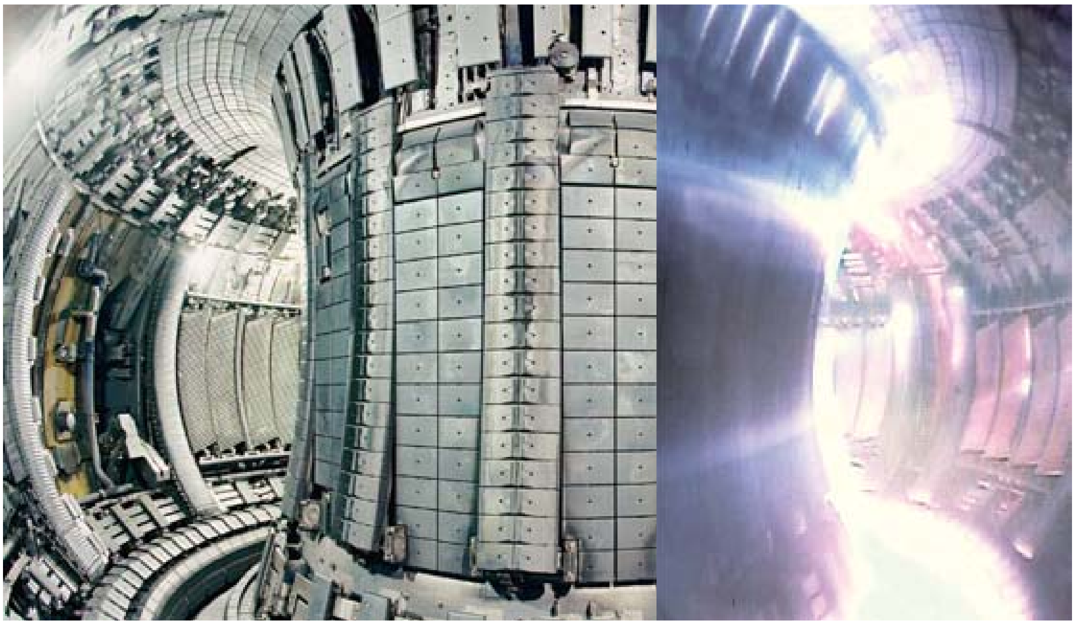
Of the many fields of investigation requiring attention from research workers, as they seek to achieve mastery of magnetic-confinement thermonuclear fusion, understanding turbulence is essential. The physics of turbulence, highly complex as it is, indeed holds the key to one of the characteristics fundamental for this technology: quality of confinement.

The physics of turbulence, a key to magnetic-confinement controlled fusion



Plasma generated in JET, during a discharge (right). At left, part of the vacuum vessel of the same machine, when not operating.

JET

Mastery, on Earth, of the energy of the stars is an aspiration which, while it is realistic, is nonetheless technologically highly ambitious. The best illustration of this, undoubtedly, is the international **tokamak** program, ITER (International Thermonuclear Experimental Reactor), requiring as it does collaboration between a number of major international powers, over several decades. As well as affording a credible alternative for the problem of energy supplies to meet the needs of humankind, controlled **fusion** is a fascinating crucible to assay research into fundamental physics, bringing together as it does many facets of this discipline. Fields of investigation range from solid-state physics, for the design of **plasma**-facing components, or the development of **superconductors** for the windings, to the physics of plasma–wall interaction, where radiation and recirculation play a key role, right through interaction of **electromagnetic waves** with plasma, magnetohydrodynamic stability of plasma, and finally the physics of turbulence.

Understanding the latter is crucial, if fusion is to be achieved, since this holds the key to one of its fundamental characteristics, the quality of confinement. It is this area this paper has elected, as a representative example of the issues in fundamental physics investigated in the context of fusion. The topics addressed here have implications well beyond the "fusion community," in fields as diverse as fluid mechanics or astrophysics, including, of course, the physics of the Sun. Aside from fusion reactions, this undertaking also takes in one topic of equal relevance to our star, the physics of magnetized plasmas, and strong analogies are to be found, for instance as regards violent ejection processes of energy and matter.

Turbulence and transport

Economic viability of fusion entails the process should be virtually self-sustaining: the energy released by fusion reactions (see Box D, ***Nuclear fusion reactions***) must not only serve to heat the water that will drive the turbines, but also to maintain the plasma at fusion temperature, between 100 and 200 million degrees. The latter constraint means that fusion power must compensate for the power losses in the plasma. This is expressed by a simple criterion, involving **ion** density and energy confinement time: $n_i \cdot \tau_E >$ Const. τ_E is a macroscopic parameter, a measure of the quality of confinement: it is the characteristic decay time of the plasma's internal energy, in the absence of heating. The path taken by magnetic-confinement controlled fusion aims to maximize τ_E, and hence to restrict transport in the region where the fusion reactions occur. Density and the constant, Const., are such that τ_E must be of the order of a few seconds. Conversely, it will be desirable to degrade confinement of the peripheral plasma, so as to spread the outgoing power over the largest possible area, thus reducing thermal stresses in wall elements.

In a tokamak, particles and heat are compelled to follow virtual surfaces, generated by the magnetic topology. These surfaces take the form of nested tori (see Figure 1). The parallel direction is given by the magnetic field lines, winding helically round these surfaces. The direction perpendicular to the field lines will henceforth be noted by index "⊥". Assuming that matter and heat transport conforms to a random-walk process along the perpendicular, or transverse, direction, this may be represented by a diffusion coefficient $\chi_\perp$, expressed in m^2s^{-1}. In this random process, heat takes time τ_E to cover the characteristic distance over which the plasma must be confined. This distance corresponds, for tokamaks, to the internal, or minor, radius a of the torus, this being of the order of a meter. tE then is given by equation: $\tau_E \approx a^2/\chi_\perp$. If perpendicular energy transport, in tokamaks, were only generated by binary Coulomb collisions, present-day machines would already have met the conditions required for fusion.

At such high temperatures, indeed, mean free path for particles is of the order of a few kilometers. The conduction associated with collisions, which is very low ($\chi_{\perp coll} < 10^{-1}\ m^2s^{-1}$), would then lead to confinement times of several tens of seconds. Values of τ_E, as measured experimentally, are much lower, being of the order of a few tenths of a second on the largest existing devices. Transport is essentially effected by turbulence, excited by gradients perpendicular to the confining magnetic field. The measured amplitude for the fluctuations of various quantities (density, temperature, etc.) is indeed in agreement with the observed amount of transport, namely: $\chi_\perp \approx 1^{-10}\ m^2s^{-1}$.

A number of issues, however, do remain open: what is the cause, and the characteristics, of this turbulence, and the associated transport? Are there ways of controlling its amplitude, and dynamics?

From instability theory...

The turbulent fluctuations observed in fusion devices originate in *instabilities exhibiting nonlinear saturation*. The behavior of a spherical marble, or bearing, at the bottom of a bottle provides a good illustration of such a situation (see Figure 2c): positioned precisely at center, the sphere will lie in equilibrium, however the slightest perturbation, however small in amplitude, will be enough to send it down the slope, closer to the walls. This is linear instability. Should the bearing's travel become large enough (nonlinear regime), it will be limited by the bottle walls: this is nonlinear saturation. The greater part of instabilities excited within the plasmas in tokamaks are *exchange instabilities*. This mechanism arises from the fact that, in tokamaks, exchanging a low-pressure *flux tube* (1) for a high-pressure flux tube releases energy: the process is thus unstable, owing to the propensity of any physical system to seek a minimum-energy state. In a highly simplified version, this instability is analogous to the Rayleigh–Bénard instability in fluids – from the name of the two physicists who investigated the phenomenon experimentally, and put it into equations. (2) Take a fluid that is heated from below. At the bottom of the pan, the liquid is hotter, and hence lighter than that at the surface. It will tend to rise under its Archimedean buoyancy, provided however that lifting force can overcome the viscous forces resisting any motion. This leads to the onset of rolls, or *convection cells*, which ensure a form of heat transport far more effective than collision conduction.

(1) Flux tube: a virtual, microscopic volume, of tubular shape, wrapping round a magnetic field line.

(2) It is instability of this type also, known as Rayleigh–Taylor instability in that context, which perturbs isotropic compression of fuel pellets, in **inertial-confinement fusion**.

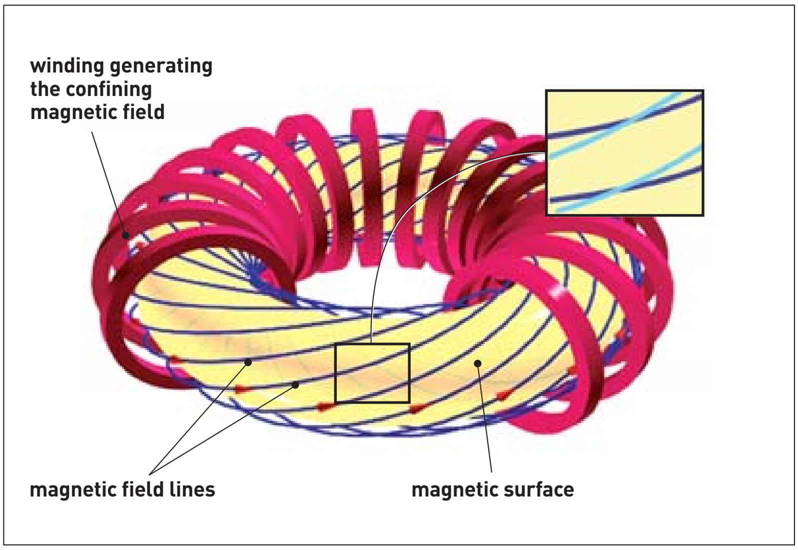


Figure 1.
Schematic representation of a tokamak's magnetic topology. Particles and heat are free to move along field lines. Collisions and turbulence generate transport perpendicular to the magnetic surfaces. The detail view shows how field lines in two different magnetic surfaces exhibit different helicity, or twist.

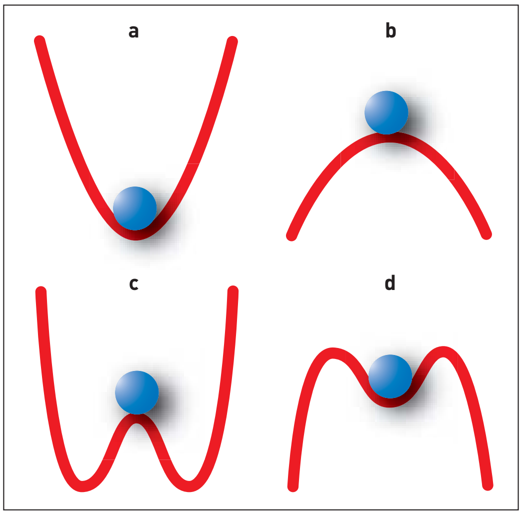
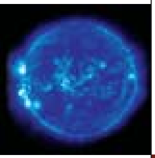
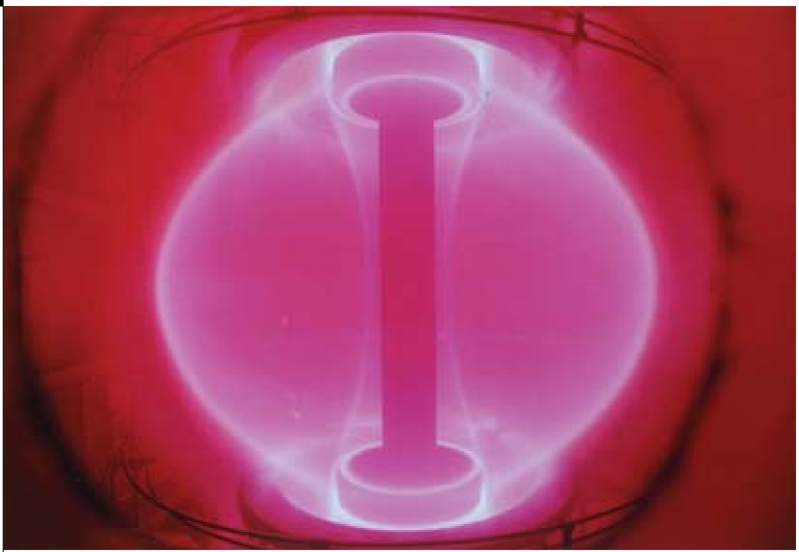


Figure 2.
Schematic representation of various stability regimes: (a) linear (L) and nonlinear (NL) stability; (b) L and NL instability; (c) L instability, NL stability; (d) L stability, NL instability.





UKAEA

Fusion plasmas have been investigated in all kinds of configurations, including spherical ones, as here in the British START device, in Culham (UK).

Two major ingredients of instability may be seen here: it is based on the existence of a temperature gradient that is colinear with gravity, and it exhibits a gradient threshold below which heat transport is not turbulent. These two characteristics are also to be found in tokamaks, with the difference, however, that gravity plays an altogether negligible role in magnetized plasma: the gravitational force affecting ions is typically 10^{14} times weaker than the Lorentz force due to the magnetic field *B*. It is magnetic topology, and more specifically field-line curvature and the fall-off in field intensity *B*, from torus axis of symmetry to the outside, which here take on a role that is the analogue of that of gravity in the Rayleigh–Bénard instability.

The temperature gradient, on the other hand, is intrinsic to the problem: core plasma is at a temperature close to 100 million degrees, whereas temperature falls to a few hundred degrees on the vessel walls, about one meter away. In most cases, this gradient is greater than the instability threshold, giving rise to turbulent transport. The convection cells, or *vortices*, here are formed by the electric potential isopotential contours. They define matter- and heat-**advection** channels, in like manner to the way low- and high-pressure regions govern wind force and direction in meteorology. Vortices develop over a spatial scale, typically, of a few cyclotron radii [(3)] in the radial direction, i.e. a few millimeters for ions. It will be seen that confinement time will be greater to the extent that this distance remains small, related to overall device scale; hence the advantage of developing large tokamaks. Vortices further exhibit motion at characteristic frequencies ranging from a kilohertz to a few hundred kilohertz.

This analogy with the Rayleigh–Bénard process shows that turbulence in tokamak plasmas is closely connected to the turbulence occurring in non-magnetized fluids. This enables, in particular, the fusion community to benefit from the breakthroughs achieved in an already long-standing discipline, the Rayleigh–Bénard instability having been much investigated from the 1980s on, as the paradigm of the transition to turbulence, developing according to a scheme analogous to that of the transition to chaos. However, plasmas are also more complex than classical fluids, which makes them more pregnant objects yet.

The ion–electron "dialogue"

Fusion plasmas are made up, in the main, of two kinds of particles: **electrons**, and **deuterium** and **tritium** ions, with a mass ratio equivalent to that between a ping-pong ball and a 10–15-kg weight. Their low inertia means electrons are extremely mobile. These two species then cover regions of the temporal and spatial manifold that are relatively distinct: spatial scales for the turbulences associated with ions and electrons typically stand in the ratio of the square roots of the masses involved (around 60), whereas the frequencies are in inverse ratio to these. Nevertheless, electrons and ions do remain on "speaking terms": indeed, being electrically charged, both are affected by the selfsame electromagnetic field. At the scales under consideration, the two species together ensure, in particular, that the plasma remains electrically neutral.

The particle–field coupling

This particle–field coupling is indeed the foundation of all transport processes in magnetized plasmas. This is a nonlinear process: fluctuations in plasma particle density and velocity generate charge and current fluctuations. The latter fluctuations control electric and magnetic field structure and evolution over time, through the Maxwell equations. These fluctuating fields in turn exert a feedback effect on the particles, whose dynamics they govern. It should be pointed out, however, that the fluctuations in field intensity *B* remain several orders of magnitude smaller than the magnetic field used for plasma confinement.

This *wave–particle interaction* has a *resonant* character: it reaches a maximum when wave phase velocity is close to particle velocity. This mechanism, known as the *Landau effect*, [(4)] plays a fundamental role in plasma physics. [(5)] It is by transferring, by resonance, their energy to the plasma's particles that the waves, linearly excited through the previously-described Rayleigh–Bénard-type mechanism, reach a nonlinear saturation regime. In tokamaks, moreover, such resonances remain located around particular surfaces, known as *resonance surfaces*, whose position is governed by the magnetic topology. We shall see further on that this important property may be put to advantage, to optimize transport.

... to numerical simulations

A number of strategies are available to the research worker, to investigate turbulence. The fluid approach consists in looking at the temporal dynamics of macroscopic quantities, known as moments, such as density, temperature or momentum, coupled to the Maxwell equations: this is the general framework for magneto-

(3) A particle of charge e and mass *m*, placed in a magnetic field *B*, follows a gyratory motion around a field line, the so-called cyclotron motion, of radius $r_c = mv_\perp/eB$, $v_\perp$, where $v_\perp$ is its velocity perpendicular to field *B*.

(4) This Soviet physicist (1908–68), mainly know for his work on phase transitions (diamagnetism and antiferromagnetism, **superfluidity** and superconductivity phenomena), was awarded the Nobel Prize in 1962. His work on the damping of electron waves in plasma (Landau effect, 1946) contributed to the setting up of plasma theory.

(5) For a detailed physical understanding of this mechanism, one can refer, in particular, to: Y. Elskens and D. F. Escande, *Microscopic Dynamics of Plasmas and Chaos*, Bristol (UK), Institute of Physics Publishing, 2002.

hydrodynamics. Phase space here reduces to the physical three-dimensional (3D) space. This approach, however, does labor under two major deficiencies. First, the number of such moments is infinite. Any truncation must then be accompanied by a *closure assumption*, whose validity is hard to guarantee in the nonlinear regime. Further, this does not allow rigorous treatment of Landau resonances, for which knowledge of the particles' velocity distribution is required. It is the more complete gyrokinetic approach that allows these issues to be addressed. In this context, the *distribution function* for the various species is computed in a five-dimensional phase space. The two extra dimensions are the parallel and perpendicular velocities, relative to the magnetic field lines. This function yields the number of particles that belong to an infinitesimal volume element of phase space. While it is satisfactory from a physical standpoint, this approach does have the drawback of being very demanding in terms of numerical resources (computation time and memory). Here, resorting to supercomputers and massively parallel computing is imperative.

Electron and ion turbulences cover a very broad frequency and wavelength domain, to the extent that present-day numerical resources are not equal to simultaneous treatment of them. [6] In practice, every investigation will concentrate on one of the two species.

Once a choice has been made, among the various options, numerical simulations are a powerful instrument, to investigate the complexity of the nonlinear regime that characterizes turbulence. 1D to 5D models, whether electrostatic or electromagnetic, taking in the complexity of plasmas to varying degrees, have enabled, in particular, an understanding to be reached of the mechanism of dominant instabilities in tokamaks, and allowed certain fundamental experimental findings to be reproduced: the order of magnitude for fluctuation amplitude (typically, under one per cent) and the amount of heat transport, $\chi_{\perp} \approx 1\text{–}10\ \mathrm{m^2 s^{-1}}$. These investigations have also highlighted that, far from being homogeneous and regular, turbulent transport can be dominated by intermittent bursts propagating in near-ballistic fashion over large spatial scales, well beyond a few cyclotron radii (see Figure 3). A major effort is currently being devoted to understanding this phenomenon. These analyses have profoundly altered our view of turbulent transport, which until then had been essentially described in terms of a diffusive process. Some of the current work is indeed directed at proposing reduced transport models, i.e. featuring just one spatial dimension, as being more representative of the dynamics of turbulent transport than an effective diffusion coefficient $\chi_{\perp}$.

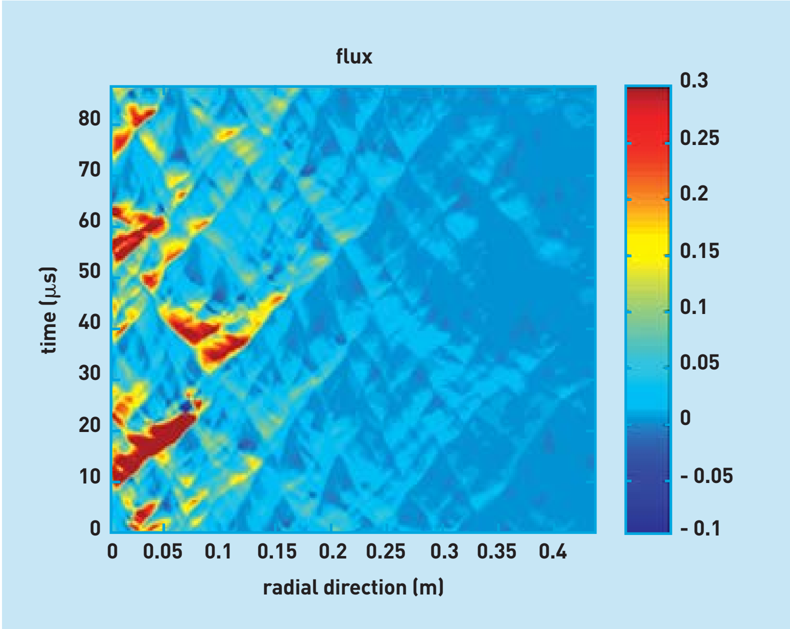
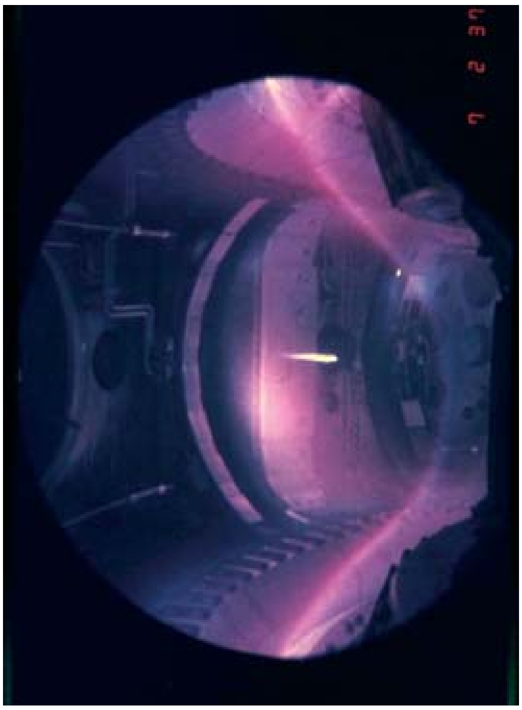


Figure 3.
Map of the turbulent particle flow resulting from a 2D fluid simulation, as a function of time and confinement direction. The system is excited by a particle source positioned at x = 0. A positive flow is directed towards the outside of the torus; amplitude increases from blue to red. Intermittent bursts are characterized by the slantwise smears on the graph. The cyclotron radius here measures about 0.34 mm.



Max-Planck Institut

Investigating the injection of fuel "pellets" into a toroidal plasma in the ASDEX device, in Garching (Germany).

Towards control of turbulence

Transport barriers

One of the aims of the investigations being pursued on turbulence is to identify regimes for which there is a reduction of transport. For the case where this transition is spatially localized, this gives rise to steep temperature and velocity gradients; this is referred to as a "transport barrier." Such regimes were first obtained experimentally, and reproduced on many machines. Indeed, they are used as reference scenarios for ITER. From a theoretical standpoint, a number of mechanisms are adduced, to account for this transition:

(6) As an example, to cover the spatial scales ranging from electron cyclotron radius to plasma radius would require, for a 3D simulation, memory of the order of some 10 terabytes (1 TB = 10^{12} bytes), which is at the limit of the capacity found in the largest of presently available computers.

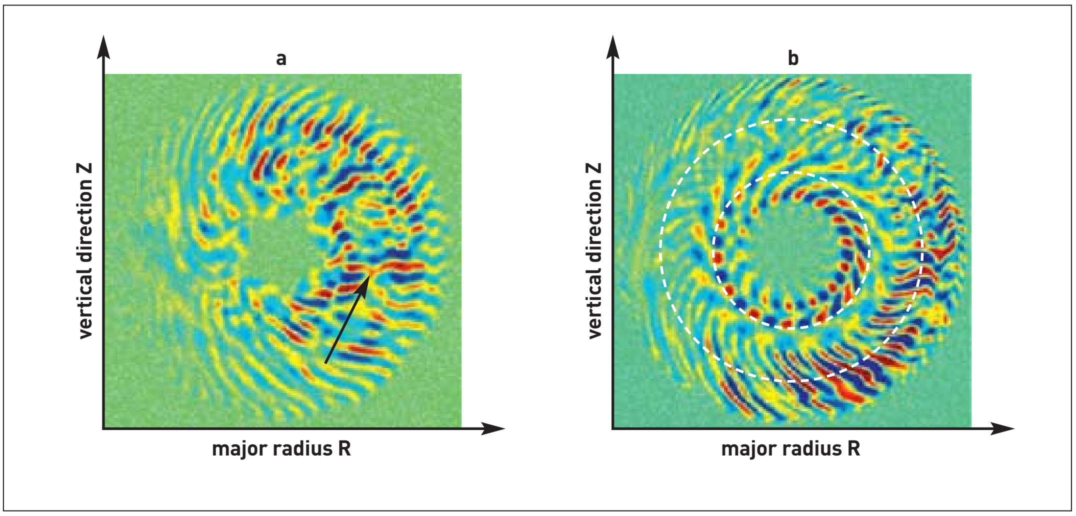
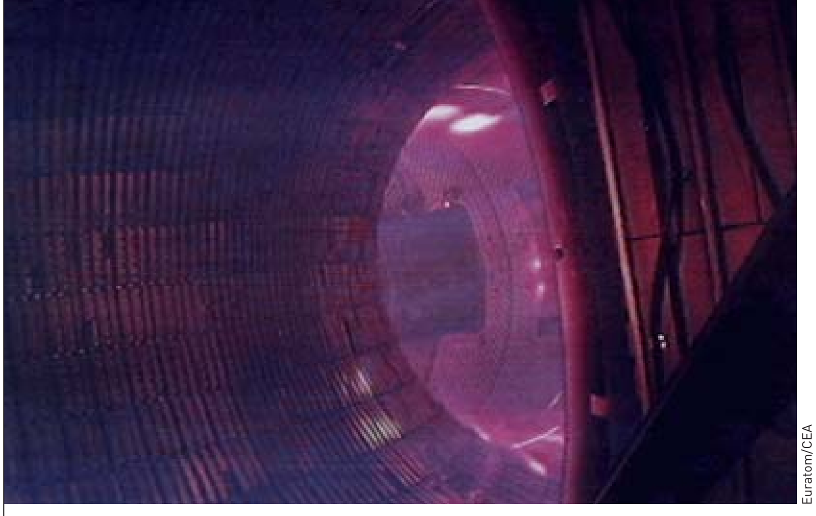


Figure 4.
Instantaneous map of electric potential across a vertical plane of the torus, resulting from 3D fluid simulations of an ion turbulence: (a) standard case, where the arrow pinpoints a large structure; (b) case where a sheared velocity is imposed within the ring materialized by the dotted lines. This region also corresponds to a minimum for q.

- shear of the velocity field turns out to be highly effective. The plasma is entrained in a non-uniform rotational motion along one of the torus's periodic directions. This inhomogeneity in rotation speed results in tearing of the convection cells, thus reducing transport. The same result may indeed be achieved through strong shear of the macroscopic magnetic field, this altering field line twist (see Figure 1). Recent investigations have shown that turbulence itself could generate its own sheared flow, this making an effective contribution to its saturation. Such large-scale flows, so-called zonal flows, are similar to those observed in atmospheric turbulence; they are particularly in evidence on the planet Jupiter;
- slight alteration of the magnetic topology allows the location of resonance surfaces to be controlled, around which – as one recalls – turbulence is concentrated. In particular, it is possible to optimize topology so as to bring such resonance surfaces further away from each other. In this case, the system may reach a regime where Hamiltonian chaos, (7) and hence turbulent transport, remains small.



The Tore Supra tokamak, operated in Cadarache (France) by the Euratom–CEA Association – a prized instrument for the investigation of long-duration discharges.

These mechanisms, often acting in complementary fashion, have been corroborated by numerical simulations (see Figure 4), and are in good agreement with experimental findings. They have made it possible to account for some of the spontaneous transitions of plasma to enhanced confinement regimes, and to suggest transport-reduction scenarios. A third avenue currently being pursued relies on chaos theory. The principle is to apply a feedback loop to turbulence: by means of small, suitably-chosen perturbations of the system's Hamiltonian, the shape and location in phase space of KAM tori (8) or trapping domains can be cleverly altered to achieve transport reduction. This technique, however, can only be of use if it shown that spatially localized transport remains effective.

Violent relaxation phenomena

While transport barriers may be generated in a variety of ways in tokamaks, it appears they are not always persistent. In particular, those developing spontaneously at the edges of the plasma, in certain conditions, are subject to violent relaxation phenomena. In near-periodic fashion, they are transiently destroyed, then allowing very large particle and heat flows to escape: some 10% of total plasma energy content may thus be dissipated over an interval of a few hundred microseconds. Such phenomena, of course, are detrimental as regards confined energy, which is thereby reduced, but equally owing to the very high stresses they exert on the wall elements intended for power takeoff. Some

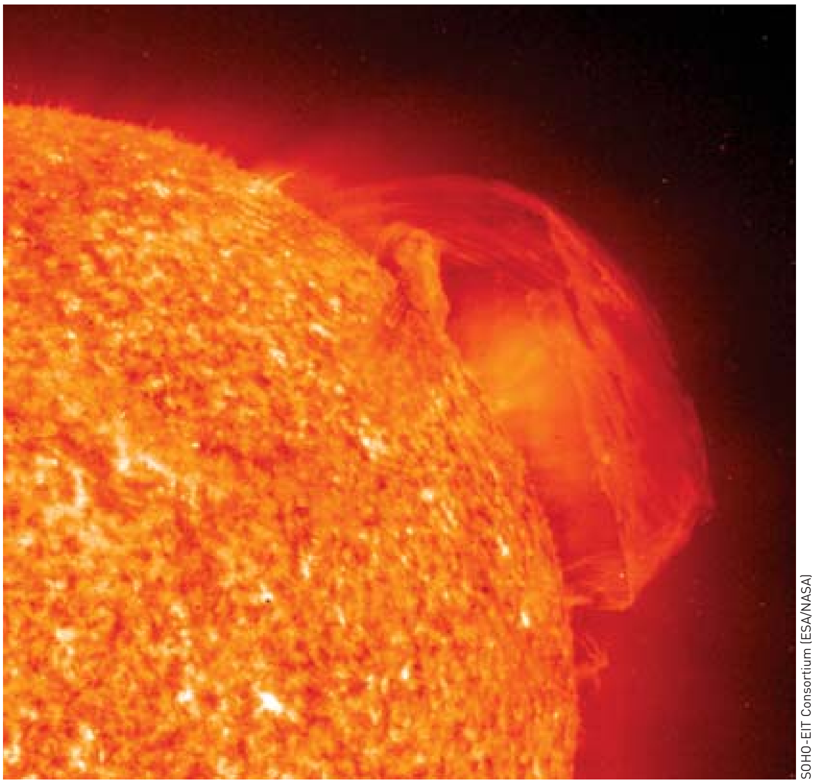
(7) Classical mechanics shows that it is possible in principle to describe the behavior of any dissipation-free system by means of a function *H*, the Hamiltonian, which is dependent on the generalized space and momentum coordinates of the *n* particles making up the system, and also, as the case may be, on time. This function *H* is often related to the system's total energy. In particular, any system whose Hamiltonian is not explicitly time-dependent has a constant-energy evolution.

(8) Named after their discoverers (Kolmogorov, Arnold and Moser), these "tori" define the volume occupied in phase space by the integrable trajectories of a system whose equilibrium Hamiltonian is subjected to small-amplitude perturbations.

turbulence simulations exhibit a similar behavior (see Figure 5), and a number of models have been put forward to reproduce such relaxations.

A strong analogy with solar eruptions

These events further bear a strong analogy to **solar eruptions** (see Box A, ***Spotlight on the Sun***). The most violent of these arise in prominences, huge arches where an intense magnetic field holds the plasma above the Sun's surface. They are characterized by the ejection of hot plasma and emission of hard **X-rays**, such bursts carrying into space up to 1% of the Sun's overall radiated power. The first feature sustaining the analogy is that, according to recent theories, solar eruptions could originate in a region that is equivalent to a solar transport barrier: the **tachocline**. This thin layer, at the interface between the **radiative region** and the convective region, is indeed characterized by strong velocity shearing. It is in this region that, through a dynamo effect, [9] the Sun's magnetic field is believed to arise. The second point of congruence could be the very nature of the instability causing these violent relaxations: in both cases, in tokamaks as in the Sun, the conditions are such as to make exchange instability the favored candidate. Other astrophysical phenomena also exhibit similarities, e.g. magnetic substorms. In any event, gaining a theoretical understanding of the detailed mechanism resulting in such relaxations still remains as a challenge to the scientific community. These analogies allow the notion to be entertained, of a conceivable universality of such relaxation processes, within transport barriers.



A huge solar prominence, observed in the extreme ultraviolet on 26 August 1997 by the SOHO satellite. Its temperature reached some 85,000 °C, for a spatial extension of the order of 350,000 km.

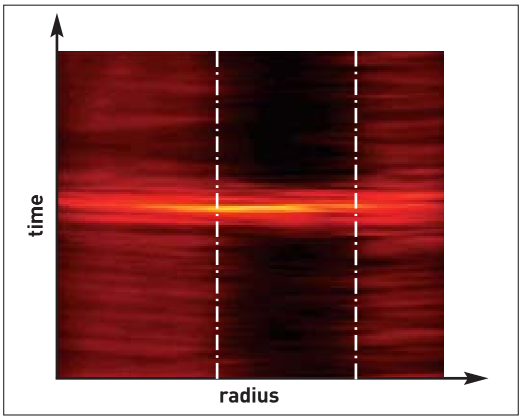


Figure 5.
Map of turbulent heat flow resulting from 3D fluid simulation, as a function of time and confinement direction. A heat source is imposed on the edge at left. The flow, directed towards the outside of the torus, exhibits increasing amplitude from black to yellow. The transport barrier, which can be seen in the central area, between the dotted lines, is transiently destroyed by a violent relaxation.

Time for ITER

The physics of fusion plasmas is a rich, complex science, sharing numerous topics with many disciplines, such as, in particular, turbulence in non-magnetized fluids, chaos theory and astrophysics. It is further enriched from such commonality of thought, and has a part in the breakthroughs that occur in all of these fields. Theoretical investigations have enabled many advances to be made, both as regards understanding of experimental findings and optimization of the scenarios implemented. In this sense, it is complementary to the engineering approach, which relies on scaling laws to predict the amount of transport, and hence confinement time τ_E, in a device such as ITER. It allows investigation of the possible onset of new phenomena, in the time remaining before the advent of the machines that will follow, thus enabling ongoing scrutiny of the adequation of the goals assigned to ITER, for the experimental scenarios being considered.

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(9) The strong variations in fluid velocity across this interface could twist the field lines of the fluctuating magnetic field, resulting ultimately in amplification of the amplitude and spatial scale of that field. The term "dynamo effect" refers to this conversion mechanism, of part of the fluid's kinetic energy into magnetic energy.

A Spotlight on the Sun

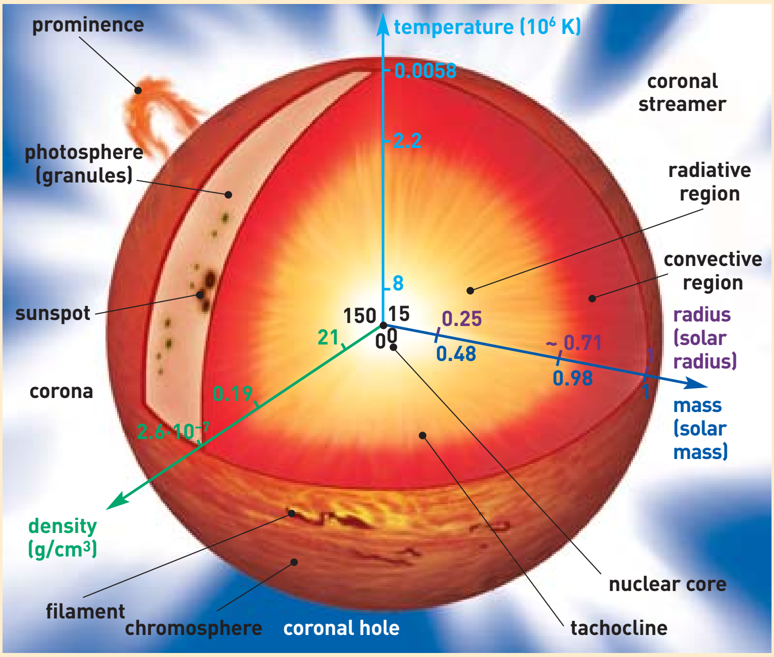


Figure.

The largest object in the solar system, the Sun accounts for some 99.8% of its total mass. Initially consisting in over 70% hydrogen and more than 25% helium, the Sun is a huge rotating gas ball.

The Sun's internal structure comprises four distinct regions (see Figure). The core, where the prevailing temperature and density conditions are extreme, is host to numerous nuclear reactions, turning hydrogen into helium. The energy released will end up as visible light at the surface.

In the radiative region, extending from the core to a distance equal to 0.71 of the solar radius, energy is transported to the Sun's surface through photon-matter interaction (radiative transport). Photons are absorbed and re-emitted millions of times in countless collisions with the atoms they encounter, which are highly ionized. It takes over one million years for photons to reach the tachocline, which is a thin transition layer, between the radiative and convective regions, that plays an essential part in the solar magnetic field.

In the convective region, owing to the lower temperature, the environment, consisting in partly-ionized atoms and neutral atoms, is more opaque. The photons' progression becomes arduous. Moreover, local density varies by a factor of one million between base and surface. Such steep temperature and density gradients cause convective motions that are observable on the surface, such as the granules (with a life span is of the order of a few minutes), or the supergranules, with sizes of the order of 1,000 km and 35,000 km respectively.

The solar atmosphere comprises four regions (see Figure). The surface, or photosphere, only some 400 km deep and with a temperature close to 5,800 K, thus presents a granulated aspect, featuring more or less dark areas. Darker areas, known as sunspots, occurring singly or in clusters, are at a temperature of 3,800 K. They appear to be black, owing to the difference of temperature with adjoining areas. They are subject to an 11-year cycle, and are associated to regions where the magnetic field is much more intense (several thousand gauss) than for the Sun as a whole (1 gauss). These sunspots may reach a diameter of 50,000 km. They can last from a few days to several months. Lighter, hotter areas, known as faculae, which may occur in isolation, but are as a rule located around clusters of sunspots, may also be observed.

Beyond the photosphere, extending for thousands of kilometers, is the chromosphere, where density goes on falling off rapidly, while temperature reaches 20,000 K. In this region are to be found plages, bright regions characteristic of the strong magnetic fields occurring with sunspots, prominences, or filaments (when seen against the Sun's disk), magnetic structures that are denser and cooler (10,000 K) than the surrounding medium, and spicules, small, short-lived (5-10 minutes) jets of matter shooting out towards the corona, at velocities of up to 20 km/s.

Between the chromosphere and corona lies the transition region, a thin, irregular layer where temperature rises abruptly.

The corona, where gas is rarefied, reaches out for millions of kilometers, and is characterized by a temperature of over 1,500,000 K, and low density. It features numerous magnetic structures, or structures associated with magnetic structures, such as coronal loops, coronal holes, bright points... In this constantly-changing region, the prominences, or filaments, appear as huge plumes of hot gases, originating in the chromosphere.

Solar activity is not constant. Repeatedly, and with intensities that are cyclical, violent eruptions occur in the active regions. These are sudden releases of high-energy particles into the interplanetary environment. Such coronal mass ejections (CMEs) may on occasion attain a height of 100,000 km, for a length of 200,000 km. According to the direction in which they are ejected, the high-energy particles thus released may interact with the Earth's atmosphere.

The Sun also expels a constant flow of charged particles, mainly protons and electrons, forming a plasma, the so-called solar wind. This propagates right out of the solar system, with a velocity of some 450 km/s. The Sun thus depletes itself by about one hundred thousand-billionth of its mass every year.

B Tell-tale spectra

The various categories of radiation are distributed across the electromagnetic spectrum according to their wavelength, from the shorter, more energetic wavelengths (gamma radiation) to the longer ones (radio waves) through visible light. The spectrum of the latter domain, for instance, may be obtained by passing light through a prism, which decomposes it into its various components, from red to purple (see Figure a). A rainbow likewise exhibits a spectrum of the visible light emanating from the Sun, through refraction in, and reflection on, water droplets.
The same principle is applied for the whole range of electromagnetic radiation, through the use of spectrographs, which analyze the spectral energy distribution of such radiation, and spectrometers, which record each component of the spectra by means of photoelectric sensors and measure radiation intensity, plotted against wavelength.
In astrophysics, spectroscopy consists in the remote investigation of bodies from the radiation emitted by them, or the alterations induced in that radiation as it encounters other bodies in its path. Spectra exhibit, between wide, continuous bands (each of which is termed a spectral continuum), discrete lines, each corresponding to a specific wavelength and, ultimately, to an energy level of an atom or molecule in the body observed. These spectral lines are of two types, emission lines and absorption lines.

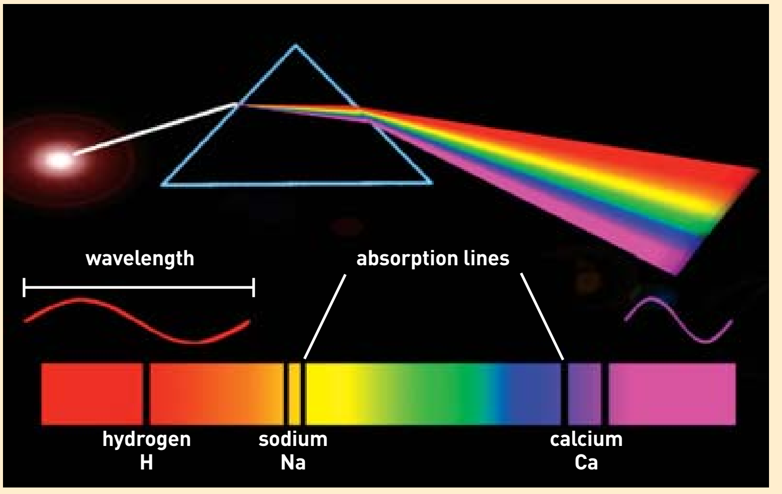


Figure a.

Bright emission lines correspond to radiation directly emitted by a body heated to a very high temperature. An emission spectrum thus allows detection of the presence of certain atoms or molecules in the emitting body.
Dark absorption lines also correspond to a specific wavelength, this being due, however, to the process whereby a radiation's intensity decreases as it goes through a material medium, to which it transfers all or part of its energy. Thus, the composition of a hot, radiating source such as the Sun may be analyzed from the absorption by its atmosphere of part of the electromagnetic radiation emitted (absorption spectrum).
Matters do not end there: analysis of spectral shift allows the relative motion of the emitting body to be estimated, thanks to the Doppler effect,[1] on the selfsame principle whereby the sound of an approaching vehicle gets higher-pitched, and lower-pitched for a receding vehicle. The apparent change in frequency (higher even as wavelength is shorter) is thus proportional to the relative velocity of observer and source. For a light source, this effect implies that lines in that source's spectrum will be shifted towards blue (blueshift), i.e. to shorter wavelengths, if it is approaching, or towards red (redshift), corresponding to longer wavelengths, if it is receding (see Figure b).
The Doppler effect is used in astrophysics, particularly to establish the radial velocity of stars or galaxies, for their perspective motion causes a shift in the lines emitted, relative to their nominal positions, or compared to the same lines emitted by a terrestrial source.
Finally, the splitting of spectral lines induced by a magnetic field (*Zeeman effect*) is used to measure the intensity of the magnetic fields associated to astronomical objects, the Sun in particular.

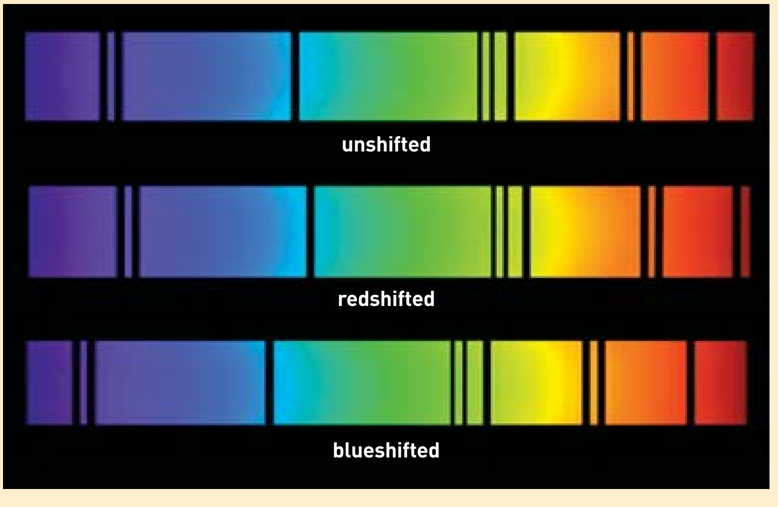
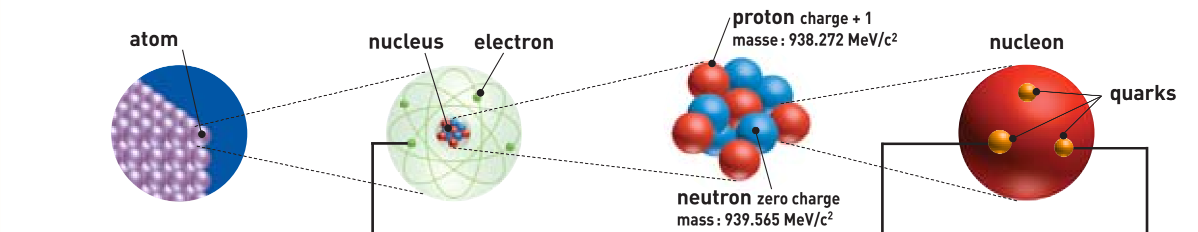


Figure b.

(1) Or, more accurately, Doppler-Fizeau effect. Discovered by Austrian physicist Christian Doppler for sound waves, the effect was extended to optics by French physicist Hippolyte Fizeau.

C Elementary particles and fundamental interactions

Neutrinos are the stealthiest particles in the standard model of particle physics, the theoretical framework describing all known elementary particles and the fundamental interactions they mediate (see Table).
The basic constituents of matter, fermions, are partitioned into two main categories: leptons, which do not respond to strong interaction, and quarks, which are subject to all of the interactions. The six quarks form three pairs (up/down, charmed/strange, beauty/top). In the lepton category, the charged leptons (electron e^-, muon μ, tau τ) are involved in the electromagnetic interaction and the weak interaction, while neutral leptons (electron neutrino ν_e, muon neutrino ν_μ, tau neutrino ν_τ) are only subject to weak interaction. In the standard model, neutrinos have zero mass, however experiments have shown they do have some mass, though very small, the exact value of which is as yet unknown. Involvement



		leptons able to move freely		quarks held captive in larger particles, they are not observed separately	
Fermions Common matter is made up of particles from this group.	first family	**electron** Responsible for electricity and chemical reactions. Charge: – 1. mass: 0.511 MeV/c²	**electron neutrino** Has no electric charge, and interacts very seldom with the ambient medium.	**down** Electric charge: – 1/3. The proton holds one, the neutron two. mass: 5 – 8,5 MeV/c²	**up** Electric charge: + 2/3. The proton holds two, the neutron one. mass: 1,5 – 4,5 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** A more massive companion to the electron. mass: 105,658 MeV/c²	**muon neutrino** Properties similar to those of the electron neutrino.	**strange** A heavier companion to "up." mass: 80 – 155 MeV/c²	**charmed** A heavier companion to "down." mass: 1 000 – 1 400 MeV/c²
	third family	**tau** Heavier still. mass: 1 777 MeV/c²	**tau neutrino** Properties similar to those of the electron neutrino.	**beauty** Heavier still. mass: 4 000 – 4 500 MeV/c²	**top** Heaviest in the family (observed in 1985): 180 times the proton mass. mass: 174 300 ± 5 100 MeV/c²

Vector Bosons Fundamental particles carrying out transmission of all natural forces.	**photon** Elementary grain of light, vector for the electromagnetic force.	**gluon** Bearer of the strong force between quarks.	**W±, Z0** (W^+, W^-, Z^0) Bearers of the weak force, responsible for some forms of radioactive decay.
Higgs Boson?	Responsible for "electroweak symmetry breaking."		

Tableau.
Constituants élémentaires.

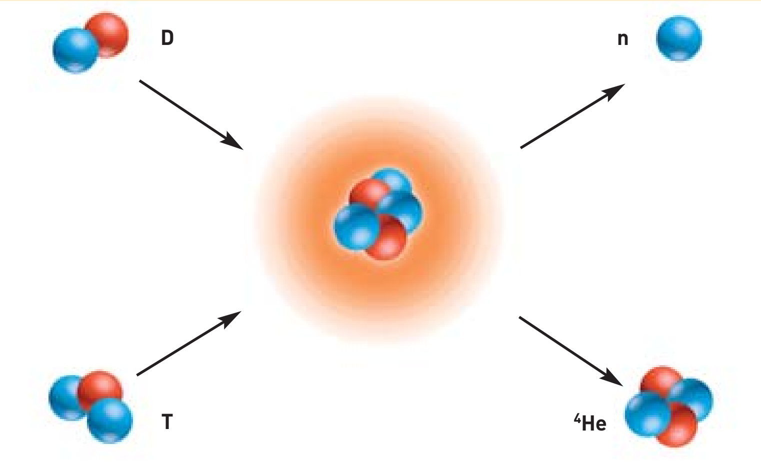
of the various elementary constituents in the fundamental interactions is governed by their quantum numbers, or interaction charges (electric charge, color charge [1]...). To every constituent of matter is associated its **antiparticle**, a particle having the same mass and opposite charges. The **gravitational force**, which is not included in the standard model, acts on all fermions in proportion to their mass.
The table of elementary constituents of matter manifests another classification – independently from their involvement in fundamental interactions – into three generations, or families. From one family to the next, charged quarks and leptons having the same charges only differ by their mass. The electron, up quark and down quark, which all belong to the first family, are the lightest massive particles. They are stable particles, and the constituents of common matter. For instance, the **proton** is made up of two up quarks and one down quark; the **neutron**, of two down quarks and one up quark. Particles in the other two families are unstable, 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, at least one elementary particle, a **boson**, must be emitted, absorbed or exchanged. The **photon** is the vector for the electromagnetic interaction, the **W^+**, **W^-** and **Z^0** mediate the weak interaction, and **gluons** act as messengers for the strong interaction.
Quarks and charged leptons exchange photons, but conserve their electric charge after the exchange, the photon having no electric charge. Since the photon's mass is zero, the electromagnetic interaction's range is infinite. 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 (80,000 MeV/c^2 for $W^\pm$, 91,180 MeV/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 nonzero 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 exchange gluons, these in turn being bearers of a color charge. Thus, 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. The range of the strong interaction is consequently very restricted – of the order of 10^{-15} m.
The graviton, the vector for gravitational interaction, has not so far been observed.
Theory predicts that another fundamental interaction mechanism exists, responsible for the mass of elementary particles, for which the messenger is the Higgs boson, which remains as yet undiscovered. This boson makes it possible to assign a mass to elementary fermions of zero mass that interact with it.

(1) Color charge: a quantum number that determines whether a particle is involved in strong interaction. The color charge can take on three values: "red," "green," or "blue" – such colors bearing no relation to visible colors. Every quark bears one of the three color charges, every antiquark one of the three anticolor charges. Gluons bear double color–anticolor charges (eight possible combinations).

fundamental interaction	messenger	actions
gravitational	graviton?	responsible for the mutual attraction of any two masses and for the law of falling bodies
electromagnetic	photon	responsible for the attraction between electrons and atomic nuclei, hence for the cohesion of atoms and molecules
weak	W^+, W^-, Z^0	the root cause of **thermonuclear fusion** inside the Sun, ensuring its longevity. β^- and β^+ radioactivity, and reactions involving neutrinos are weak interactions
strong	gluons	ensures the cohesion of the atomic nucleus

Table.
Fundamental interaction and elementary constituents.

D Nuclear fusion reactions



To achieve the fusion of two light atom nuclei, they must be brought in close proximity to each other, whereas they naturally repel one another, since they both bear a positive electric charge. If the energy this fusion releases is to be recovered, the required energy must first be supplied, to break through this barrier, and allow each nucleus to reach the region, very close to the other nucleus, where the nuclear forces make themselves felt, that are able to overcome this electrostatic repulsion, or Coulomb barrier. Once this outcome is achieved, the most energetic reaction are those yielding the fused nucleus with the highest binding energy. In the event at hand, this is the case for helium isotope ^{4}H, which comprises four nucleons (two protons p and two neutrons n).

Of the fusion reactions that yield energy as well as generating, on the one hand, a new – helium (He) or tritium (T) – nucleus and, on the other hand, a nucleon, four are, at first blush, of particular interest.* The first two are attractive, since they only involve deuterium (D), the most abundant hydrogen isotope on Earth. Mastering them may be the ultimate goal for controlled fusion, however they are by far the hardest to bring about.

$D + D \rightarrow {}^3He + n + 3.27$ MeV

$D + D \rightarrow T + p + 4.04$ MeV

The two subsequent ones, yielding the very stable helium-4 nucleus, are particularly energetic:

$D + T \rightarrow {}^4He + n + 17.58$ MeV

$D + {}^3He \rightarrow {}^4He + p + 18.34$ MeV

The fusion reaction that is most easily achieved, exhibiting as it does the highest cross-section, is that involving a deuterium (D) nucleus and a tritium (T) nucleus, their fusion yielding a helium nucleus and a neutron, with respective energies of 3.5 MeV and 14.1 MeV. Thus it is on this reaction, the so-called D–T reaction, that research work on controlled fusion has focused, whether in the context of inertial-confinement fusion or of magnetic-confinement fusion.

Production of the tritium required is achieved through a fifth reaction, involving lithium and... the neutrons from the D–T reaction.

$6Li + n \rightarrow {}^4He + T + 4.79$ MeV

$7Li + n \rightarrow {}^4He + T + n - 2.47$ MeV

The primary fuels, i.e. the true raw materials for a reactor, are thus deuterium and lithium (Li).

* These reactions are known as *thermonuclear* reactions since only a temperature of the order of about a hundred million degrees, together with other density and confinement time conditions (see main article), make it possible to bring them about. See page 8 for the table of the main nuclear reactions occurring inside the Sun.