KUNGL. VETENSKAPSAKADEMIEN
THE ROYAL SWEDISH ACADEMY OF SCIENCES

Asymptotic Freedom and Quantum ChromoDynamics: the Key to the Understanding of the Strong Nuclear Forces

The Basic Forces in Nature

We know of two fundamental forces on the macroscopic scale that we experience in daily life: the gravitational force that binds our solar system together and keeps us on earth, and the electromagnetic force between electrically charged objects. Both are mediated over a distance and the force is proportional to the inverse square of the distance between the objects. Isaac Newton described the gravitational force in his Principia in 1687, and in 1915 Albert Einstein (Nobel Prize, 1921 for the photoelectric effect) presented his General Theory of Relativity for the gravitational force, which generalized Newton's theory. Einstein's theory is perhaps the greatest achievement in the history of science and the most celebrated one. The laws for the electromagnetic force were formulated by James Clark Maxwell in 1873, also a great leap forward in human endeavour. With the advent of quantum mechanics in the first decades of the 20th century it was realized that the electromagnetic field, including light, is quantized and can be seen as a stream of particles, photons. In this picture, the electromagnetic force can be thought of as a bombardment of photons, as when one object is thrown to another to transmit a force. In a similar way the gravitational force is believed to be transmitted by particles called gravitons, but since the gravitational force is some 10^{40} times weaker than the electromagnetic force, they have not yet been detected.

The electromagnetic force holds the atom together since the nucleus and the electrons carry electric charges. The composition of the nucleus was, however, not understood in the early days of the quantum era, but there was a common belief that it consisted of protons and electrons. In 1932 James Chadwick (Nobel Prize, 1935) discovered electrically neutral radiation from the nucleus and could establish that it consisted of a new type of elementary particle called the neutron. Two years later, Eugene Wigner (Nobel Prize, 1963) showed that there must be two distinct nuclear forces at play within the nucleus, a weak force that is responsible for the radioactivity and a strong one that binds the protons and the neutrons together. Both of them act only over a very short range, of the size of the nucleus, hence they have no macroscopic analogue. Only a year after Wigner's work, the young Japanese student Hideki Yukawa (Nobel Prize, 1949) proposed that the strong nuclear force is mediated by a new particle in analogy with the electromagnetic force. However, the electromagnetic force has a long range while the strong force has a short range. Yukawa realized that, while the electromagnetic force is mediated by massless particles, photons, the strong interactions must be mediated by massive particles. The mass then gives a natural scale for the range of the force. (In quantum physics length is conjugated to mass or energy, in the sense that the fundamental parameters, Planck's constant η and the velocity of light c, can be used to convert a mass to a length scale.) Knowing the approximate range of the strong force, 10^{-15} m,

Yukawa estimated the mass of the particle, which was to be named the pion, as 100–200 MeV/c^2. Only one year after Yukawa´s work a particle in that mass range was discovered in cosmic rays by Carl Anderson (Nobel Prize, 1936), but later it was understood that this particle had too weak an interaction to be the pion. Instead, it was a heavy version of the electron, the muon. The pion was not discovered until after the Second World War, in 1947, by Cecil Powell (Nobel Prize, 1950).

Quantum Electrodynamics

During the Second World War and the years thereafter, Quantum Electrodynamics (QED) was developed. The key physicists here were Richard Feynman, Julian Schwinger, Sin-itiro Tomonaga (Nobel Prize, 1965) and Freeman Dyson. They showed that a (seemingly) consistent quantum theory could be formulated for the electromagnetic force. In particular they showed that a systematic perturbation expansion could be defined. This means that the amplitude for scattering between electrically charged particles can be written as an expansion in powers of the fine structure constant, α_{em}, which is a measure of the strength of the electric force. When computing these terms, most of them are found to be infinite. There is, however, a unique way to absorb all the infinities. This is done by interpreting them as contributions to the electron mass, its charge and to the norm of its wave function. By letting these parameters be free, it is possible to define finite values to each order in the expansion that can be compared with the experiments. The parameters are said to be renormalized. A quantum field theory in which only a finite number of parameters need be renormalized to define a finite perturbation expansion is called a renormalizable theory. Richard Feynman introduced a very useful diagrammatical formulation that was to be used routinely in all perturbative calculations, the Feynman diagrams. To each particle he introduced a propagator describing the free propagation of the particle. The specific theory then defines the interaction vertices, which are combined with propagators to build a specific diagram. In QED there are two propagators,
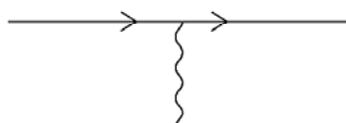
one for the electron
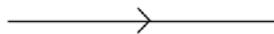
and one for the photon

There is one type of vertex.

Feynman also introduced the rule that a particle going backwards in time corresponds to an antiparticle going forward in time (hence the arrow on the electron line). The theory also describes the scattering of positrons.

For every propagator and vertex there is an analytic expression and there are definite rules for constructing a diagram. The momenta are conserved in a vertex and if there is a loop in a diagram the momentum has to be integrated. This is the root of divergences. With these rules it is possible to construct an infinite series of ever more complicated diagrams for a scattering amplitude. Consider the scattering of one electron off another electron. This is given by the following diagram:

These divergences had been known since the early 1930s . It was argued at the time that they were effects from other interactions and that they would disappear when all interactions were taken into account. It was a scientific sensation when it was shown that QED by itself could handle the divergences. The perturbation calculations were also shown to give extremely exact results. One helpful factor is the smallness of the expansion parameter, α, the so-called fine structure constant. The Lamb shift in hydrogen could, for, example be computed to a very high degree of accuracy to find precise agreement with the experiment (Willis Lamb, Nobel Prize, 1955).

Relativistic quantum electrodynamics is described by a four-vector potential field in which the time component has a negative norm relative to the space components. In 1929 Hermann Weyl constructed a *gauge invariant* formulation of the theory by introducing a local symmetry into the theory. This symmetry is the local change of the phase of the electron wave function, which cannot be gauged (measured). It is called abelian since this symmetry group is commutative, abelian. The symmetry leads to redundancy of the time and the longitudinal components of the electromagnetic field, and the physical degrees of freedom are carried only by the transverse components. The key to proving the renormalizability of QED was then to prove that the gauge invariance is still preserved by all the renormalized quantum corrections. John Ward introduced the so-called Ward identities that have to be satisfied for this to be true. This in turn provided a compact way of proving renormalizability. Both gauge invariance and the Ward identities were to be key ingredients when the non-abelian gauge theories were shown to be renormalizable some twenty-five years later.

The Yukawa Theory

Since QED had paved the way for describing relativistic many-body theories, it was natural to attempt a similar approach for the Yukawa theory. In this case, the symmetry, isospin symmetry, is global, i.e. the symmetry transformations are the same for all space-time points,

and there is no need for Ward identities. Again propagators can be introduced for the nucleons, the protons and the neutrons, and for the pions that were known to exist with the electric charge –1, 0 or 1. A natural three-point coupling was also at hand. The Feynman rules:
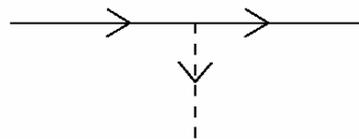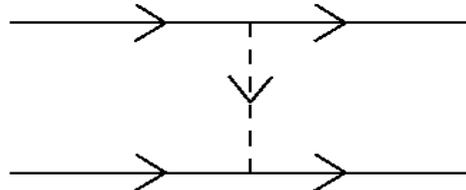
nucleon propagator
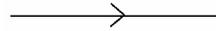
pion propagator
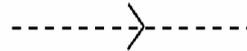
three-point vertex

the simple scattering term

describe the rough behaviour of the strong force, being the first term in a series expansion. This theory can also be shown to be renormalizable. However, when compared with the experimental results, it was found that the effective coupling strength is larger than 1 (about 14). Such a perturbation theory is meaningless, since every new order is larger than the previous one. The number of diagrams also increases rapidly with every higher order. This means that no mathematical results on asymptotic series can be used.

The Proliferation of Elementary Particles

The failure of the Yukawa field theory to describe the strong nuclear forces satisfactorily led the physics community to doubt the relevance of relativistic quantum field theories. Perhaps the success of QED was an accident; in order to describe the other forces some alternative formalism would perhaps be needed. Many such attempts were made in the following years.

However, the great experimental developments of the 1950s also showed that a theory involving only nucleons and pions must be incomplete. When the new particle accelerators at

CERN in Geneva and Brookhaven in the USA were brought into operation in 1959–60, many new strongly interacting particles were discovered. Most of them were extremely short-lived with a lifetime of 10^{-23} s. Some of them, like the pions, had a lifetime of typically 10^{-6} to 10^{-10} s. The latter ones decay by the weak nuclear force, while the short-lived ones decay by the strong force. This development showed that, in order to understand the basic laws of Nature, the basic building blocks of Nature must also be known. The physicist to bring order to this plethora of particles was Murray Gell-Mann (Nobel Prize, 1969). Gell-Mann was a dominant figure in theoretical elementary particle physics from the mid-1950s to the 1970s. He realized that in order to find a systematic description of all these particles, they must be classified by new quantum numbers. There must be other symmetries in Nature that are not directly related to space and time. In 1959 he introduced the symmetry group SU(3) to classify the particles stable under the influence of the strong force. Yuval Ne'eman also put this idea forward. The short-lived particles were also found to follow this symmetry pattern and during the 1960s it was found empirically that the spin quantum number grows linearly with the squared mass, leading to so-called Regge trajectories, i.e. diagrams showing the spin as a function of the squared mass. (The string theory came as a possible model for the scattering among these particles.) This indicated that the short-lived particles are higher excitations of the more stable ones, and in 1964 Gell-Mann and George Zweig introduced the quark concept. With the help of three quarks and their antiparticles it was possible to build up all the particles known at that time. It would have been natural to consider a quantum field theory for quarks, but field theories were quite discredited, as we have seen, and other ways were investigated to understand the physics of quarks. Gell-Mann used a free quantum field theory for quarks to extract the conserved currents of the new charges to study their commutation relations. He then postulated that the physical currents satisfy the same relations. These current algebras were studied intensively during the late 1960s and were instrumental in the developments of the theories for both the weak and the strong interactions.

Non-Abelian Gauge Theory

In 1954 Chen-Ning Yang (Nobel Prize, 1957) and Robert Mills constructed a non-abelian gauge field theory based on the isospin group SU(2) in an attempt to describe a quantum field theory for the nucleons. The Swedish physicist Oskar Klein had discussed similar ideas in 1938, but the outbreak of the war and the emphasis on other problems meant that this idea faded away. The Yang-Mills theory was criticized, especially by Wolfgang Pauli (Nobel Prize, 1945), since the theory contained a massless vector particle mediating the force. No such particle was known and, as noted above, such a particle would mediate a force with a long range instead of the short-range force of the strong interactions. The idea did not catch on. Instead, the great development around this time was the discovery by Yang and Tsung Dao Lee (Nobel Prize, 1957) that parity is broken in the weak interactions. Shortly thereafter, an effective quantum field theory (the V-A theory) was formulated for the weak interactions by Robert Marshak and George Sudarshan, and by Feynman and Gell-Mann, extending earlier ideas of Enrico Fermi (Nobel Prize, 1938). This theory was non-renormalizable so the quantum corrections could not be trusted, but since the coupling strength of the weak force is very small the first term is often good enough. This was clearly an embryo of a correct theory. Both Schwinger and Gell-Mann proposed that the underlying theory should be a non-abelian gauge field theory, but it was commonly believed that such theories were not renormalizable. Furthermore the weak interactions were also known to have a short range, while non-abelian theories lead to long-range forces. This idea was a tempting one, however, and it survived, but it was pursued only by a small number of physicists.

Spontanteous Symmetry Breaking

Another remarkable development came around 1960 when Yôichirô Nambu extended ideas from superconductivity to particle physics. He had previously shown that the BCS ground state (Nobel Prize to John Bardeen, Leon Cooper and Robert Schrieffer, 1972) has a spontaneously broken gauge symmetry. This means that, while the underlying Hamiltonian is invariant with respect to the choice of electromagnetic gauge, the BCS ground state is not. This fact cast some doubts on the validity of the original explanation of the Meissner effect within the BCS theory, which, though well motivated on physical grounds, was not gauge invariant. Nambu finally put these doubts to rest after earlier contributions by Philip Anderson (Nobel Prize, 1977) and others had fallen short of providing a fully rigorous theory. In the language of particle physics the breaking of a local gauge symmetry, when a normal metal becomes superconducting, gives rise to a finite mass for the photon field inside the superconductor. The conjugate length scale is nothing but the London penetration depth. This example from superconductivity showed that a gauge theory can give rise to small length scales if the local symmetry is spontaneously broken and hence to short range forces. In his paper of 1960 Nambu studied a quantum field theory for hypothetical fermions with chiral symmetry. This symmetry is global and not of the gauge type. He assumes that it is spontaneously broken, and he can then show that there is a bound state of the fermions, which he interprets as the pion. This result follows from general principles without detailing the interactions. If the symmetry is exact, the pion must be massless. By giving the fermions a small mass the symmetry is slightly violated and the pion is given a small mass. Note that this development came four years before the quark hypothesis. Nambu could even work out results for some scattering amplitudes for reactions emitting pions that agreed with experiments. In 1965 he proposed with Moo-Young Han that the field theory should be a non-abelian gauge theory, although they gave the fermions integer charges (in terms of the electron charge). In Gell-Mann's scheme the quarks have charges that are multiples of one-third charges. As we shall see, Nambu's field theory had all the relevant details of the correct theory , but it was perhaps too early and the focus was on other problems at the time.

Nambu's understanding of spontaneously broken gauge symmetry was incorporated in relativistic gauge field theories in 1964 by Robert Brout and François Englert and also by Peter Higgs. They showed that a spontaneously broken gauge field theory has vector particles with a mass, while gauge symmetry is still obeyed. At this stage all the relevant ingredients for a quantum field theory for the weak interactions with short range interaction were in place, but the common belief was that such a theory was non-renormalizable.

Scaling and Asymptotic Freedom

As mentioned above, the late 1960s were dominated by studies of current algebras. A new set of experiments was started in 1967 at SLAC, the linear accelerator at Stanford in the USA, where electrons were scattered off protons in deeply inelastic scattering processes. In 1968, Curtis Callan and David Gross related an asymptotic integral of the cross section to a certain commutator involving the electromagnetic current and obtained a sum rule that could be tested. This result was generalized by James Bjorken, who studied the case when the momentum approaches infinity. By performing the calculations in an unphysical region where the momentum transfer is imaginary, he proved that the cross section does not depend separately on $\nu=E-E'$ (the energy loss) and q^2 (the squared momentum transfer), which is the normal case, but only on the dimensionless variable $x = q^2/2M\nu$. He then argued that the same should be true for physical momentum transfers in the asymptotic limit. This phenomenon is

called 'scaling' and it was found to agree with the SLAC experiments (Nobel Prize to Jerome Friedman, Henry Kendall and Richard Taylor 1990).

Bjorken's paper contained far-reaching assumptions, but the fact that they led to the experimentally verified scaling had a great impact on the physics community. The idea now was to understand how a physical theory could include scaling, and in 1970 Kurt Symanzik (d. 1983) argued that only a theory with a negative so-called β-function can imply scaling; the term "asymptotic freedom" was coined for this kind of theory. As early as the beginning of the 1950s Gell-Mann and Francis Low as well as André Petermann and Ernst Stückelberg had shown that the effective coupling in quantum electrodynamics is scale dependent. (The value of $\alpha \approx 1/137$ is only valid for small momentum transfers.) This phenomenon is due to the renormalization scheme. It is true in any renormalizable quantum field theory, and scaling behaviour is governed by the β-function, which can be computed in perturbation theory. By interpreting the renormalization scheme in a new way, Kenneth Wilson (Nobel Prize, 1982) showed in the late 1960s , that the asymptotic behaviour of the coupling strength is uniquely governed by the β-function.

In the case of QED the β-function is positive, which means that the effective coupling increases with energy. Similarly it means that the effective charge diminishes the further away we measure it We can understand this intuitively in terms of screening. Virtual pairs of electrons and positrons screen the charge. This also agrees with our intuition. A negative β-function is difficult to comprehend, since it corresponds to antiscreening. The force increases the further away we move from the charge and diminishes as it approaches the charge. It is as if an invisible rubber band connected the particles. The forces we know macroscopically, like the electromagnetic force and the gravitational force, do in fact get weaker the further away they are from a charge (mass). Asymptotic freedom seemed to be completely inconsistent with quantum field theory and such theories had very low credence. Was the idea of a quantum field slowly dying? This was the situation in 1971 when Gerhard 't Hooft (Nobel Prize with Martinus Veltman, 1999) published his proof that a non-abelian gauge field theory is renormalizable even in the spontaneously broken phase. Over the next year or so 't Hooft and Veltman cleared up all the details needed to complete the proof, and the result was one of the great sensations in modern physics. It was very quickly realized that such models had been proposed previously for the weak interactions and it now became clear that these models were theoretically consistent. This led to the Glashow-Salam-Weinberg model, which during the 1970s was proven to agree with the experiments. (Nobel Prize to Sheldon Glashow, Abdus Salam and Steven Weinberg, 1979).

The Glashow-Salam-Weinberg Model not only showed that the weak interaction is also described by a quantum field theory. It also indicated a common origin for the weak interaction and the electromagnetic interaction . But what about the strong interaction?

A Quantum Field Theory for the Strong Interactions

Symanzik himself discovered a quantum field theory with a negative β-function, namely one with a scalar field with a four-point interaction with a negative coupling strength. However, a theory of this kind is not well-defined, since it does not have a stable particle spectrum. This made the idea of a realistic quantum field theory with a negative β-function even more unlikely. Many a leading theorist expressed scepticism about the possibility of a quantum field theory for the strong interactions. In the summer of 1972 at a conference in Marseille, Symanzik called attention to the need for a negative β-function and urged 't Hooft to report

on a calculation he had performed for a non-abelian gauge theory. Gerardus 't Hooft wrote the correct negative result on the board, but neither he nor Symanzik pursued it further. Consequently, the result was not spread and remained unknown to the rest of the physics community. In the USA many of the leading universities, notably Princeton, with David Gross´s group and Harvard with Sidney Coleman´s group, set up programmes to investigate all possible quantum field theories to find out if any of them could be asymptotically free. At Princeton, Gross and his collaborator, the graduate student Frank Wilczek, investigated non-abelian quantum field theories. At Harvard, the graduate student David Politzer carried out the same investigation. This calculation, nowadays standard and included in textbooks, was then quite demanding, so it took some time for the surprising result to appear. In the spring of 1973 Gross, Wilczek and Politzer reported in two consecutive papers in Physical Review Letters the coinciding result, a negative β-function. Both groups realized the significant consequences of this result, which took the physics community by storm. Gross and Wilczek and others followed up directly with a proposal for a quantum field theory for the strong interactions, a non-abelian gauge field theory based on the gauge group SU(3) for quarks with massless vector particles mediating the force. These particles were to be named 'gluons'. A similar theory had been proposed a year earlier by Harald Fritzsch and Gell-Mann in an attempt to catalogue all possible models and it was essentially the same model that Nambu had proposed many years earlier. Asymptotic freedom selected it as the unique possibility. The gauge group SU(3) introduced a 'colour' charge for every particle. A charge of this kind had already been proposed in the mid-1960's by Han and Nambu and in a similar way by Oscar Greenberg in order to solve a problem concerning statistics in the quark model.

A quantum field theory for the strong interactions had finally been established and it was named Quantum ChromoDynamics (QCD). While the problem of getting a short range interaction is solved in the electro-weak theory by spontaneous symmetry breaking of the gauge symmetry, the solution for the strong interactions is much more intricate. QCD is built not from the strongly interacting particles seen in experiments but by more fundamental particles which, through spontaneous symmetry breaking of global symmetries and asymptotic freedom, form bound states which have short range interactions.

A More Detailed Study of Asymptotic Properties of Quantum Field Theories

The remarkable result of the studies of Gell-Mann, Low, Petermann and Stückelberg concerning the renormalization properties of QED is that the asymptotic form of the photon propagator is governed by zeros in a function of the coupling constant (the charge), which is computable in a perturbation series. The underlying idea is the following: A renormalizable function contains two types of parameters, those with a positive dimension in terms of mass and those that are dimensionless. When considering a Green's function for large space-like momenta (where there are no singularities) the parameters with positive dimension can be neglected. Hence the computation can be performed as in a massless theory. In such a theory there is no scale. The idea is then that a simple dimensional analysis will decide the form of the amplitudes. This is called naïve or canonical scaling. However, it does not hold in reality, since the theories contain a hidden mass scale. When renormalizing a theory a mass scale, μ, must be introduced at which the renormalization terms are subtracted. This is performed away from the mass-shell to avoid singularities due to the masslessness of the photon. The theory cannot depend on this scale and this leads to a differential equation for the renormalized Green's functions. (These are proportional to the unrenormalized ones, which do not depend on μ; hence they satisfy the differential equation that the derivative with respect to μ acting on it is zero.) A change in the subtraction point is compensated by a corresponding change in

the charge and the scale of the momenta. In this way Green's functions for one set of momenta and charges can be related to Green's functions at other values of those parameters. In particular the asymptotic behaviour at high momenta can be related to amplitudes for some fixed values of the momenta. The ultraviolet behaviour of amplitudes can then be estimated by computing the asymptotic value for the coupling constant. This can be computed by finding the zeros of a certain function, the β-function. This function is simply

$$\beta = \mu \partial g / \partial \mu,$$

where g is the coupling constant and all other parameters are kept fixed. By scaling all momenta in a Green´s function uniformly $p \to \lambda p$ and writing $t = \ln \lambda$, the effective coupling constant g_e satisfies the equation

$$dg_e(t,g)/dt = \beta(g_e), \quad g_e(0,g) = g.$$

Suppose there exists a solution

$$\lim_{t \to \infty} g_e(t,g) = g_\infty.$$

We then say that g_∞ is an ultraviolet fixed point. Such points are determined by the zeros of $\beta(g)$. Thus if $\beta(g)$ has a simple zero at g_∞ this will be ultraviolet stable if

$$\beta(g_\infty) = 0, \quad d\beta(g_\infty)/dg < 0.$$

A zero of β at g_0 at which $d\beta(g_0)/dg > 0$ is said to be an infrared stable fixed point since g approaches such a point when $t \to -\infty$ ($\lambda \to 0$). A coupling of this kind grows with higher momenta. This is the case for QED and Lev Landau (Nobel Prize, 1962), Alexei Abrikosov (Nobel Prize, 2003) and Isaac Khalatnikov discovered as early as 1954 that the perturbation theory is meaningless when the momenta reach values of the order $e^2 \ln(p^2/m^2) \approx 1$. This means that QED is not really a consistent theory by itself.

As mentioned above, a gauge theory has a redundancy since four field degrees of freedom are used to describe two physical transverse degrees of freedom. Local gauge symmetry allows this formulation since in order to compute a physical quantity we must constrain the field, i.e. specify a gauge. Gross, Wilczek and Politzer chose to perform the calculation in the so-called Landau gauge, where the vector field A^μ must satisfy the constraint $\partial_\mu A^\mu = 0$. In order to compute the β-function, the first quantum corrections to the wave function renormalization and to the three-point coupling must be calculated. This can be done with the techniques developed by 't Hooft and Veltman. With the Feynman rules

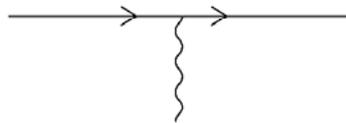Gluon propagator

Quark propagator
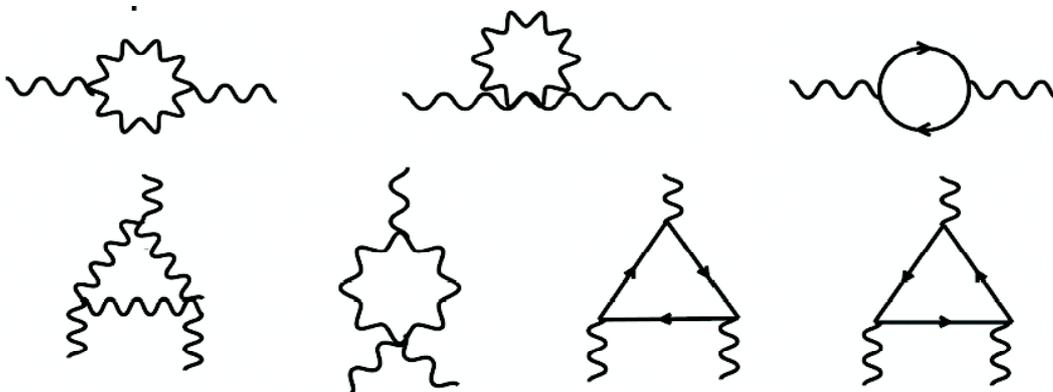
Three-point gluon coupling

Four-point gluon coupling

Gluon-quark coupling

the relevant diagrams to be calculated are:

There are also similar diagrams with a so-called "ghost" in the loops; this "ghost" is there as a consequence of the gauge invariance. The final result is

$$\beta(g) = -g^3/16\pi^2 \left[11/3\ C_2 - 4/3\ T(R)\right] + O(g^5),$$

where C_2 is the value of the quadratic Casimir operator for the gauge group in the adjoint representation, the one of the vector field, and $T(R)$ the corresponding Casimir operator for the quark representation, the fundamental one. The function $\beta(g)$ is negative as long as the latter one, which depends on the number of quarks, is not too big. In the case of the colour gauge group SU(3) it is negative as required and asymptotic freedom is proven.

Experimental Support for Asymptotic Freedom and QCD

The instant success of QED was ensured by the fact that the theoretical results could be compared with experiments and that the agreement was extremely precise. Over the years the comparisons have been further improved and for certain physical quantities the agreement is now $1:10^9$. A limit has now been reached where other interactions through higher order quantum corrections must be taken into account.

The weak part of the electro-weak theory was slightly harder to test precisely. It agreed with the old effective theory to the first order and the real tests were the new particles and phenomena that it predicted. Neutral currents were readily discovered at CERN in 1973, but it took another ten years to discover the heavy intermediary vector particles, the Z- and W-bosons, at CERN (Nobel Prize to Carlo Rubbia and Simon van der Meer, 1984). A key discovery before that was the parity breaking in atomic physics that the model predicted. This model is now very well tested and agrees with all experiments.

QCD was even more difficult to test precisely. The main reason is that the basic particles of the model, the quarks and the gluons, do not exist as free particles and cannot therefore be accelerated in a particle accelerator or be detected directly in a particle collision. Even so, the experimental verification over the years, especially at CERN's LEP accelerator is very impressive. Both Gross and Wilczek, and Politzer very quickly checked that the gross behaviour of the SLAC experiments followed from the model. The colour concept also got early support from hadron production and muon-pair production in the electron-positron collisions at the ADONE accelerator outside Rome in the early 1970s. The results were consistent with the factor 2 that three colours give rise to, in contrast to the 2/3 in the absence of colour. In the late 1970s, at PETRA in Hamburg, events with three jets were observed for the first time that could be interpreted as one gluon and two quarks that subsequently decay into hadrons.

Asymptotic freedom means that the effective coupling constant decreases with energy: by now this is very well established in the experimental results. In the figures below the effective coupling constant, called α_s, is shown as a function of energy
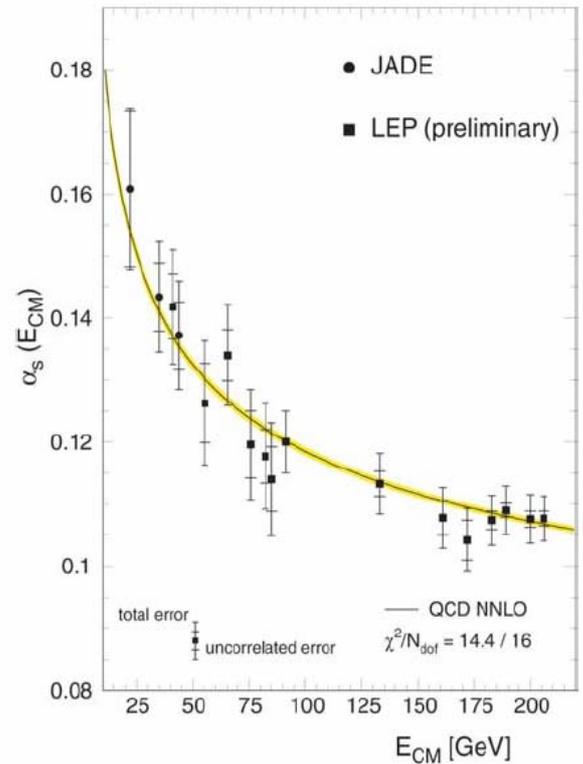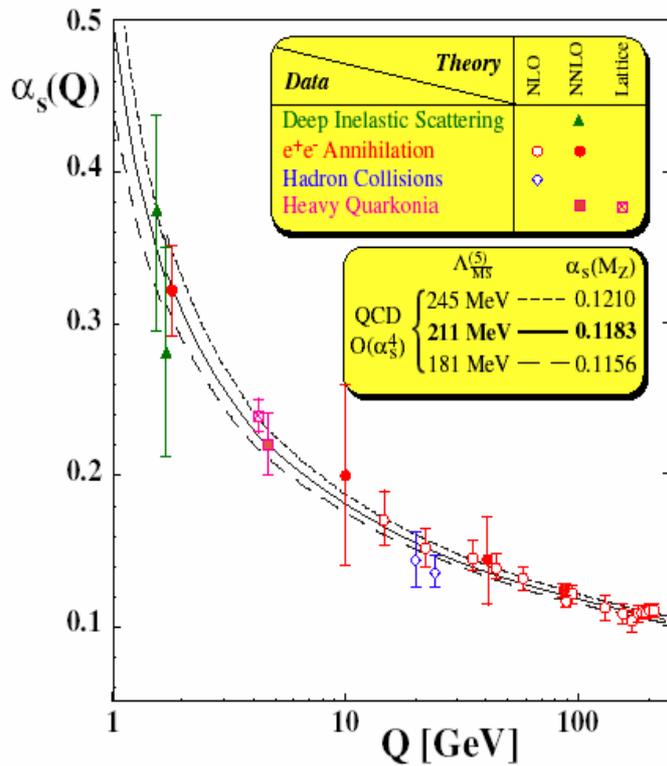
The left-hand panel shows a collection of different measurements by S. Bethke from High-Energy International Conference in Quantum Chromodynamics, Montpellier 2002 (hep-ex/0211012). The right-hand panel shows a collection by P. Zerwas, Eur. Phys. J. C34(2004)41. JADE was one of the experiments at PETRA at DESY. NNLO means Next-to-Next-to-Leading Order computation in QCD.

Although there are limits to the kind of calculations that can be performed to compare QCD with experiments, there is still overwhelming evidence that it is the correct theory. Very ingenious ways have been devised to test it and the data obtained, above all at the CERN LEP accelerator, are bounteous. Wherever it can be checked, the agreement is better than 1%, often much better, and the discrepancy is wholly due to the incomplete way in which the calculations can be made.

The Standard Model for Particle Physics

QCD complemented the electro-weak theory in a natural way. This theory already contained the quarks and it was natural to put all three interactions together into one model, a non-abelian gauge field theory with the gauge group SU(3) x SU(2) x U(1). This model has been called 'The Standard Model for Particle Physics'. The theory explained the SLAC experiments and also contained a possible explanation why quarks could not be seen as free particles (quark confinement). The force between quarks grows with distance because of 'infrared slavery', and it is easy to believe that they are permanently bound together. There are many indications in the theory that this is indeed the case, but no definite mathematical proof has so far been advanced.

The Standard Model is also the natural starting point for more general theories that unify the three different interactions into a model with one gauge group. Through spontaneous symmetry breaking of some of the symmetries, the Standard Model can then emerge. Such

theories are called Grand Unified Theories. Results from the LEP accelerator at CERN show that the three coupling constants, which have quite different values at lower energies, also have different energy dependence and coincide around 10^{16} GeV if the present curves are extrapolated. To perform this extrapolation, a new extended spacetime symmetry, supersymmetry, must be introduced. The fact that the three interactions seem to unify also raises the question of what happens to the gravitational force. Can it be unified with the other three? Gravity is such a weak force that it can be neglected at present accelerator energies. However, at energies of the order of 10^{19} GeV its strength is of the same order as the other three and cannot be neglected. There is a candidate for a truly unified theory, the 'Superstring Theory'. This theory states that the basic building blocks are one-dimensional objects, strings, which are so small that their extension is not revealed at the energies at which we measure today. The Superstring Theory contains supersymmetry as one of its basic symmetries and includes the Standard Model as well as the gravity theory. There is, however, no experimental evidence for this theory yet. Nevertheless, the framework is quite unique and there is a strong belief in the physics community that it could be the right way to find the unique theory that unifies all the interactions. Only the future can tell if this is true.

Shortly after the proof of the renormalizability of the non-abelian gauge field theories was announced, a flaw in the arguments was discovered. In certain cases there are quantum corrections that violate the gauge invariance. Such a theory is inconsistent. It is said to have an 'anomaly'. The only way to get rid of an anomaly is to show that the coefficient in front of it is zero. This is true if the theory contains full families of particles. In practice, this means that the theory cannot survive if it does not have both a u- quark and a d-quark, as well as a b-quark and a t-quark. The discovery of the t-quark completed the third family of the Standard Model, hence the model is free of anomalies. In this way the discovery of anomalies further constrained the model, making it more unique.

Finally, much work with the non-abelian gauge field theories has made it utterly plausible that they are the only consistent quantum theories in four spacetime dimensions. It is necessary for such a theory to be asymptotically free if it is to be consistent. Hence QED cannot be a consistent theory by itself, as we have already indicated. It must be combined with a non-abelian theory. A combined theory solves the problem raised by Landau, Abrikosov and Khalatnikov. The work of Gross, Politzer and Wilczek was the key not only to the correct theory for the strong interactions. It also gave us the means to understand non-abelian gauge field theories as the uniquely consistent four-dimensional relativitistic quantum theories. These three scientists made the seminal discovery that started the exciting development of QCD that we have subsequently seen. Together with the conclusions of the experiments at the LEP accelerator and all the theoretical developments, it allows us today to conclude that the enigma of the strong interactions is solved. The Standard Model is, in fact, a final solution to the attempt started by Paul Dirac (Nobel Prize, 1933) to construct relativistically invariant quantum mechanics.

Further reading

The original papers:

- D. J. Gross and F. Wilczek, "Ultraviolet Behavior of Non-Abelian Gauge Theories", Phys. Rev. Letters **30** 1343 (1973),
- H. D. Politzer, "Reliable Perturbative Results for Strong Interactions", Phys. Rev. Letters **30** 1346 (1973).

- D. J. Gross and F. Wilczek, "Asymptotically Free Gauge Theories. I", Phys. Rev. **D8** 3633 (1973).
- H. D. Politzer, "Asymptotic Freedom: An Approach to Strong Interactions", Phys. Rep. **14** 129 (1974).

Book:
- "The rise of the Standard Model of Particle Physics in the 1960s and 1970s, eds. L. Hoddeson, L. Brown, M. Riordan and M. Dresden, Cambridge Univ. Press (1997).

Link:
- http://nobelprize.org/physics/articles/brink/index.html