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The Strong Interactions*

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Abstract

Physicists have traditionally classified the forces of nature into four categories: *the strong interactions*— the short-range forces which describe the interactions between hadrons, such as the nucleon and pion and which bind protons and neutrons into atomic nuclei; *the electromagnetic interactions*— which bind electrons and nuclei into atomic and molecular systems; *the weak interactions*— which cause the radioactive decay of nuclei; and *the gravitational interactions*— which are manifest in the motion of macroscopic objects such as planets. By definition, all particles which interact strongly are called hadrons. In the period immediately after 1967, a remarkable scientific revolution occurred in which it was found that the strong interactions between hadrons could be described in terms of fundamental quark and gluon degrees of freedom which also provided a simple "periodic table" classifying the number and types of observed hadrons. The mathematical theory describing the interactions of the basic constituents of matter is called *quantum chromodynamics,* a theory in which quarks and gluons are permanently confined by increasingly strong forces at large distance. Conversely, QCD possesses the property of "asymptotic freedom"; that is, the effective strength of the fundamental forces vanishes as the distance scale goes to zero. This is the reason that high energy inelastic large momentum transfer electron-proton scattering can be rather accurately viewed as scattering from quarks that act as though they were free but are permanently confined.

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Historical Introduction

In the 1930's Yukawa postulated that the strong interactions could be explained by the exchange of a set of three π mesons acting between just two fundamental nucleons, the proton, of mass 0.938 GeV/c^2, and the neutron, heavier by only 1.3 MeV/c^2. For example a proton and neutron could scatter by the proton emitting a π^+ which is then absorbed by the neutron: $pn \rightarrow n\pi^+ n \rightarrow np$. The intermediate state is "virtual" in the sense that energy is not conserved for the brief time that the pion is in flight, as allowed for by the uncertainty principle of quantum mechanics. In this reaction, the charged π meson is exchanged between the two nucleons; the net effect is that the proton and neutron exchange their identities. The proton and neutron can also interact by exchanging a neutral pion $pn \rightarrow p\pi^0 n \rightarrow pn$. Since this process leads to the same final state as the previous reaction, the amplitudes for the two scattering processes can interfere with each other according to the laws of quantum mechanics.

In Yukawa's theory the charged and neutral pions could be arranged as the components of a vector $[\pi^+, \pi^0, \pi^-]$ in an abstract space called isospin space in analogy to the description of spin-one particle in quantum mechanics. Similarly, the proton and neutron could be thought of as the two components of a spinor $[p, n]$, in analogy to a spin-half particle. The coupling of the neutral and charged pions to the nucleons can therefore be written in analogy to the corresponding couplings of spin-one and spin-half particles in ordinary space. The fact that the theory is invariant under rotations in the abstract isospin space is called isospin or $SU(2)$ symmetry.

The π mesons predicted by Yukawa were discovered in 1947 and had a mass of 0.14 GeV/c^2. However, so many new massive and unstable hadrons have been found over the years that it became ever more difficult to consider every hadron, including the original proton, neutron and pion, as a fundamental entity. In 1964 M. Gell-Mann and G. Zweig introduced the quark model to organize the ever-proliferating zoo of "elementary" particles. They introduced three basic building blocks, the *u*, *d*, and *s*, the "up", "down", and "strange" quarks, each with fractional electric charge. The isospin of the strong interactions was still a good symmetry of the theory, reflecting the approximate invariance of the quark model under the interchange of the two lightest quarks, the *u* and the *d*. Gell Mann also introduced a generalization of isospin spin symmetry called $SU(3)$ "flavor" symmetry which extended the approximate invariance of the theory to all three of these basic quark building blocks. In this way the strange hadrons could be unified with the other strongly interacting particles.

1. The Quark Revolution

Over the past 30 years experiments at high energy accelerator laboratories have revealed that protons, neutrons, and the other subatomic hadrons, which were once considered fundamental entities, are indeed complex composites of more elementary constituents called "quarks" and "gluons" which are the carriers of the strong force. For example, the proton, which has electromagnetic charge $+1$, can be characterized as a bound state of three quarks: two *u* quarks each carrying charge $+2/3$ and one *d* quark carrying charge –1/3. Conversely, the neutron, which has zero electromagnetic charge, is a composite of two *d* and one *u* quark. Furthermore, the quarks and gluons are found to carry another type of charge termed "color: each quark comes in a triplet of three colors while gluons can exist in eight different varieties. The physical particles, the hadrons, must be color singlets with zero net color. Color is conserved in all interactions. The strong interactions of the proton and neutron and nuclei may thus be regarded as manifestations of more fundamental forces acting between their constituent quarks. The theory of *quantum chromodynamics* (QCD) provides an elegant mathematical description of the basic interactions of colored quarks and gluons, in close analogy to the way that the theory of *quantum electrodynamics* (QED) provides a precise description of electromagnetic, atomic, molecular, and chemical interactions in terms of the basic interactions of photons with charged electrons and nuclei. QCD thus provides a fundamental framework for understanding the origins of the strong interactions between hadrons, including the nuclear force.

An artist's conception of the structure of the atom and the atomic nucleus in terms of electrons and quarks is shown in Figure 1. If this picture were drawn to the scale given by the protons and neutrons, then the size of the quarks and electrons are known to be less (and possibly are much less) than 0.1mm; the entire atom would be about 10km across.

The strength of the interactions between hadrons, such as protons, anti-protons, and mesons, exceed by several orders of magnitude the strength of the electromagnetic interactions which are responsible for atomic and chemical bonds. However, the strong force between hadrons also diminishes exponentially at large distances with a range set by $\hbar/m_\pi c \sim 1.4\times10^{-13}$ cm, where $\hbar$ is Planck's constant, c the speed of light, and m_π is the mass of the pion, the least massive hadron.

Six distinct types of quarks have now been identified; they are conventionally distinguished by their "flavor" labels: *u, d, s, c, b,* and *t;* the latter three are termed the "charm", "bottom" and "top" quark respectively. All of the known hadrons can be classified as bound states of the quarks and anti-quarks. For example, the charged pion π^+ is effectively a bound state of the *u* and anti- *d* quarks, whereas its antiparticle, the π^-, is a bound state of the anti- *u* and *d* quarks.

An overview of the composition of a sample of hadrons in terms of their quark and antiquark constituents of matter is presented in Tables I(a,b,c). Spin is the value of the intrinsic angular momentum of each particle measured in units of Planck's constant $\hbar = h/2\pi = 1.05\times10^{-34}$ J-sec. The electric charges are given in units of the charge of the proton, 1.60 $\times10^{-16}$ coulombs. Masses are given in units of GeV/c^2 = 1.67 $\times10^{-27}$ kg.

The three diagrams of figure 2. show an artist's conception of the fundamental mechanisms underlying three sample physical processes: (a) neutron β decay in which a neutron decays to a proton, an electron, and an antineutrino via a virtual (mediating) W boson; (b) electron-positron annihilation through a photon or a *Z* boson into quarks and then their subsequent hadronization into charmed hadrons; and (c) the decay of a charmonium state, the η_c, through gluons and quarks into light mesons.

2. High Energy Physics Experiments

The basic tools needed for the investigation of the strong interactions are particle accelerators that allow beams of electrons, protons, heavy ions and other charged particles to be accelerated, stored, and brought into collision with fixed targets containing the element to be studied. Alternatively, two counter-rotating beams of charged particles can be brought into direct collisions with each other, producing events with a very high effective center of mass energy. The result of the collision of individual particles can be observed and reconstructed using a remarkable array of detectors, fast electronics, and computer systems which can record the vast amount of data required to identify the produced particles, measure their momenta, observe their decay, and determine other interesting features of the reaction.

The basic unit used to characterize accelerator energies is the electron volt (eV), the energy acquired by an electron accelerated through a potential difference of 1 volt. In the 1950's protons could be accelerated to energies of order of a few million electron volts (MeV). Currently, at the Stanford Linear Accelerator Center (SLAC) electrons, as well as their antimatter partners, the positrons, can be accelerated, over a distance of two miles, to an energy of fifty thousand million electron volts, 50×10^9 eV = 50 GeV, and brought into collision with fixed targets. Alternatively, the electron and positron beams can be steered into a head-on-collision in which they can annihilate and produce new particles at a center of mass energy approaching 100 GeV. At the Tevatron collider at the Fermi National Accelerator Laboratory in Batavia, Illinois, beams of protons and anti-protons (their antimatter partners) are accelerated and brought into head-on collision with total energies approaching 2×10^{12} eV = 2 TeV. At the new Large Hadron Collider (LHC) currently being constructed at the CERN laboratory in Geneva, Switzerland, proton-proton collisions will be studied at a center of mass energy of 14 TeV.

Figure 3(a) illustrates electron-positron annihilation through a γ or a Z^0 boson which then decays into a quark-antiquark pair at some finite angle. The separating $q - \overline{q}$ pair will each decay into ordinary hadrons with no net color imbalance and produce two sprays of particles; each spray of particles is termed a "jet". This is an example of a two-jet process. In Figure 3(b) the positron is replaced by a proton which consists of three quarks. Here the basic interaction is electron-quark scattering which produces an outgoing electron balanced by a recoiling quark. The remnants of the proton continue forward. Again, final state decay, or "hadronization", of the struck quark and the remaining spectator quarks will balance color, produce a multi-hadron final state, and finish this process.

In Figure 3(c) the electron is replaced by an antiproton which consists of three antiquarks. The basic interaction here is quark-antiquark scattering via an exchanged gluon (or photon). At large momentum transfers the final state consists of four jets, all of which eventually decay into hadrons.

3. Inside Hadrons

The first compelling direct evidence for the quark structure of hadronic matter was obtained at SLAC in 1967 in experiments which measured the scattering of electrons on the protons in a hydrogen target. These experiments which were carried out by an experimental collaboration from SLAC and MIT led to the 1990 Nobel Prize being awarded to J. Friedman, H. Kendall, and R. E. Taylor.

The radius of a proton R_p is approximately 0.8 fm = 0.8×10^{-13} cm. Thus, because of the uncertainty principle, momentum transfers $Q > \hbar / R_p$ are necessary to resolve any internal structure of the target proton; hence incident electron energies in the GeV regime are required. The distributions in energy and angle of the scattered electrons measured at SLAC behaved as if the proton was a composite system of point-like fractionally-charged quarks. In fact, as predicted by J. D. Bjorken, the distributions were found to depend primarily on the ratio of the square of the momentum transfer of the electron to its energy loss, a property called "scaling" which reflects the point-like nature of the constituent quarks. These experimental results inspired the point-like constituent models of J. D. Bjorken, R. Feynman, and E. Paschos which describe general hadronic reactions. These constituents have the generic name "parton". The deep inelastic scattering experiments have now evolved into a systematic program to determine the momentum distributions of the quarks and gluons within the nucleon. In fact, precise data involving hydrogen and nuclear targets with and without spin polarization has led to a rather complete characterization of these distributions. Surprisingly it has been found that a substantial fraction of the momentum and spin inside the nucleon is carried by gluons. The data also reveal the corrections to pointlike behavior as demanded by QCD; these reflect the effect of gluons in the electron-quark collisions

4. QCD and the Collisions of Hadrons

When protons collide with other protons at low energies (below a few 100 MeV), they scatter *elastically* with an angular distribution revealing the fundamental properties of the strong nuclear force. The probability that the protons scatter on each other is close to maximal in the sense that the protons are almost certain to interact if their trajectories intersect. At low energies, the interaction between protons and neutrons is sufficiently strong and attractive to allow them to bind them into nuclei. Very large interaction rates are also measured when nuclei interact with one another, reflecting in turn their composition in terms of protons and neutrons.

In hadronic collisions at GeV energies, the strong interactions can be *inelastic;* i.e. , new strongly interacting particles not present in the initial state can be produced in the reaction. The energy of the initial colliding particles is converted into the mass and energy of the final outgoing particles, consistent with Einstein's principle of mass-energy equivalence as well as overall energy, momentum and charge conservation. The new particles are primarily π mesons which from the standpoint of QCD are $(q\overline{q})$ composites of the u and d quarks and their antiparticles. In addition, one observes kaons and hyperons; these are termed "strange" particles and are composites of the s quark with u and d quarks or their antiquark partners. Anti-matter such as the anti-proton, anti-neutron, or even anti-nuclei, such as the anti-deuteron, can also be produced in high energy collisions. As the beam energy is raised to 100's of *GeV*, one observes the production of new forms of matter. The final states contain pairs of charmed c (charge $+2/3$) and bottom b quarks (charge –1/3). These particles are so heavy and short-lived that they have previously appeared in nature only at the very earliest stages of the creation of the universe and in very high energy cosmic ray events. However, over the last 20 years an entirely new zoo of hadrons containing the charm and bottom quarks have been observed, including quarkonia such as $(c\overline{c})$ or $(b\overline{b})$, charmed and bottom mesons such as $D^+ = (c\overline{d})$ or $B^- = (b\overline{u})$, and heavy baryons such as $\Lambda_c = (cud)$. In 1995, evidence for the sixth type of quark, the "top" quark t with a mass of order 175 GeV/c^2, was discovered in proton-antiproton collisions at the Fermilab Tevatron collider. However, the top quark is so heavy that it decays into a bottom quark and the W boson that carries the weak interaction, i.e. $t \rightarrow bW^+$, before it has a chance to bind with other quarks into new types of heavy hadrons.

5. General Properties of High Energy Collisions

5.1. Cross Sections:

The strength of the interaction between any two particles can be characterized by a number σ with units of area called the *cross section*. Thus if two high energy particle beams collide head on with "luminosity" $\mathcal{L}$ (the number of particles intersecting per unit area per second), then the total rate of elastic and inelastic interactions per second is $N = \mathcal{L}\sigma$ where σ is the total interaction cross section. For example, at the Tevatron collider at Fermilab, the counter-rotating protons and anti-protons collide with energies per beam up to a TeV at a luminosity of

$\mathcal{L} \sim 2 \times 10^{31}/\mathrm{cm}^2/\mathrm{sec}$. The observed rate of interactions corresponds to a cross section $\sigma_{\overline{p}p} \sim 0.5 \times 10^{-26}$ cm^2. This corresponds to a disc of radius $\sim 0.4 \times 10^{-13}$ cm. Despite the fact that the typical inelastic interaction produces hundreds of hadrons, the rate for purely elastic collisions is large, typically of order of 20% of the total rate at TeV energies. In addition, a significant fraction of the events are *diffractive;* i.e., scattering events where at least one of the incident hadrons remains intact.

5.2. Unitarity:

The elastic scattering of two protons with specific spins in the initial and final state is described in quantum mechanics by a complex amplitude $T(s, t)$ where s is the square of the center of mass energy and t is the square of the four momentum transfer. The absolute square of this amplitude times a kinematic factor gives the differential elastic cross section $d\sigma(s,t)/dt$, describing the probability for the protons to scatter at a given momentum transfer or angle. The integral of this distribution is the total elastic cross section $\sigma(s)$.

One can use probability conservation or "unitarity" to show that the imaginary part of the scattering amplitude in the forward direction, $\mathrm{Im}T(s, 0)$, is proportional to the total (elastic plus inelastic) cross section. This remarkable property is referred to as the *optical theorem*. Another consequence of general arguments is the *Froissart bound;* two of its statements are that: (1) the total cross section for the scattering of two hadrons cannot rise faster than the square of the logarithm of the energy, and (2) the elastic cross section can never be more than half of the total rate.

5.3. Regge Behavior:

A useful parameterization for a hadronic scattering amplitude at high energies is a sum of terms, each with the Regge form, $T(s,t) = \beta(t)s^{\alpha(t)}$. The coefficient $\beta(t)$ describes the fall-off of this contribution in momentum transfer and the exponent $\alpha(t)$, termed the Regge trajectory after the theorist T. Regge, describes its growth with energy, where s is the square of the center of mass energy. For example, the charge-exchange reaction $\pi^- p \to \pi^0 n$ is well characterized at high energy by one term with an exponentially-falling distribution in the square of the momentum transfer t, and a power-law energy dependence $\alpha(t) = \alpha(0) + \alpha'(0)t$ which depends linearly on t. Approximate values of the parameters are $\alpha(0) \sim 1/2$

and $\alpha'(0) \sim 1 \text{ GeV}^{-2}$. Remarkably, the Regge trajectory is related to the mass spectrum and spin of hadrons that can be exchanged in the reaction. The Regge parameterization is not exact, but as an expansion it provides an important guide to the phenomenology of high energy cross sections.

6. Comparisons between QED and QCD

Quantum Electrodynamics (QED) is a gauge field theory of uncharged photons and charged particles. A central feature of the theory is gauge invariance; i.e. , the theory is invariant even if one changes the phase of each charged field by an arbitrary phase at each point of space and time. The generator of such phase changes corresponds to the simple Abelian group U(1). In contrast, Quantum Chromodynamics is a non-Abelian gauge field theory of charged gluons and charged quarks where the charge is labeled by an index called “color”. For example, each quark is distinguished by a “color” charge, conveniently labeled R, G, or B. A basic property of the theory is its invariance under local color transformation; i.e., the color labels can be transformed arbitrarily into each other at every point of space and time without any physical consequence. The predictions of QCD are thus invariant if one applies an arbitrary rotation among the three colors of each quark field. The generators of such rotations correspond to the special unitary group $SU(3)$.

The colored quarks of QCD can be combined into color-neutral configurations in analogy to rules of addition of ordinary visible colors. In fact, in QCD, every observable particle must be a color singlet; i.e. , have no net color charge in order to have a finite mass due to the energy residing in any remaining gluon field which extends to infinity. In contrast, in QED, the theory of atomic forces, free charged particles are commonplace. In QED, the electromagnetic interactions arise from the exchange of the quanta of the electromagnetic field, the photons, which carry no electric charge. In QCD, the quarks interact via the exchange of an octet of colored gluons, the quanta of the chromomagnetic field. QCD is much more complicated than QED since the gluons themselves carry the color quantum number and thus also interact among themselves. As we shall see later, this self-interaction leads to very interesting feature that the effective coupling between colored particles becomes weaker and weaker (“asymptotic freedom”) when the particles scatter at short distances and confinement of quarks and gluons (“infrared slavery”) when they interact at large distances.

In QED, particles of opposite electric charge such as electrons and nuclei attract each other and can bind into neutral atoms. The atoms themselves can interact via multiple photon exchange or electron interchange to produce more complex systems, i.e., molecules. Similarly in QCD, quarks and antiquarks are attracted to each other and bind into color-neutral mesons $(q\overline{q})$. In addition, baryons, the $(q_R q_G q_B)$ type system, and anti-baryons, the $(\overline{q}_R \overline{q}_B \overline{q}_G)$ type system, also bind strongly into color singlets. In QCD the strong nuclear force which binds protons and neutrons into nuclei is analogous to the residual electromagnetic forces in QED which bind atoms into molecules.

In a more precise description, hadrons have given overall properties and quantum numbers. However the strong interactions can mix components of the wavefunction containing higher particle number; quark pairs and gluons are present in addition to the basic quark content. This reflects the fact that in a relativistic quantum theory, particle number is not an invariant and cannot be fixed. A hadron can be regarded as a fluctuating system of quarks and gluons with variable particle number and size. The simplest hadronic configuration is the state with a minimum number of quarks necessary to form a color singlet with the requisite other quantum numbers. However, the strong interactions will couple such a state to one with an extra gluon present. This gluon in turn can couple to a quark-antiquark pair. Thus a physical hadron eigenstate is a superposition of a complicated hierarchy of states that forms the complete representation of the particle.

QED describes the observed spectrum in atoms and in positronium (bound states of e^+e^-) with extreme accuracy. Likewise, QCD has been quite successful in describing the observed spectrum of bound states of heavy quarks such as charmonium $(c\overline{c})$ and bottomonium $(b\overline{b})$. In addition, "gluonium" states, (gg) and (ggg) composites of gluons, are predicted to be formed, but as yet these states have not been conclusively identified by experiment.

7. The Symmetries of QCD

The underlying mathematical structure of both QCD and QED is dictated by invariance principles. In local field theories, quantum mechanics allows one to consider transformations of the field operators. For example the invariance of a theory under Lorentz transformations leaves the theory invariant despite a change in the observer's reference frame. "Gauge transformations" are transformations that leave the coordinates alone but transform the charged fields by a phase. The requirement of invariance under such general phase transformations leads to a conserved current, the electromagnetic current. Gauge invariance, together with renormalizability, dictates the form of QED. Such gauge principles can be extended to non-Abelian groups, such as the color group $SU(3)_C$ of QCD. Here the demand of invariance dictates the form of the allowed couplings between the quark and gluon fields as well as the gluon self-couplings.

Another essential property of QCD is its approximate "chiral symmetry" which reflects the fact that the *u* and *d* quark are almost massless. It arises from a global transformation involving a pseudoscalar operator which acts on the fermion field. If the fermion is massless, the theory can be made invariant. This invariance, if exact, can be shown to require that the physical theory contain a zero mass pseudoscalar particle. However this symmetry is broken by the nonzero fermion masses, and the predicted zero mass pseudoscalar meson survives as Yukawa's pion, the lightest hadron.

Since the lightest two quarks, *u* and *d*, enter the theory in a symmetric way, QCD predicts that the strong interactions are unchanged if their role is interchanged. This implies for example, the equality of the proton-proton and neutron-neutron scattering amplitudes. Small corrections to "isospin invariance", the $\mathrm{SU}(2)$ symmetry mentioned earlier, arise due to the different electromagnetic charges and masses of the light quarks. In addition to this symmetry, there is a larger approximate SU(3)-flavor symmetry of the strong interactions which reflects the approximate invariance of the theory upon the interchange of any of the three lightest quarks, the *u*, *d*, and *s*. Conversely, the analysis of hadron reactions greatly simplifies if a heavy quark is present since the heavy particle tends to maintain its velocity and spin. This simplification, which is incorporated into "heavy quark effective field theory" is particularly important in the analysis of the weak decays of massive mesons and baryons containing *b* quarks into hadrons containing the charm *c* quarks.

8. Asymptotic Freedom and the Renormalization Group

Renormalization is a procedure of replacing the coupling constants and masses in a field theory by "effective" values that reflect the effect of higher order interactions analogous to electric shielding effects in matter. The amount of correction incorporated into these values depends upon the distance or momentum scale at which the quantities are measured. For example, a measurement at short distances will not be sensitive to the effects of large distance phenomena. The study of the dependence of selected quantities of the theory on the measurement scale is termed the renormalization group. QCD possesses "asymptotic freedom"; that is, the renormalizes coupling vanishes as the distance scale goes to zero. This is the reason that high energy inelastic large momentum transfer electron-proton scattering can be rather accurately viewed as scattering from free quarks. The logarithmic decrease of the coupling constant, as described below, follows from renormalization group arguments.

It is a remarkable feature of QCD that the fundamental coupling of the theory $\alpha_s(r)$, which characterizes the strength of the interactions between quarks at separation r, behaves very differently at different length scales. It decreases logarithmically at short distances, that is $\alpha_s(r) \propto 1/\log r$ as $r \rightarrow 0$. This asymptotic freedom means that the strong interaction actually becomes arbitrarily weak when the quarks are brought sufficiently close together. This implies, through the uncertainty principle, that processes involving the scattering of quarks with large momentum transfer can be computed in perturbation theory with a small effective coupling. As mentioned before, this explains the SLAC deep inelastic electron-proton scattering results. Conversely, at large distances and small momentum transfers, the strength of the effective potential grows almost linearly with r. This growth of the coupling at large r implies confinement of quarks, since infinite energy would be required to liberate a single free quark. In summary, the binding potential between a quark and an antiquark can be computed at small distances, where the coupling is weak, and approximated at large distances by forms consistent with the requirements of confinement. After fitting the free parameters, this potential allows the binding energies and transition matrix elements to be computed reliably for heavy quarkonium bound states, even including the effects of spin-orbit and spin-spin interactions.

9. The Strength of the QCD Coupling

In QED, the electromagnetic coupling is characterized by the dimensionless and essentially universal fine structure constant α which is measured thorough

Coulomb scattering at low momentum transfer, i.e. at long distance, to be of order 1/137. Since the strong coupling constant α_s in QCD depends upon the distance scale at which it is measured, and in addition on the particular process studied, characterizing its value is more complicated; however there is no ambiguity in the predictions of QCD. The conventional procedure is to define it at a large momentum scale where perturbation theory should be reliable, such as at the Z_0 mass where, roughly speaking, its value is around 0.12. The challenge then is to track α_s to smaller mass scales and larger values. The value that controls the attractive potential between heavy quarks in a quarkonium bound state, $(b\bar{b})$ or $(c\bar{c})$, is approximately 0.2.

10. QCD in the Strong Coupling Domain

QCD is inherently a strong coupling theory and perturbation calculations that expand in the coupling are not uniformly valid. For example the large distance or strong coupling behavior of QCD and its phase structure cannot be explored using weak coupling perturbation theory.

10.1. Lattice Gauge Theory:

The strong coupling regime of QCD can be explored by formulating the basic equations of the theory on a spacetime lattice. This procedure not only provides cutoffs for the problem but also reduces it to one with a finite number of degrees of freedom. Lattice gauge theory is a very computer intensive problem and many difficulties remain before a full understanding of hadronic structure can be extracted. However much progress has been made, particularly if fermion pairs are "quenched", that is, if gluons are not allowed to create virtual fermion pairs in intermediate states. Lattice gauge theory has been used to explain the hadron/meson mass ratios and has particularly successful in computing the spectrum and the decays of heavy quark $(c\bar{c})$ and $(b\bar{b})$ states. Lattice gauge theory calculations also suggest that bound states of pure gluonium should exist.

10.2. Light-Cone Quantization:

A promising method for computing the spectrum and bound state wavefunctions of QCD and other relativistic quantum field theories is to diagonalized the QCD Hamiltonian on a basis set of quark and gluon states, in analogy to Heisenberg's method for solving problems in quantum mechanics. For relativistic problems it is useful to use the "light-cone time" $\tau = t - z/c$, rather than ordinary time, since the resulting bound state wavefunctions describe hadrons moving with arbitrary momentum. In principle, the light-cone quantization method will allow the computation of the quark and gluon distributions of the hadrons directly from QCD.

10.3 Factorization Theorems for Exclusive and Inclusive Reactions:

Another approach to avoid some of the strong coupling problems is to judiciously select a kinematic regime and to divide, or to factor, the calculation into parts that can be computed in perturbation theory and to parametrize the parts that cannot. These latter parts can then be checked by comparing with other reactions in which they occur.

Processes in high energy physics are often classified as *exclusive* reactions where are all final state particles are specified, or *inclusive* reactions where a sum is allowed over all possible final states "X" within given experimental constraints. Typical inclusive reactions are deep inelastic electron-proton scattering $ep \rightarrow e'$ X, electron-positron annihilation into hadrons $e^+e^- \rightarrow \mathrm{X}$ and lepton pair production in proton-proton collisions $pp \rightarrow l^+l^-$ X. Typical exclusive reactions are electron proton scattering $ep \rightarrow ep$, Compton scattering $\gamma p \rightarrow \gamma p$, pion photoproduction $\gamma p \rightarrow \pi^+ n$ and pion electroproduction $ep \rightarrow e\pi^+ n$.

Because of asymptotic freedom, inclusive reactions involving a large momentum transfer can be computed from the cross sections for the scattering of quarks and gluons taking into account their momentum distribution in the initial hadrons. Thus one can factorize, or separate, the physics of the bound states in the form of process-independent quark and gluon momentum distributions from the physics of the process-dependent quark-gluon scattering process.

For inclusive reactions in which a final state particle with very a high transverse momentum is produced, the behavior of the cross section reflects the quark/gluon structure of the basic sub-process that produced the high-p_T particle. The form of the single-particle inclusive cross section is predicted by QCD and it depends upon the number of spectator quarks in the reaction and the number in the basic sub-process. Exclusive reactions also satisfy factorization theorems, but they are sensitive to the dynamics of the quark and gluon interactions at the quantum amplitude level, as well as the form of the wave functions describing the composite hadrons in terms of their quark and gluon degrees of freedom. At large momentum transfer, the behavior of an exclusive scattering amplitude reflects the underlying quark structure of the scattering particles and depends on the total number of quarks in the incident and final state hadrons.

11. Experimental Probes of QCD

11.1. Quark and Gluon Jet Production:

One of the simplest and most elegant ways to study the strong interactions is to use electron-positron annihilation into a virtual photon and/or Z^0 boson which in turn materializes into hadronic matter. Since the coupling of photons to all quarks is roughly the same, with sufficient energy all varieties of quarks can be produced at comparable rates. The simplest picture at high energies is that the virtual photon produces a quark and antiquark pair that are back to back in the center of mass system and rapidly separate and "hadronize" into jets.

In high energy (TeV) proton-antiproton collisions, a typical inelastic event can produce several hundred strongly interacting particles. In some of these events, jets are observed at a direction transverse to the initial colliding beams. Such events are described in QCD as due to the scattering or annihilation of the fundamental quark and gluon constituents of the beam particles. The scattered quark or gluon then fragments and hadronize into a cluster or jet of hadrons aligned along its outgoing direction.

Consider a separating pair of quarks or gluons. Each must eventually decay into hadrons and the color separation is cancelled by "color leakage" between them; this is termed a t we-jet process. Three-jet processes can result if one of the quarks emits a gluon with a distinctly different momentum. Each of these fundamental objects then decay into hadrons resulting in three distinct "sprays" of particles emerging from the interaction point. This is the manner in which the existence of the gluon was first confirmed experimentally at the Deutsches Electronen Synchrotron (DESY) in 1980.

By carefully tuning the energy of e^+e^- collisions, bound states composed of a heavy quark-antiquark pair may be produced. These states subsequently decay into light hadrons and/or photons and/or leptons; the properties of the charmed and the bottom quarks were first studied in detail in this manner.

11.2. Heavy Ion Collisions:

Nucleus-Nucleus interactions at high energy allow one to study collective effects that cannot be studied using less complex targets. During a heavy ion collision it may be possible to compress nuclear matter to the point that the nucleons strongly overlap resulting in a "quark-gluon plasma". This plasma should reflect properties of the strong interactions that cannot be explored using simpler probes and is of particular interest in the study of the early universe, the "big bang".

11.3. Color Transparency:

One of the novel features of QCD is that the interaction cross section depends on the fluctuations of the hadron wave functions. It is possible to study certain individual components of the proton wavefunction in high energy collisions where, by virtue of the time dilation property of special relativity, the fluctuations persist over a finite time. The simplest and most basic components of a hadron are produced by large momentum transfer elastic scattering. Since they are spatially small and are color singlets, they will penetrate nuclear matter more easily than the fully "dressed" and larger hadron and exhibit a much longer mean free path. They are not eigenstates, however, and must eventually decay and reappear as ordinary hadronic matter. They will have overlap with the physical hadron as well as its excited states. The resultant increase in mean free path is termed "color transparency". Studies of this effect in reactions such as proton-proton scattering in a nuclear target can provide important information on the hadron wave functions and thus on the strong coupling regime of QCD.

12. Summary

QCD is a theory that has not yet been fully solved, but its qualitative predictions are in full accord with observation. In those limited regimes in which numerical calculations can be reliably performed, it is in quantitative agreement with experiment. It is able to give a logical and unified picture of such puzzles as why quarks act as if they are free in large momentum transfer scattering but are bound so strongly that free quarks cannot exist. The color singlet combinations of the six known quarks predict the quantum numbers, general properties, decays, and interactions of the myriad of hadrons that have been observed.

Acknowledgements

Figures 1 and 2 and the Tables are adapted from the **Chart of the Standard Model of the Fundamental Particles and Interactions,** created by the Contemporary Physics Education Project , Lawrence Berkeley Laboratory.

See also Anti-Matter; Atomic Physics; Baryons; Dispersion Theory, Electromagnetic Interact ions, Elementary Particles; Gauge Theories; Gravitation; Hadrons; Heavy Ion Collisions; High Energy Physics; Isospin; Lattice Gauge Theory; Leptons; Mesons; Nuclear Interact ions; Particle Accelerators; Phase Transit ions; Quantum Electrodynamics; Quantum Chromodynamics; Quantum Mechanics; Quarks; S-Matrix Theory; Standard Model; String Theory; SU(3) and Higher Symmetries; Unified Field Theories; Weak Interactions.

Bibliography

Close, Frank, THE PARTICLE EXPLOSION, by Frank Close, Michael Marten, and Christine Sutton. N. Y., Oxford Univ. Press, 1987. 239p.

Mueller, A. H., PERTURBATIVE QUANTUM CHROMODYNAMICS, ed. A.H. Mueller. World Scientific, 1989. (Directions in High Energy Physics, v. 5) 614p.

Pagels, Heinz R, THE COSMIC CODE: quantum physics as the language of nature, by Heinz R. Pagels. N. Y., Simon and Schuster, 1982. 370p.

Perl, Martin. AN EXPERIMENTER'S LIFE: Martin Perl. By Martin Perl. River Edge, N. J., World Scientific, 1996.

Perkins, Donald H., INTRODUCTION TO HIGH ENERGY PHYSICS. 3rd ed. by Donald H. Perkins. Menlo Park, Calif., Addison-Wesley, 1987. 449p.

Peskin, Michael E., AN INTRODUCTION TO QUANTUM FIELD THEORY, by Michael E. Peskin and Daniel V. Schroeder. Addison-Wesley, 1995. 842p.

QCD: 20 YEARS LATER. Edited by P.M. Zerwas and H.A. Kastrup. World Scientific, 1993. 2v. (C92/06/09)

WWW Sources

Particle Data Group - Home Page: http: //www-pdg.lbl.gov

CERN General Physics Source - Home Page:
http: //www.w3.org/hypertext/DataSources/bySubject/Physics/Overview.html

SLAC Home Page: http: //www.slac.stanford.edu:80/highlighted. html

TABLE CAPTIONS

Table 1. The six flavors of quarks and their properties.

Table 2. Representative mesons and their dominant quark content.

Table 3. Representative baryon and antibaryons and their dominant quark content.

FIGURE CAPTIONS

Figure 1. An artist's conception of the structure of the atom and the atomic nucleus in terms of electrons and quarks. If this picture were drawn to the scale given by the protons and neutrons, then the quarks and electrons would be less than 0.1 mm in size, and the entire atom would be about 10 km across.

Figure 2. An artist's conception of the fundamental processes underlying three basic decay and formation reactions in QCD. (a) Neutron β decay: A neutron decays to a proton, an electron. and an antineutrino via a virtual (mediating) W boson. (b) An electron and positron (anti-electron) colliding at high energy can annihilate to produce D^+ and D^- mesons via a virtual Z boson or a virtual photon. (c) A representative three-body hadronic decay of the η_c meson: $\eta_c \rightarrow \pi^+ K^0 K^-$. The c and $\overline{c}$ quarks in the η_c annihilate into gluons. Quark pair production in the gluon cloud then gives in this case π^+, K^0, and K^- as final products.

Figure 3. Three basic scattering processes of the fundamental constituents which underly the strong interactions. $(\mathrm{a}) e^+ e^- \rightarrow u\overline{u} \rightarrow$ Hadrons, $(\mathrm{b}) ep \rightarrow e' u(ud) \rightarrow e' \mathrm{Hadrons}, (\mathrm{c}) p\overline{p} \rightarrow u(ud)\overline{u}(\overline{u}\overline{d}) \rightarrow$ Hadrons.

Quarks spin = 1/2		
Flavor	Approx. Mass GeV/c^2	Electric Charge
u up	0.005	2/3
d down	0.01	−1/3
c charm	1.5	2/3
s strange	0.2	−1/3
t top	170	2/3
b bottom	4.7	−1/3

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Mesons $q\bar{q}$					
Symbol	Name	Quark Content	Electric Charge	Mass GeV/c^2	Spin
π^+	pion	$u\bar{d}$	+1	0.140	0
K^-	kaon	$s\bar{u}$	–1	0.494	0
ρ^+	rho	$u\bar{d}$	+1	0.770	1
D^+	D^+	$c\bar{d}$	+1	1.869	0
η_c	eta-c	$c\bar{c}$	0	2.979	0

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Baryons qqq and antibaryons $\bar{q}\bar{q}\bar{q}$					
Symbol	Name	Quark Content	Electric Charge	Mass GeV/c^2	Spin
p	proton	uud	1	0.938	1/2
$\bar{p}$	anti-proton	$\bar{u}\bar{u}\bar{d}$	–1	0.938	1/2
n	neutron	udd	0	0.940	1/2
Λ	lambda	uds	0	1.116	1/2
Σ^-	sigma	dds	–1	1.197	1/2
Ω^-	omega	sss	–1	1.672	3/2

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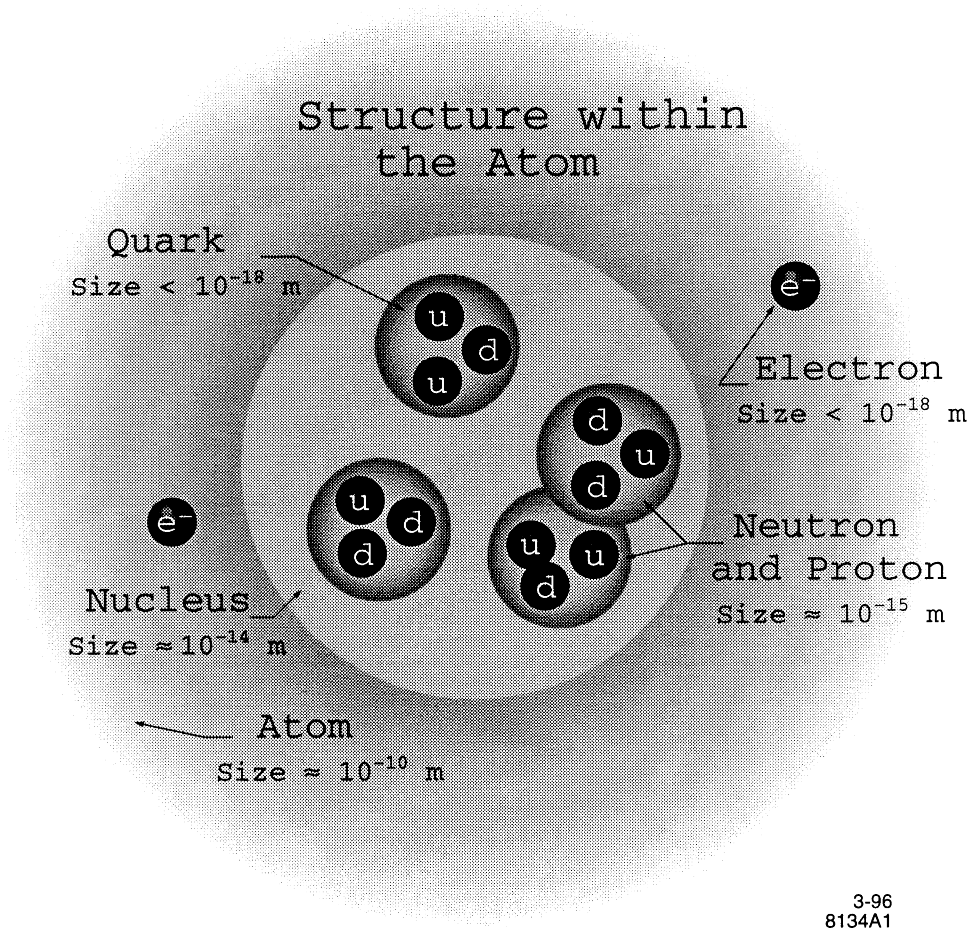
Structure within the Atom
Quark
Size < 10^-18 m
u
d
e⁻
Electron
Size < 10^-18 m
Neutron and Proton
Size ≈ 10^-15 m
Nucleus
Size ≈ 10^-14 m
Atom
Size ≈ 10^-10 m
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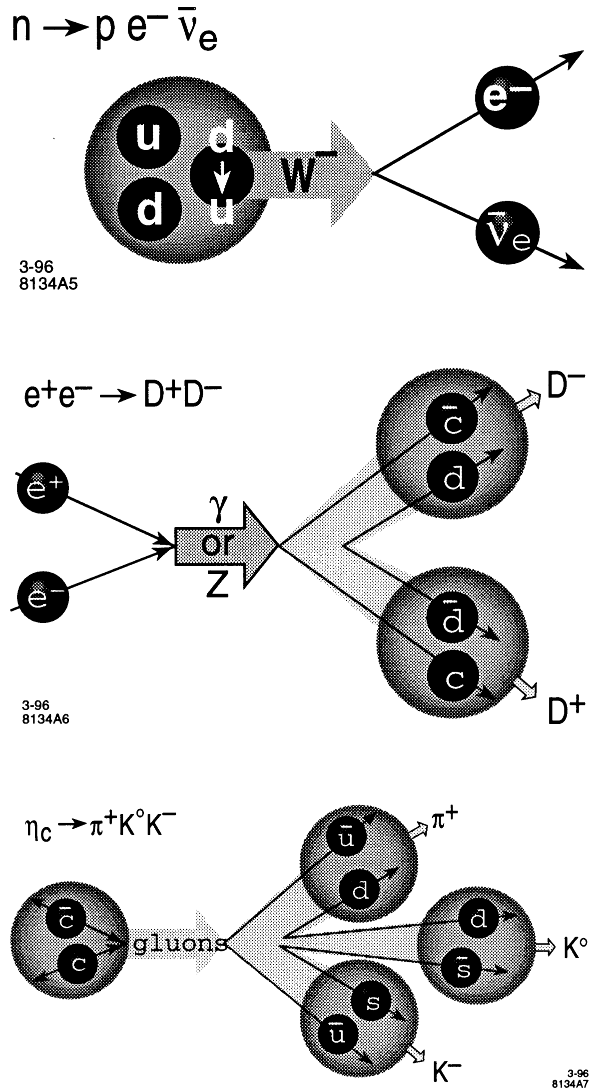
Figure 1


$n \rightarrow p\, e^- \bar{\nu}_e$
u
d
d
u
W^-
e^-
$\bar{\nu}_e$
3-96
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$e^+e^- \rightarrow D^+D^-$
e^+
e^-
γ
or
Z
$\bar{c}$
d
$\bar{d}$
c
D^-
D^+
3-96
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$\eta_c \rightarrow \pi^+ K^\circ K^-$
$\bar{c}$
c
gluons
$\bar{u}$
d
π^+
d
$\bar{s}$
K°
s
$\bar{u}$
K^-
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Figure 2

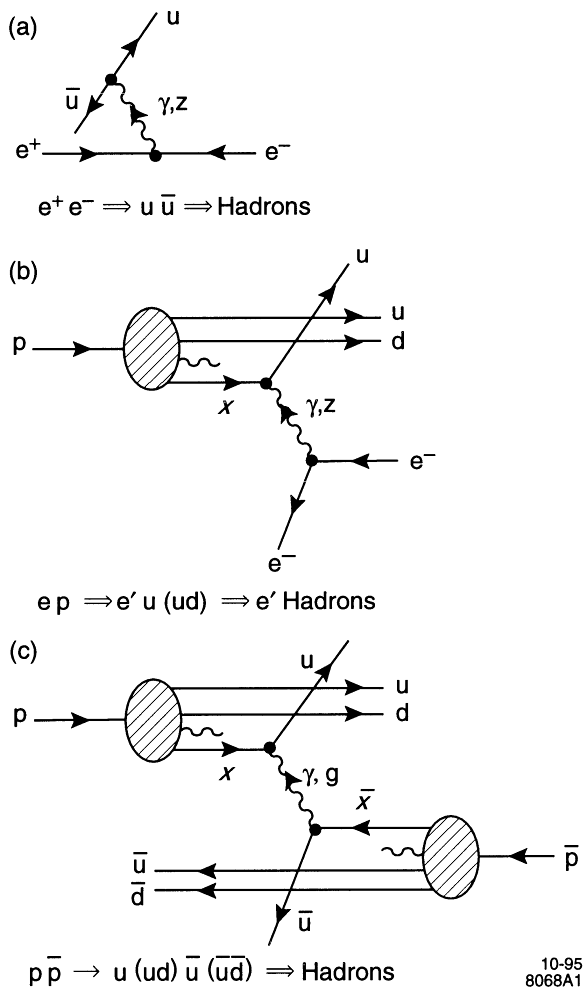
(a)
u
ū
γ,z
e+
e−
e+ e− ⟹ u ū ⟹ Hadrons
(b)
u
p
u
d
x
γ,z
e−
e−
e p ⟹ e′ u (ud) ⟹ e′ Hadrons
(c)
u
p
u
d
x
γ, g
x̄
p̄
ū
d̄
ū
p p̄ → u (ud) ū (ūd̄) ⟹ Hadrons
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Figure 3