The temperature of the core plasma in a magnetic fusion reactor must be held at more than 100 million degrees, while the plasma's periphery must remain cool. Reactor size is thus constrained by the requisite for an ability to sustain a steep temperature gradient inside the plasma, with minimal reliance on an outside power supply. Bringing down the size, and thus the cost, of a fusion machine thus entails minimizing turbulent transport, which tends to relax the temperature gradient. Precise diagnosis of turbulent transport is thus a major challenge: meeting it will enable improved understanding of transport, and enhanced ability to control it. This will be part of the remit for the ITER experimental machine.

Seeking out **turbulence** in **magnetic fusion plasmas**

In a **magnetic fusion** reactor (see Box C, ***The principle of thermonuclear fusion***), a ring, or torus, of **deuterium** and **tritium plasma** is confined by means of magnets. It is in the core of that ring, at a temperature of more than 100 million degrees, and a pressure of several atmospheres, that fusion reactions may occur. The plasma surrounding the core plays the role of an insulator; in this plasma, temperature falls off very rapidly, as distance from the core rises. The edge of the ring, coming into contact with the walls, is at a temperature of "barely" a few thousand degrees (see Figure 1).

One fundamental challenge, in fusion investigations, is to ensure adequate insulation of the plasma core, so that it may be virtually able to achieve "self-heating:" 80–90% of the heat required to sustain its temperature must be yielded by the fusion reactions set up in the core. Indeed, were the heating power to be supplied to the core, to complement "self-heating," to rise above 10–20%, too large a proportion of the electric power generated by the reactor would then be consumed, to power the heating systems.

If heat transport within the "insulator" plasma were solely governed by the collisions occurring between charged particles in the plasma, the plasma core would be adequately insulated, once it was surrounded by about 100 cubic meters of insulator plasma. Current machines, such as JET (Joint European Torus), in Europe, or JT-60, in Japan, could then enable power generation. In practice, the plasma's insulation capacity is 10–100 times lower than predicted by the collisional model. The experimental ITER (International Thermonuclear Experimental Reactor) machine, despite its 840 m^3 of plasma, should only be self-heating to about 70%. The reason for such a low thermal insulation capacity is that, on top of collisional transport,

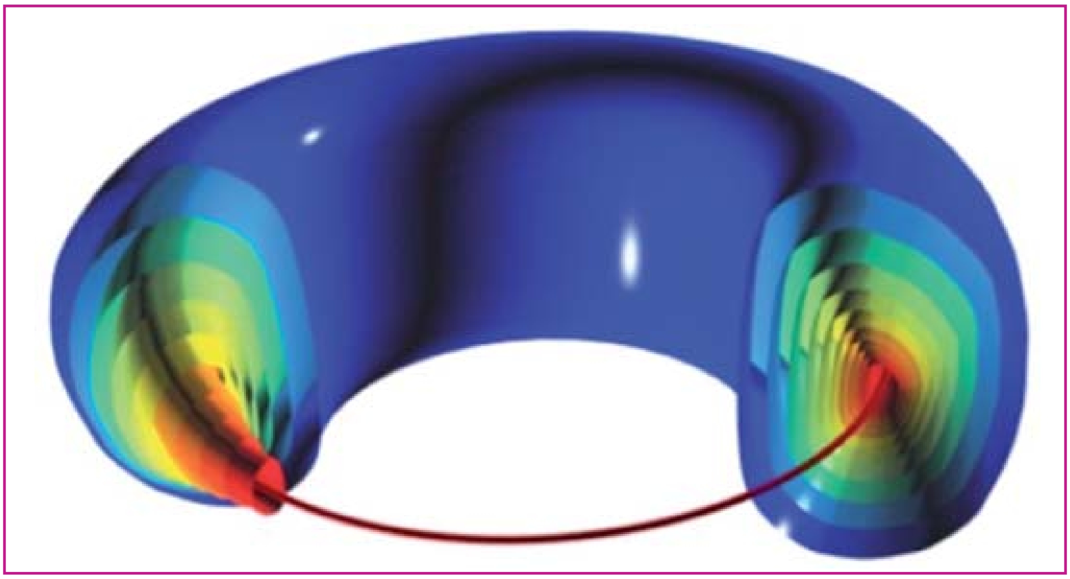
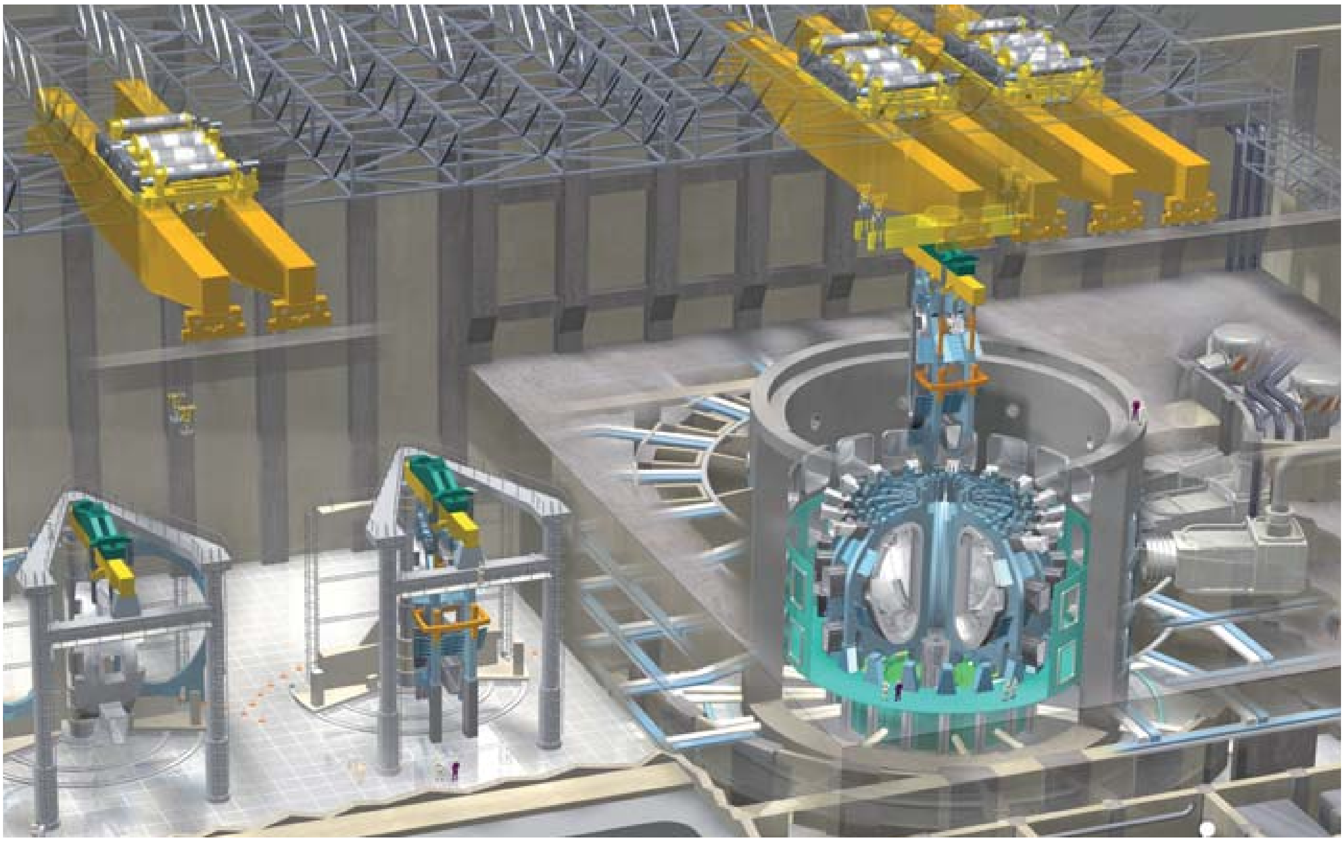


Figure 1.
Structure of the plasma ring of a magnetic-confinement fusion reactor. Shown in red, the plasma core, at a temperature of more than 100 million degrees, but at a pressure no greater than a few atmospheres. It is in the plasma core that fusion reactions occur. Surrounding the core, the insulating plasma, increasingly "cool" as distance from the core rises.



Eric Verdult/New Media Design/ITER

The ITER reactor, as it will stand inside the building housing it, at the Cadarache site (Bouches-du-Rhône *département*, southern France)

comes a degree of **turbulent** transport,(1) which proves far more effective in degrading insulation. This transport is due to small-amplitude turbulences, for which characteristic dimensions may be as small as one millimeter, exhibiting frequency spectra that range up to one million hertz.

While fusion plasma diagnostics are indispensable, to control the plasma and ensure protection of the machine, they are increasingly taking on a fundamental role in the investigation of turbulence, which is still poorly understood, even though major advances have been achieved over the past few years. Ideally, the **spatial** and **temporal resolutions** they achieve should stand, respectively, at around one millimeter, and one microsecond. The low signal-to-noise ratio such resolutions entail clearly indicates how arduous the task will be. The more so since the signals, tenuous as they often are, must be extracted from the background noise of charged particles, **neutrons**, and **photons** released by the plasma, exhibiting a broad energy spectrum.

The characteristics of the magnetic fusion plasmas to be diagnosed – apart from their temperatures, ranging from hundreds of millions of degrees to a few thousand degrees, and their densities, standing at around 10^{20} particles per cubic meter – include high magnetization (typically, 5 teslas), the presence of powerful electric fields and high current densities, at any rate for the **tokamak** configuration, the most widespread, as used for JET and ITER. The complexity of the physics of the processes being diagnosed sometimes entail turning to **modeling**, to interpret readings. It is thus prudent to use a number of different methods, to measure the selfsame physical quantity.

The challenges set by fusion plasma diagnosis may be appreciated, if one considers the number, and cost, of the devices deployed around the main fusion machines: several tens of devices, for an overall cost that may run to 10% of total costs for the machine. Far from standing still, the area of fusion plasma diagnostics is undergoing permanent change, a change driven by new issues raised by the discovery of new turbulence regimes, and developments in technology.

Without going into the detail of detection techniques, or seeking to provide an exhaustive survey, the principles of a few diagnostics are presented here, by way of illustration of the variety of approaches implemented, in the three existing categories: *passive diagnostics*, i.e. nonperturbing diagnostics, whereby signals emitted by the plasma are merely measured; *active diagnostics*, whereby it is signals from the interaction of wave/particle beams that are measured; and, finally, probes, i.e. objects introduced into the plasma (see Figure 2).

Passive diagnostics, "respecting" the plasma

"Passive" measurement of the characteristics of waves/particles emitted by the plasma, over a broad frequency/energy range, provide information on the plasma, while causing it no perturbation.

Electromagnetic radiation from the plasma

For lower frequencies (down to 100 hertz or so), measurement of the slowly varying electromagnetic field at the periphery of the plasma allows the plasma's shape and position to be determined, along with the total current circulating in it, and its pressure. At higher frequencies (up to several MHz), electromagnetic signals

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(1) On this issue, see *Clefs CEA* No. 49 (Spring 2004), p. 56

allow characterization of the turbulence arising on resonant magnetic surfaces. The magnetic field is measured through integration of the voltage read at the terminals of small coils.

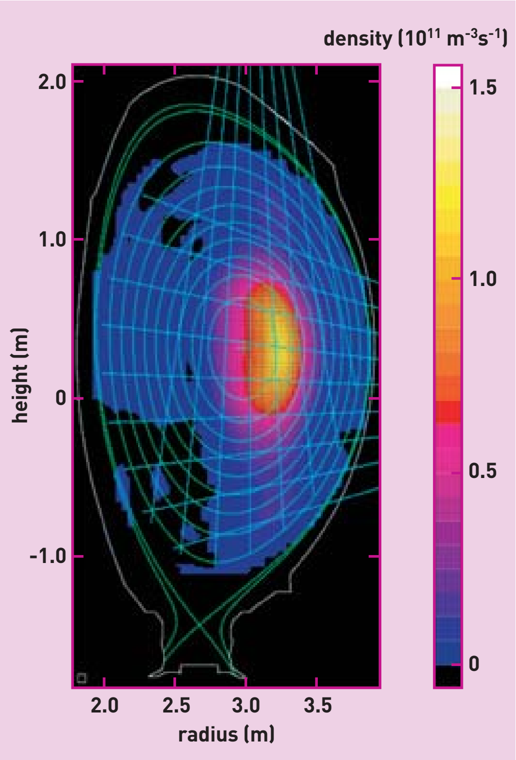
The rotational motion of the **electrons** in the plasma, along magnetic field lines,(2) generates an electron cyclotron radiation, for which the frequency, standing at a few tens of GHz or so (centimetric wavelengths), depends on the intensity of the magnetic field. Once the variation over space of the magnetic field is known, measurement of that frequency allows the emission point to be localized; measurement of the intensity allows the plasma's electron temperature to be arrived at.

Spectroscopy enables the investigation of emissions from plasma, for the region where optical techniques can be employed, in practice in a range from 10 micrometers to 1 picometer (from **infrared** to **hard X-rays**). Measurement of the **line** spectra emitted by **ions** in the plasma allows plasma ion and electron temperatures to be worked out, along with the plasma's rotation velocity.

The **bremsstrahlung** from electrons scattering on ions exhibits a continuous spectrum. Measuring this allows the plasma's impurity content to be arrived at, along with electron temperature (**soft X-rays**), and the properties of the populations of high-energy electrons, accelerated by electric fields (hard X-rays).

Fusion products

The fusion reactions occurring in the core plasma yield **gamma** rays, neutrons, and charged fusion products (**protons**, tritium, **helium 3**, **helium 4**…), either directly, or through secondary reactions with impurities. The energy of these waves/particles typically lies in the 0.5–14-**MeV** bracket.



EFDA/JET

Density mapping of alpha particles of energies higher than 1.7 MeV, in JET. These high-energy particles were produced by heating. Blue lines correspond to the sightlines of gamma-ray detectors (liquid scintillators). Precision at the center stands at around 10 cm.

Measurement of the flux of gamma rays and neutrons, along different sightlines, allows mapping, by **tomography**, of fusion reaction rates, and characterization of **alpha particle** confinement, these particles heating the plasma core.

Analysis of the neutron spectrum allows the velocity distribution for nuclei yielded by fusion to be evaluated, together with a possible collective rotation velocity for such nuclei. Neutrons are analyzed by transferring their energy to protons, by way of **elastic collisions**. These protons, being charged, may be analyzed in a magnetic field

Exhibiting high energies as they do, charged fusion products escape from the plasma in far from negligible proportions. By exposing samples to impacts from these products, and analyzing them by gamma spectrography, such charged particle fluxes may be characterized.

Neutral particles

Large numbers of neutral particles, stripped from the walls, enter the plasma, and may exchange electrons with ions in the plasma. Neutralized ions cease to be confined by the magnetic field, and exit the plasma. Analysis of these ions allows their temperature to be worked out, together with the concentrations for various ion species (e.g. the proportion of deuterium to tritium). On large machines, neutrals do not penetrate very deep into the plasma before they become ionized: such measurements are thus restricted to the plasma edge. Nevertheless, alpha particles, generated in the core plasma but poorly confined, may yet be neutralized at the edge, and be subjected to analysis.

Active diagnostics: more accurate localization

In an active diagnostic, a wave/particle beam is injected into the plasma. The energies the beams involve must be low enough not to cause excessive disturbance of the plasma, high enough however to permit extraction of the latter's response from noise. Beam modulation allows the signal-to-noise ratio to be enhanced. Localization of the measurement region may be improved, compared with passive diagnostics, provided beam propagation is well characterized.

Reflectometry

A wave traveling through a plasma of varying density undergoes reflection at the point where electron density reaches a critical value. By injecting beams of varying frequencies (20–1,000 GHz) into the plasma, the electron density profile may be mapped.

Interferometry and polarimetry

Infrared/submillimeter laser beams are aimed through the plasma along different sightlines. Using interferometry, phase change is measured by comparison with a reference beam that does not go through the plasma, allowing the electron density profile to be established. Polarimetry involves measurement of the rotation of beam polarization induced by the magnetic field, yielding the current profile inside the plasma.

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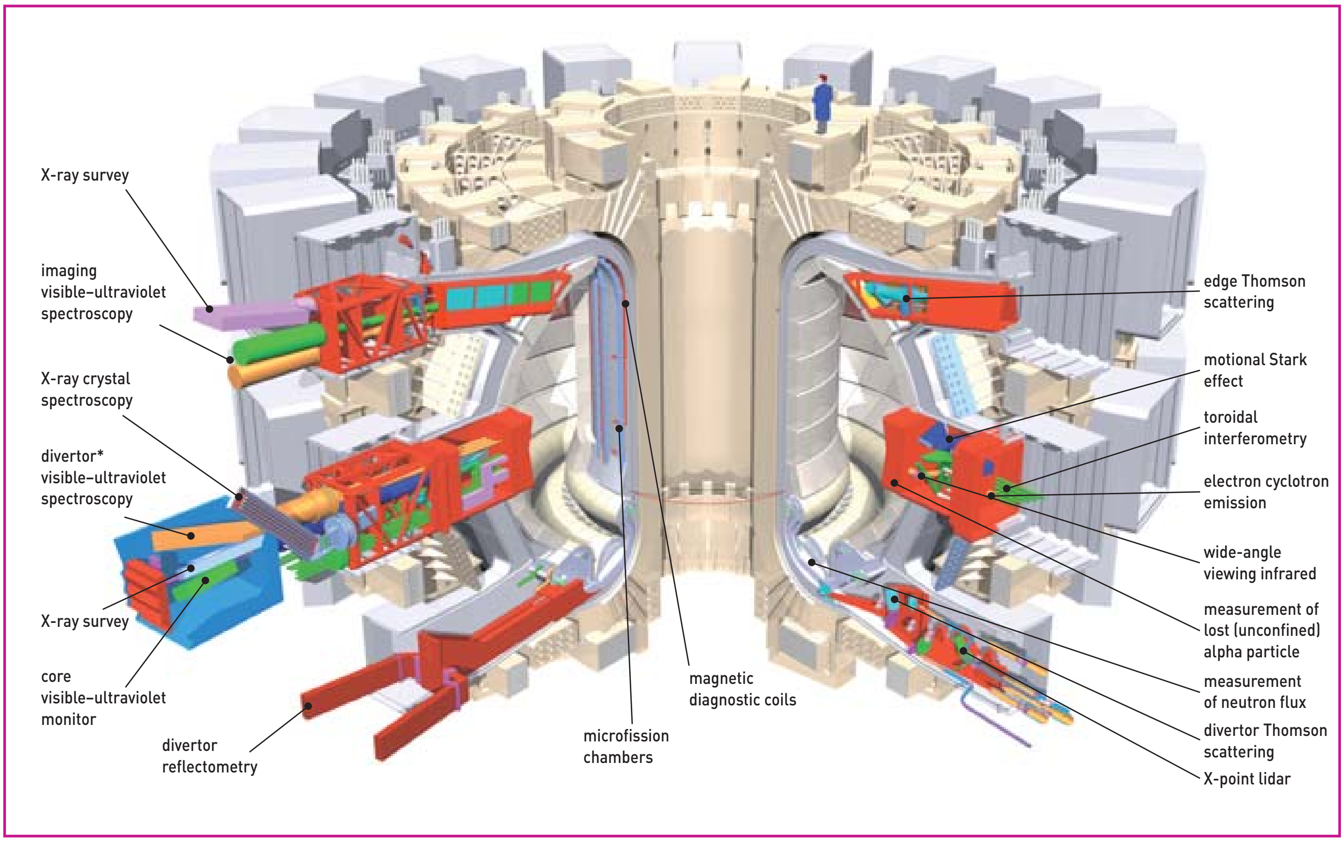
(2) Magnetic field lines are imaginary lines, tangential to the magnetic field at every point, along and around which the paths of charged particles in the plasma spiral.



* Divertor: the lower level of the machine, where open magnetic field lines intercept the wall. Heat flow is very high in this region. This region also receives the exhaust from the pumping ducts used to evacuate plasma polluted by helium, i.e. fusion "ash," and by impurities stripped from the wall

Figure 2.
The sightlines for ITER diagnostics. Of the 500 MW fusion power the machine should yield, 400 MW will come in the form of 14-MeV neutrons. Massive use of bayonet-geometry sightlines, and/or mirrors will make it possible to limit neutron flux over the detectors.

Thomson scattering

Light from a **visible**-light or near-infrared (micrometric-wavelength) laser beam is scattered by electrons in the plasma, rather like a ray of sunlight is scattered by suspended dust motes. Measurement of the intensity of the scattered light allows the density to be arrived at. The **Doppler effect** resulting from the electrons' velocity shifts the wavelength of scattered light, relatively to that of the monochromatic laser beam. Spectrum analysis of the scattered light yields the electrons' velocity distribution, and thus their temperature. By emitting very short laser pulses, and monitoring the light scattered along the entire pulse path, electron density and temperature profiles may be obtained from measurement of flight time (lidar).

Charge-exchange spectroscopy

Most of the impurities present in the plasma core have shed all their electrons, and emit no line spectra. Beams of neutral atoms (H, D, ^{2}Li, C) injected at high velocity into the plasma can penetrate into the core, where they are liable to yield an electron to core impurities (oxygen, carbon, boron…). The ions, generated in an excited state, very swiftly deexcite, emitting one or more photons; the emission is thus localized, at the intersection of the beam and sightline. The same quantities as yielded by passive spectroscopy may be obtained: impurity density, temperature, and flow speed.

Beam-emission spectroscopy

Atoms in a beam of neutrals are excited through interaction with the ions and electrons in the plasma. The spectrum of photons emitted as these atoms relax enables measurement of plasma properties, particularly electron density modulations.

Motional Stark effect

Neutral hydrogen atoms are injected with a velocity v into the plasma's magnetic field *B*. They are subject to the effects of an electric field, proportional to *v* and *B*. In this "dynamic" electric field, hydrogen **emission lines** are altered, owing to the **Stark effect**. Since the velocity of the atoms in the neutral beam is known, the magnetic field may be determined, and the current profile inside the plasma may thus be ascertained. The presence of static electric fields results in perturbations to the measurement.

Probe diagnostics, the most intrusive

The temperature and density domains involved by fusion plasmas preclude the use of devices coming into contact with the plasma, except at the edge, where probes may be introduced into the "edge plasma," which is relatively "cool," and not very dense. Mobile probes, inserted for a very brief interval, allow deeper penetration. The simplest probe consists in a conducting rod, insulated over nearly its entire length, except at the end that is immersed in the plasma. By measuring the current passing through the probe as its potential varies, the plasma's electron temperature may be derived. More complex devices allow measurement of electron density, ion temperature… It is as a rule necessary to correct readings for perturbations due to the probe's intrusion.

The challenges set by ITER

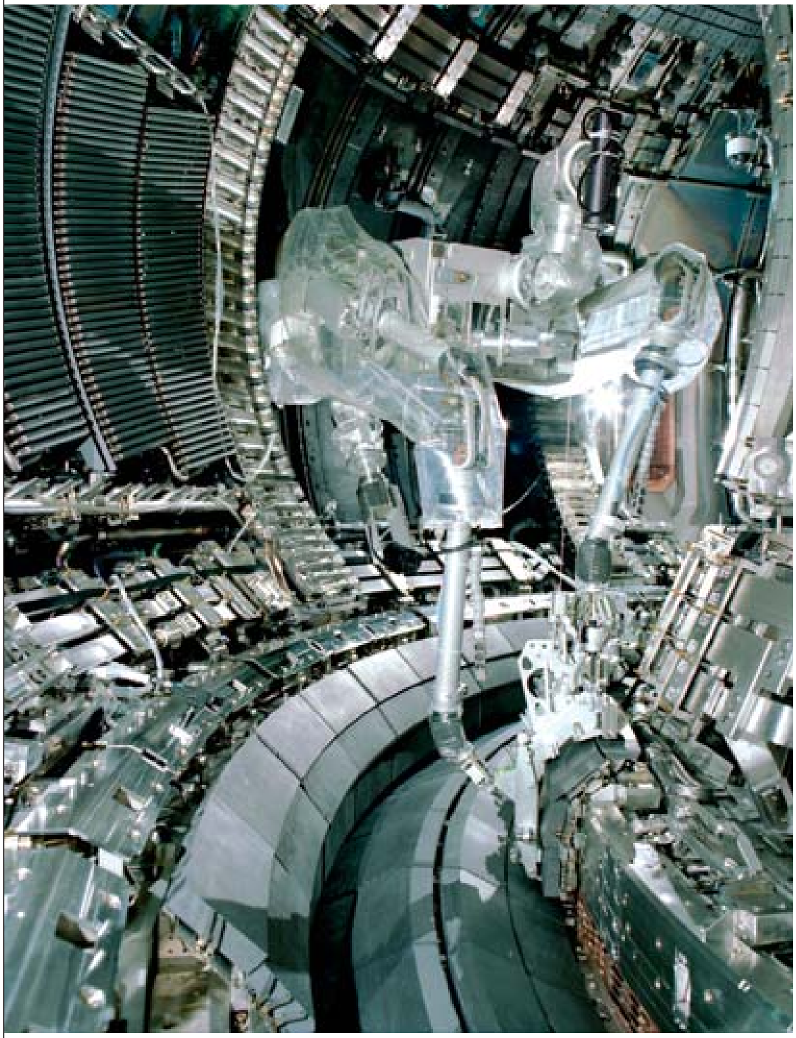
ITER's plasma will be self-heating to 70%: the amount of power available to control transport will thus be relatively low, relative to overall power. The alpha particles doing most of the heating in the plasma will, at the same time, involve a risk of destabilizing new turbulence modes. The issue will thus be to develop, for ITER, turbulence-control strategies offering much higher performance than those implemented in current machines, in which alpha effects are, at worst, marginal, and in which all of the heating power is available for control purposes. As a fusion reactor having the ability to generate power must be self-heating to 80–90%, one further stage will yet have to be gone through. Low-power turbulence control entails detailed understanding of the characteristics, and dynamics of turbulence. The requirements regarding diagnostic resolutions will thus be getting increasingly exacting, even as measurement conditions get ever more degraded.

Indeed, ten thousand times more neutrons will be produced, over the twenty years ITER will be operated, than during 23 years' JET experiments, this being the machine that has produced most neutrons to date. Diagnostics must thus be designed for remote handling, and extreme reliability, since it will quickly become impossible to enter the machine. Of the 500 MW fusion power it will yield, 400 MW will be generated in the form of 14-MeV neutrons. To restrict neutron flux over the detectors, staggered "bayonet" sightlines will have to be provided. Mirrors may thus have to be interposed in direct view of the plasma. These will be subjected to bombardment from plasma particles escaping confinement, as well as neutrons and gamma rays. Their reflectivity may further be degraded owing to redeposition of carbon or boron, stripped from the walls by plasma erosion. Methods of remediation or compensation for the degradation of reflectivity over time will have to be developed, if measurement precision is to be maintained. In the hostile environment of regions close to the plasma, optical fibers used to carry optical signals risk degrading, while the windows, serving to ensure the vacuums in the sightlines, and in the vacuum vessel remain independent, may opacify.

Diagnosis, understanding, and control of turbulent transport stand as some of the major challenges presented by magnetic fusion. Asked "What would you ask God, given the opportunity?" German physicist W. Heisenberg is said to have answered: "For God, I shall have these questions: Why relativity? And why turbulence? And I really believe he will have an answer for the first question only." Not ambitioning to find the answer to the "why" that is beyond the remit of science, plasma physicists would be content to arrive at answers as to the "how." Through development of ever more precise modeling and diagnostics, they even hope they may be able to answer that question, before they are given the opportunity to be told what the answer is…

Indeed, there is an urgent need to achieve better understanding of turbulent transport in plasmas. In the 1990s, turbulence-control methods already made it possible for regimes to be found, allowing improved plasma thermal insulation capacity. It is on the ability to control turbulence, in a self-heating plasma, that the feasibility depends, of constructing relatively compact fusion reactors, with continuous operation capability. ITER, which is due to come on stream in 2016 at Cadarache (Bouches-du-Rhône *département*, southern France), should provide crucial answers in this area. It will then become possible to anticipate generating the first **watts** of fusion electricity by the end of the 2030s, a new source of energy becoming available around 2050, that may contribute to resolving the twin energy and environmental crisis that is inescapably looming up.

> **Jean-Marc Ané**
Euratom–CEA Association on Fusion
CEA Cadarache Center

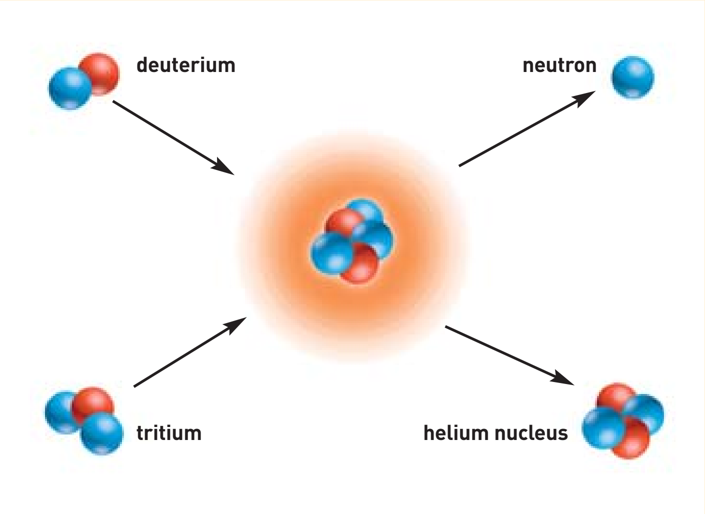

EFDA/JET

Maintenance robot for the more exposed components of the JET inner wall. ITER will require extensive use of remote handling, particularly for diagnostic maintenance.

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.

D (cont'd)

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).

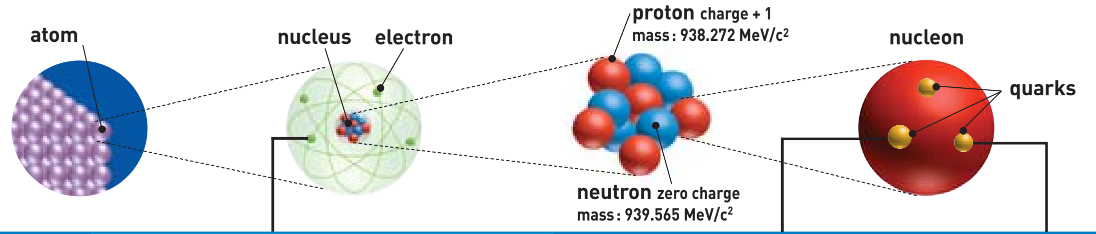
(2) To take e.g. **nucleons**: the proton holds two up quarks and one down quark, the neutron two down quarks and one up quark. A **meson** is made up of just two quarks (one quark and one antiquark).

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/c^2	**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/c^2	**up** (*u*) electric charge: + 2/3 the proton holds two, the neutron one mass : 1.5 – 4 MeV/c^2
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/c^2	**muon neutrino** (ν_μ) properties similar to those of the electron neutrino.	**strange** (*s*) a heavier companion to "up" mass : 80 – 130 MeV/c^2	**charmé** (*c*) a heavier companion to "down" mass : 1.15 – 1.35 GeV/c^2
	Third family	**tau particle** (τ) heavier still. masse : 1,776.99 ± 0.29 MeV/c^2	**tau neutrino** (ν_τ) properties similar to those of the electron neutrino.	**beauty** (*b*) tau particle. mass : 4.1 – 4.4 GeV/c^2	**top** (*t*) heaviest in the family (observed in 1995) mass : 171.4 ± 2.1 GeV/c^2
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±, Z0** W+ W- Z0 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.

B (cont'd)

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).

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(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

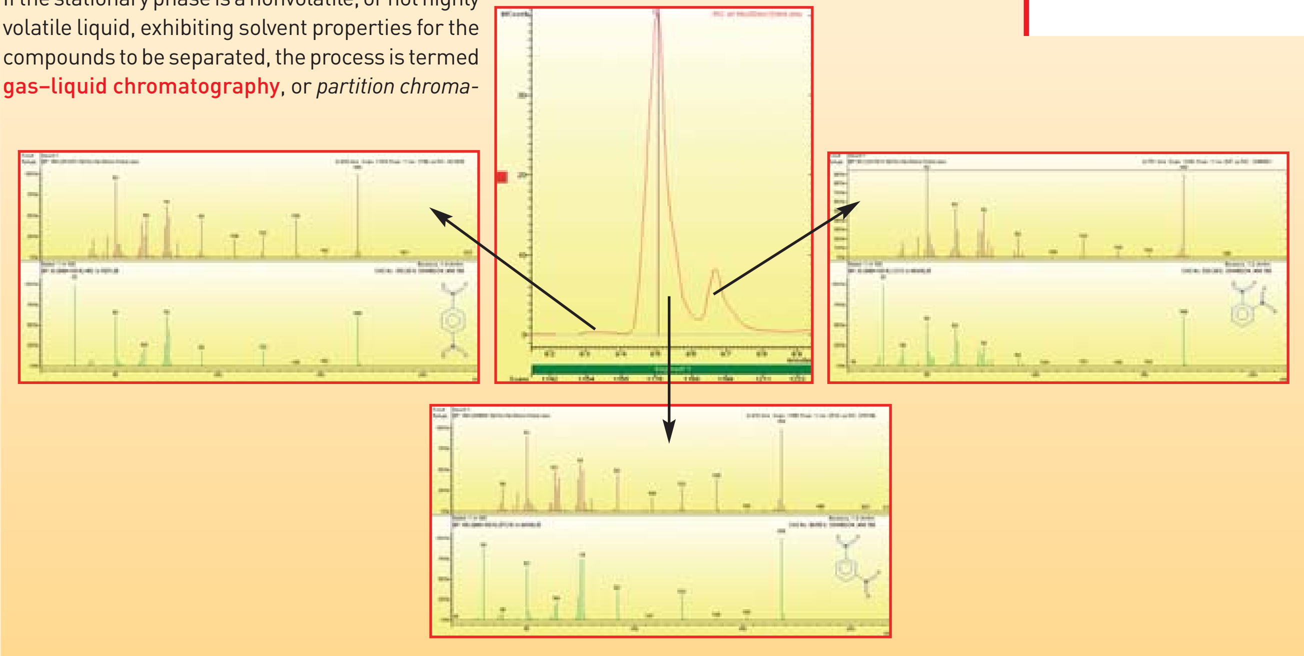

Figure.
An example of the combined use of mass spectrometry and chromatography: the separation of isomers ("sister molecules") of an explosive molecule (dinitrobenzene [DNB]), after solid-phase microextraction sampling, by gas chromatography, and their detection by mass spectrometry (SPME–GC–MS).