Instituto de Física Teórica UAM-CSIC

What are we made of?

The world of elementary particles

UAM

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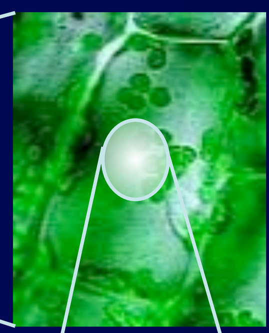
Consejo Superior de Investigaciones Científicas

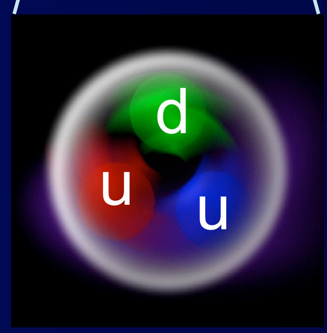
10^5 m = 100 Km
Satellite image of the Madrid area, centered on the El Pardo forest

1m
A holm oak tree in the El Pardo forest



10^{-5} m = 10 μm
Plant cell

10^{-10} m = 0.1nm
Carbon atom



10^{-15} m
Internal structure of the proton

Are atoms fundamental particles?

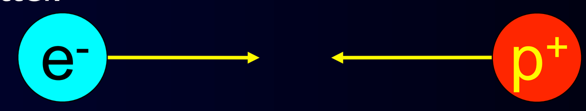
In 1911 Rutherford showed that atoms were composed of a tiny nucleus, with positive electric charge and carrying most of the atom mass, and a cloud of electrons (with negative electric charge) orbiting around it. A few years later, atomic nuclei were discovered to be made up of protons (Rutherford, 1918) and neutrons (Chadwick, 1932).

As of today, electrons are considered to be fundamental particles. However, protons and neutrons do have internal structure, as they are in fact made out of three quarks.
Quarks making up protons and neutrons are of two kinds: the up quark "u" with electric charge +2/3 and the down quark "d", with charge -1/3. A proton is composed of two "u" quarks and one "d" quark, and so has charge +1, whereas a neutron is composed of two "d" quarks and one "u" quark, so it has charge 0.

What keeps electrons in their orbits?

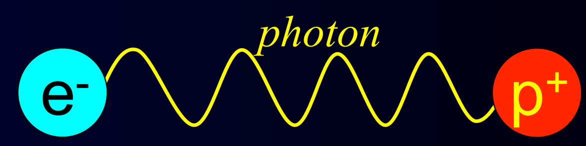
The Electromagnetic Force

Charges of opposite sign attract each other. Hence, the negatively charged electrons are attracted by the positively charged protons in the nucleus, and stay orbiting around the latter.



How is the force transmitted?

Charged particles exert electromagnetic forces among them by exchanging other massless particles called **photons.** These **photons** are also the particles **light** light is made out of.



What keeps protons inside the nucleus? And quarks inside the proton?

The Strong Force

In analogy with electrons and protons carrying electric charge, quarks carry **"color"** charge. There are three distinct kinds of colors, and different colors attract, just like opposite electric charges. Hence, quarks form bound states of three differently colored quarks to form protons and neutrons. In analogy with the electromagnetic force, which is transmitted by the exchange of **photons**, the strong force is transmitted by the exchange of **gluons**, another kind of massless particle. Protons and neutrons in the nucleus are also kept together by a remnant of the strong force.

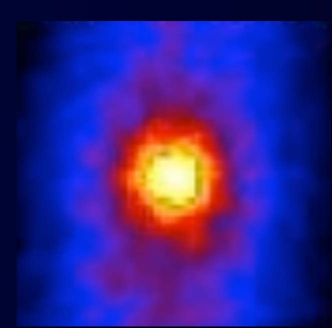
With just three particles: electrons, "u" quarks and "d" quarks one can build all atoms in the universe. But Nature is offering much more than that...

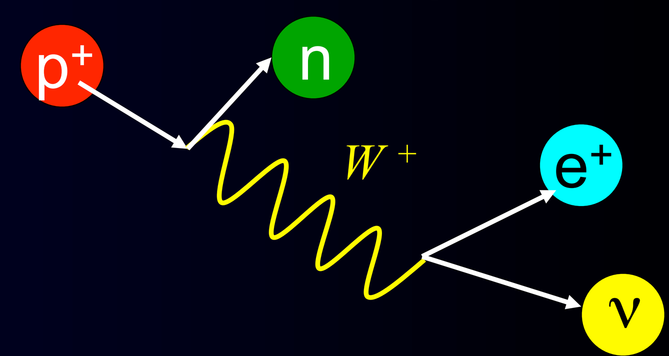
For each electron, proton or neutron there exist 10 000 000 000 **neutrinos**. These **neutrinos** are very light particles (at least, one million times lighter than electrons). The carry neither electric nor "color" charge, and they only feel weak interactions and gravity, so they are extremely difficult to detect. **Neutrinos** can travel through enormous amounts of matter with no interaction, and in fact millions of millions of neutrinos are crossing your body at this very instant.
The matter content of the universe, **the fermions**, thus correspond to the electron, the **neutrino**, the "u" quark and the "d" quark, which form the so-called **first family of particles**. However, Nature seems to have three copies of such particle family. Particles in the second and third family have the same interactions and charges (electric charge, color and weak interactions) as those in the first, but the former are much heavier.

How do stars shine?

The weak force

Stars like the Sun produce energy by the fusion of protons to form Helium-4 nuclei, composed of two protons and two neutrons. This requires an interaction capable of changing the nature of the participating particles: this is the weak force. The particles mediating the weak interaction are the W's and the Z. There are two kind of W particle, with electric charges +1 y -1 respectively, and one Z, which is neutral, like the **photon**; however, both the W's and the Z are massive. In the core of stars, protons turn into neutrons by emitting a W^+ which subsequently decays producing positrons (the antiparticle of the electron) and neutrinos ν. Besides light, the Sun thus emits neutrinos allowing us to obtain neutrino images of the Sun.





FERMIONS: Building blocks of the Universe

Leptons spin =1/2		
Name	Mass (GeV)	Electric charge
ν_L lightest neutrino*	$<10^{-9}$	0
e electron	0.0005	–1
ν_M middle neutrino*	$<10^{-9}$	0
μ muon	0.1	–1
ν_H heaviest neutrino*	$<10^{-9}$	0
τ tau	1.8	–1

Quarks spin =1/2		
Name	Approx. Mass (GeV)	Electric charge
u up	0.002	2/3
d down	0.005	–1/3
c charm	1.3	2/3
s strange	0.1	–1/3
t top	173	2/3
b bottom	4.2	–1/3

What is Antimatter?

For every particle kind there exist a corresponding **antiparticle**. They have the the same mass the the corresponding particle, but all their charges are opposite (electric charge, "color",...).

When a particle and antiparticle meet, they annihilate each other releasing large amounts of energy, often in the form of photons (light).

Bosons: The glue of the Universe

Electromagnetic and Weak spin = 1		
Name	Mass (GeV)	Electric charge
γ photon	0	0
W^- W bosons	80.39	–1
W^+ W bosons	80.39	+1
Z^0 Z boson	91.188	0

Strong (color) spin =1		
Name	Mass (GeV)	Electric charge
g gluon	0	0

What is the strongest force?

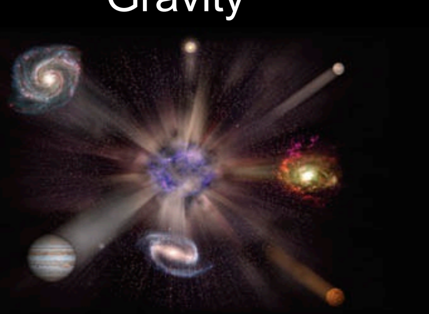
The most intense of all forces is the strong interaction, which is able to keep protons confined in the nucleus despite their electromagnetic repulsion. However, this is a very short range force and essentially vanished at distances larger than the atomic nucleus.
The electromagnetic force is the second most intense interaction, and is responsible of keeping electrons orbiting around atomic nuclei. It explains the chemical bounds of atoms to form molecules, cells, and living beings. It is a long range force, but, since matter is made up of equal amounts of electrons and protons, it is neutral and the electromagnetic force is usually not manifest a large distances.
At very large distances, the dominant interaction is gravity. This way, although the gravitational interaction is the less intense force at the level of elementary particles, it dominates at human scales, describes planetary motion and the orbiting of stars in galaxies, and ultimately controls the expansion of the universe and its final fate.

The origin of mass: the Higgs boson

To explain the masses of elementary particles, it is necessary to introduce a new particle: the **Higgs boson**. The **Higgs boson** is the particle associated with the **Higgs field** which uniformly permeates all of space and time. The Higgs can interact with the other particles, and this interaction increases the internal energy of the particle, which manifests as the appearance of a mass for the particle. The stronger the interaction of the particle with the **Higgs**, the larger the mass it acquires.
The **Higgs** particle was discovered almost 50 years after its theoretical prediction in 1964. Experiments at the Large Hadron Collider LHC at CERN in Geneva confirmed the existence of the Higgs boson on july 4th 2012. This discovery allowed François Englert and Peter Higgs to receive the Nobel Prized in Physics 2013 for the discovery of the theoretical mechanism responsible for the origin of masses of elementary particles.

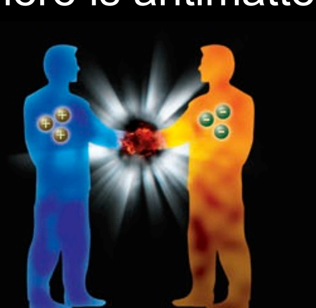
Open puzzles

Gravity



The Standard Model is a quantum theory which explains the strong, weak and electromagnetic interactions. However, we are still lacking a quantum formulation of gravitational interactions.

Where is antimatter?



The Standard Model has one antiparticle for each particle, with essentially identical interaction couplings. Why don't we observe antimatter in the universe, besides that produced in particle collisions in accelerators or cosmic rays?

Dark matter

Most of the matter in galaxies is dark matter, an invisible component which does not emit or interact with light. What is dark matter made of? Is it a new kind of particles interacting only very weakly with ordinary matter? What are its main properties?

Particle masses

The Standard Model has three families of particles, each one heavier than the preceding one. Why particles are replicated in this threefold way and what determines the values of their masses remains an open question.

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EXCELENCIA SEVERO OCHOA