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ELEMENTARY PARTICLE PHYSICS —
WHERE IS IT GOING?

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CONTENTS

	Page
1. INTRODUCTION	1
2. EVER HIGHER ENERGIES	1
3. THE CERN PROTON-ANTIPROTON PROJECT	3
4. LEP AND THE NEXT GENERATION OF ACCELERATORS	4
5. ARE THERE FINAL INDIVISIBLE CONSTITUENTS OF MATTER?	7
6. FORCES AT THE ORIGIN OF MATTER	8
7. A NEW KIND OF CHARGE: COLOUR	9
8. FROM DEMOCRITUS TO PLATO	11

1. INTRODUCTION

The main objective of elementary particle physics research is to investigate the structure and the origin of matter. During the past few centuries an understanding has been sought of the order which exists in Nature in terms of “ultimate” constituents and forces which act between these constituents. Penetrating ever deeper into the microcosmos, smaller and smaller ultimate constituents have been identified. The indivisible “atoms” of the chemists of the last century were disintegrated by the physicists into nuclei surrounded by an electron cloud; it was found that the nuclei are composed of protons and neutrons, and nowadays we believe that these particles are each made up of three quarks, but there are already speculations that even these particles could be composed of even smaller constituents. Hence we consider the following logical difficulty: either the divisibility of matter can be continued indefinitely and there are no ultimate constituents, or we find at last particles which have no internal structure and hence also no spatial extension and which correspond to mathematical points. But how can we then understand why such mathematical points have a mass, an electric charge, spin, etc.?

The second fundamental question concerns the forces acting between these constituents. Why are there different forces in Nature? (Indeed, we cannot be sure that we know all of them.) What are their fundamental differences and relations, and might it be possible to unify them all into one fundamental force?

The most fundamental question which one would like to answer ultimately is the problem why there are laws in Nature at all: why is Nature ordered and not simply in a state of chaos, and how is it possible that the laws of Nature which are derived from past experience permit us to predict events in the future?

It is my impression that in order to solve some of these problems or, at least, to get closer to a solution, it will be necessary to change radically our present concepts. But after all, every great breakthrough in physics was linked to a change in our way of thinking, and it is precisely this sharpening of our mind imposed on us by Nature which has always had consequences far beyond the limits of physics.

2. EVER HIGHER ENERGIES

Penetrating deeper and deeper in the microcosmos became possible only because higher and higher energies were available to elementary particle physicists. There are essentially three reasons why higher energies are necessary.

- i) As is well known, the resolution determining the smallest details which can be “seen” is proportional to the wavelength of the “light” used, and — since particles are used as probes — the wavelength is given by the de Broglie relation $\lambda = h/p$. With the highest energies available today details down to 10^{-16} cm can be resolved. This is quite remarkable since such distances correspond to 1/1000 of the proton radius.
- ii) According to Einstein’s relation $E = mc^2$ (where E = energy, m = rest mass of a particle, c = velocity of light), higher energies are necessary to produce heavier particles. Heavy particles have many decay channels into lighter particles and therefore usually are very short-lived. As a result, they are not easily observed in Nature, and have to be produced artificially. To be aware of the existence of such particles, and to know their properties, is essential in order to understand the structure of matter. With presently available energies particles up to about 20 proton masses can be produced, which is not sufficient as we shall see.
- iii) To understand different interactions it is necessary to study them not only at low energies (low frequencies), but also at high energies. Our comprehension of electromagnetic interactions, for example, would be very fragmentary if we had explored experimentally only the electrostatic low-energy limit.

The only way to achieve the necessary high energies, or better, energy concentrations, is to accelerate particles by electromagnetic fields. Since the acceleration procedure takes of the order of seconds, only stable charged particles are appropriate. That leaves us only with protons and electrons and their antiparticles. With respect to their properties as probes protons and electrons behave in a complementary way.

Protons are relatively easy to accelerate, and in a synchrotron the energy is limited by the product $B \times R$ (where B = the magnetic field guiding them on a circle and R = the radius of their orbit) since the momentum increases with $B \times R$. Besides increasing the radius, one tries to achieve higher momenta by using superconducting technology to increase B . The disadvantage of the proton is its very complicated structure. From lepton scattering we know that the proton contains not only three “valence quarks”, but, in addition, gluons which bind the quarks together and so-called “sea quarks” which are due to vacuum polarization. As a consequence, collisions involving protons are rather difficult to interpret, and to extract from them the fundamental information on collisions between the constituents of matter, e.g. quarks or gluons, is not easy.

This difficulty does not exist for electrons which to our present-day knowledge behave like mathematical points down to dimensions of 10^{-16} cm. On the other hand, they are difficult to accelerate in a circular accelerator, since the centripetal acceleration leads to the emission of synchrotron radiation. The energy loss due to synchrotron radiation is proportional to E^4/R (where E = energy of the electrons and R = radius of their orbit). This energy loss must be compensated by accelerating fields, and the RF power to produce these fields is proportional to E^8 . To compensate this high power of E by increasing the radius is not very efficient. Indeed, doubling the radius allows the electron energy to be increased by only about 20%. Therefore, it is not surprising that electron energies achieved in circular accelerators are much lower than those for protons (see Table 1) and the highest energies for electrons have been obtained in the

Table 1

The world's principal particle accelerators
(only the largest of their kind in each region are listed)

		Existing machines (Energy in GeV)		Proposed or approved machines (Energy in GeV)	
Europe	CERN	$pp(\bar{p}\bar{p})(2 \times 31)$ $p(450)$ $p\bar{p}(2 \times 270)$ $e^+e^-(2 \times 19)$	ISR SPS (fixed target) SPS PETRA	$e^+e^-(2 \times 50) \rightarrow (2 \times 125)$	LEP
	DESY			$ep(30 + 800)$	HERA
USA	FNAL	$p(500)$		$p(1000)$ $p\bar{p}(2 \times 1000)$ $e^+e^-(2 \times 50)$	Tevatron II Tevatron I SLC (single-pass) Isabelle
	SLAC	$e^+e^-(2 \times 18)$	PEP		
	BNL			$pp(2 \times 400)$	
USSR	Serpukhov Novosibirsk	$p(76)$ $e^+e^-(2 \times 7)$		$p(3000)$	UNK
Japan	KEK	$p(12)$		$e^+e^-(2 \times 30)$ $ep(20 + 300)$	Tristan
China	Beijing			$e^+e^-(2 \times 2.2) \rightarrow (2 \times 5.7)$	

2-mile linear accelerator SLAC at Stanford where synchrotron radiation losses are avoided. However, it seems difficult to increase the energies of electrons by an order of magnitude in linear accelerators, and in particular it does not help for storage rings. The only way out is to increase the radius by considerable factors, and this is the reason why the new Large Electron Positron Storage Ring (LEP) project at CERN will have a circumference of about 27 km.

Positrons have been used in accelerators and storage rings for quite a number of years because they are comparatively easy to produce. Antiprotons, however, are difficult to produce because of their large mass and, above all, special provisions are required to accumulate an adequate number of antiprotons with sufficiently equal momenta to be used in an accelerator. This accumulation became possible for the first time last year at CERN and will be described below.

There are two ways to use accelerated particles:

- In fixed target accelerators the accelerated protons or electrons are made to collide with nuclei (mostly hydrogen) at rest. The disadvantage is that, according to relativistic kinematics, the available centre-of-mass energy increases only with the square root of the laboratory energy. On the other hand, in these collisions, secondary particles are produced, from which secondary beams can be derived. These secondary beams can contain particles which cannot be accelerated (e.g. neutrinos, muons, pions, or kaons), but also secondary electron beams with energies up to about 300 GeV have been produced which are unobtainable in any other way. These secondary beams allow many different processes to be investigated which could not be studied otherwise.
- The other possibility is to make two particle beams collide head on, in which case the centre-of-mass energy is just the sum of the energies of the two colliding beams. The disadvantage is that because of the small cross-sections the chances for a collision are very small, and so far the most economic way is to store the beams in storage rings where they circulate for hours or even weeks and hence the chances of eventually hitting a particle of the other beam is increased enormously.

If particles of the same kind are supposed to interact, two intersecting magnetic rings with opposite magnetic fields are necessary. The proton-proton collider (Intersecting Storage Rings — ISR) at CERN (Fig. 1) is the first and so far the only project of this kind for protons. DORIS at Hamburg was originally built as a two-ring collider in order to observe electron-electron collisions, but it has never been used in this mode of operation.

More interesting and even much simpler are storage rings where particles and antiparticles collide. Because of their opposite charge, only one magnetic ring is necessary. The two largest e^+e^- storage rings are PETRA in Hamburg (energy per beam 19 GeV, to be increased to about 22 GeV) and PEP at Stanford (beam energy 18 GeV). Proton-antiproton ($p\bar{p}$) collisions in storage rings were produced for the first time at CERN in 1980. This was quite a remarkable achievement both from the point of view of technology and with respect to the new possibilities which are opened up for research. I should like to describe briefly this project.

Fig. 1 Plan of the CERN Meyrin and Prévessin sites showing the accelerators and the main experimental areas.

3. THE CERN PROTON-ANTIPROTON PROJECT

During the last few years the Super Proton Synchrotron (SPS) at CERN (Fig. 1), which for cycling fixed-target operation can accelerate protons up to 450 GeV, has been converted into a $p\bar{p}$ collider facility with a maximum energy of 270 GeV per beam. For continuous colliding-beam physics the maximum energy is lower than for cycling fixed-target operation because of the limitation of the power supplies. The centre-of-mass energy achieved in $p\bar{p}$ collisions for the first time in 1981 was $2 \times 270 = 540$ GeV, the highest energy ever produced in a laboratory. At the heart of this project is the system for producing "cooled" antiprotons (Fig. 2). Protons at 25.6 GeV originating from the PS hit a metal target, where among other particles antiprotons with an average momentum of 3.5 GeV are produced. The main difficulty is that these antiprotons are produced with momenta differing in direction and magnitude such that only a very small number of these antiprotons can be injected directly into an accelerator. Hence, a special ring, the Antiproton Accumulator (AA), has been built whose task it is to accumulate the antiprotons and cool them, i.e. homogenize their momenta. Seen from the average antiproton the other antiprotons have random velocities with respect to it and hence this motion can be interpreted as a temperature. Homogenizing the momenta in direction and in magnitude corresponds therefore to a cooling process. Cooling requires some interaction with outside, since Liouville's theorem states that phase-space density otherwise cannot be reduced. But even with interference from the outside the cooling process seems a kind of Maxwell's demon. A very ingenious method, which goes under the name of stochastic cooling, has been invented and developed at CERN. At a certain point of the circumference of the AA ring a probe detects any deviation of a bunch of particles from the ideal orbit. A signal is passed across the diameter of the ring to a point on the opposite side, and when the particle bunch arrives a kicker applies a correcting signal. In such a way cooling can be achieved in all six dimensions of phase space, and the method works so effectively that it takes only a few seconds to produce a homogeneous antiproton beam. In reality the process is much more complicated, in particular it would not work for an infinite number of particles. Fluctuations of a finite number of particles are necessary; hence the name stochastic cooling. I do not have enough time here to describe the details of this very clever method.

The antiprotons are taken through a beam transfer loop back to the Proton Synchrotron (PS) (Fig. 2), where they are injected in the opposite sense, accelerated up to 26 GeV, and then taken through a transfer channel to the SPS. To obtain a sufficient number of antiprotons takes about a day. This implies that the whole system with its many injections

Fig. 2 Site layout of the antiproton facility. The Antiproton Accumulator (AA) and the complex network of transfer tunnels were completed during the 1980 shutdown of the 400 GeV Super Proton Synchrotron (SPS). Antiprotons produced by 26 GeV/c protons from the Proton Synchrotron (PS) striking a target are "cooled" and stored at 3.5 GeV/c in the AA. Stacks of antiprotons are then sent to the PS, where they are accelerated to 26 GeV/c travelling in the opposite direction to normal proton acceleration. They can then be transferred to the SPS or the Intersecting Storage Rings (ISR) for colliding-beam experiments. LEAR is the Low-Energy Antiproton Ring under construction at the PS for experiments with near zero momentum antiprotons.

and transfer systems has to work extremely reliably, and its successful commissioning would not have been possible without the remarkable competence of the CERN engineers.

The first $p\bar{p}$ collisions were observed in August 1981, and the experimental programme started in the autumn of the same year. To accommodate the experiments, large underground halls had to be excavated (LSS4 and LSS5 in Fig. 1). A total of five Collaborations have been approved to do experiments and, soon after starting to take data, interesting results were already obtained.

One of the remarkable features at these very high energies is the large number of particles that are produced in $p\bar{p}$ collisions (see Fig. 3). One can really speak of the creation of matter, and we might be very close to the conditions under which matter was produced during the "big bang" at the origin of the Universe. In Fig. 4 the average number of particles produced in $p\bar{p}$ collisions is shown as a function of the centre-of-mass energy. This figure demonstrates clearly the new energy range which has been opened up by the $p\bar{p}$ collider.

Thus, in the coming years, the SPS will provide a unique instrument for physicists, and it is hoped that some fundamental questions, which I shall mention below, may be clarified.

4. LEP AND THE NEXT GENERATION OF ACCELERATORS

In Table 1 are listed the new projects that are either under construction or have been proposed. A remarkable tendency can be seen: whereas in the past a certain duplication of facilities in various continents was accepted as being useful, the projects of the next generation of accelerators are so big and costly that a complementarity between the various regions of the world is aimed at. Thus, in Europe the emphasis is on LEP at CERN, which was approved in December 1981 by the Member States and whose construction has already started. It has a circumference of almost 27 km and is optimized for an energy per beam close to 100 GeV (Fig. 5). However, in the first phase, beam energies of about 50 GeV are foreseen. Of the eight possible interaction regions very likely only four will be equipped initially. Discussions on the experimental programme have already started and about 800 physicists from all over the world will be involved in this programme.

Fig. 3 Enlargement of a centre of $p\bar{p}$ interaction as recorded in a streamer chamber picture (Experiment UA5: Bonn-Brussels-Cambridge-CERN-Stockholm Collaboration).

Fig. 4 Curve showing the change with energy of the average multiplicity of charged particles. The recent result of experiment UA5 confirms the increase of multiplicity with energy predicted by QCD theory at an energy higher than that so far attainable only through cosmic rays.

Fig. 5 Map showing the position of the Large Electron Positron Storage Ring (LEP). The tunnel lies between about 80 and 150 m below the surface. Four experimental areas (even numbered) will be equipped in the first phase. The SPS and PS are used as injectors.

Eventually LEP will be able to reach beam energies up to 125 GeV, for which its dipole magnets have been designed. However, this will require superconducting accelerating cavities whose development is being actively pursued and where quite encouraging results have been obtained.

Fig. 6 Energy growth of e^+e^- storage rings: $\bullet$ machines in operation, $\times$ machines under construction or being planned. The straight line corresponds to an increase of a factor of about 10 every 12 years.

In Fig. 6 the centre-of-mass energies of e^+e^- storage rings are displayed as a function of time. It can be seen that the three development stages of LEP coincide more or less with the line extrapolated from existing facilities. An energy increase by a factor of about 10 is achieved every 12 years. A similar plot (Livingston plot) has been published many times for proton accelerators and storage rings, showing a tenfold increase of laboratory (equivalent) energy every 7 years. The Tevatron and UNK fit quite well the envelope curve for the proton machines. Thus it seems that the advent of new ideas (storage rings) or new technologies (superconducting magnets and cavities), which ensured a constant growth of energies for several past decades, will make it possible to continue this trend for one or two more decades. A 10 TeV world machine for protons might be the last in this evolution. Beyond this it is very difficult to make any predictions. It is probable that completely new ideas for particle acceleration, giving much higher energy gains per metre, will become necessary. Also a reduction of costs will be unavoidable, to such an extent that not only the cost per GeV must be reduced but also the total cost of projects. In this context it is interesting to note that the total cost of LEP will be about the same as that of the SPS, indicating at least a levelling-off in the cost of projects.

5. ARE THERE FINAL INDIVISIBLE CONSTITUENTS OF MATTER?

In Fig. 7 our present-day knowledge of the constituents of matter is summarized. This scheme in a way replaces the periodic table of the elements of the chemists of the last century. Certainly, it seems to be simpler. All the particles shown in Fig. 7 are fermions, i.e. they have spin $1/2$. The implication is that for particles of each kind a conservation law exists, meaning that they cannot be produced as single particles but only in particle-antiparticle pairs. There are two classes of particles: the leptons, which do not feel the nuclear force, and the quarks, which do. Another major difference is that quarks have $1/3$ charge, whereas leptons have integer electrical charges. The particles in the first line of the scheme differ from those in the second line by one unit in electric charge. The two particles in each column form a family as regards weak interactions in the sense that they can be transformed into each other. Thus, in weak processes a u quark can be transformed into a d quark and vice versa, or an electron into an electron neutrino, etc. The mass of the particles increases from left to right. Thus, besides the electron, a heavy electron which is usually called a muon is known, and a couple of years ago a super-heavy electron, the τ particle, was detected. Each of these electron-like particles has its own neutrino. Although experimental upper limits on the masses of the neutrinos are known, one of the most interesting problems is whether the masses of these neutrinos are exactly zero or not.

Originally, three quarks (u, d, and s) were known, but in the seventies the charm quark and the beauty quark were discovered. Because of the supposed symmetry between leptons and quarks most physicists are convinced that a sixth quark, the top quark, must exist. So far we do not understand the rules governing the masses of these particles; hence it is not possible to predict the mass of a top quark. For a certain time it was hoped that it could be produced with PETRA but it seems to be heavier than the available energy would permit us to detect. Maybe it can be found with the $p\bar{p}$ collider or LEP. I cannot go into more details of this beautiful scheme full of symmetry; I only want to mention that the sum of the electric charges of all these structure particles is zero, which has some deeper implications.

Looking at the scheme of Fig. 7 a number of fundamental questions immediately arise: Why are there six leptons and six quarks? Why is six a fundamental number, not four or eight? Although no heavier leptons than the τ have been found so far (the energies are not sufficient to produce heavier quarks than the b) it cannot yet be excluded that there is an infinite number of leptons and quarks. Such a series of particles could be interpreted as excited states of one fundamental system. On the other hand, symmetry considerations could speak in favour of a finite number of leptons and quarks, but then we must ask the question: why are there two classes of particles? Several theorists have speculated that quarks and leptons might not be the ultimate constituents, but that there might be a deeper layer of matter. They introduced even smaller particles (sometimes called rishons or haplons) out of which both quarks and leptons can be composed. Such a composition of quarks and leptons would imply that the latter particles have an internal structure and above all a finite radius. So far experiments at PETRA have shown that both leptons and quarks behave like point-like particles down to dimensions of about 10^{-16} cm. This does not yet exclude completely an internal structure of leptons and quarks, and only experiments at higher energies will be able to verify all these speculations. However, independently of whether some constituents of quarks and leptons can be found, I believe that we have come to a fundamental limit in subdividing into smaller and smaller parts the constituents of matter. If this should turn out to be true, it might be the most important discovery of elementary particle physics in this century.

"PERIODIC SYSTEM" OF ELEMENTARY PARTICLES

QUARKS				LEPTONS			ELECTRIC CHARGE
ELECTRIC CHARGE	STRONG NUCLEAR FORCE			NO STRONG NUCLEAR FORCE			
$+\frac{2}{3}$			?				0
	UP	CHARM	TRUTH	ELECTRON-NEUTRINO	MUON-NEUTRINO	TAU-NEUTRINO	
$-\frac{1}{3}$							-1
	DOWN	STRANGE	BEAUTY	ELECTRON	MUON	TAU	

Fig. 7 The “periodic system” of elementary particles showing the two families, the quarks and the leptons, which are thought to be the fundamental constituents of matter. They are all fermions (spin equal to $\frac{1}{2}$) and their masses increase from left to right in the diagram. The t (top or truth) quark has not yet been found.

There are two indications for such a limit. So far, it has not been possible to isolate individual quarks. As I shall explain below, this might be due to the properties of the nuclear forces. But there seems to be an even more general argument. If we consider the ratio between binding energy and the rest masses of the constituents of certain composite structures (see Table 2) we find that this ratio increases, the smaller the size of the constituents, and it has to be much larger than 1 for sub-constituents of quarks and leptons (estimates indicate a figure of the order of 10^6). Table 2 clearly demonstrates why our previous method of describing Nature in terms of well-defined constituents, between which forces are acting, worked so well. The forces are relatively weak, such that the individuality of the constituents is not impaired by the interaction. At the level of the quarks this situation changes drastically. For sub-constituents of quarks the interaction between these particles has become so strong that it seems difficult to continue to consider these constituents as individual particles. The philosophical consequence, of course, would be that a further subdivision of matter into smaller particles is still conceivable, but practically loses its meaning. We might be forced to abandon our method of describing Nature by individual particles and their interactions.

Table 2

The ratio of binding energy to rest mass for the various constituents making up the basic composite units of matter.

Composite unit	Constituents	Binding energy/ c^2
		Rest mass of constituents
Molecule	Atoms	10^{-10}
Atomic nucleus	Hadrons (p, n, Λ)	10^{-2}
Hadron	Quarks	≈ 1
Quark	Rishons, haplons	$\gg 1$

6. FORCES AT THE ORIGIN OF MATTER

All this indicates that an understanding of the forces which we find in Nature might be the clue to an understanding of the structure of matter. The forces which we know nowadays in Nature are shown in Fig. 8, where they are ordered according to their strength. We believe that the forces do not act directly over long distances, but that they are mediated by fields which represent a special state of the space-time continuum. This was first demonstrated for the electromagnetic interactions, but we have evidence nowadays that it is also true for the weak and the nuclear forces. It could not be proved yet for gravitation which, although being the longest known interaction, is very difficult to study experimentally in the laboratory because of its weakness.

At very small distances quantum effects become predominant. The field quanta of the interacting fields are bosons (integer spin). We can imagine that the "structure" particles, the fermions, exchange these "binding particles" whereby a force is created. If it is true that all forces can be explained as an exchange of binding bosons this might be taken as an indication that all forces have a common structure, whereas their differing properties are essentially due to the different bosons. This might give us hope that all forces can finally be reduced to one fundamental force.

The best known field quantum is the photon, which has no mass and spin 1. Three years ago the binding particle of the strong interaction, which has the name gluon, was detected at PETRA. Like the photon, it has no mass and spin 1. Both carry no electric charge.

For the weak interaction the binding particles, the intermediate bosons, must have completely different properties. Since in weak processes, like nuclear beta decay, the charge of the interacting particles changes (e.g. a neutron is converted into a proton in beta decay), the intermediate bosons W^+ and W^- must have an electric charge. Since the range of this interaction is extremely short, the mass of these particles must be very high according to the uncertainty principle; hence it has not been possible to detect them experimentally so far.

A major step was achieved when Glashow, Salam and Weinberg developed a theory which tried to unify the electromagnetic and the weak interaction. One of the predictions of this theory was that, besides the two charged intermediate bosons, there should also be a neutral one, Z^0 , which in a way is nothing other than a heavy photon. In 1973 the existence of the so-called neutral currents was established at CERN; they are an indirect indication for the existence of Z^0 . Many experiments at relatively low energies are in full agreement with this theory, but what is necessary is its verification at high energies. The detection of intermediate bosons, whose mass is predicted to be 80–90 times the proton mass, would be an important step in this direction. The only accelerator which has enough energy is the $p\bar{p}$ collider at CERN and therefore a discovery of these particles in the coming years might be possible. A detailed study of their properties and a full test of the unifying theory will, however, only be possible when LEP comes into operation.

THE FORCES IN NATURE			
TYPE	INTENSITY OF FORCES (Decreasing order)	BINDING PARTICLE (Field quantum)	OCCURS IN
STRONG NUCLEAR FORCE	~ 1	GLUONS (no mass)	ATOMIC NUCLEUS
ELECTROMAGNETIC FORCE	$\sim \frac{1}{1000}$	PHOTON (no mass)	ATOMIC SHELL APPLIC. OF ELECTRICITY
WEAK NUCLEAR FORCE	$\sim \frac{1}{100000}$	BOSONS Z^0 , W^+ , W^- (heavy)	RADIOACTIVE BETA DECAY
GRAVITATION	$\sim 10^{-38}$	GRAVITON?	HEAVENLY BODIES

THE EXCHANGE OF PARTICLES IS RESPONSIBLE FOR THE FORCES

Fig. 8 The four forces in Nature. Besides their different strengths the corresponding field quanta determine the different properties of the interactions. One aim of physicists is to find a way of unifying these forces into one fundamental force which could account for all phenomena in the universe.

7. A NEW KIND OF CHARGE: COLOUR

The next question we might ask is whether the nuclear force could also be integrated in this unification process. Indeed, there are some indications. However, before such a step can be made it seems necessary to understand better the strong force by itself. For many decades only phenomenological descriptions of the nuclear force were available. Only during the last few years has a theory been developed for the nuclear force in analogy to quantum electrodynamics (QED), and this theory is called quantum chromodynamics (QCD). Recent experiments support this theory, but many details and also some fundamental questions remain to be clarified.

The name of QCD has the following origin. In contrast to the electrical charge it is supposed that for the strong interactions there are three different charges and each charge has its own opposite, that is anticharge (see Fig. 9). A neutral state can be produced as in the electric case by a combination of the charge and its proper anticharge. In QCD, however, a new possibility exists. If three charges are combined (without involving an anticharge) one can also produce a neutral state. This corresponds to the known procedure of mixing colours where three basic colours can give a white colour. Because of this analogy the three charges of the strong force are designated by colours, e.g. red, green, or blue, with their anticolours antired, antigreen, antiblue. Carriers of these anticharges and hence sources of the strong force are the quarks, whereas leptons do not carry any colour charge.

So far, in Nature only neutral, white states have been found. This implies that only two kinds of quark “molecules”, which are called hadrons, can be composed. Either a quark and an antiquark are bound together, which is called a meson; or three quarks form a particle and these are called baryons, with the proton and the neutron as the best known examples. No other combinations have been found so far, which implies that the quark “chemistry” is very simple. As mentioned above, the field quanta of the strong force are called gluons. One essential difference between QED and QCD is that the photons do not carry an electric charge, whereas the gluons are colour charged. This implies that a direct gluon-gluon interaction and even bound gluon states are possible. This important prediction of QCD has not been definitely confirmed experimentally yet, although there exist some indications for bound gluon states (glueballs).

A very remarkable experimental fact is that, so far, no free colour charges have been produced, and that no free quarks and no free gluons have been observed. The question now is whether our available energies are just not high enough to break the colour binding or whether there is a fundamental principle which forbids free colour states and allows only the existence of neutral states in Nature.

The answer to these questions might be linked to another fundamental difference between QED and QCD (Fig. 9). The strength of the coupling between an electrical charge and the electromagnetic field is determined by the size of the elementary charge of the dimensionless quantity derived from it: $\alpha = e^2/\hbar c$. This fine structure constant is a universal quantity and is, in particular, independent of the interaction energy. In QCD it can be derived from very general principles that the corresponding coupling constant α_s is indeed not a constant but depends on the interaction energy in a logarithmic way. At large energies it is small and increases with decreasing energy. The energy dependence is characterized by a parameter Λ (see Fig. 9) and this parameter, and not α_s itself, is the characteristic constant describing the strong interactions. An experimental determination of Λ is difficult since the logarithmic dependence on

	QED	QCD		
	ELECTROMAGNETIC FORCE	STRONG FORCE		
Charge Anticharge	positive negative	blue antiblu	green antigreen	red antired
Neutral matter	ATOM uncharged	MESON white	BARYON white	confinement
Field quanta	PHOTON uncharged	GLUON Colour charge		
Coupling	$\alpha = \frac{e^2}{\hbar c} = \frac{1}{137}$ Universal constant	$\alpha_s = \frac{4\pi}{(11 - \frac{2}{3} N_f) \ln Q^2/\Lambda^2}$

Fig. 9 A comparison between quantum electrodynamics (QED) and quantum chromodynamics (QCD) — the gauge field theories governing, respectively, the electromagnetic force and the strong force. In QCD there are three charges (and their anticharges) and consequently there are two different ways to form a neutral (“white”) state. The coupling α in QED is a universal constant, whereas α_s changes with energy Q . Therefore Λ is the fundamental constant characterizing QCD.

energy is rather weak. Last year several experiments at CERN were able to determine this quantity and it was found that the order of magnitude is about $\Lambda \simeq 100$ MeV, corresponding to a length of about 3 fm. The change of the coupling with interaction energy has a very important consequence. If quarks interact at small distances, the interaction energy is high, the coupling is low, and the quarks behave almost like free particles (asymptotic freedom). In this case QCD behaves almost like QED and indeed many formulae of QED can simply be adapted to QCD. The situation is completely different, however, for large distances between the quarks. Then the coupling increases, and if one tries to separate two quarks, quark-antiquark pairs are created, which combine with the original quark to form colourless, white states. This is analogous to breaking a magnet where at the breaking point a new pair of north and south poles is formed, such that the two pieces of the magnet are both dipoles and no monopoles can be produced. If this “confinement” of quarks is corroborated experimentally and is better understood theoretically, it might be one of the most important discoveries in elementary particle physics. Apart from its consequences for a better understanding of the strong interactions it would imply that we have come to a fundamental limit in subdividing the constituents of matter into smaller and smaller parts.

8. FROM DEMOCRITUS TO PLATO

I should like to come back to the questions as to why there are four interactions in Nature and what their relation might be. One big break-through in physics during the past century was the recognition that electric and magnetic phenomena are just two different aspects of one underlying unified force. This discovery was not only of extreme importance for the understanding of electromagnetic phenomena, but is also the basis of our present-day electrical engineering, radio, and television. Can we hope to unify eventually all four forces?

As has been mentioned above, it seems that all forces can be explained by the same basic mechanism, that is they are mediated by the exchange of intermediate bosons between those constituents of matter which are fermions. One difficulty in unifying forces might be their strength. How can it be that forces with such different coupling strengths can be the offspring of the same basic phenomenon? It seems that this difficulty can be overcome in the following way. The coupling strengths indicated in Fig. 8 are those determined at low energies. However, it turns out that the strength of the weak interaction increases with interaction energy, and at energies corresponding to the masses of the W and Z its strength becomes comparable to the electromagnetic interaction. Hence, at energies corresponding to distances of about 10^{-17} cm the unification of these two interactions becomes possible. On the other hand, we have seen that the strength of the strong interaction decreases with increasing energy and at about 10^{15} GeV it becomes comparable to the strength of the electroweak interaction. Hence at distances of about 10^{-29} cm a "grand unification" might become possible. We know very little about the quantum behaviour of gravitation, but some speculations indicate that this interaction could also be included in the unification at energies of about 10^{20} GeV or distances of about 10^{-34} cm. This is certainly very far away from present-day experiments.

Is the endeavour to unify all known interactions in one fundamental force just a romantic dream of the physicists or has it a more general relevance? First, I would like to come back to the question of whether Nature can be described by independent, individual constituents and forces acting between them. Above, I gave some arguments why we might have to replace this concept by more general ones. A concept that seems to be more fundamental while at the same time more abstract is that of gauge fields. Indeed, it turns out that gauge fields are at the basis of all the mentioned theories describing the various interactions. The practically infinite number of mathematically possible gauge fields is restricted by the symmetry properties of these fields. It seems therefore that the first principles of describing and understanding Nature may not be little indestructible bricks of matter, but rather abstract concepts, symmetries. It seems that modern elementary particle physics is taking us from Democritus to Plato, which eventually might have important repercussions beyond the limits of physics.

If all forces can indeed be described by gauge field theories it might in the end be possible to derive everything from just one fundamental gauge field. This could have a far-reaching consequence for our understanding of Nature. Each abstract field is related to a special structure of the space-time continuum. It is difficult to conceive that several such structures could coexist. Conceptually it certainly is much simpler if all interactions could be derived from just one space-time structure. Considering the interactions, one can furthermore find that the existence of matter, as we know it, depends very critically on the detailed properties of all interactions. Changes in the coupling of one force or the elimination of one interaction would entail a collapse of matter. It is difficult to believe that this exact coordination of the interactions could be an accident and has no deeper connection. If this connection exists, a unified field theory could also help to solve the old problem of Hume, namely the question why there are laws of Nature at all.