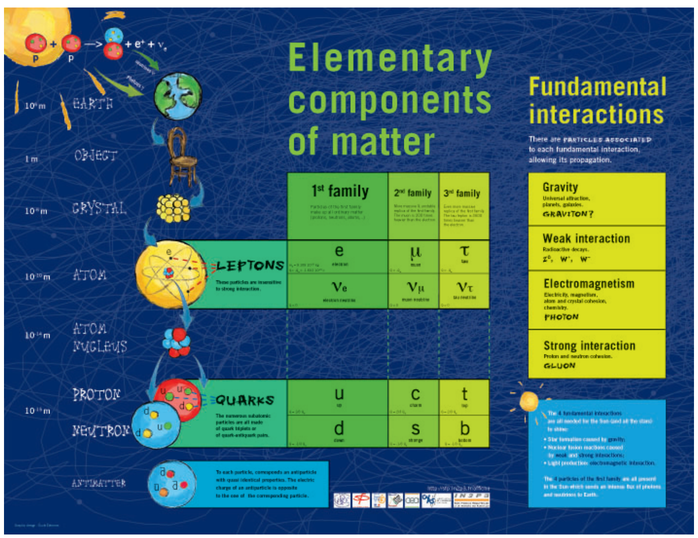
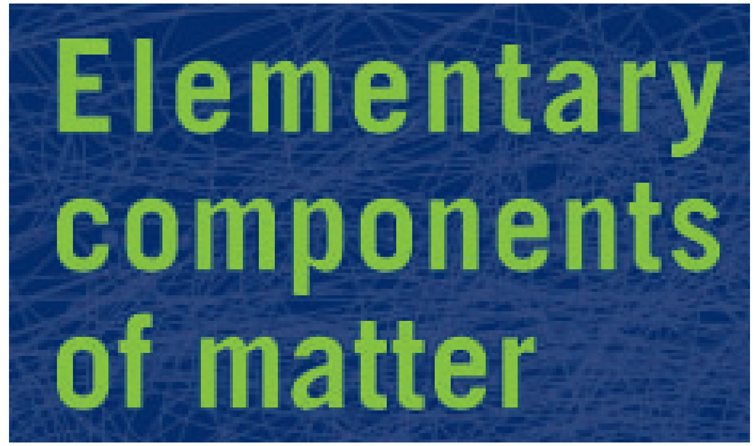
Why are the masses of matter components and interaction particles so widely dispersed?

According to the standard model of particle physics, these values come from the properties of the "Higgs boson". Physicists have been trying to detect this last particle of the standard model for more than 15 years, first at LEP, an electron-positron collider at CERN (near Geneva), and more recently in a proton-antiproton collider at Fermilab (near Chicago). Hopefully, the Higgs boson will be discovered in 2007 by the LHC, a huge proton-proton collider currently under construction at CERN.

Why is antimatter absent from our Universe?

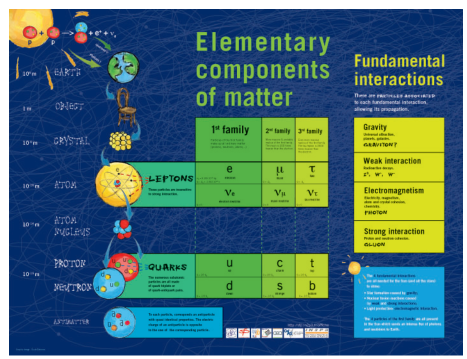
Just after the initial explosion of the Big Bang, there was as much matter as antimatter and they ought to have annihilated completely, leaving nothing. Our Universe presumably results from a very small lack of equilibrium which has led to a slight advantage for matter. Nobody knows exactly where this initial discrepancy came from, but the study of some subtle aspects of weak interactions should shed light on this issue.



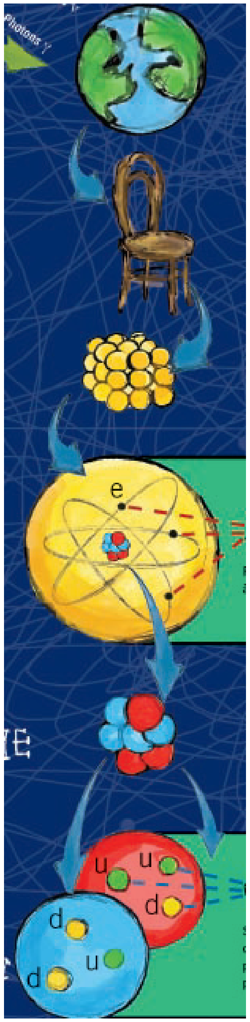


This poster presents the elementary constituents of matter (the particles) and their interactions, the latter having other particles as intermediaries. These elementary particles are point-like and have no known internal structure. Nonetheless they possess various fundamental properties making particles of one type different from those of another. The processes involving these particles are described in a unified theoretical framework, the Standard Model of particle physics, developed in the 1960's and 70's. It is based, on the one hand, on quantum mechanics, which describes the behaviour of matter at very small distances, and on the other on Einstein's special theory of relativity, which deals with objects having speeds close to that of light. By introducing parameters determined experimentally (i.e., the free parameters of the model), the Standard Model, based on a small number of elementary particles, describes all microscopic phenomena currently known.

1. What does this poster contain?



In this poster, the most important element is a classification of the components (i.e. the elementary particles) according to their type and the family to which they belong, or (o, the right) the interaction that they mediate. In addition, to the left a frieze illustrates the size and structure of various objects. In the bottom right is an outline of the processes taking place inside the Sun while a short text on antimatter is to be found at the bottom of the poster.



The frieze

The left side shows what matter looks like depending on the length scale (or resolution) considered. At the macroscopic scale, in everyday life, we encounter objects with dimensions of the order of a meter. At larger scales, astronomers look at objects far more massive and extended, such as galaxies.
At smaller scales, "ordinary" matter can be built from molecules made out of atoms. These atoms have a size around 10^{-10} m. Almost the whole mass of the atom is squeezed into its nucleus, with a radius of 10^{-15} m. The nucleus itself consists of protons and neutrons (generically called nucleons). The latter are not elementary particles: since the 1960's, we know that nucleons are formed of point-like particles, quarks and gluons.

The elementary constituents

Elementary particles are characterized by their mass, their electric charge and their spin. Spin is an intrinsic feature of elementary particles: it is analogous (but not identical) to an angular rotation and the particle has properties similar to that of a small magnet. Particles of integer spin (0,1,2...) are called bosons, whereas particles with half-integer spin (1/2, 3/2...) are referred to as fermions. The latter obey the Pauli "exclusion principle". (Particle physics is very international. Satyendranath Bose was Indian, Enrico Fermi Italian and Wolfgang Pauli Austrian-Swiss.)

Pauli's principle states that within the same system, two identical fermions cannot exist in the same quantum state. This principle explains why electrons are stacked in layers around the nucleus and do not all fall into the ground state, the one which has the lowest energy. On the contrary, there is no restriction on the number of bosons in a given quantum state. This is illustrated by lasers which take advantage of the possibility of putting a large number of photons all in the very same state.

Neutrinos are electrically neutral and have very little interaction with matter. A neutrino can pass through the earth without interacting at all ! Hard to detect, neutrinos are produced in large quantities in stellar combustion. These particles, the existence of which was proposed in 1930 to explain intriguing features of radioactive beta decay, were brought to light experimentally and found to occur in three different species: the electron neutrino (ν_e) discovered in 1956), the muon neutrino (ν_μ), 1964) and the tau neutrino (ν_τ), 2000). For a long time, physicists believed that these three neutrinos were exactly massless, but experimental results obtained over the last few years have shown that they are able to "oscillate" during flight, i.e., they can change from one flavour to another while going from sun to earth, for example. Such oscillations can occur only if the three neutrinos have slightly different masses, from which one must conclude that these particles are not massless!

4. A few questions yet to be answered

Despite the apparent simplicity of the poster's tables, many mysteries remain. Considering only the information presented in the poster, one is led to ask the following questions.

Why four interactions ?

We do not know. But we dream of unifying all elementary processes as consequences of a single interaction, as Maxwell did with electricity and magnetism, followed more recently by electro-weak unification.

Why three families ?

Once again, there is no answer. We only know that these "copies" of the constituents of ordinary matter do exist, and according to present evidence, the particles seem to come in no more than three families.

Quarks are sensitive to strong, weak and electromagnetic interactions. Their electric charges (1/3 q_e and -2/3 q_e) are fractions of the electron charge q_e whose absolute value is 1.6 10^{-19} coulomb. They cannot be observed directly individually because they are held prisoner in groups of two or three within the observed particles; thus quarks are said to be "confined".

For reasons related to invariance laws and interaction symmetries, quarks are placed in three different families. The first one contains the up and down quarks; the proton and the neutron are composed of different combinations of three quarks, uud for the proton and udd for the neutron. The other families are just copies of the first one, with heavier unstable quarks which decay into lighter quarks and leptons with a very short lifetime (below 10^{-10} s). The quark masses are quite disparate: for example, the heaviest one, the top quark, is around 180 times more massive than a proton, itself made of three light quarks Finally, each quark has a "colour charge", of which there are three types. This kind of charge, not shown in the table, plays a similar role for the strong interactions to that of the electric charge for the electromagnetic force.

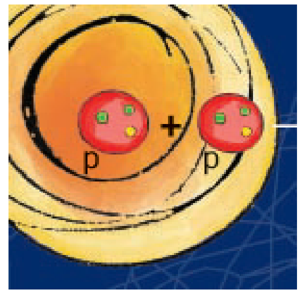
Although quarks are not observed directly in experiments, one can create and detect hundreds of types of particles called hadrons which made of either three quarks or a quark-antiquark pair. Those in the first group, such as the proton and the neutron, are called baryons ("heavy particles"), while those of the second group are referred to as mesons ("intermediate-mass particles").

Leptons

These matter particles are affected by the weak interaction but not by the strong force. The electron (e) and its companion the electronic neutrino (ν_e) are classed in the first family. Their counterparts in the two other families are the muon (μ), discovered in 1937 in cosmic rays, and the tau (τ) (tau, produced at an accelerator in 1976), together with their associated neutrinos. The electron, muon an tau are "cousins" with the same electrical charge q_e and similar properties, even though their masses are very different and their flavours distinct. As is the case for the 2nd and 3rd generation quarks, the mu and tau are unstable and can decay into lighter leptons.

Particle physicists distinguish matter particles from interaction particles (also called interaction fields). Matter particles, shown in the central table, interact with each other by "exchanging" interaction fields, shown to the right. There are three "families" of matter particles, but only those of the first family are to be found in ordinary matter. The two other families were discovered in cosmic rays and in experiments performed using high-energy particle accelerators. The matter particles are also divided into two categories, quarks and leptons, depending on whether they are sensitive to strong interactions. All matter particles are fermions.

All physical phenomena governing the Universe can be described in terms of four fundamental interactions (or forces). At the subatomic level, these interactions are distinguished according to the particles exchanged, which appear in the table to the right. All interaction particles are bosons.



The Sun

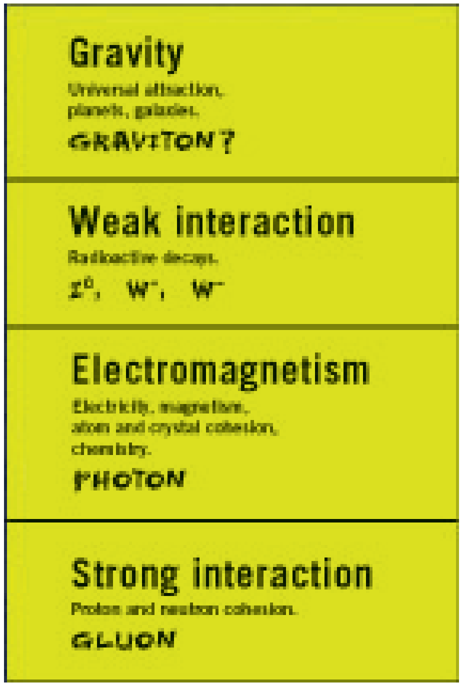
The processes occurring inside the Sun involve the four fundamental interactions, and provide a good example of the roles the interactions can play. Gravitation is so strong inside the Sun that it yields densities of hydrogen high enough to counterbalance the electrostatic repulsion between protons and to initiate the fusion reaction of two protons into a deuteron (p-n). This process is governed by the weak interaction and its rate is such that the stars burn slowly on human and cosmological time scales. After the initial fusion of proton pairs, a chain of nuclear reactions involving the strong interaction yields a large variety of heavier nuclei. The energy liberated in these different reactions undergoes transformations which convert it to electromagnetic energy, the heat and light that we receive each day.

Antimatter

Though the Universe seems to be made entirely of matter, observations and experiments have shown that each matter particle does have an antimatter counterpart, a particle whose properties are identical, but with opposite "charge". Thus one could have introduced a table of antiquarks and antileptons opposite to that listing the quarks and leptons. The antimatter that we can observe is either man-made using accelerators or produced by reactions between cosmic ray particles and ordinary matter. The first antiparticle, the anti-electron or positron, was discovered in 1932.

2. The fundamental interactions

Of the four fundamental interactions, two are part of everyday life and are the subject of "classical" physics : gravitation and electromagnetism. These two forces have an infinite range, with a strength inversely proportional to the square of the distance between the particles or groups of particles involved. In quantum theory, this implies that the particles mediating these interactions, the photon for electromagnetism, and the graviton, which remains hypothetical, for gravitation, must have an exactly zero mass.



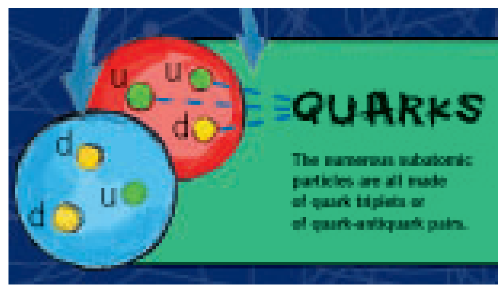
Gravitation poses a real problem for particle theorists. They do not know how to include it in the framework of the quantum field theory that has been used successfully to describe the three other interactions. In other words, a happy marriage between quantum mechanics and general relativity, which describes gravitation, would seem to be very difficult to obtain. However, this problem does not affect particle physics, in which gravitation plays only a minor role and is generally neglected due to its very weak strength.

The two other forces, i.e., the weak and strong interactions, were discovered during the 20th century through the study of nuclei. In order to explain how protons and neutrons could be bound inside nuclei, a very potent force had to be invoked to overcome the electrostatic force that tends to separate protons from each other but does not affect neutrons which are not electrically charged. This nuclear force, acting at short distances (10^{-15} m) with great intensity, is an aspect of the strong interaction, which plays an essential role in the way the various observed particles are built up out of quarks. We know that nucleons (protons and neutrons) and many other particles discovered in the last half-century are not really "elementary". They are made of quarks, interacting with each other through exchanges of gluons that "glue" them together. The gluons, whose existence was proved in 1979, have a zero mass like photons. Nonetheless the strong interaction has only a very limited range, which explains why it has no influence on a macroscopic scale or even at atomic distances.

The fourth and last interaction is the weak force which is responsible for the beta decays of elementary particles and nuclei. It is also a force with a subatomic range because of the high masses of its mediating vector particles, the bosons W and Z, 80 times heavier than a proton! These bosons were seen for the first time in 1984 at CERN, the large European research laboratory in Geneva, Switzerland. From a macroscopic point of view, the weak force is seen at work in the thermonuclear combustion of stars, where it makes possible the fusion of two protons into a deuterium nucleus (a proton and a neutron bound together) with the emission of a positron and a neutrino. One of the most significant achievements of particle physics has consisted in unifying the weak and electromagnetic interactions in a single framework in which they are described as two aspects of a single force. The crowning achievement following this theoretical success was the discovery of the W and Z bosons and the study of their properties.

3. Quarks and leptons

Quarks



Quarks are the constituents of the nucleons–which make up most of "ordinary" matter–and more generally of particles called hadrons. There are six types (or "flavours") of quarks: up (u), down (d), charm (c), strange (s), top (t) and bottom (b). These curious (and quite arbitrary) names are related to the history of the discovery of these particles. The up and down quarks have very similar properties, involving a symmetry described in a framework identical to the description of spin-1/2 particles. The strange quark got its name from the "strange" features observed initially during the 1950's in hadrons containing this quark. The charm quark, discovered in 1975, was first introduced to patch up theory and explain (by magic) why some phenomena (in particular some kinds of decays) were not observed experimentally. Finally, the top and bottom quarks, discovered respectively in 1977 and 1995, were named in analogy with the u and d quarks. The b quark is sometimes also called the "beauty" quark.