Solar radiation is as indispensable to the life of Earth denizens as it can prove hazardous to their health, in case of excessive exposure, or failure of their natural protection and repair mechanisms.

The Sun, **an indispensable, albeit dangerous friend**

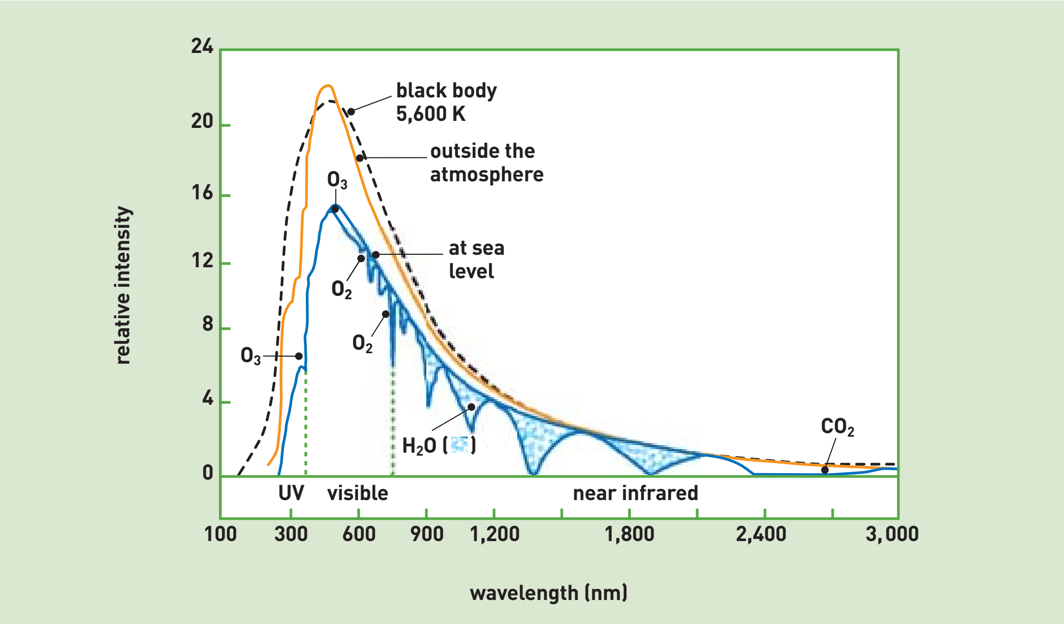
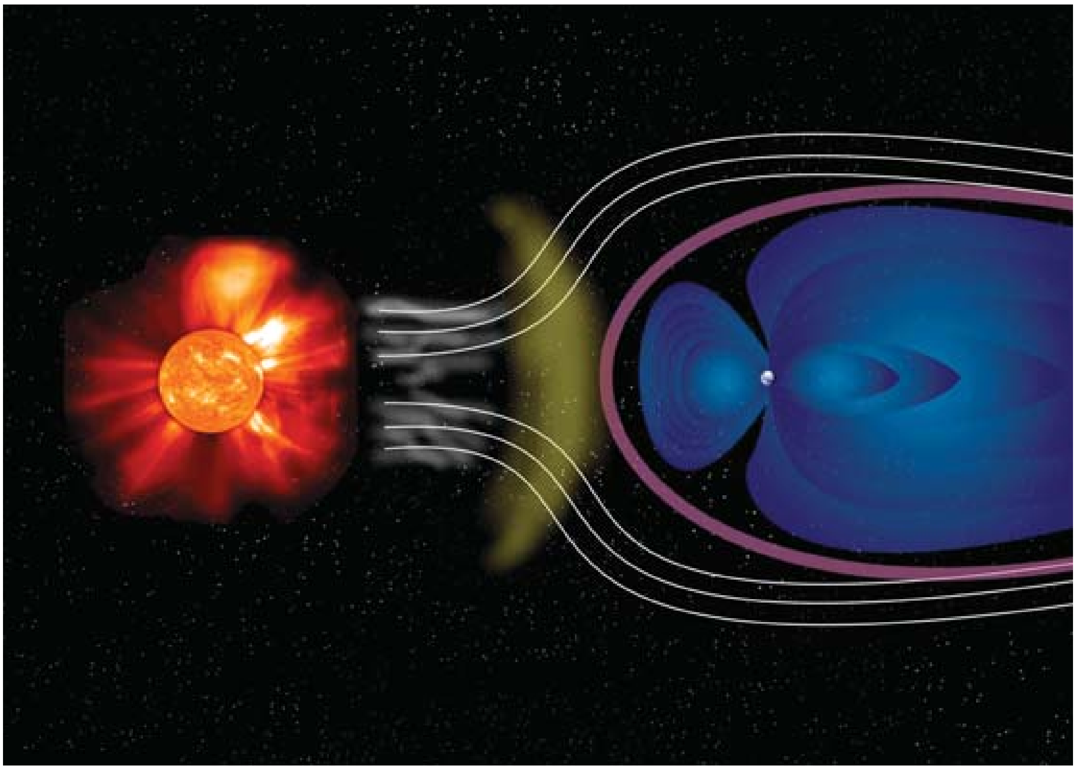


Figure 1.
Spectrum of solar electromagnetic radiation reaching the Earth's surface. Comparison between radiation prior to entering the atmosphere and at sea level (O_3 indicates absorption of UV or visible radiation by ozone, H_2O by water, and CO_2 by carbon dioxide).

In the Sun's core, thermonuclear fusion reactions turning hydrogen into helium are the cause of the formation of the solar corona, and of a constant emission of various types of radiation. After about eight minutes' journey, these reach the magnetosphere, the shield set up by the Earth's magnetic field, protecting our planet from the ionized particles of the solar wind. As it goes through the atmosphere, part of the electromagnetic radiation is absorbed by the gases composing it (oxygen, nitrogen, carbon dioxide, ozone) or by clouds. Only a fraction of the solar spectrum reaches the Earth's surface and affects us; this consists in three types of electromagnetic radiation: infrared, having wavelengths ranging from 780 to 3,000 nanometers (nm), visible, at 400-780 nm, and ultraviolet (UV), at 100-400 nm (see Figures 1 and 2).

Beneficial effects on humans, for limited doses

Present as it was since well before life emerged on Earth, solar radiation made possible the selection of organisms that had a variety of molecular and cell systems with the ability, on the one hand, to make optimum use of the radiation's energy, and, on the other, to suppress the damage it induces. Exposure, for a limited time, has many effects beneficial to our health. Synthesis in the skin of vitamin D is bolstered by ultraviolet radiation, allowing adequate calcium concentration and appropriate bone-tissue formation. This made a major contribution to vertebrate evolution. Moreover, solar radiation is by far the most decisive outside signal as regards the alternation of wakefulness and sleep, among other daily rhythms.
Concurrently, protective organs such as the skin and a number of highly effective protection systems, both chemical (redox equilibrium, and molecules with the ability to trap hazardous radicals) and biochemical (the proteins and enzymes involved in DNA metabolism; particularly synthesis and repair), were selected for, in order to counter the damage caused by cell metabolism and by chemical or physical agents in the environment, such as solar radiation.
Despite such highly sophisticated defense mechanisms, overexposure to radiation, whether willful or accidental, can have serious consequences for the entire organism. The ultraviolet component in sunlight is indeed the most prevalent carcinogen in our environment.



The Earth's magnetosphere (blue lines) shields the planet from the ionized particles of the solar wind (white lines).

ESA

James Cleaver first noted, in 1968, that cells from the skin of patients suffering from *xeroderma pigmentosum* (XP) were unable to repair the lesions caused by ultraviolet radiation. This was the first noted association between a human affection and a faulty DNA repair mechanism. Subsequently, many observations confirmed and enlarged our understanding of human cell response to damage caused by a wide variety of chemical and physical agents, in particular in patients affected by diseases associated to chromosomal anomalies or having a high **incidence** of cancer.

The skin and eyes, the main interfaces between the organism and solar radiation

The 2 square meters of human skin play an important role as a protective barrier against the environment. Moreover, the skin is involved in immune response, body-temperature control, and the reception of a variety of outside signals. The skin carries out its function of vital organ by a constant renewal of its various layers. Solar radiation affects these layers in varying fashion, according to the amount of energy yielded (see Figure 3).

The second target, the human eye, is particularly receptive to solar radiation of wavelengths ranging from 400 to 780 nm, consequently termed visible radiation. UV radiation, invisible as it is to the eye, can be particularly dangerous.

Pathologies associated to excessive exposure to solar radiation

No-one is resistant to eye disorders caused by radiation. Indeed, chronic exposure to large doses of UV without protection can, ultimately, lead to blindness.

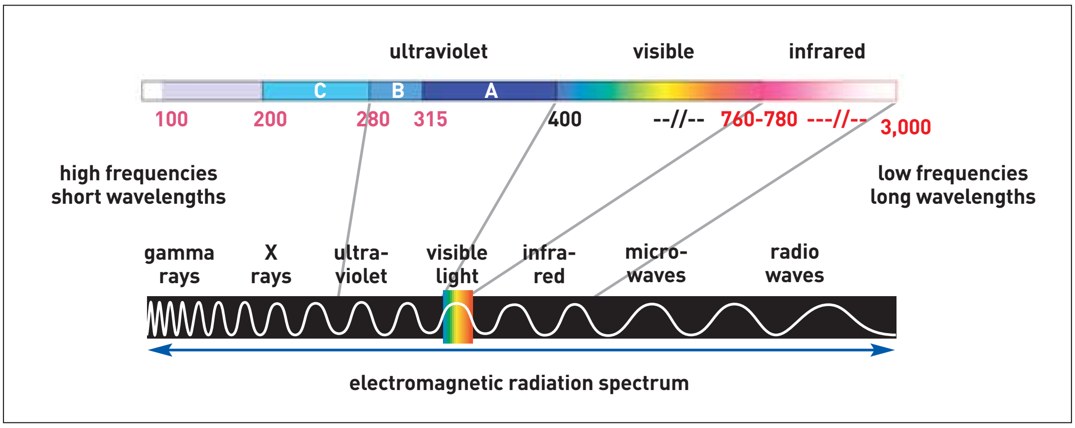


Figure 2.
Solar radiation is but one part of the various kinds of electromagnetic radiation enveloping humans at any time in their daily lives, from cosmic rays and X-rays from radiography, in the higher frequencies of the spectrum, to oven microwaves and short waves from radio broadcasts, in the lower frequencies.

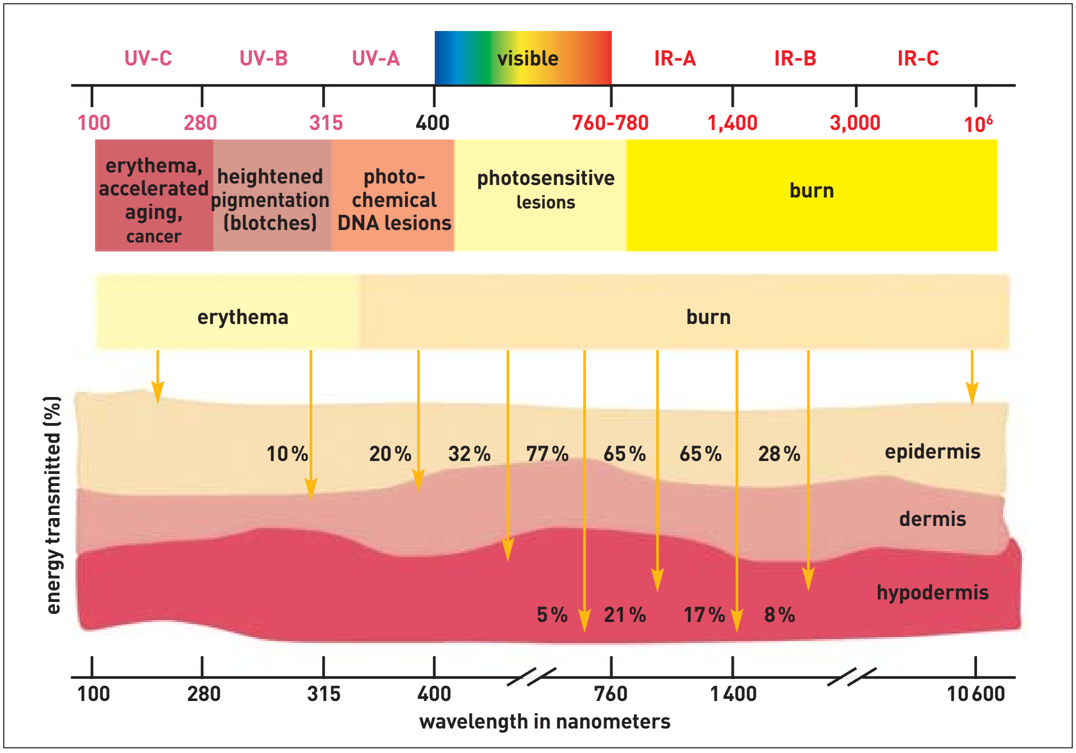


Figure 3.
Effects of solar radiation on the various layers of the human skin, as a function of wavelength.

Over 99% of UV radiation is absorbed by the anterior structures of the eye. Very little reaches the light-sensitive retina (see Figure 4). While the UV component in solar radiation is useless to human vision, it is likely that the UV radiation absorbed by the eyes contributes to aging-related alterations, and to a number of typical disorders such as cataracts (opalescence of the crystalline lens), the prime cause of blindness worldwide. According to World Health Organization (WHO) estimates, some 20% of the 20 million cases of cataract blindness are caused by the Sun, the countries most affected being those lying close to the equator. In France, 100,000 new cases each year may be ultraviolet-radiation related. Protection, especially for children (a cap and sunglasses), is indispensable, to obviate these effects. Such simple measures can also assist in prevention of skin cancer, some 80,000 new cases of which are believed to occur every year in France. Ultraviolet-induced malignant melanoma is one of the most dangerous forms of cancer, and one of the most frequently diagnosed. It was responsible for 666 fatalities in 1980, and 4,825 in 2000. Based on these effects the *dose limit for daily occupational exposure* to ultraviolet rays incident on the skin or eyes was settled on at 30 J/m^2 effective. This dose corresponds to one tenth of the mean dose causing erythema in Caucasian subjects. [(1)] Erythema, or "sunburn," is the prime clinical sign of prolonged exposure to ultraviolet radiation. Such burning occurs after exposure of 10 minutes to 6 hours, according to altitude, time of day, and other parameters such as the thickness of the ozone layer, cloud cover,

(1) Caucasian: ethnic type corresponding to white-skinned subjects of European type.

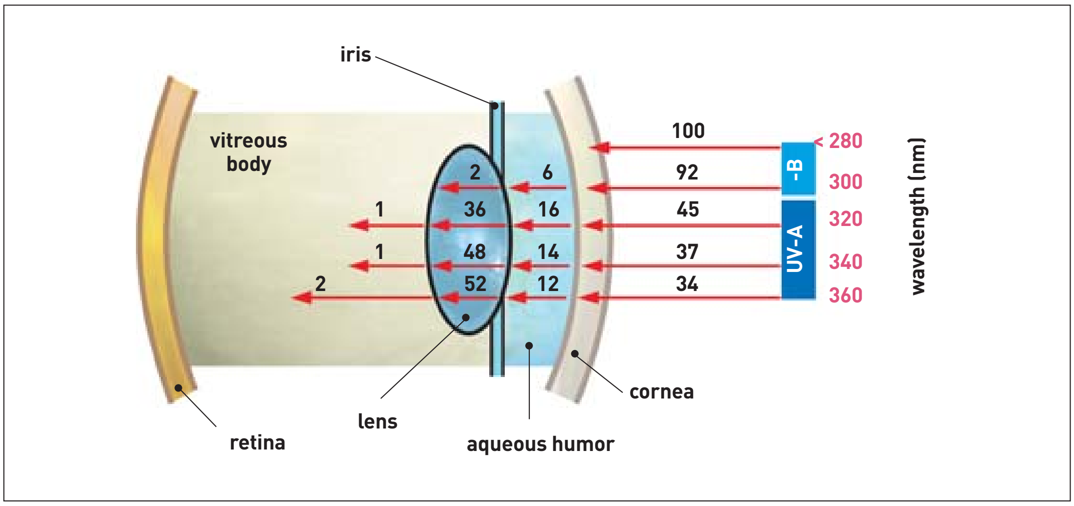
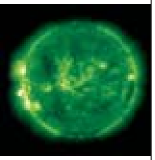


Figure 4.
Absorption of solar radiation by the various components of the eye. The figures indicate, for radiation wavelengths in the ultraviolet, the percentage of energy absorbed by each component.



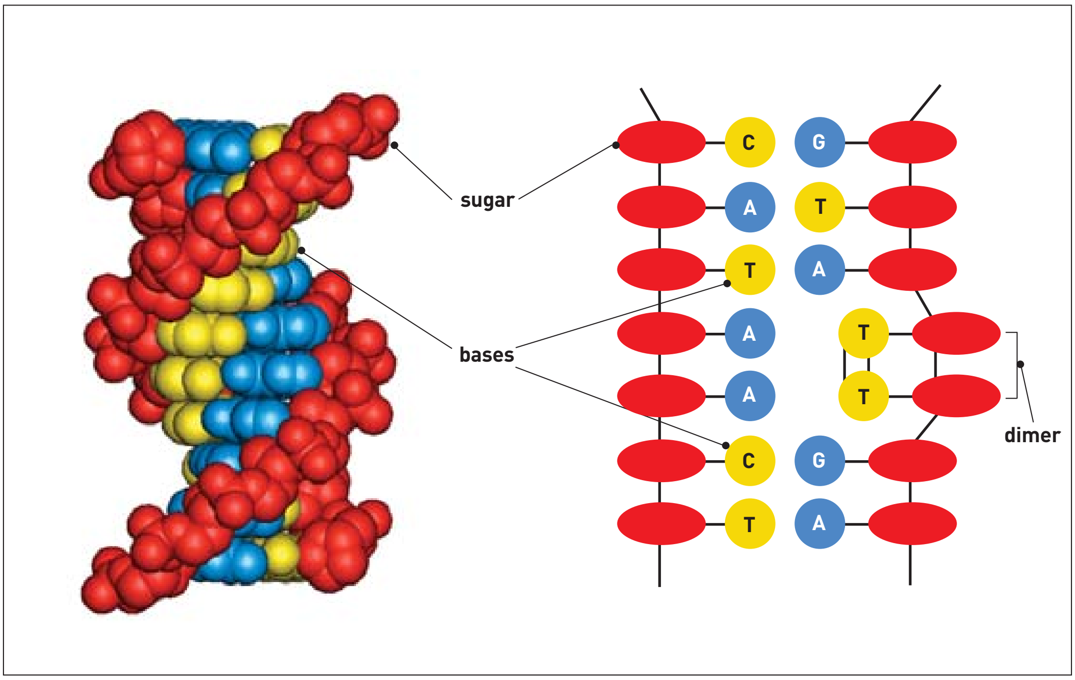


Figure 5.
Representation of the distortion caused in DNA structure by ultraviolet radiation. The thymine dimers thus formed may result in mutations in the genetic material, with serious consequences for the individual.

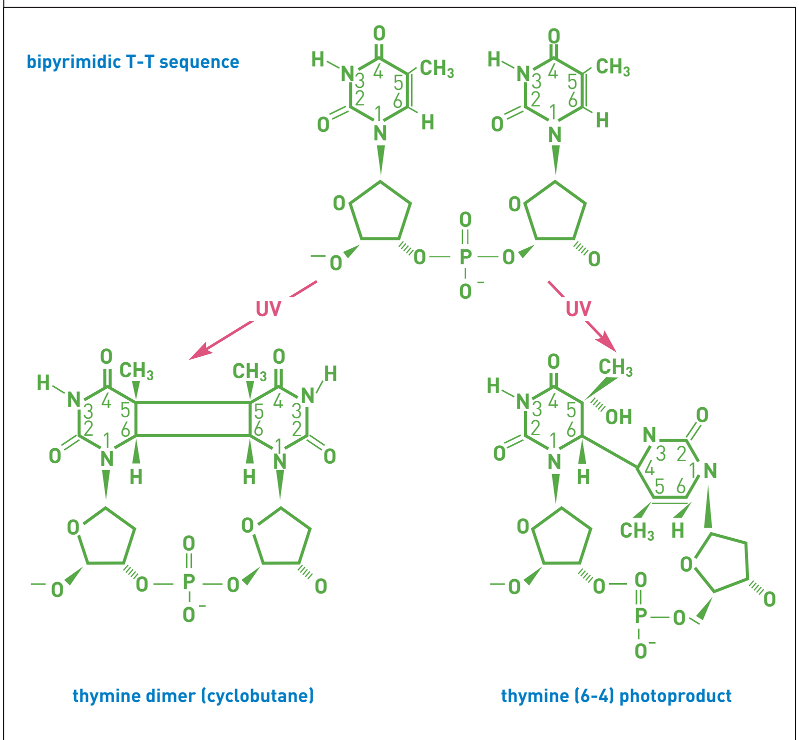


Figure 6.
Examples of thymine dimer structures generated by ultraviolet radiation.

and inherent sensitivity for each skin type. A person with very fair skin (corresponding to phototype I [(2)]) shows slight sunburn after only 10 minutes' exposure in broad sunlight, whereas a person of phototype IV can remain exposed for one hour with no reddening.

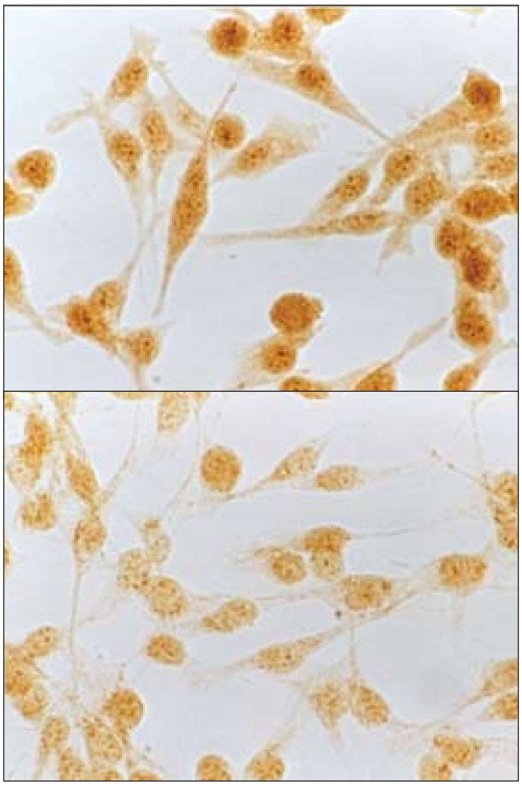
Why can solar radiation be so dangerous?

UV radiation yields energy to the molecules composing our cells, altering their chemical makeup. The various alterations thus generated activate a whole range of metabolic pathways, dedicated to neutralizing such molecular damage. The most serious consequences are alterations of DNA, the molecule that carries all the information required for cell life, and life of the individual. Ultraviolet rays set up new cross-links between adjacent pyrimidines normally found in its structure (see Figures 5 and 6). Such near-imperceptible changes can have major repercussions on the cell, leading in some cases to its destruction, or, in other cases, generating cancerous cells. Fortunately, a number of systems are on hand, having the ability the repair such lesions, with remarkable accuracy. The main mechanism involved allows the DNA fragment containing the pyrimidine dimer to be recognized and excised, and then resynthesized correctly. This repair pathway, known also as **nucleotide** excision repair system (NER), has been remarkably conserved through evolution, from bacteria to humans (see Figure 7).

Biological consequences of NER system failures

Molecular characterization of this pathway has shown it is the basis of protection against carcinogenesis attributable to solar radiation. In humans, out of all the repair systems identified so far, the NER systems plays a central role, owing to its broad damage-recognition spectrum. It consists in two main pathways: *global* **genome** *NER*, a system monitoring occurrence of distortions in the entire DNA molecule, and *transcription-coupled NER*, which specifically removes DNA damage blocking elongation of **transcribed RNA** strands by RNA **polymerases**. The NER system is the main defense against the **genotoxic** effects of solar radiation, but equally of a great variety of carcinogenic chemicals (see Figure 7). In some inherited diseases causing high sensitivity to solar radiation, **mutations**

(2) Phototype: this neologism refers to the characteristics of a subject and his skin with regard to light.
There are four main phototypes, depending essentially on skin melanin pigmentation and melanocyte density.



CEA

Introduction of the normal XPC gene into cells from XP patients sensitive to solar radiation enables them to recover the ability to repair DNA and respond to ultraviolet irradiation through activation of an SOS-type system. The number, and pigmentation intensity, of intracellular foci increase in irradiated cells (upper panel), compared with non-irradiated cells (lower panel), indicating the accumulation of kin17, a radiation-response protein which is part of the DNA-replication complex.

inactivating genes coding for proteins involved in the NER system are invariably found. Three major pathologies are linked to defects in **genes** associated to the NER system: *xeroderma pigmentosum* (XP), Cockayne's syndrome, and trichothiodystrophy (TTD). All patients exhibit DNA repair deficiency, and, in the particular case of XP patients, the hypersensitivity to sunlight is accompanied by a 1,000 times higher incidence of skin cancer than in normal subjects. This condition is found everywhere, however its incidence ranges from 1 case for 250,000 persons in Europe and the United States to 1 for 40,000 in Japan. Patients exhibit abnormally dry, squamous and pigmented skin, specific eye-tissue lesions (eyelids, conjunctiva, and cornea), as well as neurological problems. They develop skin cancer, on average, from age 8, 50 years earlier than the population of the United States as a whole. In these patients, the NER system is partly or wholly inactivated. At the molecular level, this is evidenced by the alteration of proteins involved in the NER complex, such as the XPC protein, which has the ability to recognize DNA lesions, or the XPA protein, which is involved in association of the other proteins in the complex. Changes in the structures of these proteins can block lesion recognition, or prevent formation of the repair complex. Consequently, aberrant pyrimidine dimers remain, decreasing the fidelity of the DNA **replication** process, leading to onset of mutations. This process can result in inactivation of certain genes ensuring genome stability, causing a "snowball" effect. In the longer term, this leads to a constant increase in the number of mutations caused, and cancer. It is this exaggerated mutagenesis in cancerous cells that underpins the genetic evolution allowing tumor growth.

The cellular response to solar radiation

One major responsibility of CEA is to control the effects of ionizing radiation on humans. For that purpose, it has been given the remit by government of characterizing the mechanisms whereby radiation affects DNA, cells and tissues. Such knowledge should allow precise, scientific evaluation of the hazards related to the nuclear industry. Within the Radiobiology and Radiopathology Department, at Fontenay-aux-Roses (near Paris), the Genetics of Radiosensitivity Laboratory is charged with identifying and characterizing the genes of DNA metabolism involved in cell radiosensitivity, and to specify the biological effects resulting from inactivation of DNA-repair genes. This fundamental research work requires complementary experimental approaches, *in vivo* in humans and rodents, *ex vivo* in cell cultures, and in vitro through characterization of the molecular mechanisms of replication and repair of genetic material. Such knowledge is essential for the understanding of the molecular basis of mutagenesis, and prediction of possible evolution towards carcinogenesis. Paradoxically, the initial response to non-ionizing UV radiation appears to be independent of the DNA repair system subsequently mobilized. Whether the NER system is defective or not, irradiation of human cells causes in like manner accumulation of protein p53, a guardian of the genome, together with massive **activation** of numerous genes and proteins involved in ultraviolet response, as confirmed by many teams the world over. CEA research workers were thus led to hypothesize that, aside from their inability to repair DNA, the cells of XP patients are also affected with respect to other metabolic pathways significant in cancer formation.

A new signaling pathway identified for radiation-induced damage

Working in close collaboration with Dr Alain Sarasin (of the Gustave-Roussy Institute at Villejuif, near Paris), they analyzed the differences prevailing in gene **expression** between cells from XP patients and normal donors. One gene, designated *KIN17*, was thus identified, encoding a protein of the DNA replication complex. Its expression increases 16 hours after UV irradiation. As a point of interest, this process is reduced, or even absent, in some cells from XP patients. Conserved from yeast to humans, the *KIN17* gene encodes a protein belonging to the so-called "zinc-finger" family, located in certain regions of the cell nucleus. A fraction of this protein is associated to chromosomal DNA, being part of a high-molecular-weight complex essential to its replication. Expression of this gene increases after ionizing or ultraviolet irradiation.
On the other hand, other radiation-response genes show increased expression after UV exposure in XP cells, regardless of the status of the NER repair system. Primary fibroblasts from XP patients deficient in XPA or XPC protein are unable to activate the *KIN17* gene

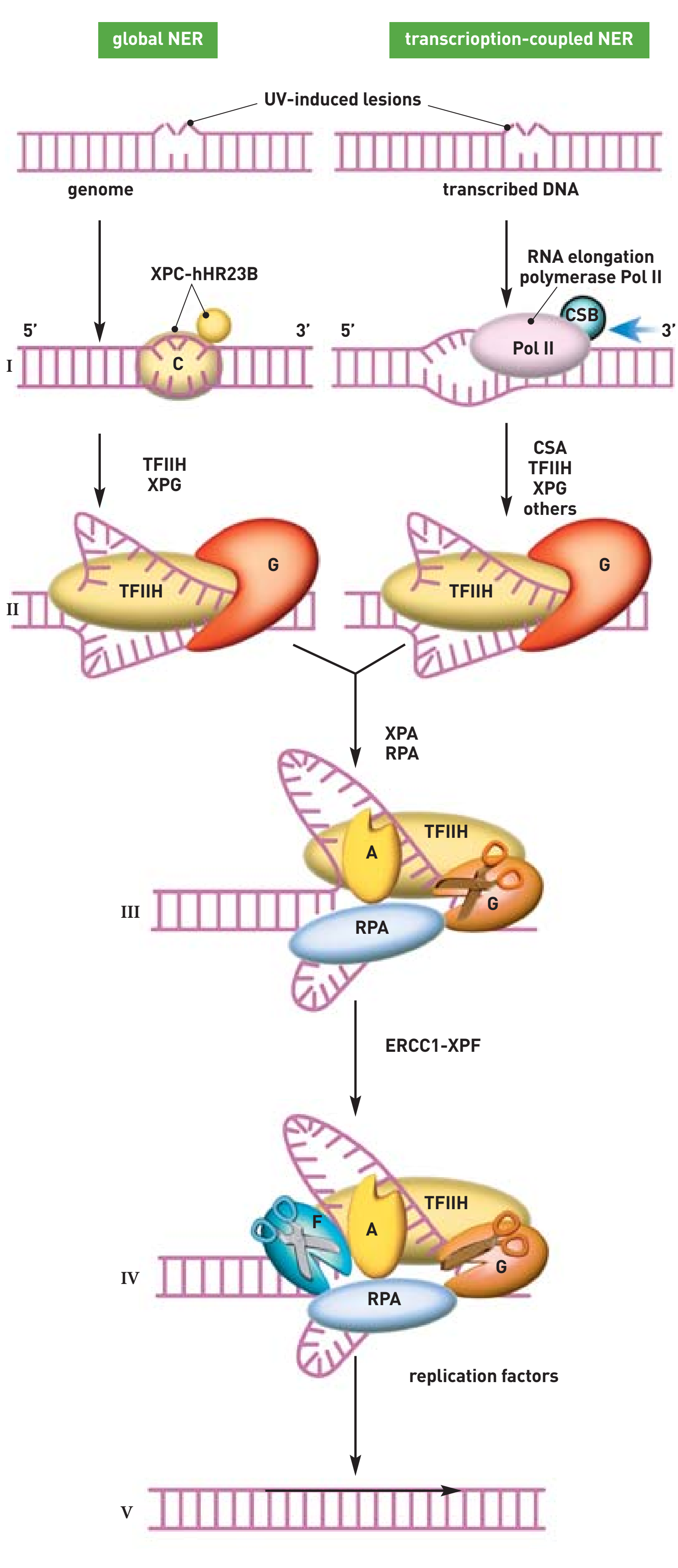


Figure 7.
Model of the DNA repair mechanism by nucleotide excision repair (NER), according to Hoeijmakers, Nature, 2001, 411, pp. 366-374 (courtesy Nature).

after UV exposure. However, this inability disappears as soon as the cDNA for the normal XPC gene is introduced into these primary fibroblasts (lines derived from a metastasis from one XP patient). These "XPC-complemented" cells recover a functional NER system, and a normal survival rate after UV irradiation. Detection of the kin17 protein shows that the XPC-complemented cells exhibit an increase, together with nucleoplasmic relocation, for this protein similar to that observed in normal cells (see Illustration, p. 99). The XPA or XPC proteins, apart from their role in the NER repair system, are thus involved in a damage-signaling pathway, resulting in particular in increased expression of certain genes, including *KIN17*.
This cell model thus makes it possible to highlight the significance of this signaling pathway in the development of radiation-induced tumors, and to evaluate the contribution of this response to radiation in carcinogenesis prevention.

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Life Sciences Division
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A Spotlight on the Sun

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

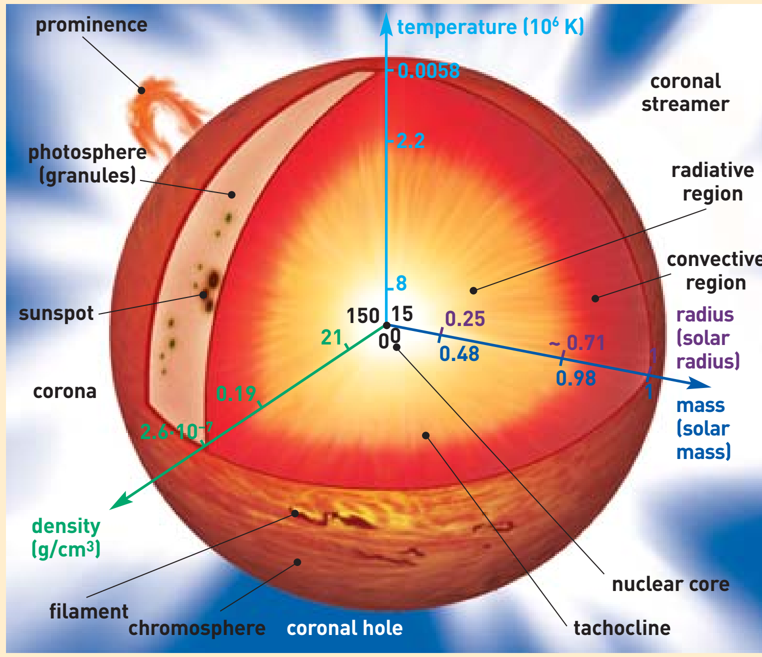


Figure.

(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.

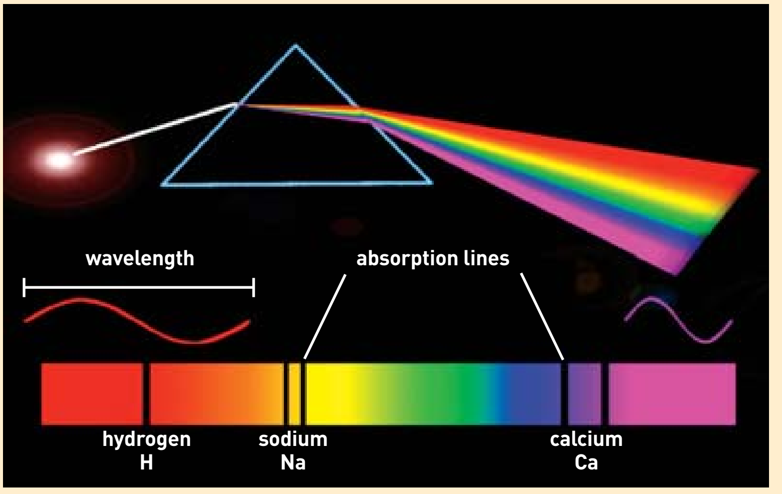


Figure a.

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.

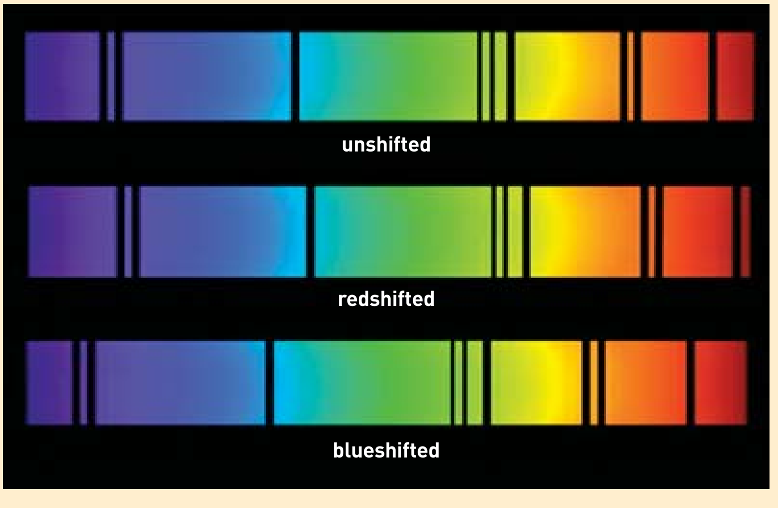
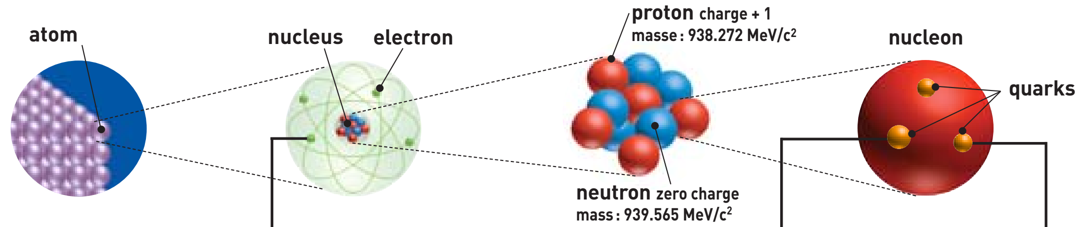


Figure b.

(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.

(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).

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.

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.

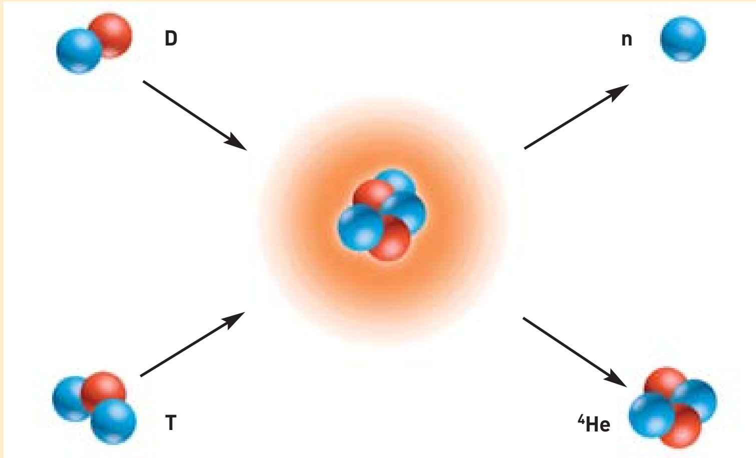
D Nuclear fusion reactions

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.

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

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



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

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

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

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

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