

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 participation 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 *gene-*

rations, 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 **Z⁰**. 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/c² for W[±], 91 GeV/c² for Z⁰), the range of the weak interaction is tiny – of the order of 10⁻¹⁸ m. Since W[±] bosons have a non-zero electric charge, fermions exchanging such bosons undergo a change in electric charge, as of nature (*flavor*). Conversely, since the Z⁰ 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 Z⁰. On the other hand, a neutrino has the ability to exchange a Z⁰ 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).

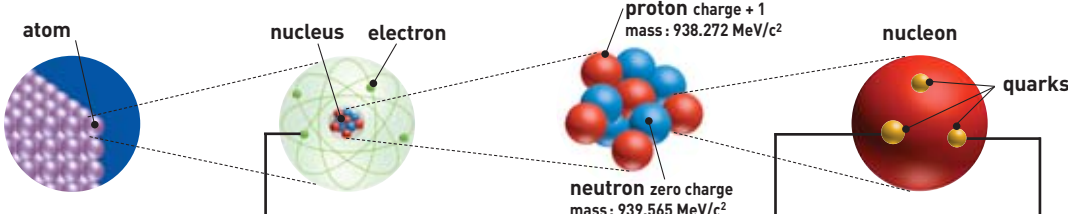
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when a gluon exchange takes place between quarks, the latter exchange their respective colors. Gluons have zero mass, however, since they do bear a color charge, they are able to interact

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.	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.	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	charm (c) a heavier companion to "down" mass: 1.15 – 1.35 GeV/c ²
	tau particle (τ) heavier still. mass: 1,776.99 ± 0.29 MeV/c ²	tau neutrino (ν_τ) properties similar to those of the electron neutrino.	bottom (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 bearers of the weak force, responsible for some forms of radioactive decay	
Higgs boson?	responsible for "electroweak symmetry breaking"			

Tableau 1.

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

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

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

The strong and electromagnetic interactions are formalized, respectively, in the theories of **quantum chromodynamics**, and **quantum electrodynamics**.

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

All the predictions of the standard model have been corroborated by experiment, except for just one, to wit, the existence of the **Higgs boson(s)**, which particle (particle(s)?), 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.