What is the World Made of?

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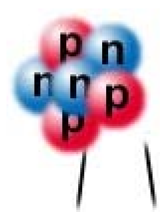
I. INTRODUCTION

Even in ancient times people asked the same question? Greeks (Empedocles, Aristotle) thought that the basic building components of the physical world were earth, air, fire and water. Chinese (in Pinyin, Wu Xing) believed that these were earth, wood, metal, fire and water. Indians (Samkhya-Karikas by Ishvarakrsna c. 3rd century AD) visualized the world as made of five elements**:** space, air, fire, water and earth. Today we know that the word is made of atoms and space.

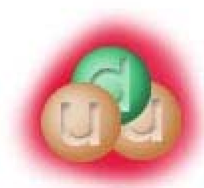
But this lecture is about the fundamental building blocks of the world. By fundamental we mean a structure less entity – not made of anything smaller. The Greek word "atomon"

ατομον

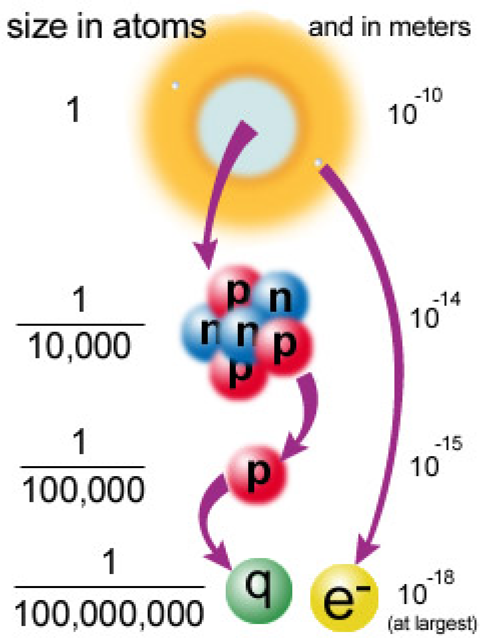
although means "that which cannot be divided", but around 1900 people began to realize the atom, as a permeable ball with bits of electric charge bouncing around inside. Many experiments using particle probe started to look into the atom. Scientists soon realized that the atom has a tiny, dense positive nucleus and a cloud of negative electrons.



The nucleus is also not fundamental. It is made of protons and neutrons. A proton (p) and a neutron (n) are also composed of even smaller particles called quarks. Are quarks fundamental? Experiments till date have not revealed any structure of quarks and therefore we believe that the quarks are fundamental. So the present picture is that stable



matter we see around is made of space and atoms. Every atom has a tiny nucleus surrounded by a cloud of electrons. The nucleus consists of even smaller constituents – the protons and neutrons. The p and n themselves are made of structure less quarks. The quarks and electrons are believed to be fundamental.



The nucleus is about ten thousand times smaller than the atom. The quarks and electrons are at least ten thousand times smaller than that. We don't know exactly how small quarks and electrons are; they are definitely smaller than 10^{-18} m, and they might literally be points. May be in future someone may show that quarks are also composite but we adhere to the present faith that quarks are fundamental.

II. WHAT IS THE WORLD MADE OF? (PREVIEW)

A simple and comprehensive theory has been developed to explain what is the world made of. It requires only 6 quarks and 6 leptons as fundamental particles:

6 QUARKS are : up (u), down (d), strange (s), charm (c), bottom (b) and top (t)

6 LEPTONS are : electron (e), electron - neutrino (ν_e), muon (μ), muon - neutrino (ν_μ), tau (τ), tau - neutrino (ν_τ)

The typical names make them easier to remember. A type of fundamental particle is called a flavour. In this model (called the Standard Model) there are six flavours of quarks and six flavours of leptons. For each fundamental matter particle there is a corresponding antimatter particle (called antiparticle). When a matter and antimatter particle meet, they annihilate into pure energy in the form of a force carrier.

To explain electromagnetic, weak and strong interaction phenomena the model requires 12 force carriers: 1 for Electromagnetic force, 3 for weak force and 8 for strong force. These force carriers are:

$$\text{photon } (\gamma);\ \text{W - bosons } (W^{\pm}),\ \text{Z - boson } (Z^{0}) \text{ and eight gluons } (g_i\ (i = 1, 2, \ldots\ldots, 8))$$

All the known matter particles are composites of quarks and leptons, and they interact by exchange of force carrier particles. Feynman diagrams help in imagining these exchanges:

The free electron or quark line, 

the free photon line, 

the free (?) gluon line 

are shown. The electromagnetic interaction occurs via exchange of photon. The diagram shown here represents elastic electron-muon scattering. For this process

$$d\sigma \quad \propto \quad \text{(Kinematical factors)} \quad \times \quad \text{(Dynamical factors)}$$

$$\text{(Dynamical factors)} \quad \propto \quad |\,\text{matrix element}\,|^2$$

$$M \quad \propto \quad \text{(electron current)} \times \text{(photon propagator)} \times \text{(muon current).}$$

✔ ✔ ✔

The weak interactions occur via exchange of W- boson or Z-boson. The strong interactions occur via exchange of gluons. Note that while photon and gluons do not carry any electric charge, the weak force carriers W-bosons do carry electric charge.

This model does not include gravitational interaction. One reason is that we don't know how to include it. The masses of the particles are:

Particle masses in GeV ($1\,\mathrm{GeV} = 1.78 \times 10^{-27}$ kg)

$\nu_e \approx 10^{-8}, \nu_\mu \approx 0.002, \nu_\tau \approx 0.02$

$e = 0.000511, \mu = 0.106, \tau = 1.777$

$u = 0.003, d = 0.006, s = 0.1$

$c = 1.3, b = 4.3, t = 175$

$\gamma = 0, W^\pm = 80.4, Z^0 = 91.2, g_i = 0$

(convert mass in kg unit....in the presence of EM or/and WEAK or/ and STRONG interaction GRAVITATION does not matter.)

The quarks and leptons behave differently. The three leptons: electron, muon and tau each have -1 unit of charge while the corresponding neutrinos are all neutral. A quark flavour carries two kinds of charges: electric charge and colour charge. The electric charge on u, c, t is $+2/3$ unit each while that on d, s, b is $-1/3$ unit each. I shall discuss about colour latter.

A fractional charged particle has not been observed directly. When Gell-Mann and Zweig proposed the quark model in 1964, only three quarks (u, d, s) were required to explain the composite structure of all the hadrons known at that time. There exist two categories of hadrons: Baryons and Mesons. A Baryon is composed of three quarks (qqq); a meson is composed of a quark and an antiquark pair. The proton is composed of (uud) and the neutron is composed of (ddu). Initially the quarks were thought to be some kind of mathematical entities. The masses of uud does not add up to give proton mass:

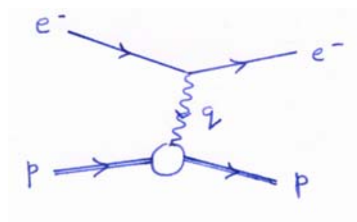
u + u + d = proton

mass: 0.003 + 0.003 + 0.006 $\neq$ 0.938

This indicates that the quarks might be moving too fast inside the proton so that the kinetic energies compensate for the mass difference or it might be the potential energy. Only experiments can decide whether fast moving quarks are there or not.

III. IS QUARK A REAL PARTICLE?

If a proton is composite of three quarks (uud) there must be a way to verify this conjecture. One performs scattering experiments to probe the structure of the proton. In the elastic e – p scattering one does not break the proton. The scattering explores only the gross features like charge and magnetic moment distributions of the proton.

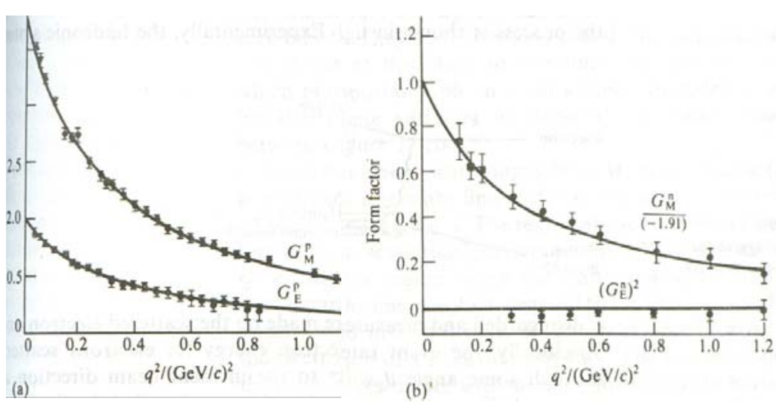


For the process:

$$M \propto \text{(electron current)} \times \text{(photon propagator)} \times \text{(proton current)}$$

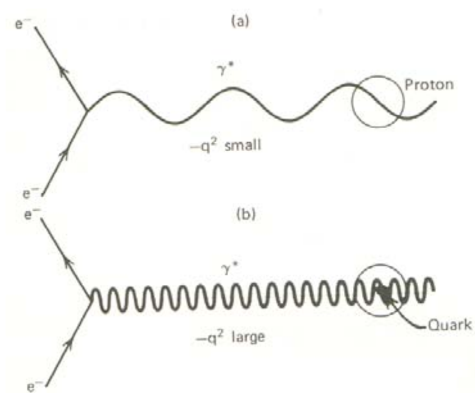
✔ ✔ ?

Using all possibilities, the ignorance is grouped in terms of two unknown functions: G_E and G_M , called the electric and magnetic form factors, respectively. Measurements of the cross sections at various energies allow us to infer the form of G_E and G_M experimentally. The results are shown here. Fig. (a) Proton form factors, (b) neutron form factors. The

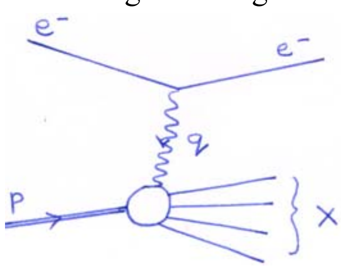


measurements do not reveal the structure of the proton or neutron. These reveal that the rms radius of the proton is about 0.8 fermi.

To break the proton one has to impart a large energy to the exchanged photon. One studies the inelastic scattering e p → e X.



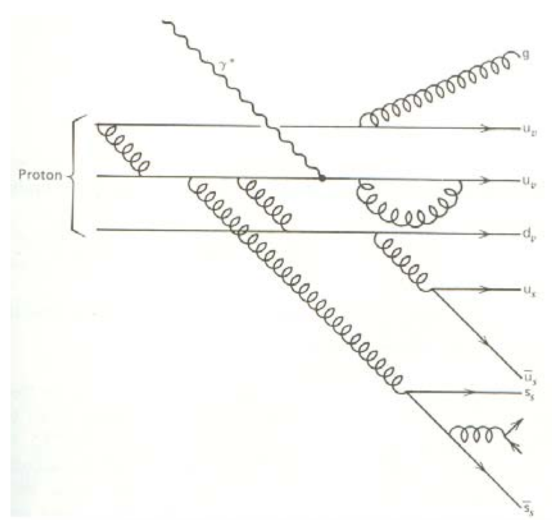
Again the ignorance about the structure of the proton appears in the form of two unknown functions F_1 and F_2 which appear in the differential cross section:

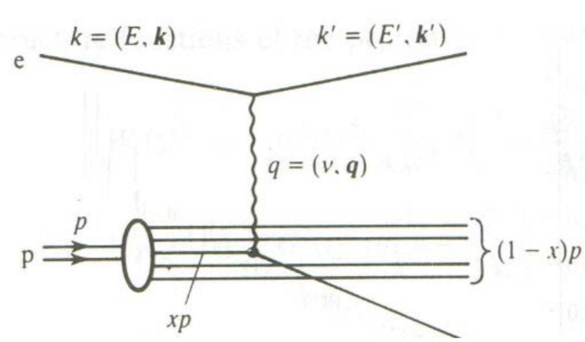


$$d\sigma \propto \left(F_2 \cos^2 \frac{\theta}{2} + \frac{2 F_1}{M} \sin^2 \frac{\theta}{2} \right).$$

These functions are called the structure functions. The form of these functions depends on the model assumed for the structure of the proton.

In one successful model, known as the parton model, the proton is assumed to be made of point like constituents called partons, which may be charged or neutral. To cut short the discussion, the charged partons are assumed to be spin ½ valence quarks u^v, d^v, .. and sea quark u^s, d^s,…(with corresponding antiquarks in the sea) . The uncharged partons are assumed to be gluons.





The diagram illustrates the e – p scattering. Since photon interacts with charged particles only the e – p scattering probes only the charged partons. The photon strikes say the i^th^ parton having a momentum = x p (where p is the momentum of the proton) and the rest of the partons are just spectators. It is called the spectator parton model. The photon when has right value of parameter x,

$$x \equiv Q^2 / 2M\nu$$

where $Q^2 = -q^2$, then it is absorbed by the parton carrying fraction x of the proton's momentum. The structure functions $F_{1,2}$ depend only one variable x in this model. If $f_i(x)$ is the probability that the i^{th} parton carries momentum fraction x then a detailed mathematical analysis leads to the following relations:

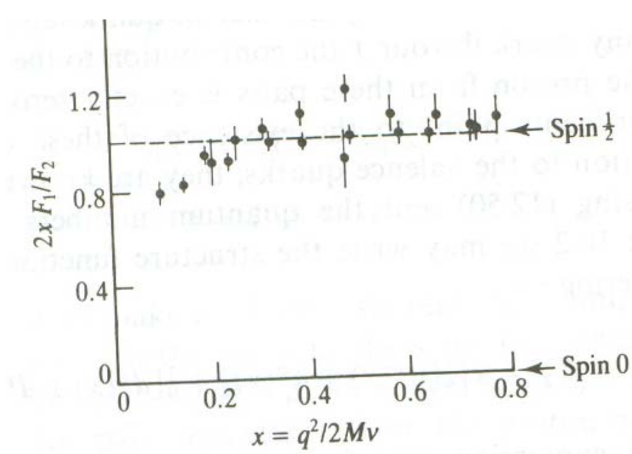
$$F_2(x) = \sum_i e_i^2 \, x f_i(x)$$

$$F_1(x) = \frac{1}{2} \sum_i e_i^2 \, f_i(x)$$

These satisfy the so-called Callan-Gross relation:

$$2x F_1(x) / F_2(x) = 1 \quad \text{(for spin 1/2 partons)}$$

This ratio would have been zero if calculations were performed by assuming that partons have spin 0. A series of e – N scattering experiments were performed at Stanford Linear Accelerator Centre. The results are shown in this figure and these conclusively favour spin ½ partons.



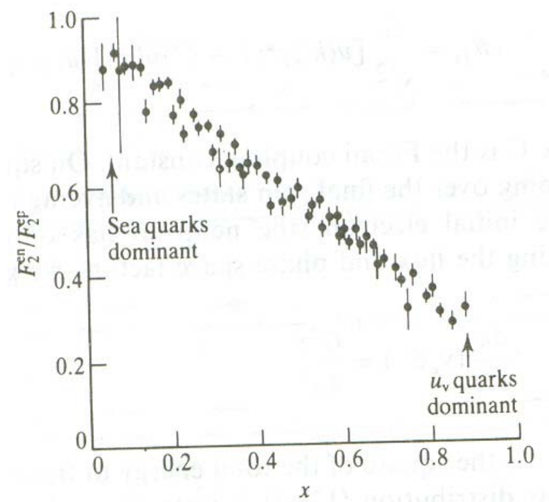
IV. MORE EVIDENCES IN FAVOUR OF QUARKS

Sea Quarks: The theoretical calculations for e – n and e – p inelastic scattering suggest that the ratio

$$F_2^{en}(x) / F_2^{ep}(x) \rightarrow 1 \quad \text{if sea quarks dominant}$$

$$F_2^{en}(x) / F_2^{ep}(x) \rightarrow 1/4 \quad \text{if } u_v \text{ quarks are dominant}$$

The SLAC measurements performed in 1973-74 reveal that at very small values of x the ratio appears to be approaching unity while at large values of x it is consistent with ¼ suggesting that sea are quarks dominant at small x and valence quarks at large x.



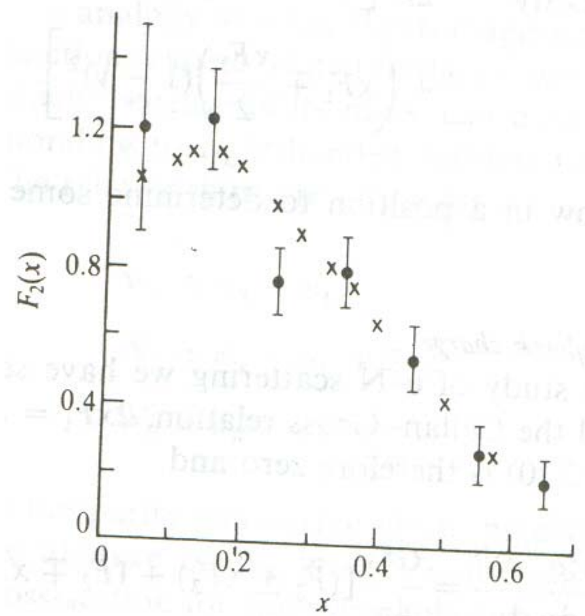
Fractional quark charge:

The interactions of electron with quarks are sensitive to the electric charge of the quarks but the interactions of a neutrino or antineutrino are not sensitive to the electric charge of the quarks. Theoretical considerations reveal that if we consider inelastic electron – nucleon scattering and neutrino – nucleon scattering then for fractionally charged quarks the following relation should hold:

$$F_2^{eN} \geq \frac{5}{18} \times F_2^{\nu N}$$

The equality holds if we neglect the sea quark-antiquarks contributions.

A comparison of $F_2^{\nu N}$ (•) measured at CERN and F_2^{eN} (×) measured at SLAC is shown in the figure below. The electron results have been multiplied by (18/5). The measurements support the fractional charge hypothesis.



Number of valence quarks:

The electron – quark interactions are mainly electromagnetic in character and are vector interactions. However the neutrino – quark interactions are weak interactions which are of V – A nature. Because $|M|^2$ contains terms arising due to the interference of vector and axial-vector interactions the differential cross-section for neutrino – nucleon scattering involves another structure function called $F_3^{\nu N}(x)$. It is found that

$$F_3^{\nu N}(x) = 2\left[Q(x) - \bar{Q}(x)\right]$$

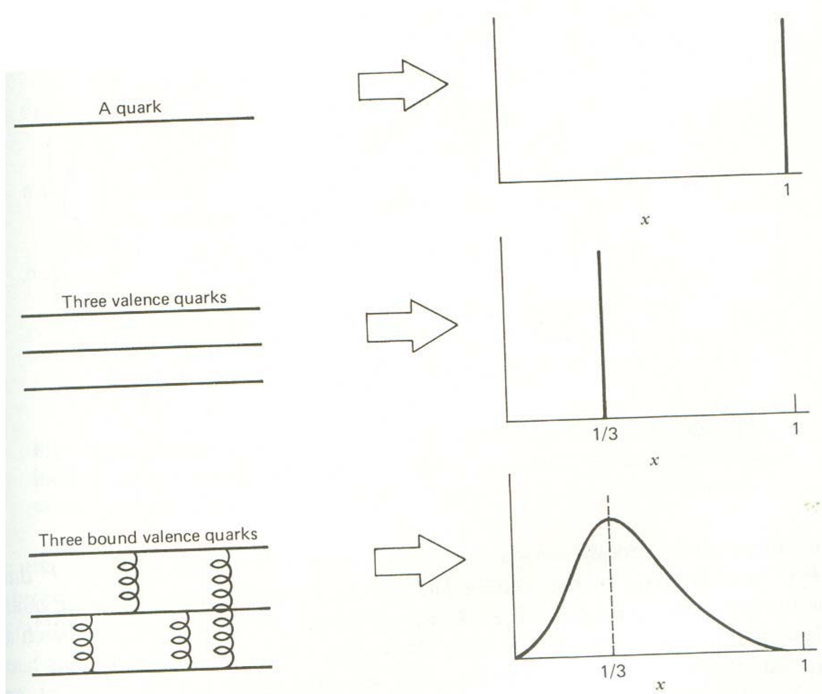
That is it measures the difference between quark and antiquark concentrations in the nucleon. Since the sea contains equal numbers of quarks and antiquarks the integral of F_3 must equal the number of valence quarks, i. e.

$$\int_0^1 F_3^{\nu N}(x)\,dx = 3$$

This sum rule is known as Gross- Llewellyn Smith rule. In 1979 measurements at CERN supports this sum rule.

Quark and antiquark momentum distribution:

The quark and antiquark momentum distribution in a nucleon has been measured at CERN and the Fermi Lab. At CERN neutrino nucleon scattering and antineutrino nucleon scattering experiments were performed. The neutrinos interact with d or $\overline{u}$ quarks only while antineutrino interacts with $\overline{d}$ or u quarks only. The theoretical calculations then give:



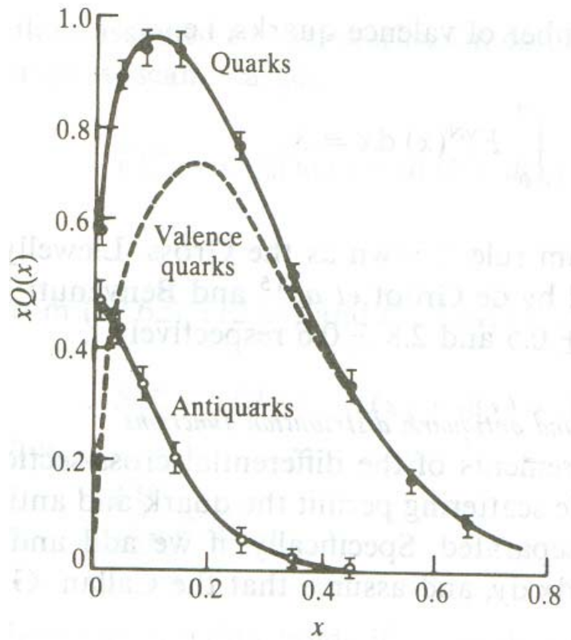
$$d\sigma\,(\nu_\mu\, N \rightarrow \mu^- X) \;\propto\; \left[Q(x) \;+\; \frac{1}{4}(1+\cos\theta)^2\, \overline{Q}\,(x) \right]$$

$$d\sigma\,(\overline{\nu_\mu}\, N \rightarrow \mu^+ X) \;\propto\; \left[\overline{Q}\,(x) \;+\; \frac{1}{4}(1+\cos\theta)^2\, Q(x) \right]$$

where $Q(x)$ and $\overline{Q}(x)$ are the quark and antiquark momentum distribution functions.

The momentum distribution functions pictured for various composition assumed for the proton are shown in the figure here.

The quark and antiquark momentum distribution functions extracted from the analysis of deep inelastic scattering experiments is as shown here. The data reveals that only 54 % of the proton's momentum is carried by the charged partons, i.e. valence quarks and sea-quarks-antiquarks. The rest 46 % is carried by those partons, which do not interact with the neutrinos and/or antineutrinos. The deep inelastic electron scattering data also supports this fact). Physicist claims that this momentum is carried by gluons.



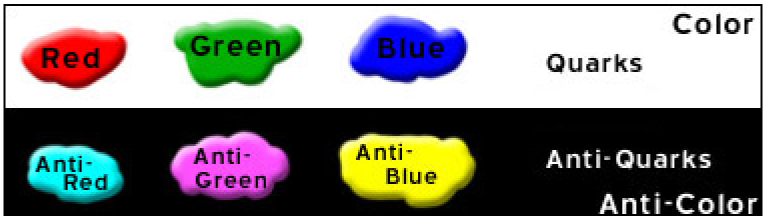
V. COLOUR CHARGE

Colour charge was introduced to explain the $J_3 = 3/2$ Δ^{++} quark structure .

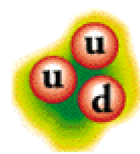
It is described by the symmetric wave function

u↑u↑u↑

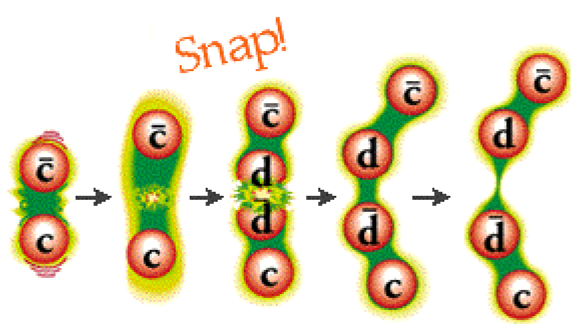
where we expect antisymmetric under the exchange of identical fermion quarks. The problem can be resolved by introducing colour charge, denoted symbolically by R, G



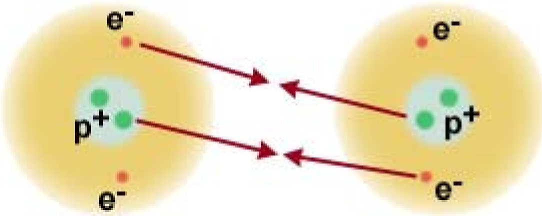
and B. Each flavour of quark is of three types distinguished by "colour charge". The three quarks that make up the Δ-state are now distinguished by their colour charges u_R u_G u_B . All particle states have net zero colour (i.e. unchanged by rotations in the R, G, B space). A youthful way to visualize the colour charge is by associating the three possible colours of the quarks by the spots of primary red, green and blue light focused on a screen. The antiquarks are assigned complementary colours: cyan $(\overline{R})$, magenta $(\overline{G})$ and yellow $(\overline{B})$.



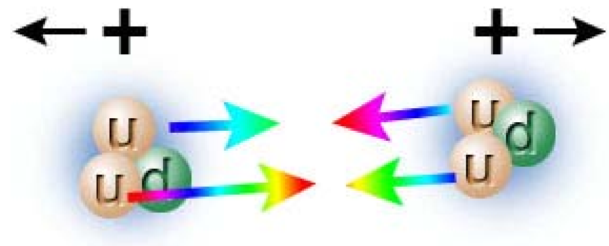
The colour charge endows quarks with a new colour field, which binds the quarks in hadrons. The quanta of the colour field are gluons. The gluons carry colour and anticolour. There are eight types of gluons. One cannot isolate quarks and gluons. They are confined in colour neutral particles called hadrons. The confinement (binding) results from multiple exchanges of gluons among the colour-charged constituents. As colour-charged particles (quarks and gluons) move apart, energy in the colour force between them increases that is eventually converted into additional quark antiquark pairs.



Like the residual electromagnetic force between neutral atom depicted in the diagram here, we can also envisage residual colour force. The strong binding of colour-neutral protons and neutrons to form a nucleus is due to residual strong interaction between their colour-charged constituents. It can also be viewed as the exchange of mesons between the nucleons.



Residual E-M force in action: the atoms are electrically neutral, but the electrons in one are attracted to the protons in another, and vice versa!



The quantum theory of colour field is called Quantum Chromo Dynamics (QCD).

Evidence of colour:

The cross section for production of all types of hadrons in electron-positron annihilation is given by

$$\sigma\,(e^- e^+ \rightarrow \text{hadrons}) = \sum_q \sigma(e^- e^+ \rightarrow q\bar{q})$$

$$= 3\sum_q e_q^2\, \sigma\,(e^- e^+ \rightarrow \mu^- \mu^+)$$

This leads to the prediction that

$$R \equiv \frac{\sigma\,(e^- e^+ \rightarrow \text{hadrons})}{\sigma\,(e^- e^+ \rightarrow \mu^- \mu^+)} = 3\sum_q e_q^2$$

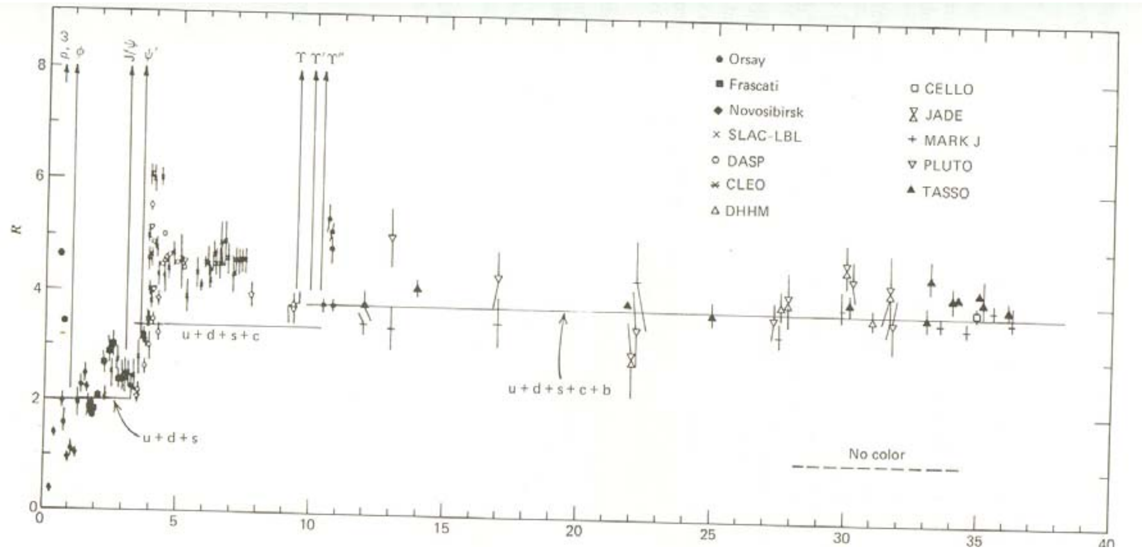
The factor 3 is due to the colour. The R therefore directly counts the number of quark flavours and the colour.

R = 2 for u, d, s,

= 10 / 3 for u, d, s, c,

$= 11 / 3$ for u, d, s, c, b.

These predictions have been verified by experiments (see below). The value of R ≈ 2 below the threshold for producing charmed particles at ≈ 2 ($m_c + m_u$) ≈ 3.7 GeV. Above the threshold for all five quark flavours (≈ 2 m_b ≈ 10 GeV), R ≈ 11/3. The



measurements also confirm that there are 3 colours since R = 11/3 is for three colours only.

VI. QCD AND PHYSICS NOBEL PRIZE 2004

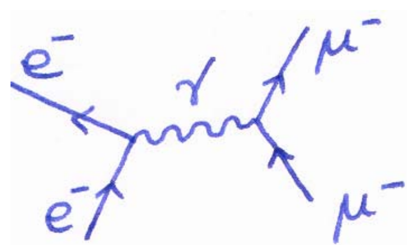
Quoted from the Press Release: The 2004 Nobel Prize in Physics

" What are the smallest building blocks in Nature? How do these particles build up everything we see around us? What forces act in Nature and how do they actually function?

This year's Nobel Prize in Physics deals with these fundamental questions, problems that occupied physicists throughout the 20th century and still challenge both theoreticians and experimentalists working at the major particle accelerators.

David Gross, **David Politzer** and **Frank Wilczek** have made an important theoretical discovery concerning the strong force, or the 'colour force' as it is also called. The strong force is the one that is dominant in the atomic nucleus, acting between the quarks inside the proton and the neutron. What this year's Laureates discovered was something that, at first sight, seemed completely contradictory. The interpretation of their mathematical result was that the closer the quarks are to each other, the *weaker* is the 'colour charge'. When the quarks are really close to each other, the force is so weak that they behave almost as free particles. This phenomenon is called "asymptotic freedom". The converse is true when the quarks move apart: the force becomes stronger when the distance increases. This property may be compared to a rubber band. The more the band is stretched, the stronger the force."

Charge renormalization in QED



In QED systematic perturbation expansion could be defined. The amplitude for scattering say e μ → e μ can be written as:

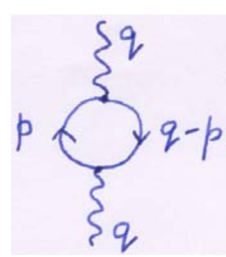
$$amplitude \sim \alpha \times (\cdot\cdot) + \alpha^2 \times [....] + \alpha^3 \times \{....\} + \cdots\cdots$$

where $\alpha = e^2 / 4\pi^2$. If only the first order term is considered then,

$$amplitude \sim \text{(electron current) (photon propagator) (muon cuurent)}$$

e **e**

However, when second order terms, specially arising from vacuum polarization modifications in photon propagator are considered then,



$$amplitude \sim \text{(electron current)}\,\text{(photon propogator)}\,(1 - \frac{e^2}{12\pi^2}\log\frac{M^2}{m^2})\,\text{(muon current)}$$

e e

where M^2 is a cut-off introduced to replace ∞ as the upper limit in loop integration. This defines a renormalized charge:

$$e_R = e\,(1 - \frac{e^2}{12\pi^2}\log\frac{M^2}{m^2})^{1/2}$$

with the interpretation,

$$\frac{e_R^2}{4\pi} = \frac{1}{137}$$

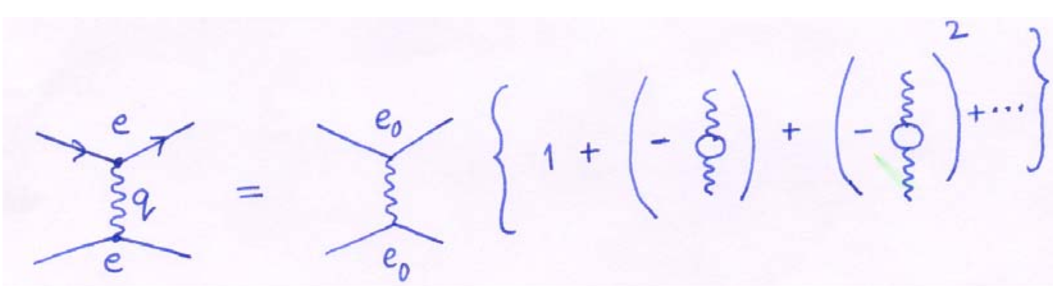
This is first step in the so-called "renormalization". In the process of renormalization one has to introduce a free parameter μ with the dimensions of mass. But physically measured quantities like $(amplitude)^2$ should not depend on the choice of math's developed by human brain. This requirement leads to an equation called "renormalization group equation"

$$\mu\frac{d(\text{amplitude})}{d\mu} = (\mu\frac{\partial}{\partial\mu}\Big|_e + \mu\frac{\partial e}{\partial\mu}\frac{\partial}{\partial e})\,(\text{amplitude}) = 0$$

Here $\mu\frac{\partial e}{\partial\mu} \equiv \beta$ is called the beta-function.

Charge screening in QED

Considering various order corrections due to vacuum polarization we note that

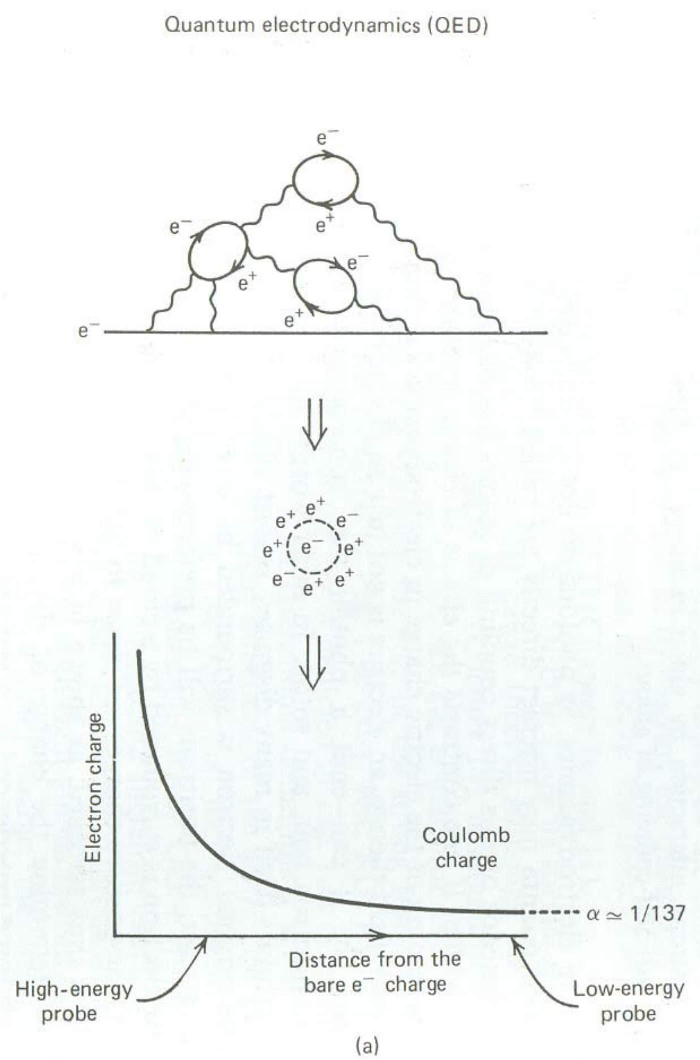


We define $-q^2 = Q^2$, then the above leads to the following value of α for large Q^2:

$$\alpha(Q^2) = \frac{\alpha(\mu^2)}{1 - \frac{\alpha(\mu^2)}{3\pi}\log(\frac{Q^2}{\mu^2})}$$

α is thus a running coupling constant. It describes how the effective charge depends on the separation of the two charged particles.

In this figure the screening of the electric charge is illustrated. In QED an electron can suddenly emit a photon, or it can emit a photon that subsequently annihilates into an electron positron pair, and so on. Suppose we want to determine the charge of an electron by measuring the coulomb force on a test charge.. The result

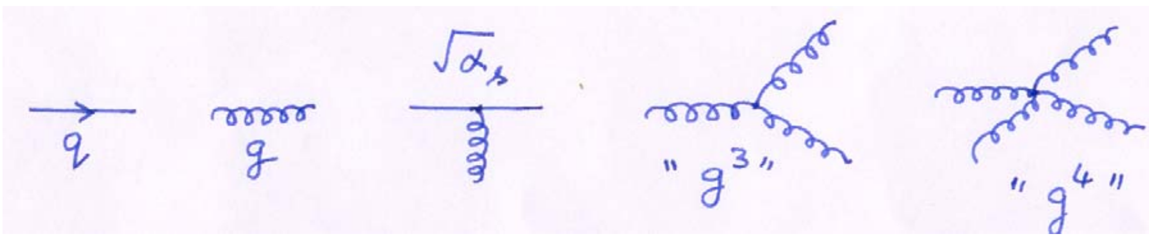


(a)

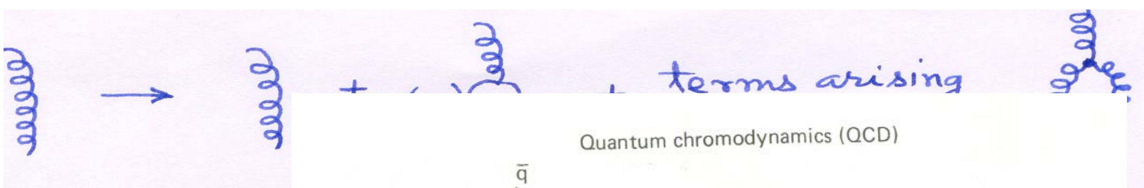
will depend on where we place the test charge. The closer one approaches the electron; larger is the charge one measures.

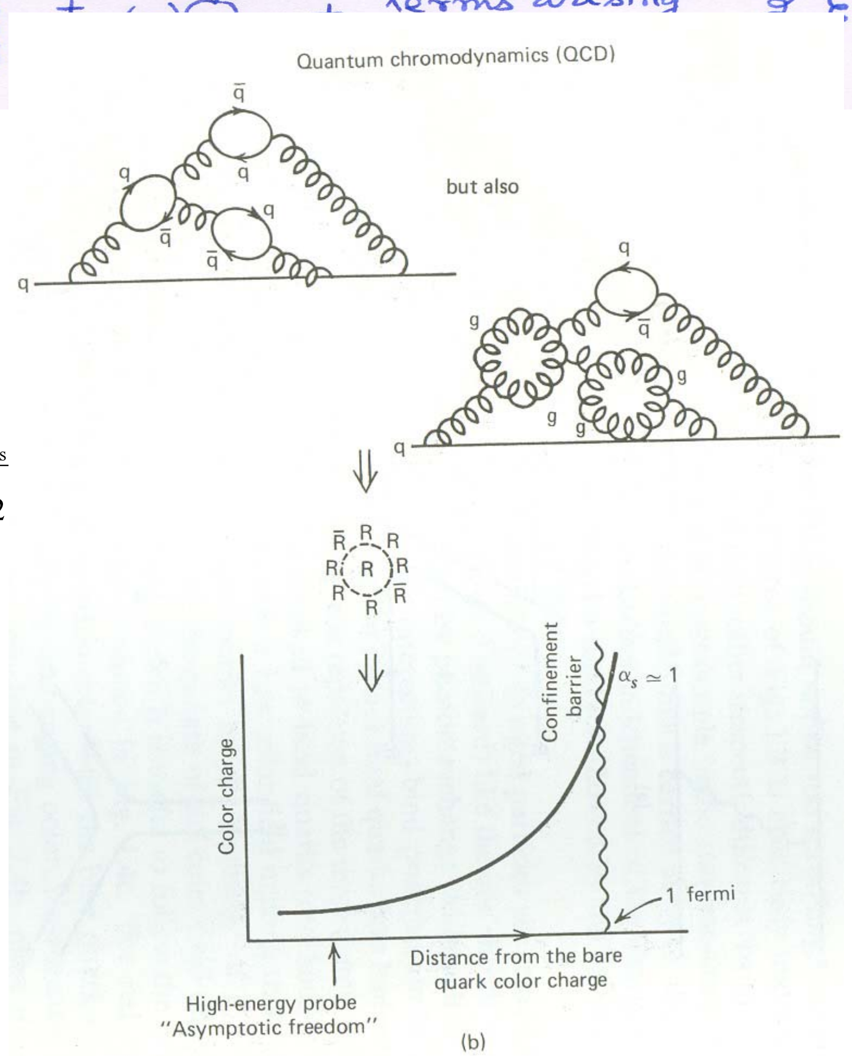
QCD

The QCD is the quantum theory of quarks, gluons and their colour interactions.



The colour field quanta are gluons. It is a non-Abelian theory, i.e. gluons have self-interactions. In this case the gluon propagator corrections are of the of the following type:





These corrections make the strong interaction α a running coupling constant. It is given by

$$\alpha_s(Q^2) = \frac{\alpha_s}{1 - \frac{\alpha_s(\mu^2)}{12\pi}(2}$$

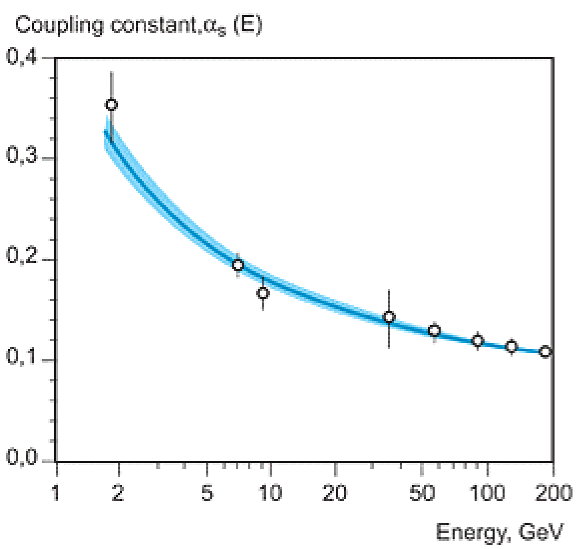
Here n_f = number of quark flavours. At present it is 6. Note that the 6 flavours make the second term in the denominator to change sign. As a result, for high energies the value of α_s decreases. This is called the "asymptotic freedom". By now it is very well established in experimental results.

The parameter μ with the dimension of mass remains as the relic of the renormalization. As can be seen from the above equation and diagram, at sufficiently low Q^2, the effective coupling will become large. It is customary to denote the Q^2 scale at which this happens by Λ^2. The choice of Λ^2 is arbitrary. One way to define it is to write the solution of the above equation as:

$$\alpha_s(Q^2) = \frac{12\pi}{(33 - 2n_f)\log(Q^2/\Lambda^2)}$$

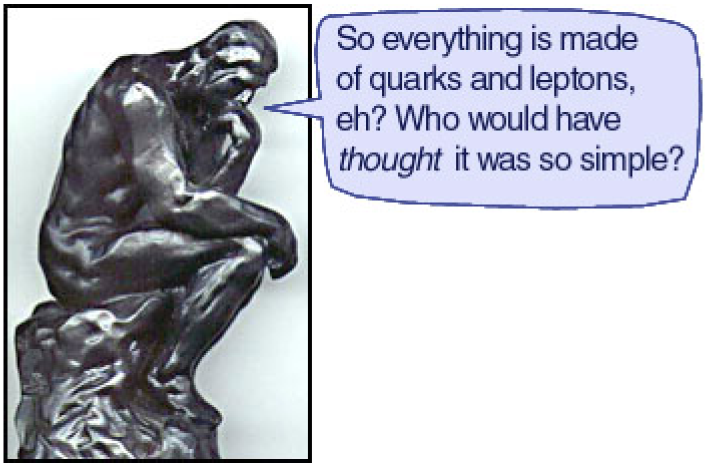
The parameter Λ is regarded as a natural mass scale, which separates a world of hadrons from a world of freely interacting quarks and gluons. $\Lambda \sim 200$ MeV.

In the figure below the effective coupling constant α_s is shown as a function of energy. It shows the value of the running coupling constant as a function of the energy scale E. The curve is a prediction of the asymptotic freedom in QCD and it agrees very closely with the measurements that have been made.



Essence:

The principle of “asymptotic freedom” determines that the renormalized QCD coupling is small only at high energies, and in this domain high-precision test similar to those in QED, can be performed using perturbation theory. In high Q^2 region the quarks



and gluons behave as though they are free particles. This is precisely the behaviour observed in deep-inelastic scattering processes in the quark-parton model. The “asymptotic freedom” emerges naturally from QCD. For $Q^2 \sim \Lambda^2$, the quark gluon coupling becomes large. This large coupling is responsible for the confinement of quarks and gluons in the form of bound states of hadrons with masses ~ few times Λ.

Link(for more information on Physics Nobel Prize 2004)

http://nobelprize.org/physics/laureates/2004/public.html

Original Papers (Physics Nobel Prize 2004)

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Books: e.g. for first reading☹☹

NUCLEAR AND PARTICLE PHYSICS, W. E. Burcham and M. Jobes, Addison-Wesley Longman (1995).

QUARKS & LEPTONS, F. Halzen and A. D. Martin, John-Wiley & Sons (1984).