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WHAT IS THE UNIVERSE MADE OF? PARTICLES AND COSMOLOGY

José Bernabéu Alberola

Departamento de Fisica Teórica and IFIC, University of Valencia-CSIC Dr. Moliner, 50, E-46100 Burjassot (Valencia), Spain E-mail: Jose.Bernabeu@uv.es

Abstract

This question has been formulated by all civilizations. In the natural philosophy of the Greeks, the four elements theory, complemented with quintessence, represents the precursor answer to the one given by elementary particle physics these days in terms of quarks, electrons and neutrinos, with interactions mediated by the fundamental forces. The present instrumentation with accelerators, detectors and computers has spectacular applications in other fields too. The frontier of elementarity is connected with the physics of the biggest, the Universe as a whole, which in its first instants after the Big-Bang was composed of energy and non-aggregate mater such as studied in particle physics laboratories today. Recently, the Cosmology has entered in a Golden Age with discoveries of great impact, leading to a second Copernican revolution: the kind of matter in our constitution, and that of all known objects, only represents a 5% of the total of matter-energy in the Universe. There is a 25% of dark matter, which nature is unknown to us, and a 70% of still more mysterious energy, with the given name of dark energy.

Key words: Particles, Cosmology, Quarks, Dark Energy.

Resumen

¿De qué está hecho el Universo? Partículas y Cosmología. Esta pregunta ha sido formulada por todas las civilizaciones. En la filosofía natural de los griegos, la teoría de los cuatro elementos, complementada con la quintaesencia, representa la respuesta precursora a la proporcionada hoy por los físicos de partículas elementales en términos de quarks, electrones y neutrinos, interaccionando entre ellos mediante las fuerzas fundamentales. Los medios puestos en juego, aceleradores, detectores y computadores, tienen aplicaciones espectaculares también en otros campos. La frontera de la elementaridad se halla conectada con la de lo más grande, el Universo como un todo, que en sus primeros instantes después del Big-Bang estaba formado por energía y materia no-agregada tal como se estudia hoy en los laboratorios de física de partículas. Recientemente, la Cosmología ha entrado en una Edad de Oro con descubrimientos de enorme impacto que han provocado una nueva revolución conceptual de tipo copernicano: la materia de la que nosotros, y todo lo conocido, estamos hechos sólo representa un 5% del total de materia-energía. Hay un 25% de materia oscura, cuya naturaleza nos resulta desconocida, y un 70% de energía aún más misteriosa, bautizada como energía oscura.

Palabras clave: Partículas, Cosmología, Quarks, Energía Oscura.

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1. Introduction

The present research in Elementary Particle Physics, initiated in the XX century, represents the most ambitious organized effort carried out by the human civilization with the aim to answer the question of the title of this article. However, all civilizations in the History have speculated about the nature of things. After some initial considerations made by the Mileto and Pitagoric schools of natural philosophy, the Greeks put forward very interesting ideas on this subject. Empedocles (500-430 b.C.) invented the four-elements theory of Matter: earth, air, fire, water (Fig. 1). Empedocles' world-view is of a cosmic cycle of eternal change, growth and decay, in which two personified cosmic forces, Love and Strife, engage in an eternal battle for supremacy.

The "atomists", in their search of maximal simplicity, imagined that the true elements were, in essence, of identical nature, but with different sizes and forms to explain the variety of matter (Fig. 2). The atoms would be indivisible and inalterable, separated by the vacuum to allow their motion. Democritus (460-371 b.C.) (Fig. 3) was a follower of Leucipo and he is recognized by his fundamental ideas about the atoms. Although invisible to the human eye, all the world is explained on this corpuscular basis. The sensations would be a consequence of the interaction of the atoms with the senses.

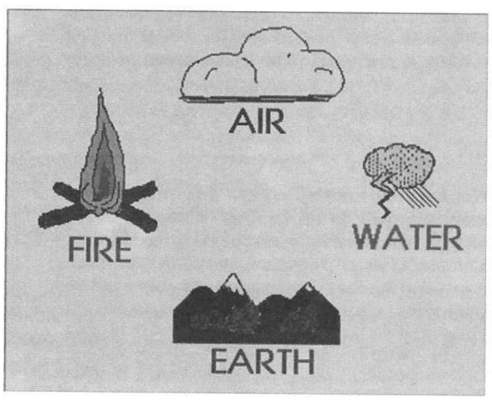


Fig. 1. Empedocles' theory of the four elements.

Plato (427-347 b.C.) changes the materialistic interests which had centered the philosophy. The atoms in collision and motion as imagined by Democritus were substituted by the world of "Ideas" as the last reality. To each object there is a correspondence with an idea, and the "knowing" is the way towards its essence.

Aristotle (385-347 b.C.) (Fig. 4) discarded that the ideas could have a reality independent of the objects themselves. The ideas would only express "qualities" of the substances and the reality is attributed to the substances. Aristotle denies the atomism and the vacuum and accepts the four-elements theory, but adding one more: the quintessence. He divided the world into two very different parts: the terrestrial constituted by the four elements and the heaven with the quintessence as the unique element. In the heaven, the Sun and planets would move in perfect circles, with any other change becoming impossible and the Universe would be eternal, with neither a beginning nor an end.

In spite of the important merits of Aristotle in the systematics of the knowledge and his original contributions to Logics, his authority on Natural Philosophy along the Middle Age prevented the birth of the scientific development until the XVI century. The scientific methodology established by Galileo and Newton was the trigger of the most important advances made in the knowledge of the world and the nature of matter.

The atomism could not reappear until the birth of Modern Chemistry in the XIX century, with the atomic hypothesis by John Dalton. His early studies on gases led to development of the law of partial pressures (known as Dalton's law), which states that the total pressure of a mixture of gases equals the sum of the pressures of the gases in the mixture, each gas acting independently. On the strength of the data gained in these studies he devised other experiments

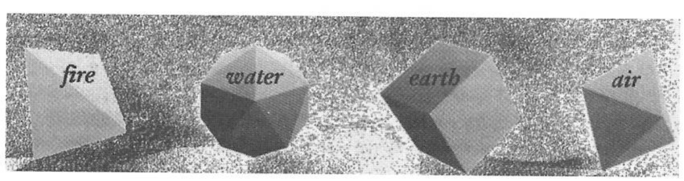


Fig. 2. The "atomists" view with different forms and sizes.

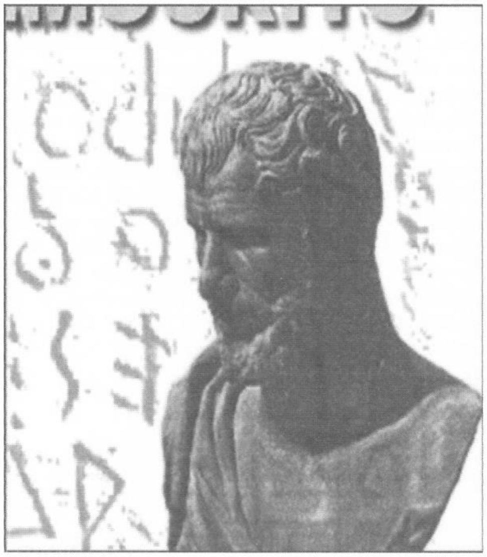


Fig. 3. Democritus (460-371 b.C.).

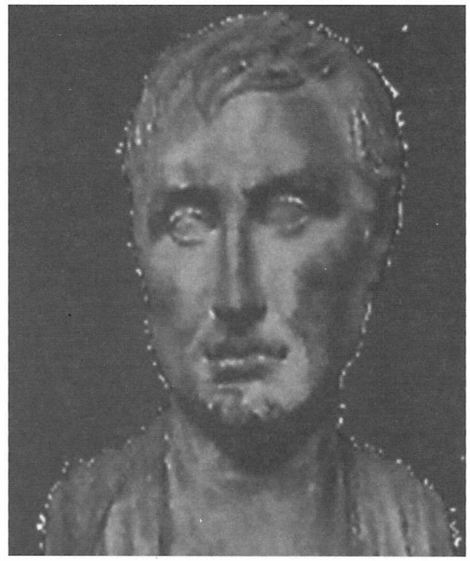


Fig. 4. Aristotle (385-347 b.C.)

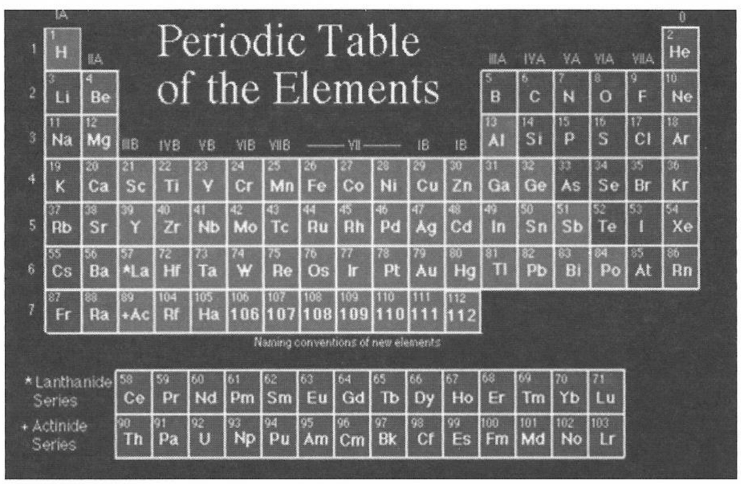


Fig. 5. Periodic Table of the Elements: Mendeleïev.

that proved the solubility of gases in water and the rate of diffusion of gases. His analysis of the atmosphere showed it to be constant in composition to 15,000 feet. He devised a system of chemical symbols and, having ascertained the relative weights of atoms (particles of matter), in 1803 arranged them into a table. In addition, he formulated the theory that a chemical combination of different elements occurs in simple numerical ratios by weight, which led to the development of the laws of definite and multiple proportions. These were the cornerstones of the atomic theory of matter.

Dmitri Ivanovitch Mendeleïev is a Russian chemist mainly known by his Periodic Classification of the Elements (Fig. 5). He showed that the chemical properties of the elements are directly dependent of their atomic weight and that they are periodic functions of this weight. Mendeleïev became a prestigious Professor and, in the absence of a good text on Chemistry, he wrote his Principles of Chemistry in two volumes (1868-1870). This book became a classic. In writing this book, Mendeleïev tried to classify the elements according with their chemical properties. In 1869, he published his first version of what became the Periodic Table. In 1871, he published an improved version, leaving empty boxes for some elements that were still unknown. His Table and his theory were better accepted with the successive discovery of the three elements that he had predicted: gallium, germanium and scandium. In observing the Periodic Table, one is puzzled by the fact of calling "elements" to atomic objects which are about 100 different. What looks more elementary? The four-elements theory of the Greeks or the 100-elements theory of Mendeleïev? Independently of esthetics or beliefs, Science shows that the first is wrong and the second, although complicated, was correct to explain the structure of matter for scales of 10^{-10} meters.

The later discovery of the electron by JJ Thomson in 1897 helped to bring understanding of the atom as a composite object and the key property of the "elements" in the Periodic Table to be the atomic number and not the atomic weight. The electron became the elementary constituent in entering the XX century.

In Section 2 we describe the present knowledge in the structure of matter, going down from atoms to atomic nuclei, then to nucleons and then to quarks to the scale of 10^{-18} meters. In Section 3 the present Elementary Constituents known from Particle Physics, as well as the Fundamental Forces responsible of all known phenomena in Nature, are given and explained in terms of their properties. In Section 4, the installations needed to develop the field of particle physics are described: Accelerators, Detectors and Computers, as well as some of their spectacular applications to other fields of Science and Technology. Particle Physics, particularly in this role of High Energy Physics, represents a chapter of Big Science and needs an International Organization. In Section 5, the European Laboratory for Particle Physics (CERN) is presented and its leading role in both the frontier of scientific knowledge and in international cooperation is made apparent. Section 6 makes a comparison of the two frontiers of the microscopic Particle Physics and the infinitely macroscopic Cosmology, pointing out the intimate connection between the two fields. In Section 7, the origin of the elements, from ligh to heavy nuclei, is discussed, so that it will become clear that we are part of (at least) a second generation of stars. Section 8 moves to Observational Cosmology, with the study of the Expansion of the Universe and the Cosmological Principle. With present day knowledge, in Section 9 the History of the Universe is reconstructed, identifying those fossil-like relics which keep track today of phenomena which occurred in the Early Universe. The paper concludes in Section 10 with the announcement of a Golden Age in Cosmology, with novel unexpected results and a Second Copernican Revolution in the answer to the question: What is the Universe made of?

2. Structure of matter

The studies in chemistry, biology, condensed matter physics, atomic and molecular

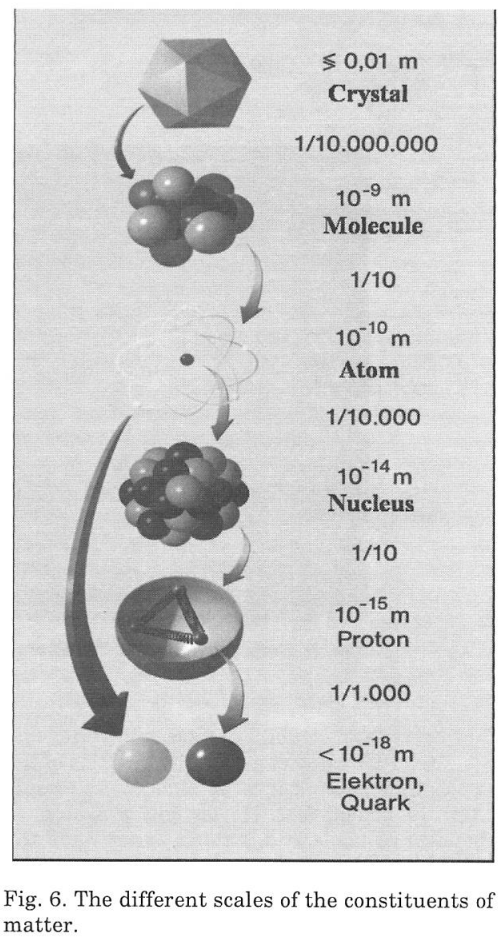


Fig. 6. The different scales of the constituents of matter.

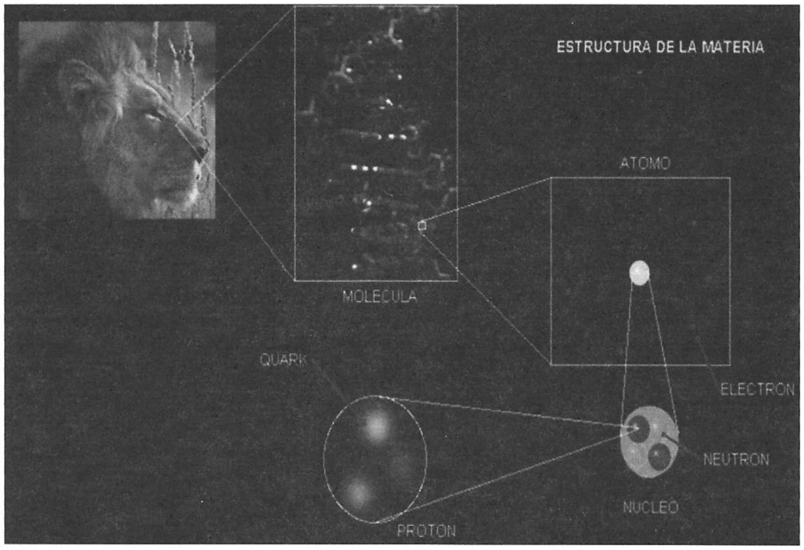


Fig. 7. The Structure of Matter.

physics, nuclear physics, astrophysics, cosmic rays and elementary particle physics have shown that all known matter in the present cold Universe is an aggregate of atoms for distances above 10^{-10} meters, with the mass proportional to its volume. Below this atomic scale, the atom shows a detailed structure and we have been able to explore distances in the last decades up to 10^{-18} meters (see Fig. 6 and Fig. 7).

Inorganic crystals or living cells are all made of molecules when arriving to distances of the order of 10^{-9} meters. There is no intermediate fundamental structure from macroscopic bodies to molecules. On the scale 1/10 of molecules, we find the atoms. Below this distance, the atom is a conglomerate of electrons up to the atomic nucleus. Why atoms like to be organized in terms of molecules, in spite of the electrostatic repulsion between two or more nuclei, is one of the great triumphs of quantum physics, giving an explanation of the chemical bonding in terms of the quantum behaviour of the electron. Crystal lattices have the so-called valence electrons shared by the whole lattice and quantum mechanics predicts the different behaviour as a metal, insulator or semiconductor.

The electronic configuration of atoms in terms of the possible quantum states, taking into account the Pauli principle that every electron must be in a different state, gives a perfect explanation of the symmetries and periodicities of the Periodic Table of Elements. To reach the scale of the atomic nucleus, the central agent providing the attractive force for the bound states of the electrons, one has to go down at least four orders of magnitude.

The nuclear radii have values between 10^{-14} and 10^{-15} meters in going from heavy to light nuclei. This gap between the atomic and nuclear scales is explained in terms of the different range of the acting forces in atoms and nuclei, respectively. Nuclei are not elementary and, when explored at distances below their radii, one discovers their compositeness in terms of protons and neutrons. Contrary to electromagnetism, nuclear forces binding protons and neutrons are very intense and short-ranged, so that the constituents are packed at these small distances.

The proton is the most simple nucleus, that of the hydrogen atom, and when observed at small enough distances shows itself as a composite object, it has an structure. Similarly for the neutron. The developments in the field of elementary particle physics along the decade of the 60's in the XX century had produced a proliferation of particles with strong interactions, the so-called hadrons, and relations among their properties. These relations could be understood in terms of symmetries, so that the "elementary" proton and neutron had six partners. Similarly for other hadrons with different partners. It became clear that if there were some elementary building blocks, there would most probably be fewer than eight. What might these building blocks be like? Gell-Mann and Zweig first proposed the Quark Model. In the next Section we discuss the experimental evidence in favour of the quarks and their elementary behaviour up to the distances of 10^{-18} meters explored today.

3. Elementary Constituents and Fundamental Forces

At the most small distances explored today, the world appears in terms of quarks and leptons as the elementary constituents of matter. The quarks have a mutual strong interaction, which is absent for leptons. As seen in the Table (Fig. 8), there are three families of quarks and leptons, identical in their charges and differing in their increasing masses. The quarks have fractional charges: +2/3 for up-quarks (u, c, t), -1/3 for down quarks (d, s, b). The leptons have integer charges: -1 for charged ones (e, μ, τ), 0 for neutrinos (ν_e, ν_μ, ν_τ). The Table of particles has to be accompanied by that of antiparticles, with all the corresponding charges of opposite signs.

The proton, of charge +1, is constituted by three quarks u, u, d confined in its interior. The neutron, of vanishing charge, is formed by the three quarks u, d, d, all of them of the first family. These are Baryons and from them one generates all the so-called Baryonic Matter of the present long-lived Universe. There are other Hadrons, called Mesons, composed from quark-antiquark. All hadrons (baryons and mesons) have integer charges. In the Laboratories of Particle Physics one has been able to create heavier particles which are composed from the quarks of the second and third families. These artificially produced particles decay with very short lifetimes.

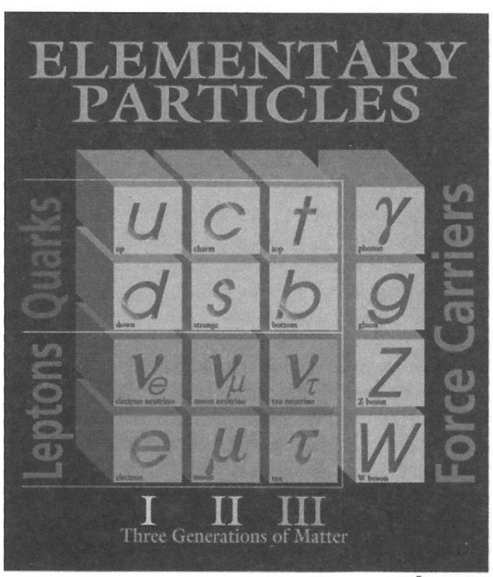


Fig. 8. Elementary Particles.

Similarly, we have seen that all stable atomic matter contains electrons, the charged lepton of the first family. Muons, Taus and Neutrinos are produced artificially in the Laboratories of Particle Physics. Muons are also produced copiously in the interaction of cosmic rays (protons and nuclei) with the earth atmosphere. Neutrinos are produced by stars, like our Sun, and other cosmic phenomena. As we will see later, the neutrinos constitute a background cosmic radiation in our present Universe.

All the known phenomena and the aggregation of matter are explained under the influence of a few kinds of forces. The fundamental forces among the constituents of matter are: gravitation, electromagnetism, weak and strong (Fig. 9). In the theory of elementary particles, the combination of quantum mechanics with relativity has led to an scheme, Quantum Field Theory, which explains among other new phenomena the existence of antiparticles and the creation and annihilation of particles. The unifying concept of all interactions is the Field, a modification of the space-time properties around the particles that feel the interaction. There are no actions at a distance, but the field mediates the interaction. At the quantum level, the fluctuations of the field correspond to the intermediate bosons. Hence these forces are "exchange-forces" described by the exchange of bosonic particles.

The gravitational interaction is very feeble and negligible for elementary constituents at low and present energies of the Particle Physics Laboratories. However, it regulates the Large Scale Behaviour of the Universe, due to its coherent character -the mass is an additive property- and its long range. The range of the interaction is inversely proportional to the mass of the intermediate boson, in the gravity case the graviton with null mass. The graviton has not been detected up to now and we have only indirect evidence of the gravitational waves. The formulation of Universal Gravitation by Newton in the XVII century represented the first unification of forces for the free-fall in the earth and the celestial motions. Einstein's General Relativity, formulated in the XX century, is the present classi-

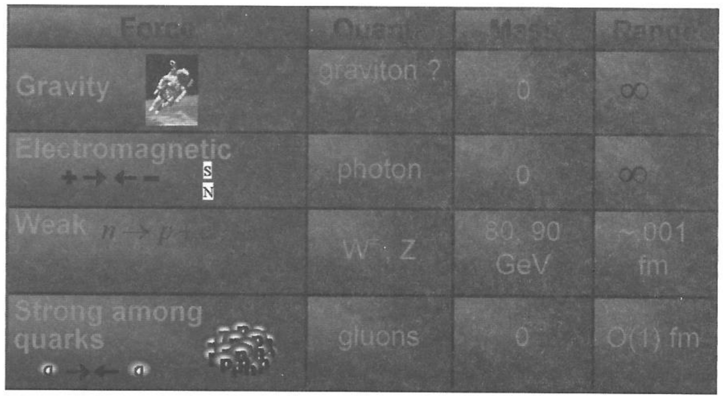


Fig. 9. The Fundamental Forces.

cal theory of Gravitation, with matter and energy as the source of the interaction. We still do not have a consistent theory of Quantum Gravity.

All elementary particles, with the exception of neutrinos, have electric charge and feel the electromagnetic interaction. This force has an infinite range, due to the null mass of the photon, the mediator of the interaction. The intensity is given by (the square of) the electron or proton charge. Atomic nuclei bind the electrons in the atom by means of the electromagnetic interaction and its residual effects control the aggregation of atoms to build macroscopic matter. The unification of electric and magnetic phenomena by Maxwell in the XIX century was the second great synthesis in the History of Science. Since the middle of the XX century, Quantum Electrodynamics is the most powerful theory developed by the scientific community, able to predict properties and phenomena in Nature with admirable precision. It is the prototype of a quantum field theory and has permeated the ideas to describe weak and strong interactions.

The conversion of one neutron into one proton, accompanied by the emission of one electron and one antineutrino, is the so-called beta radioactivity. This process, like the proton-proton fusion in the Sun that generates all the energy arriving to the Earth, is governed by the weak interaction. At low energies this force behaves like a weak interaction with null range, i.e., a "contact" interaction. At energies of 100 GeV (1 GeV = 10^9 eV, 1 eV= energy gained by an electron when applying a d.d.p. of 1 Volt), however, the weak interaction has a magnitude similar to electromagnetism and its range is, although very small, not vanishing. The explanation of the short range lies in the large mass of the intermediate bosons responsible of the weak interactions, W± and Z. The discovery of these particles at CERN in 1983 represented a fundamental experimental step in the understanding of the Standard Model of unified electro-weak interactions. This third synthesis is a spectacular achievement of physics in the second half of the XX century.

Each one of the quarks can have three different varieties or "colours": red, yellow, violet. The colour charge is the one responsible of strong interactions, similar to the fact that electric charge is responsible of electromagnetic interactions. Strong interactions are thus blind to the kind of quarks: u,s or t, which are distinguished by electro-weak interactions. The three quarks of the proton or neutron have to have different colours to generate a colourless baryon. Although protons and neutrons do not have a colour charge, there is a residual strong interaction among them that builds atomic nuclei. This phenomenon for strong interactions is similar to the residual interaction among neutral atoms that builds molecules in electromagnetic interactions.

The strong interaction between two quarks is mediated by the coloured gluons (they appear in eight different colours). Although gluons are massless, they generate an interaction increasing with the distance between quarks, so that quarks and gluons remain confined within distances of the order of 10^{-15} meters and they convert into hadrons above these distances. Except for the top quark, the lifetime for this hadronization is smaller that the lifetime for the decay. The top quark is so heavy that its decay lifetime, although governed by weak interactions, becomes very short and one is able to extract its detailed properties from its decay products without the contamination of the hadronization process. The short range of strong interactions is thus due to the confinement property of quarks and gluons at long distances, where the intensity becomes very strong. When the quark separation is diminishing, the intensity of the interaction is disappearing, so that the quarks behave like quasi-free particles without interaction. This regime applicable at small distances is called of "Asymptotic Freedom". We conclude that the intensity of the strong force runs with the distance (or the energy).

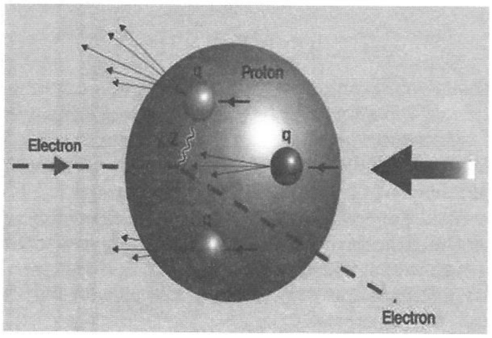


Fig. 10. Collision of electrons with protons.

4. High Energy Physics: Accelerators, Detectors, Computers

Particle Physics needs, in order to develop its objectives, special installations able to produce, detect and analyze massive particles and to penetrate into the interior of matter up the smallest possible distances (see Fig. 10). When the emphasis is put in these installations, the field is also named as High Energy Physics (see, for example, that of the corresponding Division in the European Physical Society: High Energy Particle Physics).

All this wording refers to the fact that it is necessary to probe the matter with high energy particles, either produced in the "artificial" accelerators of the Laboratories of Particle Physics (Fig. 11) or in the "natural" phenomena associated with cosmic rays.

The need of high energy to create new massive particles is exemplified by Einstein's relativistic Equation

$$E = mc^2,$$

which indicates the way to invest energy E to produce mass m and the contribution of mass to the energy balance of a given process. The present limit to a mass created in the Laboratory is that of the top quark, about 180 proton masses, as directly discovered in 1994 in the Tevatron proton-antiproton Collider at FermiLab, near Chicago. The most massive mediator discovered up to now is the Z for weak interactions, produced

Fig. 11. The components of an accelerator.

by the Super proton-antiproton Synchrotron at CERN in 1983.

The need of high energy to probe small distances is exemplified by De Broglie's quantum Equation

$$\lambda = h / p,$$

where λ is the wavelength of the distance probe, h the Planck constant and p the momentum of the particle. When the probe particle, let us say an electron, penetrates into the proton target in the process

$$e + p \rightarrow e + X$$

at the highest possible energies, one realizes that there is a proliferation of events in which the electron suffers a large momentum transfer, changing the outgoing direction in large angles. This is only possible if the target consists of punctual centers for the dispersion, giving a proof of the existence of quarks in the proton interior. The argument is very similar to the one used in Rutherford's experiment to indicate the presence of a nucleus in the atom interior.

Another example of Laboratory accelerator is given by LEP, the electron- positron Collider that was providing energies between 100 and 200 GeV at CERN, the European Laboratory for Particle Physics, between the years 1989 and 2000 (see Fig. 14). It gave precise studies of the properties of the massive Z and W± particles through their production and decay. At 200 GeV, De Broglie's Equation tells us that we have explored distances up to 10^{-3} fermis = 10^{-18} meters. LEP's circular tunnel of 27 Km of circumpherence is the longest in the world and it is being prepared to allocate the future proton-proton Collider LHC (Large Hadron Collider) which will start operation in 2007 providing energies of 14 TeV (1 TeV = 1000 GeV = 10^{12} eV).

One example of the other type, a source of cosmic rays, is the explosion of a Supernova star. The most massive stars, with a mass above four solar masses, do not have a quiet end in their evolution. On the contrary, they have an explosive end ejecting the external shells of the star containing medium and heavy nuclei. The remnant is either a neutron star in rotation (a pulsar) or a black hole.

We have seen that the production and study of the elementary particles needs the use of accelerators. These machines provide high energy particle beams able to penetrate in the matter interior giving information on the constituents. It is very natural and useful the use of the practical unit of energy electron-Volt (1 eV is the energy acquired by an electron when subjected to a d.d.p. of 1 Volt). With energies of a few eV's it is possible to ionize the atoms (the extraction of electrons) and to produce chemical phenomena like the burning of a carbon piece. One million higher energies, 1 MeV = 10^6 eV, intervene in phenomena which affect the atomic nucleus, such like the process in nuclear reactors. To study the properties of elementary particles, one needs energies from a few GeV to the highest values of several TeV to be reached in the near future by LHC.

The only way to reach the needed high energies, or better, concentrations of energy, is the acceleration of charged particles by means of electromagnetic fields. As the acceleration mechanism takes times of the order of seconds, in practice only stable charged particles are appropriate. This leaves electrons, protons and their antiparticles only. When comparing their properties as probes, electrons and protons are quite complementary. The protons are easier to accelerate to high energy due to their small energy loss by syncrotron radiation. In a syncro-tron, the energy is limited by the product B x R, where B is the magnetic field and R is the orbit radius. To reach higher energies, besides increasing R, in the last years the field has developed the use of technology of superconducting magnets to increase B. The disadvantage of the proton is its complicated structure, with a distribution of quarks and gluons in its interior. As a consequence, in the collisions with proton beams the results depend both on the fundamental interaction responsible of the collision and on the proton structure in a convoluted way.

Contrary to protons, electrons behave like structureless objects, so that they are a better probe for other systems. Their difficulty in acceleration from a circular accelerator is due to their small mass, leading to a high emission of syncrotron radiation induced by their centripetal acceleration. The energy loss due to syncrotron radiation is proportional to E^4/R, where E is the electron energy and R the radius of the orbit, and it is so severe that LEP of CERN was probably the last electron syncrotron in the energy scale. The future is a new technique associated with a Linear Collider. It is thus no surprise that the energies reached in electron accelerators are much smaller than those reached with protons.

The positrons have been used in accelerators and in storage rings for many years and they are relatively easy to produce. However, the antiprotons are more difficult to produce, because they are much heavier, and, on top of that, they are very difficult to accumulate in an intense beam. The use of antiprotons is of high interest to allow the annihilation with protons and the subsequent production of new particles. The technique to have a good antiproton beam was only developed in the last decades, with the $S\bar{p}pS$ at CERN in the 80's and the Tevatron at FermiLab in the 90's.

There are two ways to use accelerated particles:

1) in fixed target accelerators, protons or electrons are made to collide with matter (particularly, hydrogen) at rest. In these collisions secondary particles are produced which, in some cases, can be managed as secondary beams with time dilation. One has thus generated pion, kaon, antiproton, muon and neutrino beams at high energies, which allow the study of new processes not accessible from primary beams.

2) the other possibility is the use of two beams of particles which collide almost frontally, so that there is a considerable gain of energy, as compared with case 1), due again to the phenomenon of relativistic kinematics. The disadvantage is the small rate of expected events, so that one needs to storage the beams in closed orbits to circullate for hours or weeks, increasing the opportunities for a collision. If the particles in the Collider are of the same type, one needs to build two magnetic rings to cross with opposite magnetic fields. For the LHC, the proton-proton Collider at CERN, one has developed the idea of having "two in one": the two rings in the same magnet with non-uniform magnetic field. Much easier are the storage rings with collisions of particles and antiparticles in opposite directions. Due to the opposite charge, it is enough to have a single magnetic ring, such as it is the case for (e^+e^-) or $(\bar{p}-p)$ Colliders.

Due to the energetic gain, in the last years all the high energy accelerators, with total energy above 10 GeV or so, are of the Collider type 2). At LEP of CERN, electrons and positrons went through the vacuum chamber, concentrating the beams by means of 1300 focusing magnets and guiding them by means of 3400 bending magnets. The beams were accelerated by means of radio-frequency cavities, up to the highest values of 100 GeV per beam, and reestablish the energy loss by syncrotron radiation.

When two particles collide, there is a final state of equal or different particles that are scattered or produced. The Detection systems are used to determine the characteristics of the particles intervening in the collisions. They provide information on the momentum of the particles, on the time of the detection and, in many cases, on their identification. There are many types of detectors, but almost all of them are based on the ionization phenomenon, in which a high energy charged particle extracts electrons from the atoms that it encounters in its way. Historically, one has distinguished two categories for detectors:

1) the visual detectors, in which the ionization provokes a perturbation leaving a permanent track on the detector following the trajectory of the charged particle. Examples were the emulsions or bubble chambers.

2) the electronic detectors, in which the electric perturbation produced by the ionization is used to generate electronic signals which provide information on the space/time of the particle detected. In the last years, the evolution in the detection systems has led to a large set of electronic detectors in the experiments. An ideal detector should be able to identify possible signals of a new and unexpected behaviour and to observe the particles produced in the collision, providing a measurement of their energy-momentum and identifying their nature.

In a detector, the hermeticity is a very important property. The collision region should be completely closed, with the following produced particles:

- Leptons, i.e., electrons and muons, besides neutrinos. Neutrinos do not leave any track, but they may be detected from the "missing energy" which is not deposited in the external calorimeters.

- Photons, the light components, and their massive partners the W± and Z particles which may be detected from their decay products.

- Hadrons, i.e., the particles which interact by means of strong interactions: protons, pions, kaons and their antiparticles.

In the figure 12 you may see one of the two detectors that detected at CERN the Z and W± mediators for the first time.

One may ask whether quarks and gluons can leave a signal in the detector. As we know, due to the confinement property, they cannot propagate beyond 1 fermi or so. Then there is no direct signal at longer distances, because they hadronize. However, at high energies the hadrons thus generated from a basic constituent contain the energy-momentum flow transmitted from the initial quark or gluon. One thus expects to observe "Jets" of hadrons. They are in fact regularly observed, and DESY presented for the first time evidence of the gluon jet coming from the basic process $e^+e^- \to q\bar{q}g$.

At present, the typical hermetic detector contains the following subdetectors in going from the beam pipe to the outer region:

1) The vertex detector, near the beam pipe, around the collision point, in order to ex-

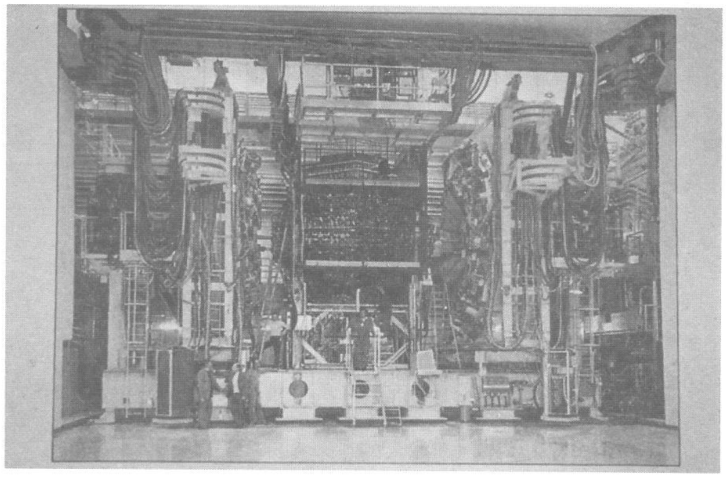


Fig. 12. Detector of the W±, Z discovery at CERN.

tract the maximal information on the produced particles with short lifetime, which leave very short tracks.

2) The track chamber, which identifies and measures the properties of the outgoing charged particles.

3) The electromagnetic calorimeter, which measures the electromagnetic energy of electron and photon showers coming from the collisions.

4) The hadronic calorimeter, to measure the hadronic energy.

5) The muon counters, which detect the deeply penetrating muons.

Frequently, the detector also contains a magnet to provide a magnetic field which gives a curvature to the charged particle tracks and measures their momenta. Furthermore, one needs a powerful instrumentation for the data taking and quick processing, with the objective to filter and register the data in the short time available between two successive collisions.

The experiments in particle physics illustrate the powerful set of technologies at their disposal, some of them have generated important technological benefits and have had applications in other fields. One finds quite often an intimate connection between new discoveries and technological innovation. One important example was the use of vertex detectors at LEP, which allowed to detect matter-antimatter mixing, when the b-quark intervenes, through the resolution of a few microns.

Intense beams and massive detectors produce an impressive amount of data, so that one has to have the support of the velocity and power of the electronic numerical calculus. In the figure 13 one sees the computing reconstructed image of an electron-positron collision at LEP, just as observed in the LEP detectors.

In the collision products there are tracks of hadrons which are organized as Jets, so that this detection is a proof of the production of quarks and gluons in this annihilation process. One may realize the power of the vertex detector able to distinguish the primary $e^+ e^-$ collision vertex from the secondary vertices for the decay of short-lived particles.

The particle physics experiments have to process such a high rate of data that one has to organize huge collaborations of physicists in a decentralized way, with participation of the Laboratory with the installations and many other Institutes and Universities around the world. One understands why the developments of the electronic networks for communication and the world wide web for information at a distance were invented by scientists integrated in high energy physics Laboratories. The next step, in front of the problem of data analysis that LHC experiments at CERN will represent, is the GRID system to integrate at the world level the calculational capability of computers separated geographically.

Besides this role of analysis of experimental data, the computers are an integral part of the control systems which have to be constructed for the complex experiments and the big experimental installations, including the particle accelerators. Particle Physics is an essential part of basic science, with the main objective of

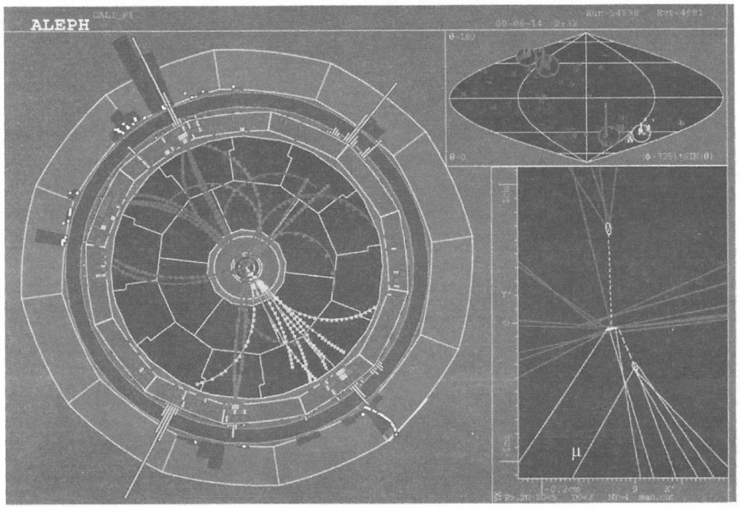


Fig. 13. Computing reconstructed image of an electron-positron collision at LEP.

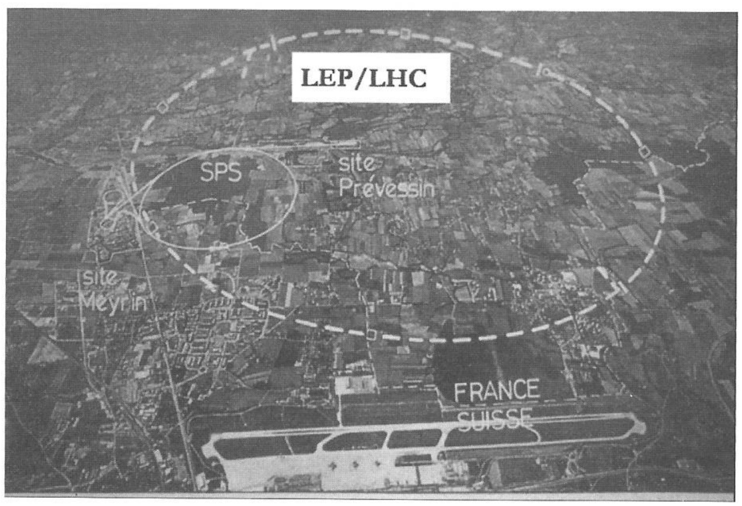


Fig. 14. CERN: European Laboratory for Particle Physics.

the advance in knowledge. As such, it is human culture. However, it has more and more a technological and economic role at the highest level, due to the enormous facilities which are needed in high energy physics. Applications are visible in many fields at the technological level, as well as in medicine, including therapy, diagnostics and medical imaging techniques.

5. International Organization: CERN

CERN is the European Laboratory for Particle Physics, the world's largest particle physics centre. Here physicists explore what matter is made of and what forces hold it together. Its site is on the border between Switzerland and France, near Geneva. In the map you may see (Fig. 14), among other parts, a representation of the circumpherence for the LHC accelerator, the same that was used for LEP.

CERN exists primarily to provide particle physicists with the necessary tools. These are accelerators, which accelerate particles to almost the speed of light and detectors to make the particles visible. Founded in 1954, the laboratory was one of Europe's first joint ventures and includes now 20 Member States. In the Table I the 20 countries are listed, together with their respective contribution to the CERN budget.

Member States have special duties and privileges. They make a contribution to the capital and operating costs of the CERN programs, and are represented in the Council, responsible for all important decisions about the Organization and its activities.

Some States (or International Organizations) for which membership is either not possible or not yet feasible are Observers. 'Observer' status allows Non-Member States to attend Council meetings and to receive Council documents, without taking part in the decision-making procedures of the Organization.

Scientists from 220 Institutes and Universities of non-Members States also use CERN's facilities.

Physicists and their funding agencies from both Member and non Member States are responsible for the financing, construction and operation of the experiments on which they collaborate. CERN spends much of its budget on building new machines (such as the Large Hadron Collider), and it can only partially contribute to the cost of the experiments.

Observer States and Organizations currently involved in CERN programs are: the European Commission, India, Israel, Japan, the Russian Federation, Turkey, UNESCO and the USA.

Table I. Member States of the International Organization: CERN

	Miembros	(%)	
Alemania	22.33	Hungria	0.52
Austria	2.23	Italia	11.75
Bélgica	2.68	Noruega	1.59
Bulgaria	0.16	Polonia	1.76
Dinamarca	1.83	Portugal	1.16
España	6.93	R. Unido	17.66
Finlandia	1.32	R. Checa	0.53
Francia	16.04	R.Eslovaca	0.21
Grecia	0.98	Suecia	2.45
Holanda	4.37	Suiza	3.50

CERN organization is designed for the very specific needs of a scientific community. The Council is the highest authority and has the ultimate responsibility for all important decisions. It controls CERN's activities in scientific, technical and administrative matters.

The Council is assisted by the Scientific Policy Committee and the Finance Committee.

The Director General, appointed by the Council, manages CERN and is authorized to act in its name. He is assisted by a Directorate and runs the Laboratory through a structure of scientific, technical and administrative Departments. The present Director General is the French Robert Aymar.

CERN employs just under 3000 people, representatives of a wide range of skills-physicists, engineers, technicians, craftsmen, administrators, secretaries, workmen.

The scientific and technical staff designs and builds the laboratory's intricate machinery and ensures its smooth operation. It also helps prepare, run, analyse and interpret the complex scientific experiments.

Some 6500 visiting scientists, half of the world's particle physicists, come to CERN for their research. They represent 500 universities and over 80 nationalities.

6. The two Frontiers

Taking as Reference the human scale, in the preceding Sections we have penetrated to the infinitesimal small scales of the elementary constituents of matter, from 1 meter to 10^{-18} meters. In the next Sections we will move, on the contrary, to the highest infinitely large scales of the Cosmos, from 1 meter to more than 10^{+25} meters (Fig. 15). The most remarkable conclusion is that the Cosmos exploration at these enormous distances connects with the research being made in particle physics laboratories. What is the interest of going so far in our astrophysical and cosmological studies? As we will see later, there is a Cosmological Principle stating that, on a global scale, the Universe should be uniform and isotropic. This means that its PRESENT observation in other regions or in different directions should not give something fundamentally different from what is observed near here. The point is that: 1) the Universe is not static and has evolved with time; 2) any signal transporting information cannot travel with a velocity higher than that of light. As a consequence, the observation here and now of signals coming from very far distances provides information of the Universe at the times in which the signal left the source, i.e., on the primordial Universe! The

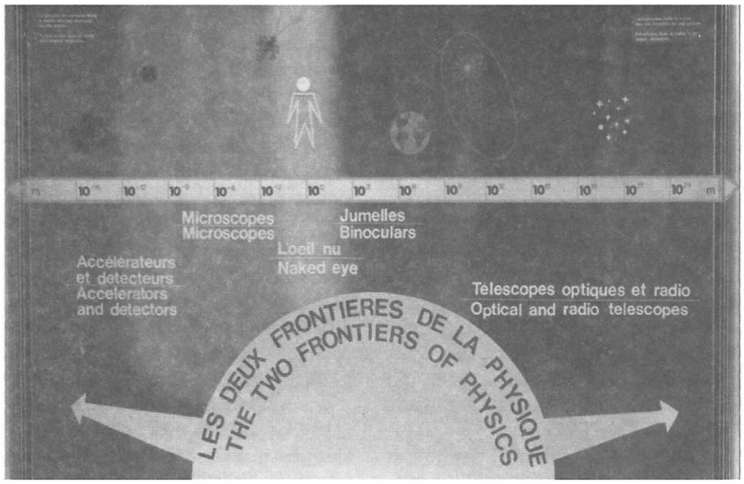


Fig. 15. The two Frontiers of Physics: Particle Physics and Cosmology.

early Universe was extremely dense and extremely hot, with average particle energies so large that matter could not exist in the aggregate form that it is observed today. The surprising link between particle physics and cosmology is that we re-create in the particle physics Laboratories the conditions under which there was a plasma of energetic particles for the structure of matter in the early Universe!

From the motions near the Earth surface until the large-scale behaviour of the present Universe, gravitational interactions play an essential role. All the other fundamental forces are screened: weak and strong interactions due to their short range, electromagnetic interactions because aggregate matter is organized in terms of neutral atomic-molecular components. One of the great achievements of Newtonian mechanics, including the Law of Universal Gravitation, was the understanding it brought to the motion of planets in the solar system. Astrophysical evidence, such as observations of the motions of binary stars around their common center of mass, shows that gravitational interactions also operate in larger astronomical systems, including stars, galaxies and nebulae.

7. The Origin of Elements

The visible Universe is formed at present by aggregate matter of the elements as given in the Periodic Table. Most of these, the oxygen we breathe, the iron in our blood, the uranium in our reactors, were formed during the lifetimes and explosive deaths of stars in the heavens around us. A few of the elements were formed before the stars even existed, during the birth of the universe itself.

A full understanding of the origin of the elements requires a description of their build-up from their common component parts (e.g., protons and neutrons) under conditions known to exist, or to have existed, in some accessible place. It is the role of nuclear physics, a discipline developed during the XX century, to provide this understanding. The most relevant property to be considered is the so-called Nuclear Binding Energy per Nucleon (proton or neutron). The total energy at rest of a (composite) bound state of protons and neutrons is smaller than the sum of their contributions from the individual masses. Taking into account the relativistic concept of mass as rest energy, one has

$$M c^2 < \sum_{i=nucleons} m_i c^2$$

The difference is precisely the binding energy and what is relevant in our discussion is the value of this quantity per nucleon. This is represented in the figure 16, where we see that it is increasing from light to medium nuclei (in the iron region) and then decreases.

From the viewpoint of energy balance, one understands why the FUSION of two light elements into a medium one is energetically favourable. This is the road followed by the living

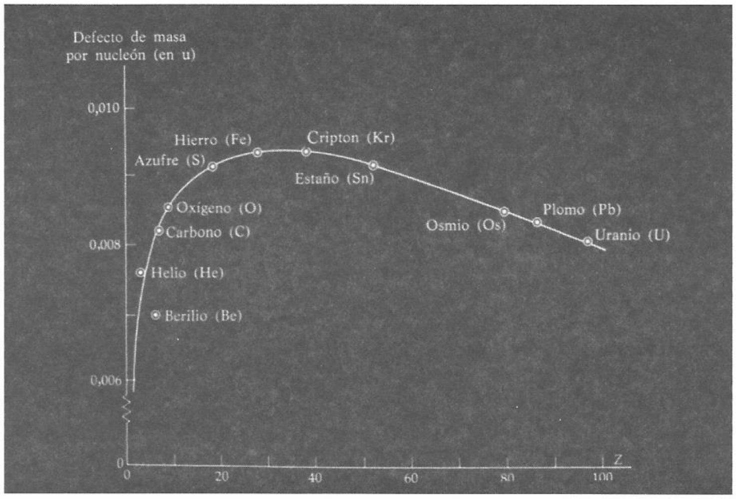


Fig. 16. Nuclear Binding Energies.

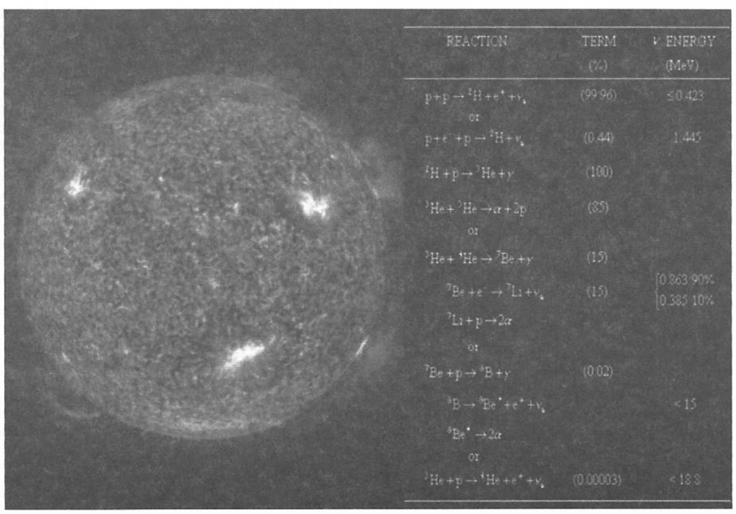


Fig. 17. Solar Nuclear Fusion.

stars to generate energy, at the time that they produce new elements of increasing mass in the Periodic Table. This activity is able to provide an outgoing pressure able to compensate the ingoing gravitational pressure of the star, leading to a dynamical equilibrium. In a beautiful paper entitled "Energy Production in Stars", Bethe (1939) considered the individual nuclear reactions of the light nuclei, from hydrogen to oxygen. This publication established the role of the fusing of hydrogen into helium and demonstrated their quantitative agreement with observations. The fundamental process is that protons combine to form a deuteron, which is then transformed into ^4He by the further capture of protons. The net process, with the present (2005) physics knowledge, is

$$4\ p \rightarrow {}^4He + 2\ e^+ + 2\gamma\ + 2\ \nu_e,$$

where e+ is the positron, the antiparticle of the electron, γ is the photon of electromagnetic radiation and ν_e is the (electron) neutrino. The positrons are annihilated with the electrons of matter, providing additional energy to that generated in the fusion process itself. The net energetic balance is that an energy of 26,72 MeV is liberated through the emission of photons and neutrinos. These messengers are a precious source of information about the Sun interior (Fig. 17). However, the interactions of photons with the Solar matter keep them in the Sun for millions of years, being unable to escape. On the contrary, the neutrinos have a very weak interaction and, in 8 minutes, reach the Earth surface. These neutrinos have been detected here in the last decades, giving a definitive proof that the present energy production by the Sun is obtained from the nuclear fusion reaction.

As to the build-up of the heavier elements, however, no stable build-up process beyond the mass-4 nucleus had been found in earlier times. No stable mass-5 nucleus exists, so the addition of a neutron or proton to ^{4}He does not work. It was later realized, however, that it is possible to form ^{8}Be from ^{4}He at a sufficiently high ^{4}He density and temperature and so bypass the mass-4 barrier. So it was that recognition in the 1950's of the crucial role of ^{8}Be, unstable though it is, in the build-up of the elements that provided a convenient stepping stone for the formation of ^{12}C through the addition of a helium-4 nucleus. The process of fusion is then open to heavier elements until it reaches the region of iron, the most stable nuclei. What is called today a living star corresponds to this evolution in the formation of elements.

Beyond iron, the energy balance is reversed and the exothermic reaction is that of FISSION of a heavy nucleus into two medium ones. This is the method of energy generation used by humans with the present nuclear reactors. This needs to have the fuel of uranium at our disposal. How was it produced? Much of the build-up of the heaviest elements goes on in a few violent minutes during the last instants of the life of very massive stars, in which their outer shells are thrown outward in Supernova explosions. When a very massive star exhausts its fuel for fusion reactions, the pressure balance is broken and the gravitational self-interaction leads to a quick implosion of the external regions into a very dense core of neutronized matter. The bounce provokes a violent and spectacular explosion which ejects the outer material into the space. In the figure 18 you may appreciate the beautiful Supernova explosion in the Crab Nebula as seen today, after

Fig. 18. Supernova explosion in the Crab Nebula.

1000 years of its first observation by the Chinese astronomers. This mechanism accounts both for the formation of the heavy elements as well as for their introduction into interstellar space. The remnant is a "dead" neutronized body with nuclear density known as a "neutron star", able to explain the observed pulsar behaviour. Thus, the total picture seems close to complete. Besides the fact that one has to provide the basic hydrogen to start the nuclear fusion life, the quantitative calculations say: Although the burning of hydrogen into helium provides the Sun and the other stars with their energy and with building blocks for the formation of the heavier elements, about ninety percent of the helium found in stars must have been made before the birth of the Galaxy. We have to face then an explanation in the Early Universe!

8. The Expanding Universe

Until early in the XX century it was assumed that the Universe was static: stars might move relative to each other, but there was not thought to be any overall expansion or contraction. The discoveries made in the 20's of the XX century may be considered the start of Observational Cosmology.

Measurements by Edwin Hubble indicated shifts in the wavelengths of the spectra of galaxies in motion relative to the earth. For distant galaxies these shifts are always toward longer wavelength. This shows that the galaxies are receding from us and from each other and the increase in the wavelength is called the "redshift" (Fig. 19). The observed Doppler shift

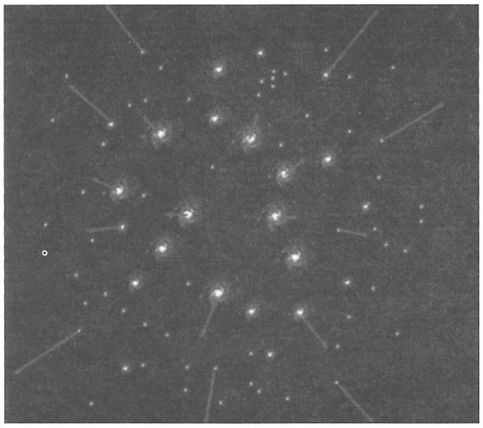
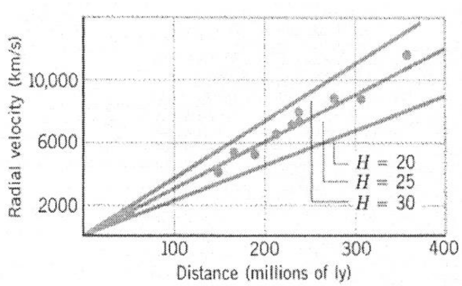


Fig. 19. The Expanding Universe.

Gráfico I



(analogous to the shift in the tone of sound due to the motion of the source) provides the value of the recession velocity.

As shown in the graph I, the results for the recession velocity as a function of the galaxy distance led Hubble to a remarkable conclusion: The velocity of recession v of a galaxy is proportional to its distance r from us. This relation

$$v = Hr$$

is "Hubble's Law", where H is a constant over space at any given time. Its current best value is about 2.2×10^{-18} / s.

Another aspect of Hubble's Law is that this v-r proportionality is the only law which leaves the same relative distribution of galaxies at different times. There is no privileged point in the linear distribution, as shown in the figure 20, and this is valid for all directions. The distribution at times t and 2t are the same if V=Hr. On the contrary, these distributions look very different at times t and 2t if v=constant. There is no particular reason to think that our galaxy is at the very center of the Universe, even if it is the reference for our observations. At any given time, the Universe looks the same, no matter where in the Universe we are. This fundamental idea is the Cosmological Principle. There are local fluctuations in density and temperature, but on average, the Universe looks the same from all locations. Thus the Hubble constant is constant in space and the laws of physics are the same everywhere. The observational evidence of the Cosmological Principle is illustrated in the map of temperatures of the sky, to be compared with the map of temperatures of the Earth surface (Fig. 21). The last distribution does not satisfy the cosmological principle and the systematic deviations are apparent.

An appealing hypothesis suggested by Hubble's Law is that at some time in the past, all matter and energy in the Universe was far more concentrated than it is today. It was then blown apart in an immense explosion called the BIG BANG, giving a kinetic energy to the Universe. When did this happen? According to Hubble's Law, the time t needed to travel a distance r is about $1/H = 1.4 \times 10^{+10}$ years. This is the present age of the Universe after the Big Bang.

In Einstein's theory of general relativity, the increased wavelength comes from the expansion of space itself. This is not an easy concept to grasp, but the figure 20 with the linear distribution of galaxies at different times shows the compatibility with this new view. An alternative habitat would be in two space dimensions: the surface of a sphere with the radius R increasing with the cosmological time. There is no center in the expanding surface and all point objects in this surface space are receding from each other. The space would seem infinite, although it is bounded. The quantity R, outside our space, is the radius of curvature, as well as a varying "scale factor" which changes with the expansion. Any length that is measured in intergalactic space is proportional to R. In this view, the increase of wavelength with the cosmological time is a "cosmological redshift" rather than a Doppler shift due to a relative motion of the galaxies. The farther away an object is, the longer its light takes to get to us, and the greater the change in R and wavelength. If the distance in Hubble's Law is large enough, the velocity of expansion will be greater than the

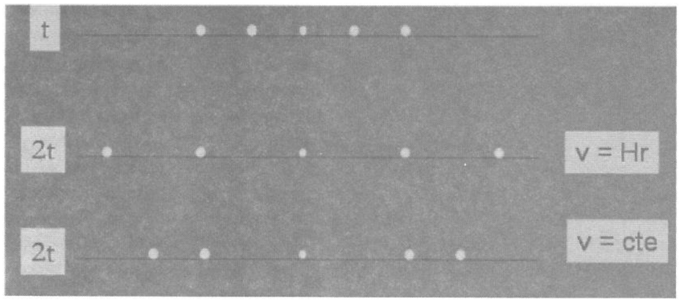


Fig. 20. The v-r proportionality of Hubble's Law compared with a constant velocity.

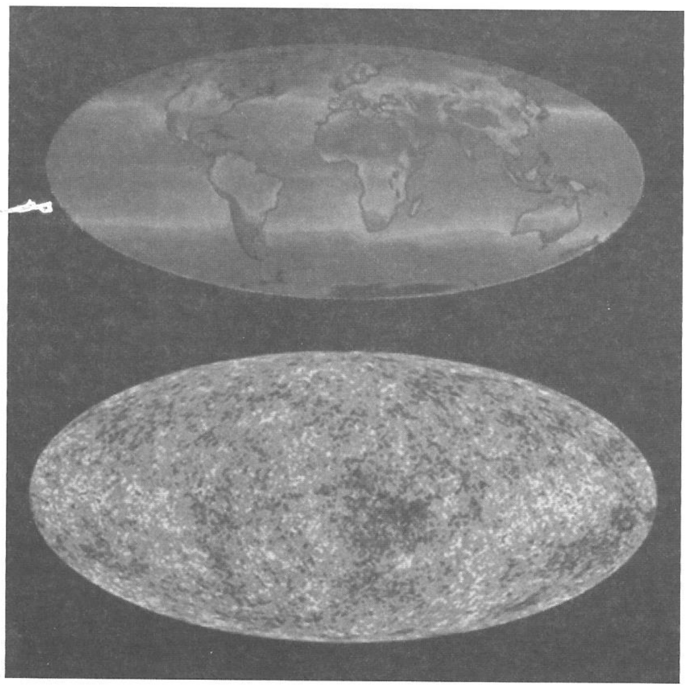


Fig. 21. Comparison of the temperature distribution in the Earth and the Universe.

velocity of light. There is no problem with this result, it merely tells us that such a region of the Universe is beyond our horizon for an observable Universe: no signal from it is able to reach us. To conclude, we have to speak of EXPANSION OF SPACE WITH TIME and the Big Bang was not an expansion in space.

9. The History of the Universe

The figures 22 and 23 are graphical descriptions of the History of the Universe, with the characteristic sizes, particle energies and temperatures at various times. The model is based on some observational cosmological facts, as well as on the present theory of particle in-

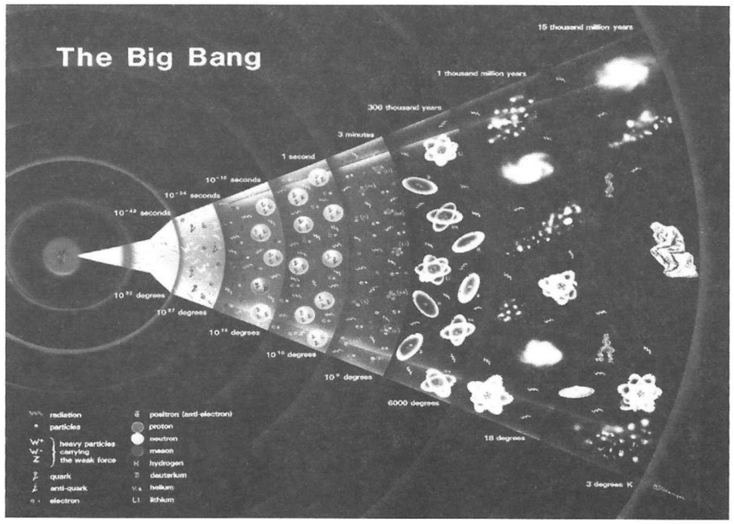


Fig. 22. The Big Bang: Space expands in Time.

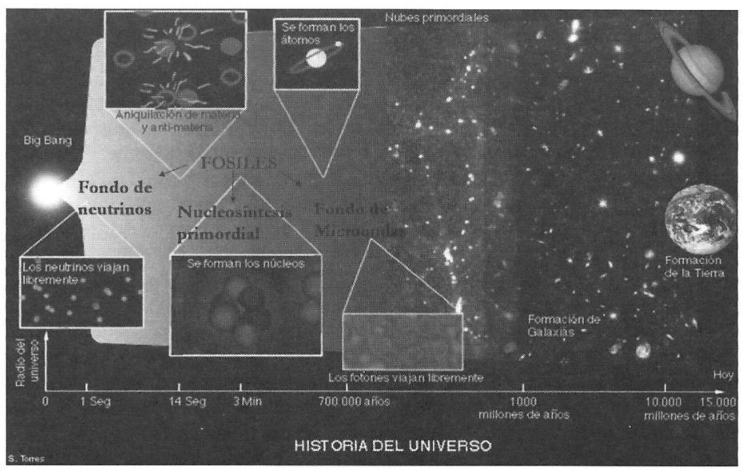


Fig. 23. The History of the Universe.

teractions, tested in the laboratories of high energy physics up to energies of several hundreds of GeV's. At sufficiently higher energies and shorter distances, the gravitational interaction becomes strong and unified with the other three interactions. This energy E_p is called the Planck energy and its value is given by 1.2 x 10^{+19} GeV, as determined by the physical constants of Nature: the Planck constant, the velocity of light and the Newton constant of gravitation. The presence of these constants calls for a relativistic quantum theoretical description of gravitation. The corresponding Planck time is about 10^{-43} s, so that, if we mentally go backward in time, we have to stop at this Planck time because we have no adequate theory of quantum gravity.

At Planck's time, the temperature of the Universe was about 10^{+32} K, with an average energy per particle equal to Planck's energy. In agreement with present speculations in particle physics, in the period between 10^{-43} and 10^{-35} s, the strong and electroweak interactions were unified, with transitions between a soup of quarks and leptons violating baryon and lepton numbers. Thus by the end of this period, in appropriate conditions, the Universe may have had unequal numbers of quarks and antiquarks after their decay into leptons. This could provide an explanation of BARYOGENESIS, the fact that the present Universe is made of matter and not of antimatter. A fundamental remnant of this phenomenon is the low value, 10^{-10}, of the ratio of baryon to photon numbers. But the theory is far from being conclusive in the quantitative description of these facts. By 10^{-35} s the temperature had decreased to about 10^{+27} K and the average energy to 10^{+14} GeV. At this energy, the strong force separated from the electroweak force and baryon number and lepton number began to be separately conserved. In the "inflationary" model of the Universe, necessary to understand some puzzling cosmological properties of the present Universe, there was in these early times a very rapid expansion, with an exponential increase of the scale factor R by a factor 10^{+50} in a time interval of 10^{-32} s. At this time the Universe was a mixture of quarks, leptons and the intermediate bosons responsible of the interactions: gluons, photons, W±, Z. It continued to expand and cool from the inflationary period to a time 10^{-12} s, when the temperature was about 10^{+15} K and typical energies of a few 100 GeV. It is highly probable that this earlier history will have to be completed and rewritten in the future, with the advent of new knowledge in particle physics and cosmology. We do know from the cosmological observations in the last few years that there is more structure in the Universe than that described by these elementary constituents and we may expect new surprises with the results to be obtained with the new accelerator LHC at CERN since 2007.

After a time 10^{-12} s, we enter into the historical description of the Universe evolution that has been tested in particle physics from accelerators, besides having at our disposal some remnants from these times which may be considered as cosmological fossils to be studied in detail. The average particle energies were not high enough to keep the W±, Z bosons in equilibrium and disappeared after their decay.

A particularly significant moment in the evolution of the Universe occurred with the "quark-hadron transition", when the energy decreased to the point that quarks, antiquarks and the gluons formed nucleons and other particles that participate in the nuclear force. This occurred at about 10^{-6} s, when the temperature was some 10^{+13} K, corresponding to an energy of around 1 GeV. On the time scale of 1 s, only the nucleons among all hadrons are stable, but free neutrons decay by weak interactions, so that, at 100 s, neutrons and protons existed in about a 1:7 ratio. The energies were the typical ones for nuclear binding, 1 MeV, and the so-called BIG-BANG NUCLEOSYNTHESIS began. It is a great thiumph of the Big-Bang Cosmology that the calculations of the abundances of the light elements produced in this primordial nucleosynthesis have reached an spectacular agreement with the observed abundances. This completes our present view of the origin of the elements. At about the same time of 1 s, other important phenomenon takes place: NEUTRINO DECOUPLING. In the earlier Universe neutrinos were kept in equilibrium via their creation and annihilation in weak interaction processes at high energies, because this interaction rate was greater than the expansion rate. At temperatures below 1 MeV, neutrino interactions are too weak and the light neutrinos decouple from the plasma. The stable neutrinos have been there since then, only affected in their distribution of energies by the cooling of the Universe up to now. The present neutrino temperature in the Universe is 1.96 K. This background neutrino radiation is still waiting to be detected!

In the time period between 1 s and 300000 yr, the energy density of electromagnetic radiation was greater than that of matter, so that it is sometimes called the "radiation era". We had light charged atomic nuclei, matched by an equal quantity of negative charge in the form of free electrons in equilibrium with electromagnetic radiation.

The energy density of radiation decreased more rapidly with the temperature, due to the vanishing photon mass, so that at roughly 300000 yr the two energy densities were equal. The corresponding temperature of some 3000 K was no longer high enough to keep electrons and ions from combining into stable neutral atoms. Without free electrons, electromagnetic radiation no longer interacts as strongly with matter. The Universe becomes "transparent" because radiation decoupled from matter. The wavelengths of this radiation increase as the Universe expands and they are a measure of the scale factor. What was black-body radiation at 3000 K at the moment of decoupling has become, through the expansion of the Universe, radiation at 2.7 K. This BACKGROUND RADIATION of the Universe was first discovered and measured in 1964 by Penzias and Wilson. The fact that we observe this radiation, a directly observable relic of the Big Bang, is another great triumph of the Big-Bang model for Cosmology.

After the formation of atomic hydrogen and helium when the Universe was 300000 yr old, one enters into the "matter-dominated era". Then stars formed, as did galaxies. Galaxies are grouped into clusters and there are large regions with no visible matter. The understanding of the present large scale structure of the Universe is one of the important problems in Cosmology.

10. The Second Copernican Revolution. Perspectives

We have seen that there is no centre in the Universe and, on average, the Cosmological Principle operates. Our galaxy, the Milky Way, has no special status and our Solar System is an ordinary one residing in the suburbs of the Galaxy, as shown in the figure 24. These facts may be considered a continuation of the First Copernican Revolution: the human being, the Earth, the Sun and the Milky Way do not represent, in any sense, any centre of the Universe.

The granular structure of the Universe is thought to have developed from small, random fluctuations in a uniform energy density, forming small clumps of higher density. Such clumps act as seeds, gathering matter into them under the influence of the gravitational force. The process is much like the formation of clouds. The initial density fluctuations that started the process must have begun at a time not too late in the evolution of the Universe. The 3-K background radiation that we see today, after 14000 million years, has to contain a memory of these fluctuations. In 1992, the COBE satellite discovered non-uniformities and anisotropies in the background radiation consistent with the observed granularity of the matter distribution. These anisotropies in the temperature distribution have now been studied in detail by the WMAP satellite and they are able to measure the matter-energy content of the Universe. The results are spectacular:

1) The total content is compatible with the critical density of mass-energy, the one for which the energy balance of the Universe, including all kinetic and potential energies, gives a total vanishing value.

2) In terms of the critical density, the contribution of Matter to the content of the Universe is MATTER = 30%. We know from the Primordial Nucleosynthesis that the contribution of ordinary "baryonic" aggregate matter in our Universe is about 5% (about 2% is visible), so that we conclude that there is an unconventional DARK MATTER = 25%. The need of Dark Matter with gravitational interaction has been present in Cosmology for several decades, in order to explain the observed curves of rotation of galaxies. It is also needed to explain the Large Scale Structure of the Universe.

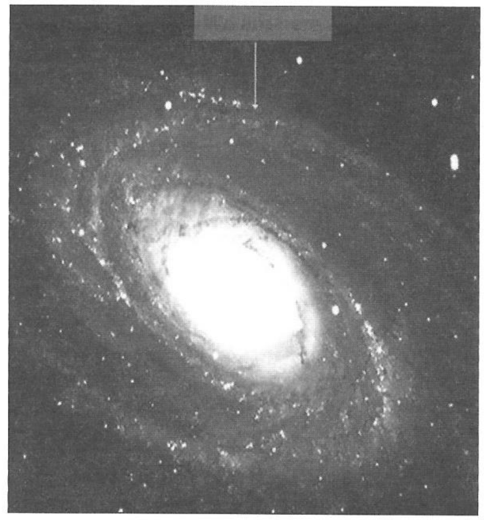


Fig. 24. The Milky Way, our Galaxy.

3) Again in terms of the critical density, there is a contribution from a novel repulsive pressure which covers the remaining 70% of energy density. One has then discovered an unknown positive contribution to the energy balance which goes under the name of DARK ENERGY = 70%! The result is becoming compatible with recent results which show that the observed Expansion of the Universe, instead of diminishing its velocity (as gravitation would imply), is accelerated due to a kind of repulsive force.

These results, obtained with the turn of the XXI century, have revolutionized the Cosmology. We have entered into a Golden Age in which novel unexpected results will lead to novel ideas and concepts. If Dark Matter had the interest of its connection with unknown massive particles, still to be discovered in particle physics, in the case of Dark Energy the question is to know what form of energy is the one that covers 70% of our Universe. In a sense, we do not know what the Dark Matter is and we do not know what we are talking about with the name of Dark Energy.

To the author, this appears like a Second Copernican Revolution: not only we are not in the centre of the Universe (there is no centre!), but most of the content of the Universe is of a kind completely different from that from which we, the human beings, are made of!

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