end is electron elastic scattering, as seen above. The typical dimension in the problem at hand thus becomes the size of a **nucleon**, i.e. about 1 *fermi* (10^{-15} m). A minute size, still about 1,000 times larger than the range of the weak interaction. The electromagnetic interaction consequently remains overwhelmingly dominant: typically, one million photons are exchanged for every one Z^0… Investigating the Z^0's contribution thus appears about as promising as searching for a pinhead in a haystack. Though a good magnet does prove highly effective in sorting out magnetic material from hay! Likewise, if elastic scattering is subjected to the "filter" of parity symmetry, the "weak" contribution will be perfectly set out from the remainder, as the only one to violate parity.


CERN

Chen Ning Yang and Tsung Dao Lee were awarded the Nobel Prize for Physics in 1957, for their demonstration that the parity principle is invalid for interactions governed by the weak interaction.

The experimental technique thus comes down, in its principle, to that suggested by Lee and Yang: to wit, measuring the differences in counting rates between a process and its mirror image. HAPPEx made use of the CEBAF accelerator's 3-**GeV** ($3 \cdot 10^9$ electronvolts) electron beam. Such an energy is a requisite, if a spatial resolution is to be achieved comparable to the size of a proton. The beam is directed onto a liquid **hydrogen** target (the atomic nucleus of hydrogen being a proton), and a **helium**-4 target (complementing the former, since the helium nucleus comprises 2 protons and 2 neutrons). Part of the scattered electrons are captured by two high-resolution **spectrometers**[2] offset by 6 degrees on both sides of the beam axis (see Figure 2). This instrument selects "elastic" events only, deflecting them onto the detectors. But how to measure precisely the difference in counting rates as found with this setup, and as would occur in a mirror setup, without needing to "turn over" the accelerator and experiment hall? The trick consists in using a beam of **polarized** electrons. In such a beam, electron **spin** is aligned with the direction of propagation (right polarization), or in the opposite direction (left polarization). Reversing beam polarization is physically equivalent to flipping over the accelerator. One is then "through the looking glass"…

Principle of the measurement

If N_R be the number of "right" electrons, and N_L the number of "left" electrons, as detected over equal intervals, $N_R - N_L$ will characterize the difference between the process and its "mirror reflection." This difference is proportional to the number of Z^0 particles exchanged, since only parity violation can give rise to it. And now our pinhead has been sorted out from the hay…! Experimentally, the quantity considered is in fact the difference, divided by the sum, this being defined as the *parity violation asymmetry* (A_{PV}). This carries the benefit of making the measurement independent from many experimental parameters. This quantity is extremely small ($1.6 \cdot 10^{-6}$ for hydrogen, $6.4 \cdot 10^{-6}$ for helium), just as the ratio of the number of Z^0 exchanged, over the number of photons exchanged. This was nevertheless measured, to within a few percent, by HAPPEx. To that end, large numbers of scattered electrons had to be built up, namely some 100 thousand billion electrons.

Such measurements were made possible by the recent development of intense, nearly fully polarized beams. Electrons are extracted from the surface of a gallium arsenide crystal by means of a laser. Electron left or right polarization is determined by the left or right circular polarization of the laser light. This setup allows the required number of scattered electrons to be built up over a few months, a common duration for most accelerator experiments. This corresponds, on the other hand, to several million electrons detected per second. The detectors, designed by the DAPNIA technical departments at CEA Saclay, are optimized to handle very high counting rates, and to withstand the intense radiation generated by the electron flux, depositing an **equivalent dose** of several **megarads** (**Mrad**).

Mastering all the components of the measurement

A major technical challenge is that of sustaining beam stability, when electron polarization is reversed. Thus far, we have considered that switch as involving perfect parity symmetry. In practice, the switch from right to left circular polarization of the laser light for the source requires that an optical component in the laser path be actuated. Each reversal may then slightly alter the parameters of the incoming electron beam, rea-

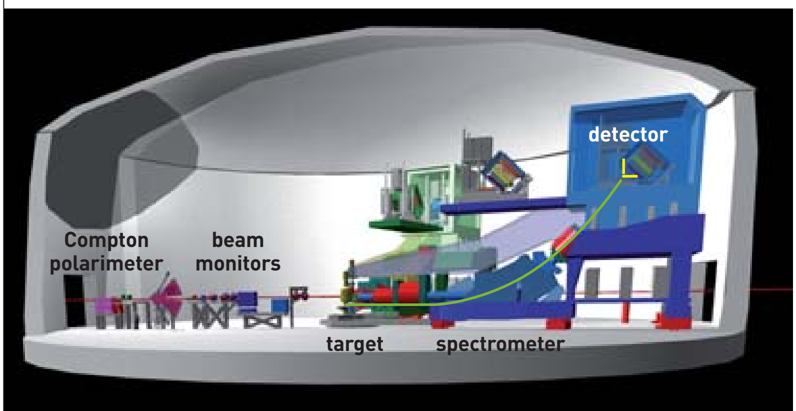


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Figure 2.
The main components set up in the HAPPEx experiment hall.

(2) A set of magnetic elements (dipoles, quadrupoles) allowing very precise selection of charged particles, according to their momentum.

ching the experiment hall (intensity, position, energy…). It will be readily understood that if, for instance, beam position shifts between two polarization states, counting rates N_R and N_L, as returned by the detectors, will differ, however this will have nothing to do with the exchange of Z^0. This would be an instance of *false asymmetry*, generated by faulty equipment. To minimize such false asymmetries, left–right reversals are carried out at a high frequency, in effect 30 times per second, to suppress effects due to slow drifting of the beam. Residual false asymmetries, constantly measured by position and beam current monitors, are eliminated by feedback systems, acting on the electron-source laser. HAPPEx set a record in this respect, by keeping the "left" and "right" beams to the same average positions – to 1 nanometer! Such precision was achieved by averaging continuous beam position measurements through the entire duration of the experiment. Ultimately, overall false asymmetry generated by beam "flaws" was brought down to $1 \cdot 10^{-8}$, i.e. less than 1% of APV.

It is on such extremely high precision, of course, that the degree of relevance depends, of the new light to be shed by the Z^0 on the nucleon. Mastery must thus be achieved for all components in the measurements, to the same level. Concurrent with stability control for the beam, ascertaining its polarization (P_e) is another major technological challenge, taken up by DAPNIA's Nuclear Physics and technical departments, at CEA, in collaboration with the Particle Physics Laboratory (Laboratoire de physique corpusculaire – CNRS), at Clermont-Ferrand (France). Indeed, the spin of the electrons extracted from the source crystal is predominantly aligned (or anti-aligned) with the beam direction, though not wholly so. However, by definition, only those electrons that are so aligned participate in the mirror symmetry being used by the experiment. Other electrons merely dilute the A_{PV} signal, and the dilution factor is equal to P_e. Thus, a 50% polarized beam will halve the sought-for signal, with respect to a fully polarized beam. No theoretical prediction can enable the required precision to be achieved, with regard to P_e, which must therefore be measured. For that purpose, DAPNIA designed a *Compton polarimeter*, a complex device set up on the beam line, its principle being based on interaction between the electron beam and a laser beam resonating within an optical cavity(3) (see Box 2). One major characteristic of the Compton polarimeter is that the electron beam experiences very little perturbation from the laser, this allowing continuous measurement of polarization in actual experiment conditions. With the development of a new analytical method, the precision achieved for P_e is 1%, for a beam

A detector for the HAPPEx experiment, set up at the exit of the magnetic spectrometer. The active component in the detector, a gold color in the photograph, is made up of alternating polished brass and silicon strips. The electron flux is intercepted by these strips, in which it produces a luminous signal, which is taken up by the silicon, and propagated to photomultipliers, which may be seen at either end.

(3) A device comprising two mirrors, separated by an integer multiple of the wavelength of the incident light, successive back-and-forth travels of which allow amplification of the light power as it builds up.

The Compton polarimeter

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Parity violation experiments invariably rely on presence of one (and one only) polarization in the experiment. In the case of electron scattering, this polarization is that of the electrons in the beam. Ascertaining this parameter is decisive, as regards the ultimate precision to be achieved for the measurement. The Compton polarimeter installed in Hall A at the Jefferson Laboratory (JLab) is thus a device carrying out continuous measurement of beam polarization, through the experiment's duration. It is based on the interaction of the polarized electron beam with the photons of a laser beam, likewise polarized (see Figure). This process is known as *doubly polarized Compton scattering*. Due to the presence of a second polarization, the process involving "right" electrons is no longer the image, as obtained through parity, of the process involving "left" electrons. A variation in interaction probability, when electron polarization is reversed, thus turns out to be well allowed by the laws of electromagnetism. The measurement once again relies on measuring an asymmetry, this times however running to several percent. The theory of quantum electrodynamics very accurately predicts that asymmetry. The polarization of the electron beam is simply derived from the ratio of the experimental asymmetry, over the theoretical asymmetry (laser polarization is close to 100%, this being well controlled).

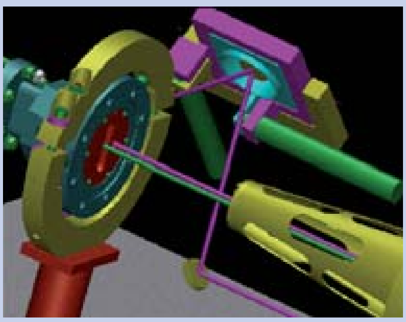
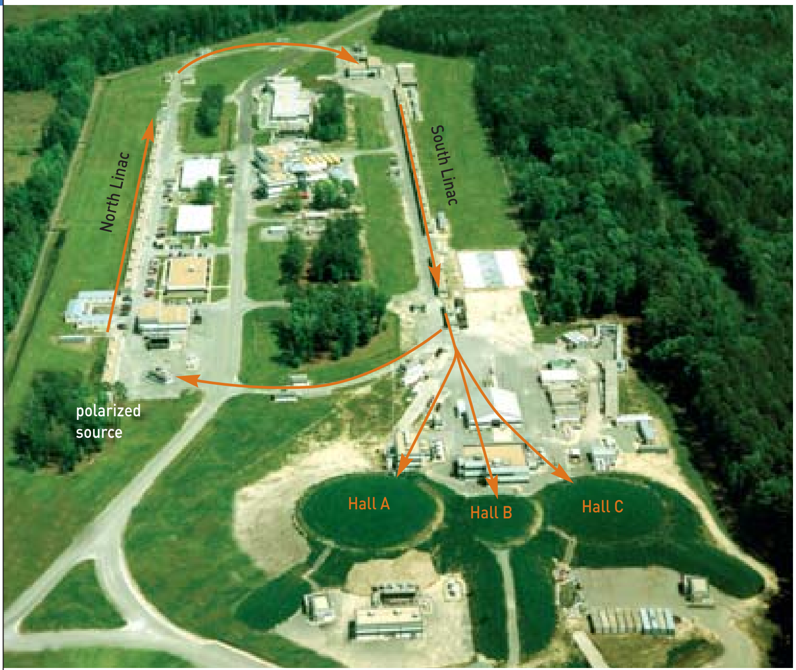


Figure.
At the core of the Compton polarimeter, the laser beam (purple ray) is injected into the accelerator tube, nearly parallel with the electron beam (green). The optical cavity's entrance mirror is held in position at the extremity of the conical part, a few millimeters from the beam. The two beams intersect inside the cavity, where laser power is amplified by a factor 6,000. The entire cavity is kept in a vacuum inside the accelerator's beam tube (not shown here for the sake of clarity).



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Seen from the air, CEBAF, the central element at the Thomas Jefferson National Accelerator Facility.

energy of 3 GeV. A new record to be notched up for HAPPEx, this making the Compton polarimeter a key component for this measurement, as for future high-precision experiments, to be carried out at the CEBAF accelerator.

Exploring the proton's "sea of particles"

What picture of the proton is the *weak* probe sending back to us, via the HAPPEx experiment? Our current understanding of the proton is of a system of three basic quarks, so-called *valence quarks*, bound by the strong nuclear force (see Box B, ***Fundamental interactions and elementary particles***). That force's behavior is analogous to that of a cord linking the quarks. When the quarks draw in to a very short distance, the cord is slack, and the quarks are almost free. When quarks draw away, to distances comparable to the proton radius, the cord becomes taut, and intensity of interaction reaches a very high level. There is then a high probability that this interaction energy will materialize into a quark–antiquark pair, lasting an instant within the proton before it is reabsorbed. The valence quarks are thus seen to swim in a spawning of quark–antiquark pairs (see Figure 3), constantly appearing and being annihilated. Interaction of quarks among themselves plays a crucial part, as regards the proton's properties. For instance, the mass of the sole three valence quarks only accounts for 1% of the proton's total mass. All of the remaining mass resides in the *dynamics* of the strong interaction. This complexity in the structure of the proton is detected by experiments, and predicted, in qualitative terms, by the theory of strong interaction. Quantitative computation, however, starting from the basic principles of the theory, is still beyond our reach. An understanding of the proton thus involves considering models – of increasing sophistication – of its internal structure, drawn up on the basis of experimental findings. Another, highly promising approach is to solve numerically the equations of the theory of strong interaction, by means of so-called *lattice calculations*.

The originality of HAPPEx is its ability to uncover, selectively, the contribution from the "strange" quarks inside the proton. This is a type of quark that is not represented in the valence quarks, but which does appear naturally in quark–antiquark fluctuations. Through the complementary light it sheds, the Z^0 thus behaves as a selective probe for "sea quarks." The HAPPEx experiment is able to access, in particular, the contribution from strange quarks to the distribution of electric charges within the proton, and to its magnetic moment. The finding is compatible with a zero value, and the precision of the measurement makes it possible to set upper bounds of 1% for the contribution to charge distribution, and less than 4% for **magnetic moment**. The experiment has thus just established, through high-precision measurement, that this "sea" of strange quarks makes an astonishingly small contribution to the proton's electric and magnetic properties.

This in no way calls into question the presence of strange quarks and antiquarks inside the proton, however it does entail that their distributions, within the nucleon's volume, must be well-nigh identical! This is an important piece of data, failing as it does predictions from a number of theoretical models, and this now provides a datum point for lattice calculations.

Thanks to the major technological advances achieved with respect to polarized electron beams, the weak probe is thus becoming a new tool, of service in investigations of the atomic nucleus. With the records it set in terms of precision, HAPPEx marks a milestone in our understanding of the proton's internal structure, opening up many further prospects. A vast experimental program is proposing to use Z^0 on the proton, in conjunction with inelastic scattering processes, to test other aspects of its quark structure. For heavier nuclei, the Z^0 presents unique advantages, as regards achieving a better understanding of neutron distribution, data that is of interest to nuclear and atomic physicists, and astrophysicists. Finally, a complementary approach, taken up concurrently, consists in testing the weak interaction itself, by making use of a target of well-known structure. One thing is certain: after 50 years' experimentation, parity violation yet stands at the juncture of many avenues, and is proving to be a choice guide, in the astonishing physics of the infinitely small.

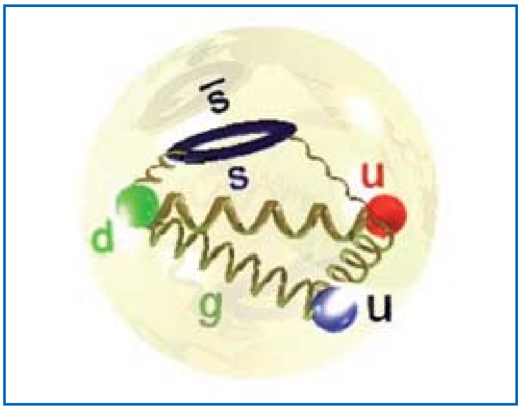

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Figure 3. Schematic showing the proton's three valence quarks: two up quarks (*u*) and one down quark (*d*). The interaction between quarks is shown by the exchange of gluons, the messengers for the strong interaction. One of these is oscillating into a strange–antistrange quark pair.

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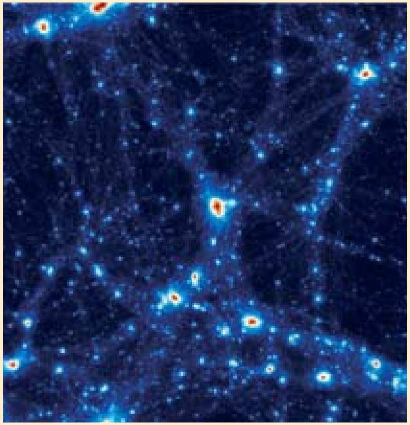
A The standard cosmological model

The **standard cosmological model**, i.e. the currently agreed representation of the Universe, is based on a theory of **gravitation**, Einstein's **general relativity**. This model takes into account a degree of expansion of the Universe, as evidenced by the observations made by US astronomer E. P. Hubble, showing that **galaxies** are receding from one another at a rate that increases with distance.
The model's basic assumptions are that the Universe is *homogeneous*, i.e. that it exhibits throughout identical properties (at a cosmological scale, at any rate), and *isotropic*, i.e. its appearance remains unchanged, in whichever direction it is viewed.
Three parameters characterize the evolution of the Universe, in this model: **Hubble's constant**, first, which characterizes its rate of expansion; **mass density** (the ratio of its own density over a *critical density*); and the **cosmological constant**. Introduced by Einstein in the guise of a force acting against gravitation, in order to account for a stable Universe, this constant rather corresponds to the manifestation of the action of *dark energy*, in an expanding Universe. [1]

If mass density is less than, or equal to, 1, that expansion will carry on indefinitely. The latest observations would appear to support a density of matter equal to 1, this implying a "flat" Universe (i.e. one where the sum of the angles in a triangle is precisely equal to 180°).
The current standard cosmological model involved a radius of the observable Universe of some 45 billion light-years, with an age of around 13.7 billion years, as counted from an initial "singularity" (primordial explosion) known as the **Big Bang**, followed, some 300,000 years later, by an uncoupling of matter and radiation, leading to a stage of **inflation**.
The model further makes it possible to account for the **cosmological background** (diffuse radiation), at a temperature of 2.7 K, and for the fluctuations in radiation/density leading, very early on, to the formation of the initial "seed" structures for the galaxies.



D. Aubert/CEA-C. Pichon (IAP)

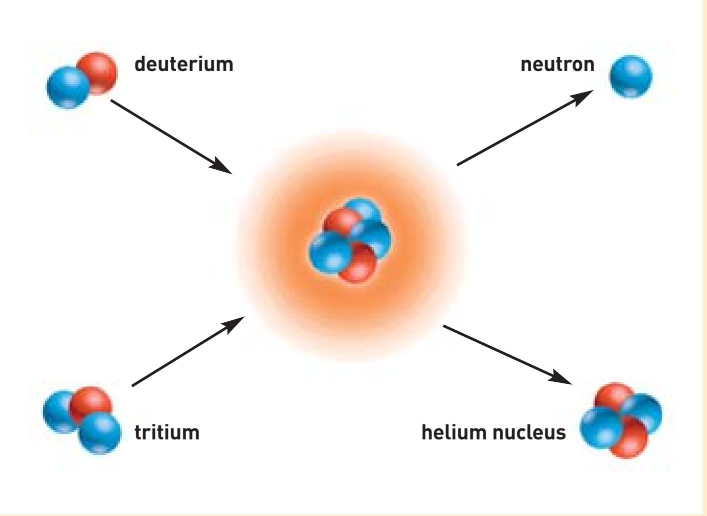
Numerical simulation of a universe during formation, carried out in the context of the Horizon Project, bringing together, around a program targeted at the investigation of galaxy formation, the numerical simulation activities of a number of French teams, including the DAPNIA team (CEA). Its aim is to gain an understanding of the physical mechanisms leading to the structure and distribution of the galaxies around us – and particularly our own, the Milky Way.

(1) Interpretation of measurements from the WMAP (Wilkinson Microwave Anisotropy Probe) space probe, and from SDSS (Sloan Digital Sky Survey) leads to a value close to 71 (km/s)/Mpc ± 0.03 for Hubble's constant, however surprises as to the value of this parameter remain a possibility, should the disconcerting composition of the Universe, whereby 95% of the Universe is made up of dark matter and dark energy, in fact turn out not to be correct.

C The principle of thermonuclear fusion

The **fusion** reaction that is most readily effected is that between **deuterium** (D) and **tritium** (T), two **isotopes** of **hydrogen** (see Figure). This reaction requires that the DT mix be brought to a temperature of 100 million degrees, and that it remain confined for a time meeting the *Lawson criterion*: the product of density by confinement time must be greater than 10^{20} s/m^3. To set up the conditions for fusion of a **light-element** plasma, two confinement methods have been developed: **magnetic confinement**, in tokamaks, corresponding to a stationary regime, where density of the order of 10^{20} m^{-3} is maintained for several seconds by means of a magnetic field; and **inertial confinement** by **laser** beams, or particle beams, an explosive regime where density reaches 10^{31} m^{-3} for some 10^{-11} s.

For further information: see Clefs CEA *No. 49, pp. 45–76.*



D Spectroscopy and spectrometry

Spectrometric methods are subdivided, as a whole, into two main categories, radiation spectrometry – itself comprising absorption spectrometry, emission spectrometry, Raman scattering spectrometry, and nuclear magnetic resonance spectrometry – and mass spectrometry.

Radiation spectroscopy and spectrometry[1] cover a ensemble of analytical methods allowing the composition and structure of matter to be ascertained, based on investigation of the spectra yielded by the interaction between atoms and molecules, and various types of electromagnetic radiation, emitted, absorbed, or scattered by the former.

Depending on their energy, photons interact selectively with the various electron shells, or levels, making up the electronic structure of the atom, or molecule. The electrons involved are *core electrons* (close to the atom's nucleus), for X-rays,[2] *peripheral electrons* (furthest from the nucleus, and involved in chemical bonds) for light absorbed, or emitted, in the near ultraviolet and visible region. In the infrared radiation region, it is the leap from one *molecular vibration* level to another that is involved, the switch from one molecular *rotation* level to another for microwave radiation, and atomic nucleus spin for NMR.

Absorption spectrometry

Those spectroscopy methods that rely on absorption make use of the Beer–Lambert law, setting out the proportional relation between the intensity of light absorbed, and the amount of absorbing matter:

$$A = \log (I_0/I) = \varepsilon\, l\, C,$$

where A stands for the absorbance of the medium traversed, I_0 for incident light intensity, I for transmitted light intensity, ε is the characteristic molar extinction coefficient, for a given wavelength, for the substance investigated – expressed in L mol^{-1} cm^{-1} – while l stands for the thickness passed through, expressed in centimeters, and C is the concentration, in moles per liter.

By measuring the medium's absorbance, for a given wavelength, the concentration of a substance, in a sample, may thus be determined.

In an absorption spectrum, as recorded by means of a spectrometer, *absorption peaks* correspond to the wavelengths the medium is able to absorb. Just as the spectrum from the Sun's light is obtained by making it pass through a prism, which breaks it up, spectrometers analyze the spectral distribution of the whole range of electromagnetic radiations, separating them out according to wavelength, by means of a reflection diffraction grating. Spectra exhibit peaks, each one corresponding to a specific wavelength.

Depending of the type of sample to be analyzed, and the performance level being sought, in the laboratory, absorption spectrometry is used either on molecules in liquid or gaseous phase, or on atomic vapor, obtained through thermal breakdown of liquid or solid samples.

Molecular absorption spectroscopy, in the UV–visible region, affords simplicity of use, however it is only applicable to samples of moderate complexity, since, owing to the width of *molecular absorption bands*, absorption spectra, as a rule, do not allow specific discrimination of every constituent, in a complex mixture.

In infrared (IR) spectrometry, absorption is the outcome of molecular vibration and rotation processes. Infrared absorption spectra thus allow the nature of chemical bonds to be determined, that make up a molecule, by ascertaining the bond's elasticity constant (influencing vibration frequency, as for a spring), thus confirming structural hypotheses.

As the number of atoms increases, the spectrum rapidly exhibits growing complexity, and interpretation becomes highly problematical, especially for organic compounds.

Atomic absorption spectrometry, in this respect, brings higher performance, since absorption by atoms yields very narrow absorption lines. Very precise measurements are thus feasible, even when the sample consists in a complex assembly of chemical elements. Atomic absorption is a reference technique for the analysis of trace elements in a wide variety of samples, in particular for biological samples.

Emission spectrometry

Atoms or molecules brought to an excited state may deexcite by emitting radiation, known as *emission radiation*. When the excitation is caused by selective absorption, by the atoms or molecules to be analyzed, of electromagnetic radiation, this represents a fluorescence emission (or a phosphorescence emission, depending on the electron excitation state involved).

As with absorption, fluorescence may be applied, in the UV–visible radiation region, to molecules, or atoms. X-ray fluorescence spectrometry, on the other hand, refers to the X radiation emitted by atoms excited by absorption of X-radiation. Fluorescence techniques are more complex to implement than is the case for absorption techniques, since they entail that the particle subjected to analysis be selectively excited by a monochromatic radiation. On the other hand, since the radiation emitted is likewise specific to the particle, fluorescence spectrometry involves a double selectivity, resulting in very low background noise, thus making it peculiarly well suited for the measurement of very low concentrations.

Emission of radiation may also occur when atoms are thermally excited, in an environment brought to high temperatures. Emission spectroscopy is based on the fact that atoms, or molecules excited to high energy levels deexcite to lower levels, by emitting radiation (emission, or luminescence). This differs from fluorescence spectrometry in that excitation is not applied selectively, rather it involves indiscriminately all of the particles making up the medium. Emission lines thus correspond to radiation directly emitted by a body brought to a high temperature, and the emission spectrum allows the detection, and quantification, of all atoms present in the emission source.

Raman spectrometry

Interactions between matter and electromagnetic radiation also give rise to scattering processes, such as elastic scattering, and inelastic scattering. Scattering may occur when the interface between

(1) The term "spectrometry," initially used only to refer to recording and measurement techniques, has tended to become synonymous with "spectroscopy," as the eye was supplanted, for observation purposes, by other receptors and instruments, while the visible region now only formed one special region, in analytical terms.

(2) It should be noted, at the same time, that X-ray crystallography is not deemed to be a spectroscopy method, in the strict sense of the term.

two media is encountered, or as a medium is passed through. This process, in most cases, is an "elastic" one, in other words it takes place with no change in frequency for the radiation forming the beam involved. Elastic scattering of solar radiation by the atmosphere is, for instance, responsible for the blueness of the sky, observed when the eye is not directed towards the Sun (*Tyndall effect*). Indeed, scattered intensity is all the greater, the shorter the radiation wavelength, which, in the case of the solar spectrum, corresponds to the color blue.

As regards spectrometry, the main use of scattering concerns *Raman spectrometry*. This involves the inelastic scattering of incident radiation by the molecules making up the sample. The difference between scattered radiation frequency, and incident radiation frequency allows the identification of the chemical bonds involved. Raman spectrometry is a technique that is widely used for structural analysis, to complement infrared spectrometry, and mass spectrometry.

Nuclear magnetic resonance spectrometry

The principle of nuclear magnetic resonance (NMR) is based on the fact that an atom has a *magnetic moment*, just like a spinning charge acting as a tiny magnet, governed by quantum mechanics, aligning in a magnetic field as the needle of a compass in the Earth's magnetic field. The principle of NMR consists in inducing, and detecting, the transition, for the nuclear magnetic moment, from the lowest energy level to the highest energy level, through absorption of electromagnetic radiation of a wavelength lying in the radiofrequency region: when the energy of the photon precisely matches the energy difference between the two levels, absorption occurs. Nuclei having numbers of protons, and neutrons that are both even exhibit zero spin. Carbon 12 and oxygen 16 atoms, which are very widespread in nature, thus have zero spin. On the other hand, hydrogen only has one single proton, and its nuclear magnetic moment equals 1/2: it may thus take on two possible energy states, corresponding to the two orientation states of its spin, relative to the magnetic field. Measuring the resonance frequency in the electromagnetic field allowing transition from one of these energy states to the other enables the molecules to be analyzed. This frequency is fixed, however the various nuclei in a molecule do not all resonate at the same frequency, since their magnetic environment is modified by their chemical (electronic) environment.

C. Dupont/CEA

Spectromètre de masse d'ions secondaires utilisé au CEA pour réaliser des mesures isotopiques rapides sur un échantillon par exemple prélevé sur une installation aux activités nucléaires suspectes.

Many NMR spectra exhibit more peaks than there are protons in the nucleus, owing to the interactions between protons and their neighbors. Two nuclei may interact within the molecule, though they are separated by several chemical bonds: this is known as interatomic coupling. This interaction endows the NMR spectrum with a fine structure.

Mass spectrometry

Mass spectrometry is a highly sensitive *detection* and *identification* technique, allowing determination of molecular structures, and thus of a sample's composition. This is not, strictly speaking, a form of spectrometry, since it is not concerned with discrete energy levels. What is its principle? A compound introduced into the device is vaporized, and subsequently ionized by an electron bombardment source (at 70 eV). The ion thus obtained, termed a molecular ion, allows the compound's molar mass to be determined. Breaking chemical bonds within the compound may yield characteristic fragment ions. These are then sorted according to their mass/charge ratio in an *analyzer*, through application of a magnetic and/or electric field, then collected by a *detector*, which amplifies the signal associated to the ions, which arrive with varying delays. A data processing system converts the information from the detector into a mass spectrum, readout of which, by comparing it with reference spectra, allows the identity details of the molecule to be drawn up. Through use of a high-resolution mass spectrometer, the exact mass of the compound may be determined, together with isotope percentages for each constituent atom.

Choice of ionization method is directly related to the nature of the sample, and the type of analysis. If mass spectrometry has gradually adapted to meet the growing demands from chemists, and biologists (separation of increasingly complex, highly polarized mixtures, determination of ever higher molecular masses on samples of ever more constricted sizes), this is essentially due to advances in *ionization techniques*, these including secondary ion mass spectrometry (SIMS), chemical ionization, thermospray ionization, and fast atom bombardment (FAB) sources, further comprising, from the 1980s, matrix-assisted laser desorption ionization (MALDI), and electrospray ionization (ESI), together with advances in *detection techniques*, from time-of-flight (TOF) measurement to "ion traps" (ITs), through quadrupoles (MS or Q).

In proteomics, for instance, only MALDI, ESI and SELDI (surface-enhanced laser desorption ionization) are employed.

Ion mobility spectrometry (IMS) is a chemical analysis technique in the gaseous phase, which consists in subjecting a gas to an electric field. Ionized molecules acquire a velocity that is characteristic for the ion, since this depends on mass, and charge. Arrival of the ions on one of the plates generating the field results in a current, which is recorded. The length of time after which a peak occurs can be related to the nature of the ion causing it.

Scientists often make use of a coupling of devices each belonging to one of the two main families of analytical techniques (see Box E, *What is chromatography?*), e.g. of a chromatograph with a mass spectrometer (or an electron-capture detector [ECD]), particularly for the investigation of trace complex mixtures.

B Fundamental interactions and elementary particles

The standard model of particle physics is the reference theoretical framework describing all known elementary particles (see Table 1) and the fundamental interactions these particles are involved in (see Table 2). The basic constituents of matter, known as fermions, are partitioned into two main categories, as determined by their partcipation in the fundamental interactions, or forces (the gravitational, electromagnetic, weak, and strong forces), which are mediated by vector bosons, the fundamental particles which carry out the transmission of the forces of nature[1] (see Table 2). Whether a particle belongs to the category of fermions, or to that of bosons depends on its spin (i.e. its intrinsic angular moment, or internal rotation moment), depending on whether it exhibits half-integer spin (fermions) or integer spin (bosons).
At the same time, to every constituent of matter is associated its antiparticle, a particle having the same *mass*, but the opposite *charge*. The positron is thus the positively charged antiparticle of the electron, which exhibits a negative charge.

Leptons and quarks

Fermions include, on the one hand, leptons, which may travel freely and do not participate in the *strong interaction*, which ensures the cohesion of atomic nuclei (it is consequently termed a *nuclear* interaction), and, on the other hand, quarks, which participate in all interactions but are not individually observed, enmeshed and confined as they are within hadrons, the particles susceptible to strong interaction, of which they are the constituents.[2]
In the lepton category, charged leptons participate in the *electromagnetic interaction* (which ensures the cohesion of atoms and molecules, and in the *weak interaction* (which underlies decay processes, in particular β radioactivity). Neutral leptons, or neutrinos, for their part, participate in the weak interaction only. Exhibiting very low mass, there is one type of neutrino for each type of charged lepton.
Independently from their involvement in interactions, the basic constituents of matter are classified into three *generations*, or *families*, of particles. From one family to the next, quarks and leptons having the same charges only differ by their mass, each family being heavier than the preceding one.
The electron, up quark (symbolized *u*) and down quark (symbol *d*), which belong to the first generation, are the lightest massive particles, and are stable. These are the sole constituents of normal matter, so-called baryonic matter (a baryon is an assembly of quarks), which is made up of protons and neutrons, this however only accounting for 4% of the Universe's energy content!
Particles in the other two families are heavier, and are unstable, except for neutrinos, which on the other hand exhibit non-zero mass, but are stable. These latter particles may only be observed or detected in the final states resulting from collisions effected in accelerators, or in cosmic radiation, and rapidly decay into stable first-generation particles. This is why all the stable matter in the Universe is made up from constituents from the first family.
According to quantum mechanics, for an interaction to take place between particles of normal matter, at least one elementary particle, a boson, must be emitted, absorbed, or exchanged. The photon is the intermediate (or vector) boson for the electromagnetic interaction, the W^+, W^- and Z are the intermediate bosons for the weak interaction, and gluons are those of the strong interaction, acting at quark level.
As to the graviton, the putative vector for the gravitational interaction, it has not so far been empirically discovered. The gravitational force, which acts on all fermions in proportion to their mass, is not included in the standard model, due in particular to the fact that quantum field theory, when applied to gravitation, does not yield a viable scheme, as it stands. While gravitational effects are negligible in particle physics measurements, they become predominant on astronomical scales.

Interaction ranges

Quarks and charged leptons exchange photons. The photon having no electric charge, these particles conserve their electric charge after the exchange. Since the photon's mass is zero, the electromagnetic interaction has an infinite range. Having no electric charge, neutrinos are the only elementary fermions that are not subject to electromagnetic interaction.
In the electroweak theory (a unification of the weak and electromagnetic interactions), the weak interaction has two aspects: charged-current weak interaction, for which the interaction vectors are the W^+ and W^-; and neutral-current weak interaction, for which the mediator is Z^0. These two forms of weak interaction are active between all elementary fermions (quarks, charged leptons and neutrinos). The mass of these bosons being very large (about 80 GeV/c^2 for $W^\pm$, 91 GeV/c^2 for Z^0), the range of the weak interaction is tiny – of the order of 10^{-18} m. Since $W^\pm$ bosons have a non-zero electric charge, fermions exchanging such bosons undergo a change in electric charge, as of nature (*flavor*). Conversely, since the Z^0 boson has no electric charge, fermions exchanging one undergo no change in nature. In effect, neutral-current weak interaction is somewhat akin to exchanging a photon. As a general rule, if two fermions are able to exchange a photon, they can also exchange a Z^0. On the other hand, a neutrino has the ability to exchange a Z^0 with another particle, though not a photon.
Only those quarks that have a color charge[1] exchange gluons, these in turn being bearers of a color charge. Thus,

(1) The participation of basic constituents in fundamental interactions is governed by their *interaction charges* (electric charge, color charge), or "conserved quantum numbers." *Color charge*, a quantum number that determines participation in strong interactions, may take one of three values: "red," "green," or "blue" (these colors bearing no relation to visible colors). Every quark bears one of these color charges, every antiquark one of the three anticolor charges. Gluons are endowed with double color–anticolor charges (eight combinations being possible).

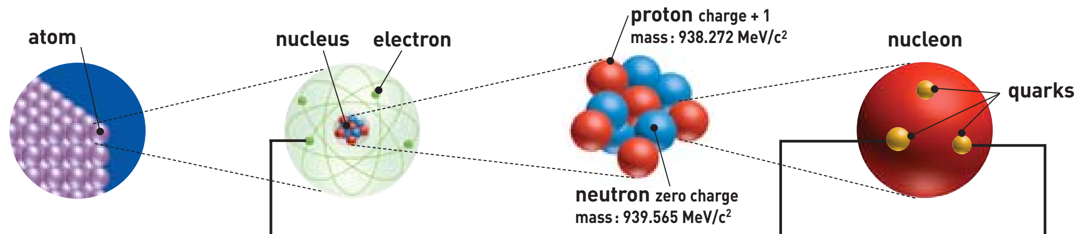
(2) To take e.g. nucleons: the proton holds two up quarks and one down quark, the neutron two down quarks and one up quark. A meson is made up of just two quarks (one quark and one antiquark).

B (cont'd)

when a gluon exchange takes place between quarks, the latter exchange their respective colors. Gluons have zero mass, however, since they do bear a color charge, they are able to interact together, which greatly complicates theoretical treatment of this interaction. The range of the strong interaction is consequently very restricted – of the order of 10^{-15} m.

The quest for unification

The theoretical framework for the standard model is quantum field theory, which allows a quantitative description to be made of the fundamental interac-



		leptons able to move freely		**quarks** assembled into triplets, or quark–antiquark pairs, to form the many subatomic particles	
Fermions Normal matter is made up of particles from this group.	First family	**electron (e)** responsible for electricity and chemical reactions charge:- 1 mass : 0.511 MeV/c²	**electron neutrino** (ν_e) has no electric charge, and interacts very seldom with the ambient medium.	**down (*d*)** electric charge: - 1/3 the proton holds one, the neutron two mass : 4 – 8 MeV/c²	**up (*u*)** electric charge: + 2/3 the proton holds two, the neutron one mass : 1.5 – 4 MeV/c²
Most of these particles were around just after the Big Bang. Presently only to be found in cosmic rays, and around accelerators.	Second family	**muon (μ)** a more massive companion to the electron. mass : 105.658 MeV/c²	**muon neutrino** (ν_μ) properties similar to those of the electron neutrino.	**strange (*s*)** a heavier companion to "up" mass : 80 – 130 MeV/c²	**charmé (*c*)** a heavier companion to "down" mass : 1.15 – 1.35 GeV/c²
	Third family	**tau particle (τ)** heavier still. masse : 1,776.99 ± 0.29 MeV/c²	**tau neutrino (ν_τ)** properties similar to those of the electron neutrino.	**beauty (*b*)** tau particle. mass : 4.1 – 4.4 GeV/c²	**top (*t*)** heaviest in the family (observed in 1995) mass : 171.4 ± 2.1 GeV/c²
Vector bosons Fundamental particles carrying out transmission of natural forces.		**photon** elementary grain of light, vector for the electromagnetic force	**gluon** bearer of the strong force between quarks	**$W^\pm$, Z^0** bearers of the weak force, responsible for some forms of radioactive decay	
Higgs boson?		responsible for "electroweak symmetry breaking"			

Tableau 1.
Table showing the twelve elementary constituents for which the standard model describes the interactions involved. The three charged leptons (electron e-, muon, μ^-, tau particle τ^-) are subject to electromagnetic and weak interactions, neutrinos (ν_e, ν_μ, ν_τ) are only affected by weak interaction, and the six quarks (up, charm, top – or *u*, *c*, *t* – bearing a charge of 2/3; and down, strange, bottom – *d*, *s*, *b* – bearing a charge of – 1/3) are subject to all three interactions. Every elementary constituent has its antiparticle, having the same mass, and algebraic quantum numbers (such as electric charge) of the opposite sign.

tions between elementary particles, while respecting the principles of *special relativity*, as those of quantum mechanics. According to the latter theory, if one seeks to observe a microscopic structure at high temporal and spatial resolution, this entails transferring to it an amount of energy–momentum, the greater, the higher the resolution being sought. However, according to the theory of relativity, such an energy–momentum transfer is liable to undergo transformation, yielding particles not present in the initial state: fermions may be generated, or annihilated, in particle–antiparticle pairs, while bosons may be so in any arbitrary number.

All processes involving one and the same fundamental interaction are interrelated. The quantum field theory approach, in which properties of **symmetry** play a fundamental part, seeks to describe all of the processes relating to each fundamental interaction, within overarching theoretical constructions.

The strong and electromagnetic interactions are formalized, respectively, in the theories of **quantum chromodynamics**, and **quantum electrodynamics**. The weak interaction, for its part, is not subject to a separate description, being described jointly with the electromagnetic interaction, in the unified formalism of **electroweak theory**. Theories of the *grand unification* of all fundamental interactions do exist, however they remain as yet lacking any experimental validation.

All the predictions of the standard model have been corroborated by experiment, except for just one, to wit, the existence of the **Higgs boson(s)**, which particle (particles?), it is hoped, will be discovered with LHC. The **Higgs mechanism** is thought to be responsible for the mass exhibited by elementary particles, the eponymous boson making it possible for zero-mass fermions interacting with it to be endowed with mass. This would allow the unification, at high energies, of the weak and electromagnetic interactions within the electroweak theory, while effectively accounting for the **breaking** of this **electroweak symmetry** at low energies, taking the form of two interactions, which may be seen as distinct at that energy level (see *The electroweak interaction from one accelerator to the next: the LHC roadmap and the yardstick of LEP measurements*, p. 23).

Going beyond, or completing the standard model?

The standard model features a set of parameters (such as the masses of elementary particles, or the intensities of fundamental forces) which are "anchored" in experimental findings. It is, in any event, a theory that is liable to be improved, or further elaborated, or even surpassed and left behind. It does not account in any way for the classification of the constituents of matter into three generations of particles, whereas it is precisely the existence of these three generations which makes it possible to account for **CP** (charge–parity) **invariance violation** (meaning that a physical process involving the weak interaction is not equivalent to its own mirror image), a violation that is in all likelihood the source of the matter–**antimatter** imbalance, running in favor of the former, in the primordial Universe. The model neither allows quantum treatment of gravitation, nor does it fully account for the fundamental property of *confinement*, which prevents quarks from propagating freely outside hadrons.

To go beyond, or to complete the standard model, research workers are mainly exploring two avenues:

– **supersymmetry** (widely known as SUSY) would associate, to every particle (whether a boson or a fermion) in the standard model, a partner from the other series, respectively a fermion or a boson. Supersymmetric partners would, at first blush, be highly massive, the lightest of them being a particle interacting very weakly only. This would be an ideal candidate to account for the **hidden matter** (or **dark matter**) in the Universe, accounting as it does for some 21% of the Universe's energy content, the remainder (close to 75%) consisting in a **dark energy**, the nature of which likewise remains to be determined. These WIMPs (acronym for "weakly interacting massive particles") are actively being sought (see *EDELWEISS II, the quest for dark matter particles*);

– the **substructure** path assumes there could be a new level of elementarity, underlying the particles in the standard model (or some of them). This would lead to a veritable blossoming of new, composite particles, analogous to hadrons, but exhibiting masses two to three thousand times heavier.

It should be noted that, whereas supersymmetry theories yield predictions that agree with the precision measurements carried out at LEP, the theories propounding substructures (or their simpler variants, at any rate) fail to do so. As for the more complex variants, these are encountering difficulties at the theoretical level.

fundamental interaction	associated particles (messengers)	actions
gravitation	graviton?	having an infinite range responsible for the mutual attraction of any two masses and for the law of falling bodies
electromagnetic interaction	photon	having an infinite range responsible for the attraction between electrons and atomic nuclei, hence for the cohesion of atoms and molecules
weak interaction	W^+, W^-, Z^0	responsible for β^- and β^+ radioactivity, reactions involving particles as neutrinos
strong interaction	gluons (there are 8 gluons)	ensures the cohesion of the atomic nucleus

Tableau 2.
Fundamental interactions, their vectors, and effects.

E What is chromatography?

Chromatography, together with the various forms of spectroscopy and spectrometry (see Box D, *Spectroscopy and spectrometry*), represent the two major basic analytical techniques, the former serving for the separation, the latter for the identification of the constituents of a substance.

Chromatography (from the Greek *khrôma*, "color," and *graphein*, "to write"), allows the *separation* of the constituents of a mixture in a homogeneous liquid or gaseous phase, as blotting paper might spread out in concentric rings a liquid poured onto it.

A chromatograph comprises a sample injection device, a *column*, a detector, and a recording and analysis system. Its principle is based on the equilibrium of compound concentrations, between two phases coming into contact: the *stationary phase*, in the column, and the *mobile phase*, which moves across it. Separation relies on the differential displacement of constituents inside the column, passing through in times that are proportional to their size, or depending on their structure, or affinity for the stationary phase (polarity...). As they reach the far end of the column, a *detector* measures, on a continuous basis, the quantities of each constituent.

The most common form of chromatography is gas chromatography, carried out on gaseous samples, or samples that may be vaporized without incurring breakdown. The mobile phase is a gas (helium, nitrogen, argon, or hydrogen), constantly sweeping through the column, which is placed in a thermostat oven. Detectors allow the selective analysis and identification of highly complex mixtures.

If the stationary phase is a nonvolatile, or not highly volatile liquid, exhibiting solvent properties for the compounds to be separated, the process is termed gas–liquid chromatography, or *partition chromatography*. If the stationary phase is an adsorbent solid (silica, alumina, zeolites, or polymers), this is gas–solid chromatography. Within this same family, of adsorption chromatography processes, liquid–solid chromatography is characterized by its stationary phase, this being a polar solid.

In high-performance liquid chromatography (HPLC), the sample must be wholly soluble in the mobile phase (elution solvent). The latter must be kept at high pressure (hence the alternative name of *high-pressure* liquid chromatography), to ensure a constant flow rate inside the column, and preclude any loss of head. HPLC involves solute–mobile phase–stationary phase exchange mechanisms, based on partition or adsorption coefficients, depending on the nature of the phases in contact.[1]

A chromatographic analysis yields a chromatogram, this being a graphical representation of the evolution of a parameter (intensity of the detector signal), related to instantaneous solute concentration, as function of time. This exhibits *peaks*, rising above the *baseline*, which obtains in the absence of any compounds (see Figure).

(1) There are two further types of liquid chromatography, *ion chromatography*, and *exclusion chromatography*.

N.B: This Box reproduces a number of excerpts from a presentation by Pascale Richardin, head of the Datation Group at the Research and Restoration Center of the French National Museums Administration (Musées de France), taken from the pages dealing with analytical methods, as posted on the site : ttp://www.culture.gouv.fr/culture/conservation/fr/biblioth/biblioth.htm

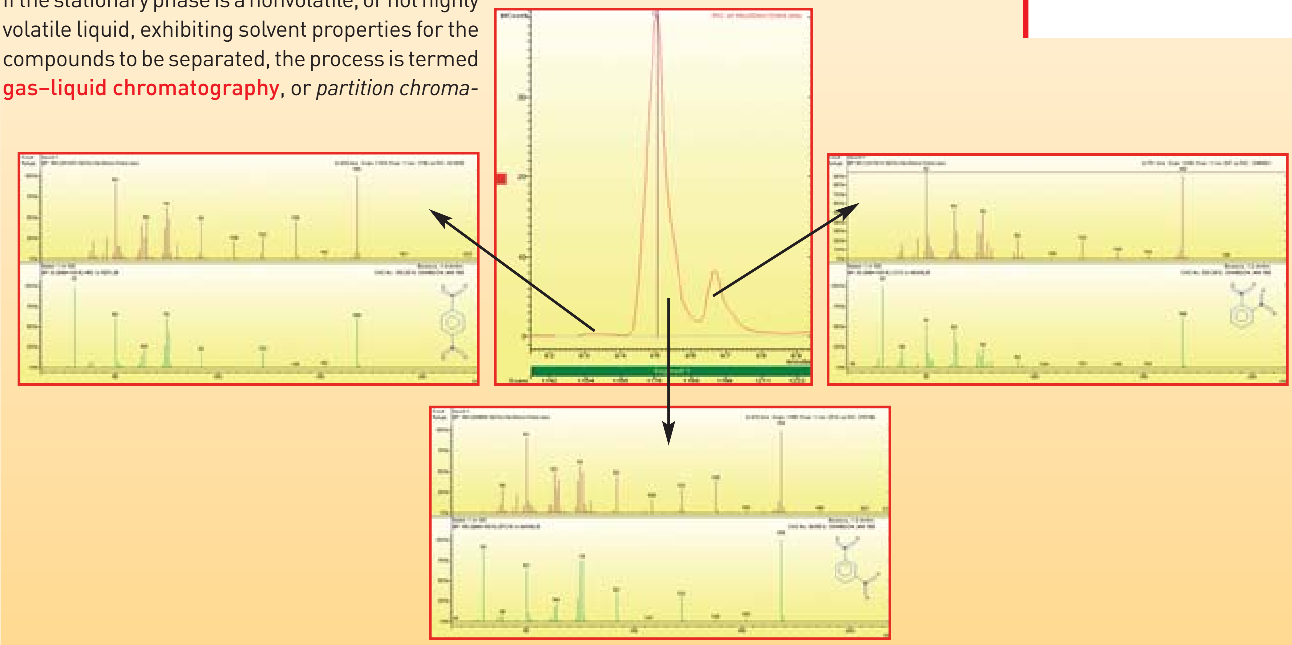


Figure.
An example of the combined use of mass spectrometry and chromatography: the separation of isomers ("sister molecules") of an explosive molecule (dinitrobenzene [DNB]), after solid-phase microextraction sampling, by gas chromatography, and their detection by mass spectrometry (SPME–GC–MS).