# The Elementary Particles in the Development of the Universe

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Mr. President of the Academy,
Messrs. Colleagues,
Mr. Minister,
Ladies and Gentlemen :

I express my warm thanks to President Konomis and colleague Contopoulos for their warm and friendly addresses. It is a great honor for me to belong, as corresponding member, to the Academy of Athens, whose standards are high and reputation international. Beyond the honorary distinction, I consider it my duty to continue contributing to the advancement of science internationally, and especially in Greece.

From this podium I wish to express my gratitude to my teachers in Greece and the United States from whom I learned to investigate the secrets of nature. Especially, I thank my Professors H. Bethe, T. Kinoshita, K. Wilson, K. Gottfried and the late D. Yennie at Cornell University, and Professors J. Bjorken and S. Drell at Stanford University. There are many others I wish to thank, but the time does not allow me to mention them by name. I thank my colleagues at the University of Dortmund for their confidence in me and the many collaborators from the four corners of the earth. With them I must also thank my family, my wife and children and my brothers and sister for their understanding and support, assuming, many times, responsibilities that were mine.

A special gratitude I owe to my parents, who inspired me with their love for learning. Their appreciation for education was so high that they considered the education of their children, all their children, an extension of their own desire for knowledge.

At this point I would like to refer briefly to my education in high school (Gymnasium). Dr. Contopoulos has already generously described my scientific career. While in high school, I bought and read, beyond the required courses, books from the universities. Some of them are still on my bookcases at home and I show here in Picture 1 the title pages of three of them:

"Physics" by D. Hondros,
"General Mathematics" by J. Xanthakis, and
"Atomic and Nuclear Physics" by K. Alexopoulos,

whom I met several years later, and I am glad that he is among us today.

For my talk, I have selected the title "The elementary particles in the development of the Universe", in order to cover two topics from my own research and describe them in the framework of the development of the universe.

The stars, as we observe them at night, look like jewels pinned to the sky. In fact, on a clear night, the whole sky looks like a jewel and for this reason the ancient Pythagoras introduced the word KOSMOS [1], which in Greek means just that: jewel. His careful selection of the word is confirmed by observations in the $20^{th}$ century, when the observational resolution increased tremendously. With the observation of many galaxies the pictures look even more beautiful. In Picture 2 I show a view of the deep universe, taken recently by the Hubble telescope.

Δ. ΧΟΝΔΡΟΥ

ΤΑΚΤΙΚΟΥ ΚΑΘΗΓΗΤΟΥ ΤΗΣ ΦΥΣΙΚΗΣ ΕΝ ΤΩ ΑΘΗΝΗΣΙΝ ΕΘΝΙΚΩ ΚΑΙ ΚΑΠΟΔΙΣΤΡΙΑΚΩ ΠΑΝΕΠΙΣΤΗΜΙΩ

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ΙΩΑΝΝΟΥ Ν. ΞΑΝΘΑΚΗ

Τακτικού Καθηγητού Πανεπιστημίου Θεσ/νίκης

# ΜΑΘΗΜΑΤΑ Γενικών Μαθηματικών

Διδαχθέντα
Κατά τά Ἀκαδημαϊκά ἔτη 1945-1948 εἰς τούς φοιτητάς της Γεωπονίας, Δασολογίας καί Χημείας τοῦ Πανεπιστημίου Θεσ/κης

Θεσσαλονίκη, 1948

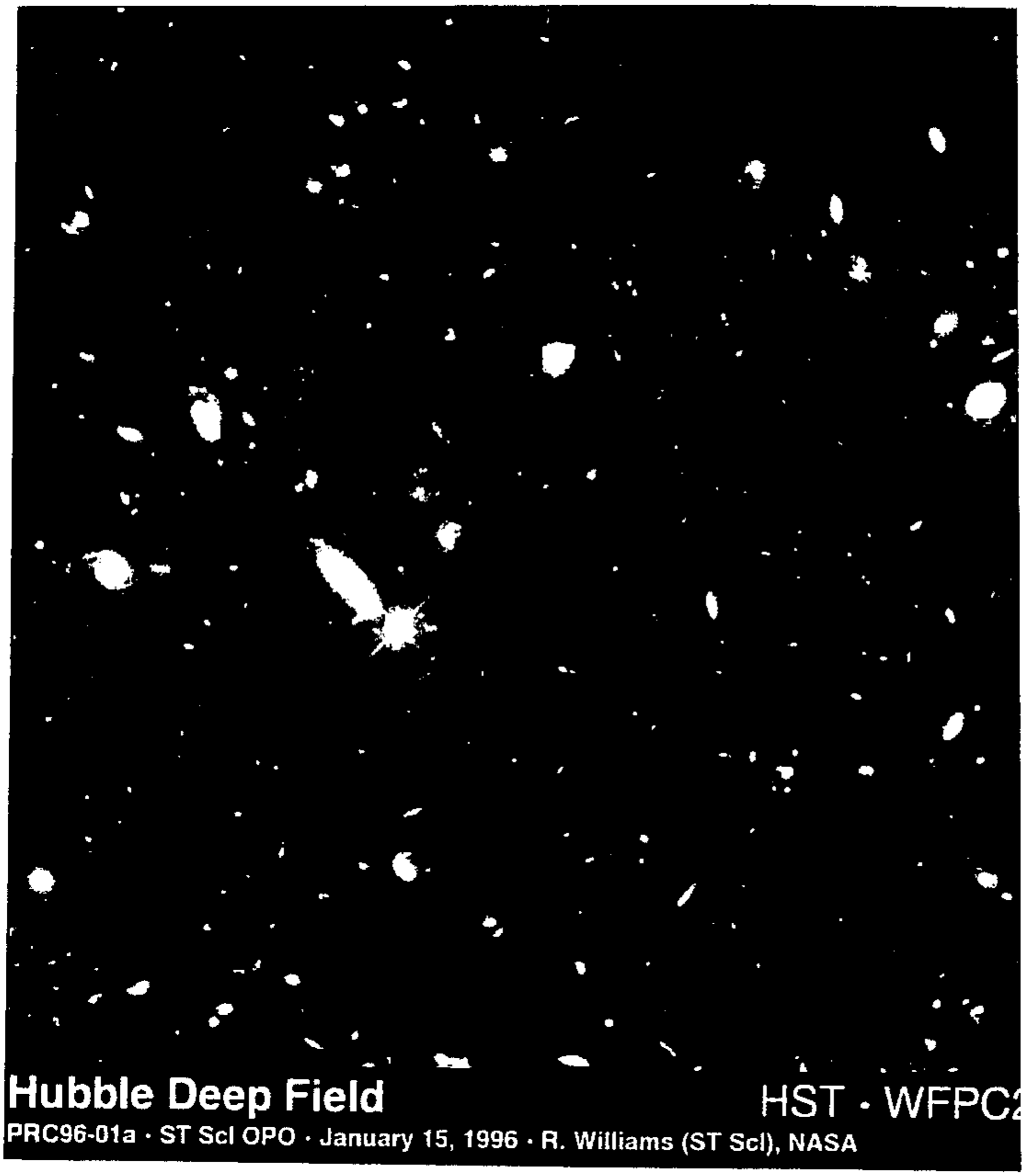
Κ. Δ. ΑΛΕΞΟΠΟΥΛΟΥ

ΓΕΝΙΚΗ ΦΥΣΙΚΗ

ΤΟΜΟΣ ΤΡΙΤΟΣ

# ΑΤΟΜΙΚΗ ΚΑΙ ΠΥΡΗΝΙΚΗ ΦΥΣΙΚΗ

ΑΘΗΝΑΙ • 1956



**Hubble Deep Field** HST · WFPC2

PRC96-01a · ST ScI OPO · January 15, 1996 · R. Williams (ST ScI), NASA

Today we know that the universe is a dynamic system that is developing continuously. In every star there are forces that determine its future. The gravitational force squeezes the matter of a star, trying to collapse it to a point. On the other hand, the strong and electromagnetic forces resist the attraction of gravity. There are four forces which determine the development of the stars:

1. Gravity: governs phenomena of astronomy and cosmology;
2. Weak force: } these two forces have been united in the
3. Electromagnetic force: } electroweak theory;
4. Strong force: determines thermonuclear reactions.

With new discoveries over the last 30-40 years in the laboratories we have come to understand many properties of the forces and of the particles on which they act. At the same time it has become evident that there are astronomical phenomena which cannot be explained by gravity alone, but include the systematic interactions of elementary particles. Finally, there are some particles which have been discovered in cosmic radiation. This is a radiation which continuously bombards the upper layers of the atmosphere. The fact that the UNIVERSE at large distances (Macrocosm) is related to the reactions at very small distances (Microcosm) is one of the important discoveries of the past 40 years. The symbiosis and collaboration of colleagues working in Cosmology with those working in elementary particles has led to a rapid increase of our knowledge.

The field of elementary particles is my field of research and I will describe two topics from my work:

1. The Quark-Parton Model, and
2. The creation of a Baryon asymmetry in the universe.

Our view today is that the Universe started with the Big Bang with many particles flying at very high energies and in different directions. At such high energies it is impossible for atoms and nuclei to exist and there was a mixture of particles, antiparticles and radiation: Photons, W-Bosons, Gluons, etc. There were, at that time, equal amounts of matter and antimatter. A natural question is: What were these particles? The question also has practical consequences, because the number of families of the particles determines subsequent phenomena; for example, the amount of hydrogen and helium and other nuclei, which formed later on and survive up to our time.

Let us begin with the atoms. When we investigate the atoms at short distances, we observe the nuclei and the electrons. The electrons seem to be basic and they do not change in the interactions (they only change their momentum). The nuclei, on the other hand, change in nuclear reactions from one to another. Then it was discovered that the nuclei contain protons and neutrons. The interactions among protons or neutrons or with one another produce new particles. They have been classified in groups, which we call representations of a group. Particles belonging to one representation have similar masses and other common properties like spin, parity, etc. In the period 1950-1967, experiments at accelerators discovered many particles, which could be classified in representations of the group SU(3). As two examples, I show in figure 1a the octet of baryons which have masses close to 1 GeV (giga-electron volt) and are distinguished from each other by other properties (denoted by $I_3, Y$) called quantum numbers. Similarly, figure 1b depicts the octet of mesons.

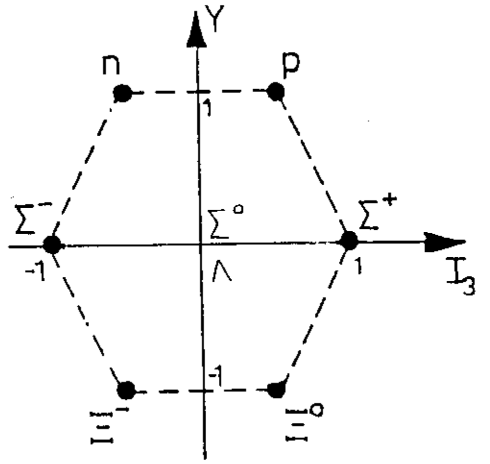



Figure 1 a

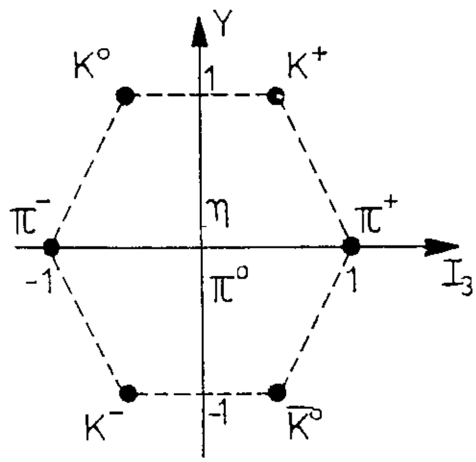



Figure 1 b

The physicists Gell-Mann and Zweig [2], independently from each other, introduced a more basic concept, the quarks, and proposed that the large number of particles can be classified in terms of quarks. The quarks are unusual particles with charges which are fractions of the charge of an electron. Table 1 describes the lightest quarks with their electric charges and another property, the isospin.

| Quark | Electric Charge | Isospin |
|---|---|---|
| up : u | 2/3 e | 1/2 |
| down : d | - 1/3 e | 1/2 |
| strange : s | - 1/3 e | 0 |

Table 1

With the quarks we can construct the mesons and baryons as bound states. For instance, the mesons are bound states of a quark and an antiquark, as follows

$$\pi^+ = (u\bar{d}), \qquad \pi^0 = \frac{1}{\sqrt{2}}(u\bar{u} - d\bar{d}), \qquad \pi^- = (\bar{u}d)$$
$$K^+ = (u\bar{s}), \qquad K^0 = (d\bar{s})$$

with the bar over a letter denoting antiparticles, that is antimatter. These bound states are analogous to the hydrogen atom, which consists of a proton and an electron, bound by the electromagnetic force. Similarly, the quarks and antiquarks form bound states under the influence of the strong force.

The fact that the quarks explain the classification of hadrons leads to the expectation that they must be produced as free particles in high energy collisions. However, intensive experimental searches from 1960 up to now have not succeeded in producing free quarks.

This motivated most of the physicists in 1967-68 to consider them as mathematical concepts or a mnemonic for classifying particles. At that time I finished my Ph.D. degree and went to Stanford University as Postdoctoral Fellow.

New experiments on the scattering of electrons on protons indicated that the production of particles at large angles was larger than expected from calculations, where the protons were considered to contain a uniform distribution of matter [9]. The second choice was to consider the proton made up of point-like constituents, like the indivisible atoms of Democritos.

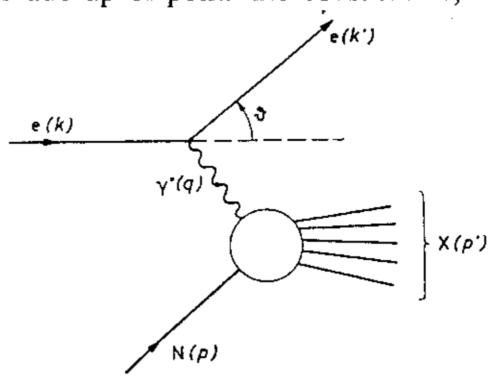



Fig. 2

Figure 2 shows the inelastic scattering of an electron on a proton. The exchange of light (photons) is represented by the wavy line $\gamma$, which acts like a spring between the electron and the proton producing the force.

Any suggestion that the proton is made of constituents, like the quarks, faces the difficulties that

(1) quarks are not produced in the reactions, and
(2) they do not leave any other sign of their existence.

Because of the shortage of time, I will concentrate on the development of the physical ideas. The cross-section for the reaction depends in general on two structure functions. Professor Bjorken proposed [3] that the structure functions satisfy a scaling law; that is, they do not depend on the energy-transfer, $\nu$, and the momentum-transfer squared, $Q^2$, of the electron separately, but on the ratio [3]

$$\omega = \frac{1}{x} = \frac{2M\nu}{Q^2},$$

where M is the mass of the proton. Bjorken's proposal has been confirmed by experiments to a good degree of accuracy. Deviations from scaling have also been observed and understood. The variable $x$ is known as Bjorken's scaling variable.

It was a lucky coincidence that at the end of the summer of 1968 Professor Richard Feynman visited our laboratory in order to speak to high school students. At my own initiative I mentioned to him the new experimental results and explained along general lines the work of Bjorken, and I asked if he had any opinion on this subject. Together we visited our colleague P. Tsai in his office, who showed us figures of the experimental results. The discussion impressed Feynman so much that he decided to extend his visit to the Laboratory. We dined together that evening and discussed the deep inelastic results.

Next morning when we met to go to the Laboratory, he mentioned to me that he explained Bjorken's scaling as the scattering of electrons from fundamental constituents. The variable x determines the fraction of the proton's momentum carried by the constituents. In addition, he christened the elementary constituents "partons" [4], from the Latin root PARS, PARTIS and the Greek ending "on". This follows an old tradition of hellenizing words, where the addition of a Greek ending brings them into Greek and other vocabularies. Feynman did not wish to commit himself on the specific properties of partons. Feynman spent the rest of the day at the Laboratory explaining his arguments several times.

It immediately became evident to Bjorken and myself that we could identify them with the quarks and that we could construct a theoretical picture for the proton and neutron. Equally important was our proposal that the quantum numbers of the basic constituents could be investigated and measured experimentally. The results of our investigations are described in ref. [5]. The diagram in figure 3 is now the basic representation of a proton.

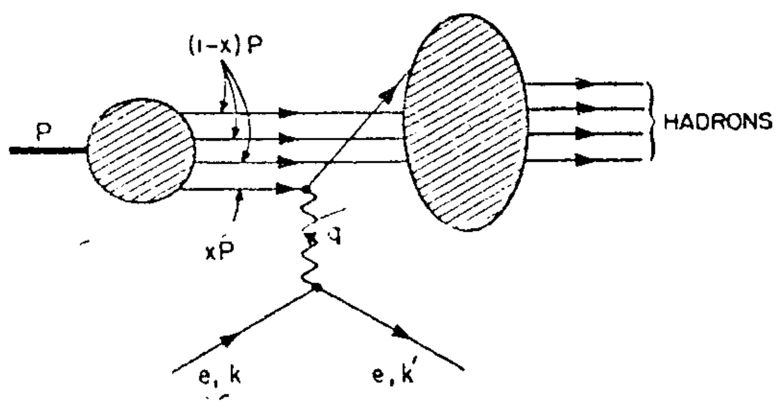



Fig. 3

The article defined the quark-parton model. In the article we present a picture of the proton as it moves with infinite momentum. The proton consists of two up-quarks with charge 2/3 e and a down-quark with charge –1/3 e. The quarks are surrounded by a cloud or a sea, as we called it, of quark-antiquark pairs. An external electron scatters from one of the quarks or antiquarks in the proton leaving traces of its quantum numbers in the strength and other characteristics of the reaction. The properties of the quarks were determined by their group classification but we could not determine properties of the pairs, which were identified later on with the gluons. In the same article [5] we discussed the neutron and described its structure function (being smaller than that of the proton).

The experimental group of the MIT-SLAC collaboration continued their experiments at SLAC and their results [6] agreed more and more with Bjorken's scaling [3]. At the same time they compared the experimental results [7] with theoretical models without being able to decide which model was preferable.

On the theoretical side, our proposal was not the only one. There were competing articles, some of them arguing that all hadrons were important and they interact with one another and each of them can be considered as a bound state of the others, etc. The only thing missing, in the opinions expressed in many articles, was a theoretical formalism for producing bound states. These proposals are known as Particle Democracy, Vector Meson Dominance, etc. The picture remained confused for quite some time. Today we know that the quark-parton model gives the correct picture. Professor Kotsákis in a small book [8] published in 1971, describes the situation as follows:

"To what extent the partons and the quarks are identical is still an open scientific problem.

In conclusion, in the physics of elementary particles, there are now two tendencies, those who believe in the existence of fundamental constituents of matter (and these are probably quarks and partons) and those who adhere to nuclear democracy, according to whom all particles are fundamental and bound states of each other. The future will show ... if one or both of these ideas will be replaced by others."

Experimental groups have continued investigations on deep inelastic scattering at higher energies and at various laboratories up to now. As time went by, the quarks of the 60's transformed from mathematical ideas to particles. The electrons in the experiments scatter from the partons within the proton and measure their quantum numbers.

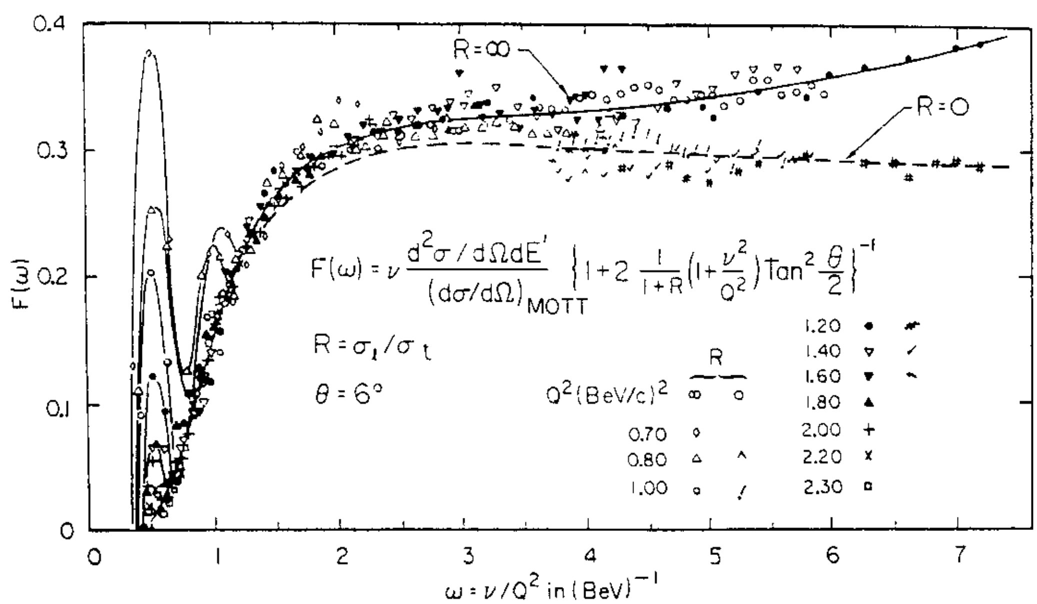


FIG. 2. Plot of the data as a function of $\nu/Q^2$.

Fig. 4.

In figure 4, I show the first experimental [9] results of the MIT-SLAC collaboration. It is evident that the data cluster around two curves, which correspond to two limiting values of the parameter R. For other values of R the points cluster around curves which lie between the two curves. In figure 5, I show subsequent results of the MIT-SLAC group as a function of the variable $x = 1/\omega$. One should note that the data begin at $x \approx 1/10$ and reach the value 1, that is, the parton carries a momentum from one tenth up to the whole momentum of the proton.

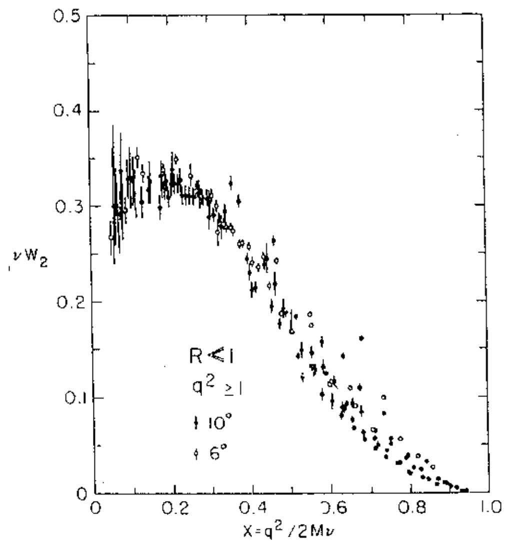


Fig. 5

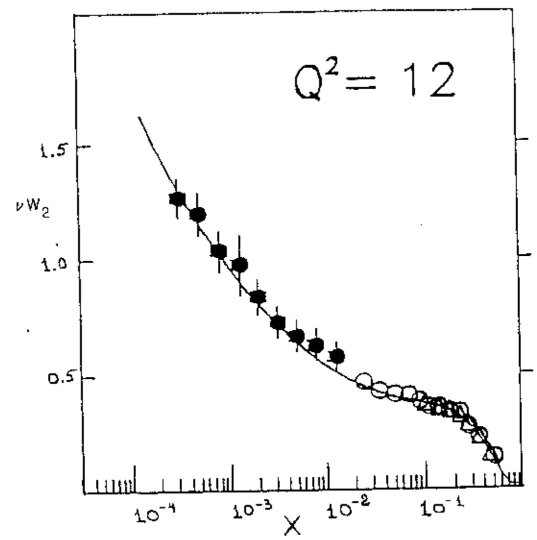


Fig. 6

As mentioned already, the experiments were repeated in various laboratories extending the region of $x$. The most recent results are from the laboratory DESY [10] in Hamburg. Figure 6 shows their results, that extended the variable $x$ to very small values $x \approx 10^{-4}$. Two new discoveries became evident in the new experiments:

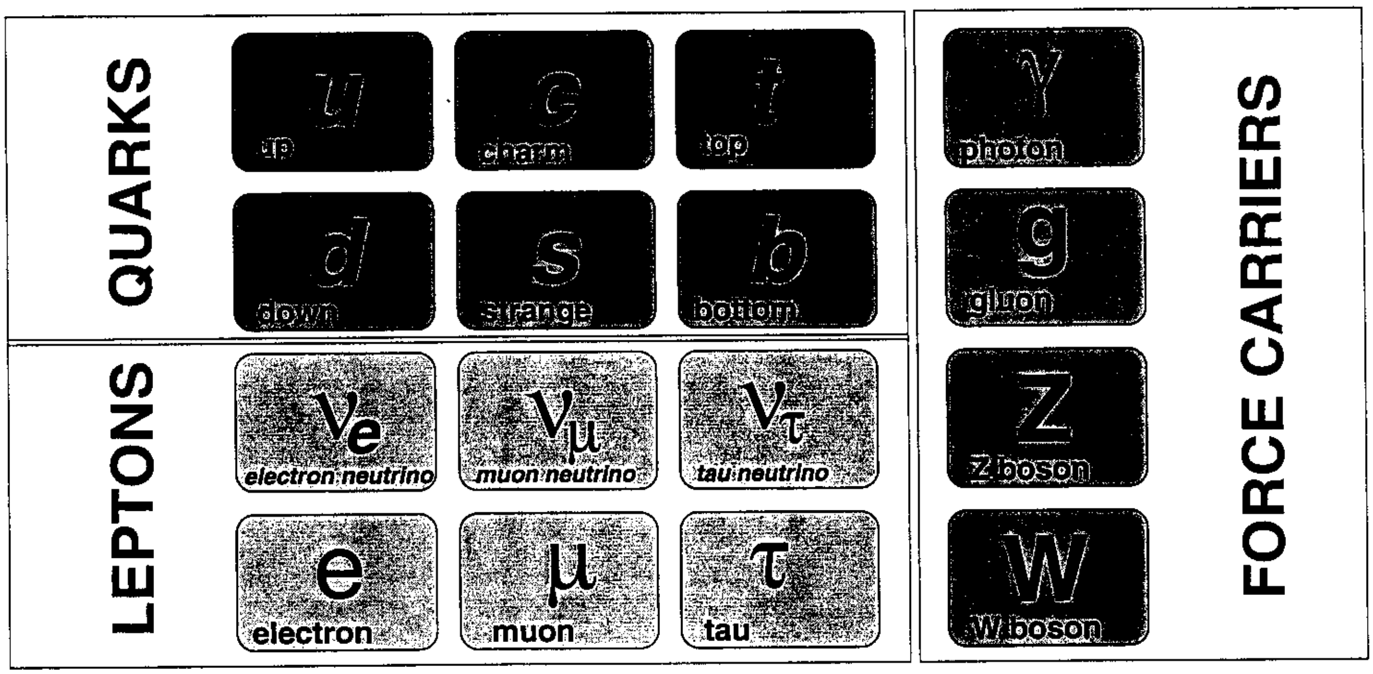
(i) the observation of scaling violations, and
(ii) the increase of the structure function at small $x$ (Fig. 6), indicating that there are many more quark-antiquark pairs carrying a small fraction of the proton's momentum.

Both observations have been explained as perturbative corrections from the theory of quantum chromodynamics, QCD [11,12]. The same theory also predicts that the force between quarks is weak at short distances but becomes very strong at large distances [11], providing a basis for developing an explanation why the quarks do not appear as free particles.

In summary :
1) The quarks have been established as the basic units of matter and their number is six.
2) All hadrons can be constructed as bound states of quarks, antiquarks through their interactions with gluons.

The table in the third picture shows the three generations of fundamental particles. Up to 1970, there were three quarks; the up, down, and strange. Studies in the rare decays of K-mesons demanded the existence of a 4$^{th}$ quark [13], which was discovered and christened "charm". Later, intensive experimental studies discovered two additional quarks; the bottom and the top. In each column of the table there is one generation of particles. To the first generation belong the up and down quarks together with the electron and its neutrino. The next two generations are shown in the next two columns. In the fourth column are the

# ELEMENTARY PARTICLES




**I II III**

**Three Generations of Matter**

particles which act as mediators between the quarks or the leptons creating the forces. For example, the photon mediates the electromagnetic force, the gluon the strong force and, finally, the two heavy particles *W* and *Z* mediate the weak force.

Now that we know the building blocks of the universe we can briefly describe its development. After the Big Bang, the universe was at very high energy ($10^{19}$ GeV). In this epoch the four forces were united into a single form. There were no atoms or nuclei, but instead the universe consisted of a mixture of quarks, antiquarks, leptons, antileptons and radiation. There were equal amounts of matter and antimatter. How is it possible that the anti-matter disappeared and today only matter remains?

This separation took place at the second stage of the universe when the strong force began to separate from the electro-weak force. At that stage an asymmetry was formed between matter and antimatter which survives to this day. The disappearance of antimatter is not only a theoretical problem, but an important subject which is investigated experimentally. Astronomical observatories look at distant galaxies searching for matter-antimatter annihilation producing energetic $\gamma$-rays. If there are islands of antimatter in the universe, then the cosmic radiation, which consists mostly of particles, will interact with them producing energetic explosions with the emission of light. Furthermore, there must exist supernovae of antimatter which produce anti-nuclei which become part of the cosmic radiation. Intensive searches of anti-nuclei in the cosmic radiation have not detected any heavy anti-nuclei. For these and several other reasons we accept that the original antimatter disappeared. The simplest explanation is that when the matter meets antimatter, they annihilate one another leaving only radiation. A part of the original radiation survives as black body radiation which was discovered experimentally. The temperature of this radiation is very small because, as the universe expands, it also cools down. Smaller temperature corresponds to lower energies. Thus, when the average energy in the universe reached MeV (million electron volts), the quarks bound together to form protons and neutrons, which in turn formed the nuclei. Finally, as the temperature reaches the eV (electron volt) level, nuclei and electrons bound together to form atoms.

Studies on the disappearance of antimatter with the survival of a small amount of matter* are based on three requirements, proposed by Professor A. Sácharov [14]. An asymmetry is generated when three requirements are fulfilled:

- violation of baryon and/or lepton number
- violation of the quantum numbers C and CP
- deviation from thermodynamic equilibrium.

Sácharov's proposal has been studied extensively [15], especially in unified theories, but the calculations lead, in general, to an amount of antimatter smaller than what we observe today. I will return to a recent proposal later on. Before I come to this topic, it is necessary to explain in a few words the symmetries C and CP.

In everyday life we observe many symmetries. These occur in natural structures, like plants, organisms, crystals, etc. or in human constructions like bridges, buildings, etc. Most of the symmetries depend continuously on a variable. For example, when we rotate a circle

* Small in comparison to the total mass of the universe.

through an angle $\theta$ around the axis passing through its center, it looks the same. We can turn the circle through small or large angles. This transformation is called continuous because we can vary $\theta$ continuously. In fact, between any two rotations we can find another intermediate angle of rotation.

All symmetries, however, are not continuous. When we look at our image in a mirror there are two states: ourselves and the image – there is no image in between. The same is true with time. In physical equations time develops in the future. We can change the sign of time in equations and then the interactions develop in the past. Again there are two directions: past and future. We call such transformations discrete. Physicists discuss several discrete transformations:

- The transformation C (charge conjugation) changes particles to antiparticles.
- The transformation P (parity) denotes the reflection of space, in other words, we form the mirror image of a state.
- CP is the combination of the above two transformations where one transformation follows the other.

It has been established that the physical states of the particles $K^0(\bar{s}d)$ and $\bar{K}^0(s\bar{d})$ are not symmetric under the transformation of CP. The physical states are

$$K_L : (K^0 + \bar{K}^0) + \varepsilon (K^0 - \bar{K}^0)$$

with specific mass and life-time and

$$K_s : \varepsilon (K^0 + \bar{K}^0) + (K^0 - \bar{K}^0)$$

with different mass and life-time. The transformation CP brings the change $K^0 \to \bar{K}^0$ and $\bar{K}^0 \to K^0$. A simple substitution verifies that the two states are different under the exchange $K \leftrightarrow \bar{K}^0$. Physicists say that the states violate the symmetry of CP, because of the parameter $\varepsilon$, which has been measured to have the value

$$\varepsilon = (2.271 \pm 0.017) \times 10^{-3},$$

which is small, but different from zero.

Today there are big experiments in Europe, the USA and Japan trying to detect CP-asymmetries in the decays of $K^0$ and the heavier mesons $B^0$. My group in Dortmund has published articles which make predictions for the magnitude of such phenomena of the $K^0$ mesons [16] and properties of the mesons $B^0$ [17]. In addition, we have studied the generation of matter-antimatter asymmetry and proposed that it is possible to construct a form of matter which is not symmetric under the transformation of CP. It is possible to add a right-handed neutrino to each generation of quarks and leptons and then the interactions of the theory produce neutrino states analogous to $K_L$ and $K_S$. The neutrinos are neutral particles which have only weak interactions. They pass through the earth with very few of them interacting with their surroundings. In Quantum Mechanics all particles are described by waves, like the light. The neutrinos are also waves developing in the future. When we


Fig. 7a


Fig. 7 b

reverse the sign of time and and make it negative, we obtain a wave developing in the past. Such waves describe antiparticles, as follows from the theory of Dirac. For this reason in diagrams illustrating reactions, we introduce arrows (see figure 2), whose direction distinguishes particles from antiparticles.

The neutrinos have another property: we can construct quantum states which are mixtures of neutrinos and antineutrinos. Let us represent the neutrino by $N_1$ and the antineutrino by $N_1^c$. The physical state

$$N_1 + N_1^c$$

is called the Majorana neutrino. In a theory with Majorana neutrinos, we may be able to introduce a small CP asymmetry which in turn produces a difference between matter and antimatter. There is a proposal with Majorana neutrinos, whose decays [18] produce more leptons than antileptons. Our proposal is that the self-energy of the neutrinos (their interactions with themselves) produces CP-asymmetric states [19]. The physical states are

$$\psi_1 = a_1 N_1 + b_1 N_1^c + c_1 (N_2 + N_2^c)$$

$$\psi_2 = a_2 N_2 + b_2 N_2^c + c_2 (N_1 + N_1^c)$$

with the constants $a_1 \neq b_1$ and $a_2 \neq b_2$. The decays of $\psi_1$, for instance, produce more leptons than antileptons. This excess appears in each one of the decays but does not survive on the large scale in the universe, because the inverse reactions (recombinations) wash out the excess. The excess survives and appears at large scales when the recombinations cease to take place.

At the beginning of the universe there were equal amounts of matter and antimatter. As the universe expands, the temperature decreases. The energy of each particle also decreases, as shown in figure 8. At some stage, the energy of each particle becomes smaller than half the mass of the heaviest neutrino. This neutrino decays, but cannot be reproduced because its decay products do not have enough energy. Decays are taking place but the recombinations are no longer possible and the universe deviates from thermal equilibrium. Over the course of time the energy for each particle becomes smaller than half the mass of the lightest Majorana neutrino. As a result the universe deviates even more from thermodynamic equilibrium. Every heavy neutrino decays and leaves a signature of its presence in the excess of the produced leptons.

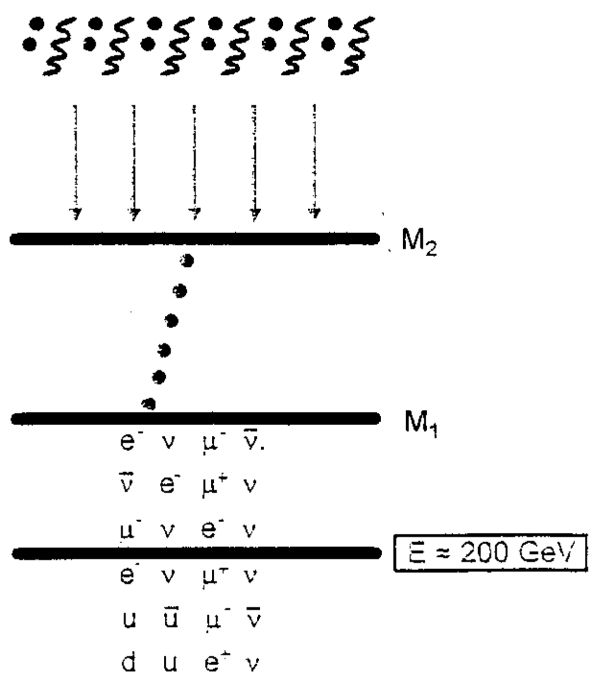



Fig. 8

According to the picture that I have described, the formation of the states $\psi_1$ and $\psi_2$,and their subsequent decays produce an excess of leptons. At a later epoch part of this excess is transformed into an excess of quarks. This development requires the expansion of the universe, which is necessary to create an arrow of time, developing into the future.

This proposal was made in 1994, when the view of most physicists was that the neutrinos have a very small or zero mass. In the meanwhile, an experimental group has observed phenomena which require the neutrinos to have a small but non-zero mass. The observations were made in mines deep in the earth in order to decrease the background of neutrinos from the surroundings. The experimental group of Superkamiokande in Japan has observed that the number of neutrinos produced at the top of the atmosphere decreases significantly when they reach the detectors of the experiment [20]. This phenomenon is explained as an oscillation of neutrinos of the second generation to neutrinos of the third generation [20]. They have also been able to measure the difference of the square of the masses and found

$$m_\mu^2 - m_\tau^2 \approx 10^{-2}(eV)^2 .$$

Other experiments observe neutrinos which are produced in the center of the sun and travel through space reaching the earth. It has been observed that only half of the solar neutrinos reach the earth. The explanation is again an oscillation of neutrinos from the first generation to those of the second generation [21]. In conclusion, the neutrinos have small masses and make the proposal for the existence of the states like $\psi_1$ and $\psi_2$ more attractive and perhaps more realistic.

In this talk I have tried to present a picture for the development of the universe and to emphasize that its development is closely related to the elementary particles. The quarks play an important role at the first stages of the universe and in understanding the elementary particles. The partons are basic units within the hadrons and have been identified with the quarks and the gluons.

Studies in both fields are continuing because there are unsolved problems. Some important problems are:

1. The masses and properties of neutrinos. (Are the neutrinos of Majorana or Dirac type?)
2. Masses for all the particles are produced by the Higgs particle(s) which has not been discovered yet.
3. New observations with telescopes and other detectors mounted on satellites, or on earth or under the sea (Nestor, Antares, Amanda, etc.) are looking for new phenomena from the universe.
4. Experiments with new accelerators (B-factories, LHC, Tesla, etc.) will investigate new aspects of the topics I have described.

In the future we expect close collaborations in the fields of elementary particles and cosmology and I hope this will continue revolutionizing our knowledge.

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