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A Glimpse into The World of Quarks

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Introduction

Quarks are fundamental variety of matter, like leptons. All hadrons (baryons and mesons) are made up of these fundamental units, quarks. The Mendeleev's periodic table of atomic elements, in 1869, pointed towards a fundamental structure of matter common to all atoms. Nearly 50 years later, the discovery that atoms consisted of electrons revolving a nucleus confirmed this. Similarly, the observation of a periodic pattern among the existing hadrons (called as the *eightfold way pattern*), during 1960, pointed the possibility of a more fundamental variety of matter-quarks- out of which all hadrons, including protons and neutrons , are formed. With the discovery of the 6th and the last quark –the *top* quark- in 1995, at Fermi Lab, confirmation about the existence of the all the quarks was proved.

Eightfold way Pattern of Hadrons

To understand the eight fold way pattern, we can consider an example of mesons-π mesons, k mesons and η meson. These mesons have electrical charges of 0, ±1. They also have *strangeness* of 0 (π and η mesons) or +1 (k^+ and k^0) or -1 (k^- or $\overline{k^0}$). If we draw a diagram with the amount of strangeness on the vertical axis and the amount of charge along the horizontal axis (for historical reasons the charge axis is at an angle), mesons occupy various points on this figure. The pattern is a hexagon with two mesons (π^0 and η) at the centre as shown in Figure 1.

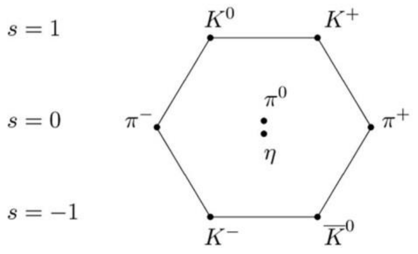

Figure 1

A similar type of figure can be drawn for the baryons (the neutron, proton, Λ, Σ and Ξ). The same hexagonal pattern emerges when we place particles on the figure with again two particles at the centre (see Figure 2).

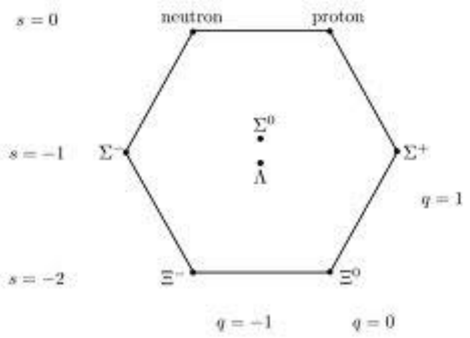

Figure 2

This similarity in the two patterns is very striking. This common pattern of eighths, for the baryons and mesons were named as the *Eightfold way*, by Gell-Mann.

A similar pattern can be drawn for Δ, Σ^* and Ξ^* baryons. In this case instead of simple hexagon, we can find a hexagon with extra particles at the top corners. Gell-Mann predicted that a group of ten particles should exist and the pattern can be completed by extending the pattern at the bottom, thereby forming an inverted triangle, as shown in the Figure3. The particle that completes the decuplet pattern has strangeness of –3 and has negative charge. Gell-Mann named it as Ω^-. He predicted the mass of the particle to be around 1680 MeV.

In 1963, at Brookhaven Laboratory and independently at CERN, the predicted particle was found. Its strangeness was -3, its charge was negative, and its mass was 1679 MeV.

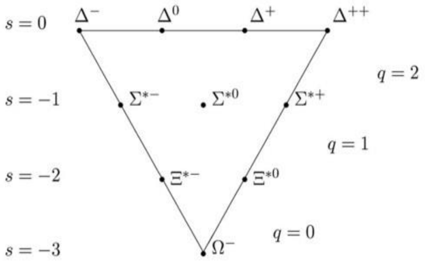

Figure 3

M.Gell-Mann and G.Zweig's Quark Model

The repetition of the common properties among the elements led to a regular pattern- the Periodic table. This also hinted that the atoms are made from fundamental constituents. The Eightfold way patterns of hadrons hint that the supposedly elementary hadrons are built from more fundamental constituents.

Deeply inspired by the above fact, in 1964, Murray Gell-Mann and George Zweig independently proposed that the eight fold way patterns would arise naturally if all the known hadrons were built from just three types of quarks. Two of these, known as *up* and *down* quarks (u and d), are sufficient to build the baryons that have zero strangeness. Strange hadrons contain the third variety the *strange* quark (s).

According to them, quarks carry electrical charges, which are fractions of a proton's charge: the u quark has a charge of +2/3 and the d quark has a charge of -1/3.

For Each and every quark there is an antiquark having the same mas and spin as its quark counterpart but possessing opposite sign of charge and strangeness. Thus, the s quark has a charge of -1/3 and strangeness of -1, the antiquark $\bar{s}$ has a charge of +1/3 and strangeness +1. Thus, we find the following

Quark	Electrical charge	Strangeness
u	+2/3	0
d	-1/3	0
s	-1/3	-1
$\bar{u}$	-2/3	0
$\bar{d}$	+1/3	0
$\bar{s}$	+1/3	+1

Table 1

According to Gell-Mann and Zweig, each baryon is a cluster of three quarks and each meson is a system of only two quarks (a quark and an antiquark). For example, a proton is a mixture of two *up* quarks and one *down* quark

$$u + u + d \rightarrow p$$

The net charge of the combination is

$$+(2/3) + (2/3) + (-1/3) \rightarrow +1$$

Thus, two up quarks and one down quark will have the same charge as a proton.

To explain the eightfold way pattern of the hadrons, we have to see all possible combinations of quarks. It is given in the Table 2

Cluster	Strangeness	Charge	Examples
uuu	0	2	Δ^{++}
uud	0	1	Δ^{+}, p
udd	0	0	Δ^{0}, n
ddd	0	-1	Δ^{-}
uus	-1	1	Σ^{*}, Σ
uds	-1	0	Σ^{0*}, Σ^{0}, Λ
dds	-1	-1	Σ^{-*}, Σ^{-}
uss	-2	0	Ξ^{0*}, Ξ^{0}
dss	-2	-1	Ξ^{-*}, Ξ^{-}
sss	-2	-1	Ω^{-}

Table 2

From the above table, it is clear that, if we consider the clusters where at least one quark differs from the other pair, then we can find the eight members of the octet that contains the proton, neutron and so on. Similarly the column of ten particles corresponds to the decuplet of particles containing the Ω^{-} (see Figure 3).

To build various mesons, we have to consider the clusters containing two quarks, one of which must an antiquark. We can see that there are nine possible combinations, as shown in the Table 3

Cluster	Strangeness	Charge	Examples
$u\bar{s}$	+1	+1	k^+
$d\bar{s}$	+1	0	k^0
$u\bar{d}$	0	+1	π^+
$u\bar{u}$	0	0	π^0
$d\bar{d}$	0	0	η
$s\bar{s}$	0	0	η'
$d\bar{u}$	0	-1	π^-
$s\bar{u}$	-1	-1	k^-
$s\bar{d}$	-1	0	$\bar{k}^0$

Table 3

Earlier, it was mentioned that eight mesons are sufficient to complete the correspondence between the eightfold way pattern of mesons (Figure 1) and that of the baryons, consisting of proton and so on (Figure 2). But, from the Table 3, we can see an extra ninth meson η'. Later, the discovery of this ninth meson, gave the hint of breaking of the direct correspondence between the two patterns. Today we recognise that baryons do occur in families of eight or ten but mesons occur in nine (nonets).Another family of nine mesons with of spin of 1 also exist, consisting of ρ^-, ρ^0, ρ^+ and ω^0 with masses 770 MeV; k^{*-}, k^{*0}, k^{*+} and $\bar{k}^{*0}$ with masses 890 MeV and the ϕ^0 with mass 1020 MeV.

Quarks are Fermions and they carry a spin of 1/2. Three spin 1/2 quarks combine to a total spin of 1/2 or 3/2. The eight members of the family containing proton and so on, each have a spin of 1/2; the ten members of the family containing Δ^{++} and so on, have a spin of 3/2. All the mesons shown in the Table 3 have a spin of 0, as they are combinations of two quarks (a quark and an antiquark).

The Charm Quark

The theory of electromagnetic and weak interactions, developed by S.Glashow, A.Salaam and S.Wienberg, was built on the observation that leptons $[(\nu_e, e^-)$ and $(\nu_\mu, \mu^-)]$ and quarks (u, d) form pairs. Although this is fine for the leptons and u and d quarks, but leaves the s quark in isolation and out of the weak interaction.

It was M. Gell-mann, in his original theory of quarks, doubted the possibility of a fourth quark that formed a pair with the s quark, by analogy with the leptons. In this way he maintained the symmetry between leptons and quarks. But this idea was then dropped because not a single hadron containing the fourth quark was found.

S.Glashow, with J.Illipoulis and L.Maiani, in 1970, discussing on the strangeness changing neutral interactions, predicted that the existence of a fourth quark, named as *charm* quark (c quark). They showed that everything with the weak interaction theory would be perfect for both leptons and quarks, if the c quark carries a charge of +2/3, like the u quark and if the quarks form two pairs similar to the leptons $[(u, d)$ and $(s, c)]$.

Many efforts were made to observe hadrons containing c quark. Finally, during November 1974, a team led by Burton Richter, at Stanford, and independently, by Samuel Ting, at MIT, discovered a particle built from a charmed quark and charmed antiquark $(c\bar{c})$ - J/ψ meson. Richter annihilated electrons and positrons at the start and produced J/ψ meson, but Ting produced the meson first and detected it by its subsequent decay into an electron and positron. Both of them found that the mass of the J/ψ meson to be 3095 MeV. Hence the mass of a c quark is of the order of 1500 MeV. Later many charmed mesons like $(c\bar{d})$, $(c\bar{u})$ and their antiparticles $(\bar{c}d)$, $(\bar{c}u)$ and charmed baryons like Λ_c consisting of c, u and d quarks were detected.

Last Generation of Quarks

The lepton pair (ν_e, e^-) has many properties in common with the quark pair (u,d) , namely, they have no internal structure, have spin 1/2, and respond to electromagnetic and weak interactions. These lepton and quark pairs are known as the *first generation* of elementary particles.

Similarly, the lepton pair, the *muon* (the heavy version of the electron) and its neutrino, (ν_μ, μ^-), has many properties in common with the quark pair (s,c). These lepton and quark pairs are known as the *second generation* of elementary particles.

In 1975, Martin Perl, at Stanford, discovered a particle, named as *taon* (τ). Its mass was about 2000 MeV. It was found that, just as the *muon* is a heavier version of the electron, the *taon* is a yet heavier version of both of them. After many years of study, it appeared that *taon* is a structure less elementary particle, electrically charged and partnered by a neutrino (ν_τ). Thus, the pair (τ, ν_τ) forms a *third generation* of leptons.

As there is a third generation of leptons, many physicists argued that there should also exist a third generation of quarks, to restore the lepton-quark symmetry. This new quark pair was named as *top* (t) and *bottom* (b). They were predicted to have electrical charges of +2/3 and -1/3, just as was the case for the first generation (u,d) and the second generation of quarks (s,c).

In 1977, a group of physicists led by Leon Lederman working at Fermi lab discovered a massive particle known as the *Upsilon*, Υ, which was produced in proton-proton collisions. Just as the J/ψ meson is a bound state of $c\bar{c}$ (*charm* quark and its antiquark), the Υ meson is made from $b\bar{b}$ (*bottom* quark and its antiquark). This meson has a mass of 9.45GeV, nearly three times as massive as the J/ψ meson and ten times that of the proton. Hence, mass of the *bottom* quark is nearly 5 GeV. Mesons with *bottom* quark with *up*, *down*…etc. antiquark and *bottom* baryons such as Λ_b made from *bud* also exist and have been detected experimentally.

Finally, the discovery of *top* quark took a very long time, because the *top* quark turned out to be very massive, its mass was found to be around 180 GeV. In 1995, the *top* quark was discovered at Fermi lab. The experiment involved the collisions of protons and antiprotons at energies up to 1 TeV. The life time of the *top* quark or its antiquark, is very small, of the order of $10^{-24} s$. Hence they decay immediately before having a chance to bind to one another. So there is unlikely to be a $(t\bar{t})$ analogue of the J/ψ $(c\bar{c})$ or Υ $(b\bar{b})$.

Coloured Quarks

All quarks have spin of 1/2 and so they should obey the Pauli's exclusion principle. A spin 1/2 particle can spin either of two directions-clockwise or anticlockwise- allowing at most two quarks to have same energy. It is natural to expect that hadrons are formed when each quark is in its lowest energy state. But the particle Ω^-, which consists of three identical *strange* quarks, is forbidden to exist contrary to clear evidence that it does (see Table -2).

Oscar Greenberg observed this problem with the Pauli's exclusion principle in 1964, soon after the idea of quarks was proposed. To resolve the problem he suggested that quarks possess a new property called "colour", which can be recognised similar to electric charge except that it occurs in three varieties - red, yellow and blue variety. So quarks have colour charges. Quarks carry positive colour charges and antiquarks carry negative colour charges. Hence, a *strange* quark can occur in any of the three varieties, written as s_R, s_Y and s_B. Similarly, the s*trange* anti quark has three varieties - $\bar{s}_R$, $\bar{s}_Y$ and $\bar{s}_B$.The three varieties of *up* and *down* quarks can be written similarly.

Thus, if one of the strange quarks in Ω^- carries the red colour charge, while one has yellow colour charge and the other one blue, then they are no longer identical and so Ω^- can exist.

Quarks and Colour Forces

Quarks experience all the four forces of nature, particularly the strong nuclear force. An idea began to hold that colour might be the source of the strong forces acting between quarks, as soon as quarks were discovered to have colours.

The colour interactions are similar to the interactions among electric charges. As, like electric charges repel and unlike charges attract, like colours repel and opposite colours attract. Thus, two red quarks repel but a red quark and anti-red quark attract. The same thing is true for yellow and blue coloured quarks. Using this, the existence of mesons can explained easily- just as positive and negative electric charges attract to form net uncharged atoms, so, positive and negative colours, carried by quark and antiquark, attract to form net uncoloured mesons.

Now, different colours can attract one another but less intensely than do the opposite colours of quark and antiquark. Thus, a red quark and a blue quark can attract each other and the attraction becomes maximised if they cluster with a yellow quark. Thus, when three quarks cluster together, each one with a different colour, there is a formation of a colourless baryon. Thus, clusters of quark and antiquark of opposite colours or of three different coloured quarks, leads to the net uncoloured hadrons.

It is worth noting that, as leptons do not have colours, they do not experience strong forces. Hence, it can be said that leptons are colour blinded to strong forces.

Quantum Chromo Dynamics and Gluons

Combining electrostatics with relativity and quantum theory leads to a theory called as *Quantum Electro Dynamics* (QED). Here, we discuss relation between electric charge and electromagnetic forces. Similarly, *Quantum Chromo Dynamics* (QCD) is a theory of quark forces generated by coloured quarks. Thus, as QED for electric charge, so is QCD for colour.

In QED, photons, massless and spin 1 particles, are the carriers of the electromagnetic forces between electrically charged particles. Analogously, in QCD, *Gluons* are the carriers of the force between coloured quarks. Like photons, gluons must be massless and spin 1 particles.

Continuing the analogy, as the acceleration of an electric charge leads to radiation of photons, we expect, the acceleration of coloured quarks must lead to radiation of gluons.

As QCD is similar to QED, we expect similar behaviours for the forces between quarks in clusters and electromagnetic forces between nuclei and electrons. Such similarities are observed in the hyperfine splitting between some energy levels of the atom or quarks clusters.

Although QED and QCD are equivalent, the replacement of two electric charges by three colour charges causes the two forces to behave spatially in different ways. Thus, electromagnetic force has an infinite range whereas the colour forces have a range of the order of $10^{-15}m$ (one fermi). QCD also predicts that when the coloured quarks are close to one another than a fermi, the forces between them are almost non-existent; then, as quarks move apart, the energy in the force field between them grows. According to QCD, it would take an infinite amount of energy to separate the quarks by more than a fermi. Thus, it is impossible to separate an individual quark from the neighbourhood quarks. The consequence is that quarks are permanently confined in clusters- the baryons and mesons.

The Stanford Linear Accelerator Centre (SLAC) experiments on the scattering of high energy electrons from quarks, that were apparently free and yet stayed confined in clusters, confirmed this phenomenon.

Discovery of Quarks

The evidence for quarks trapped inside a proton and a neutron came from a series of experiments at SLAC in California, in 1968. Here, electrons, accelerated up to 20 GeV, were fired at targets containing protons (example, liquid hydrogen).

The electron's negative charge causes it to be attracted or repelled by the *up* and *down* quarks with electrical charges +2/3 and -1/3. The spin of the quarks have magnetic effects which exert forces on the moving electrons. Thus, it is possible to predict what should happen when high energy electrons are fired towards protons and to determine where the charge of the proton is concentrated.

If the charge on the proton is uniformly distributed throughout the volume then the electron beam would pass through with little or no deflection. However, if the charges are localised on the three quarks then the electron would occasionally pass close to a concentration of charge and be violently deflected form its path.

In the experiments conducted at SLAC, the analysis of the distribution of the scattered electrons showed that the proton is indeed built from entities with spin 1/2.

Similar results were observed at CERN, Geneva, in 1970, where neutrinos were used as probes in place of electrons. The experiments showed that protons have constituents having electrical charges which are +2/3 and -1/3 fractions of the proton's charge.

The way that the electrons scattered from the quarks within the proton revealed that quarks appeared to be almost free inside the proton as if they are hardly glued together at all. So, one would expect quarks to be easily ejected from the proton.

Plans were made to eject quarks by firing very high energy electrons. For a year there were hopes that individual quarks might emerge, but these hopes were short lived.

It is analogous to quarks being held to one another by an elastic band that is slack. The quarks are free, but after being struck they recoil and the elastic becomes tighter, preventing them from escaping. The elastic may be become so stretched that it snaps. The two new ends created have quarks on them, and so mesons are formed but not free quarks. Thus, it is not possible to observe free quarks.

Detection of Gluons

As mentioned earlier, acceleration of electric charges and coloured quarks emit photons and gluons, respectively. Both the emissions can be observed in the electron-positron annihilation process, at very high energies. An electron and a positron combine and produce a photon, which can then convert into a quarks and an antiquark, as shown below.

$$e^- + e^+ \to \gamma \to q + \bar{q}$$

But the quark and antiquark carry both electric charge and colour and, therefore, they radiate photons and gluons. So, we have

$$\begin{aligned} e^- + e^+ \to \gamma \to (q + photons + gluons) + \\ (\bar{q} + photons + gluons) \end{aligned}$$

After the production quark and antiquark move in opposite directions. As they separate, the energy in the force field between them grows to such an extent that, new quarks and antiquarks are produced. The initial quark and antiquark cluster together with these newly created ones forming baryons and mesons. Thus, instead of original quark and antiquark, two oppositely directed jets of hadrons emerge. By studying these jets, the properties of quarks or gluons can be found out.

Several examples of these hadron jets were observed during the collisions of electrons and positrons at 100 GeV of energy, at CERN, using Large Electron Positron (LEP) facility.

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