

# Physics 30 Lesson 38 Quarks

Before or during the reading of this lesson you may want to visit the following websites:

<http://particleadventure.org/frameless/startstandard.html>

[http://nobelprize.org/educational\\_games/physics/matter/1.html](http://nobelprize.org/educational_games/physics/matter/1.html)

## I. Development of quark theory (mostly optional)

As more and more hadrons were discovered it became clear that they were not all elementary particles. This theoretical quandary was addressed independently in 1963 by two American physicists, Murray Gell-Mann and George Zweig. They proposed that all known hadrons were composite particles – i.e. hadrons were each made up of a cluster of two or more particles. While Zweig called the particles “aces”, Gell-Mann light-heartedly called them **quarks** from the phrase “Three quarks for Muster Mark” in James Joyce’s novel *Finnegans Wake*. (Gell-Mann and other physicists, along with some high school physics teachers, mistakenly believe they have a sense of humour.) To account for every hadron known at the time, Gell-Mann and Zweig proposed the following quark properties:

- ⇒ Quarks interact primarily via the strong nuclear force.
- ⇒ There are three varieties, or **flavours**, of quarks and antiquarks. These quark flavours came to be called **up** (u), **down** (d), and sideways (s). Later, the sideways quark was renamed the **strange** (s) quark to describe particles that interact strangely – i.e. they interact primarily via the strong force yet decay only via the weak nuclear force.
- ⇒ Each quark was assigned a baryon number of  $+\frac{1}{3}$  and each antiquark a baryon number of  $-\frac{1}{3}$ .
- ⇒ All baryons are composed of three quarks and all antibaryons are composed of three antiquarks. When baryon numbers are added together they add up to +1 for a baryon and -1 for an antibaryon.
- ⇒ All mesons are composed of one quark and one antiquark. When baryon numbers are added together they add up to 0 for a meson – i.e. a meson is not a baryon.
- ⇒ Each quark and antiquark has a spin of  $\frac{1}{2}$ . The quark spins add up to the spin of the composite particle.
- ⇒ The most radical idea was that each quark had a **fractional charge**, either  $-\frac{1}{3}$  or  $+\frac{2}{3}$  of the fundamental electron charge. When the quark charges are added together the result was the observed integer charge of the baryon or meson.

Characteristics of quarks and antiquarks*									
Quarks						Antiquarks			
	Flavour	Symbol	Charge	Spin	Baryon number	Symbol	Charge	Spin	Baryon number
1 <sup>st</sup> generation	Up	u	$+\frac{2}{3}$	$\frac{1}{2}$	$+\frac{1}{3}$	$\bar{u}$	$-\frac{2}{3}$	$\frac{1}{2}$	$-\frac{1}{3}$
	Down	d	$-\frac{1}{3}$	$\frac{1}{2}$	$+\frac{1}{3}$	$\bar{d}$	$+\frac{1}{3}$	$\frac{1}{2}$	$-\frac{1}{3}$
2 <sup>nd</sup> generation	Strange	s	$-\frac{1}{3}$	$\frac{1}{2}$	$+\frac{1}{3}$	$\bar{s}$	$+\frac{1}{3}$	$\frac{1}{2}$	$-\frac{1}{3}$
	Charm	c	$+\frac{2}{3}$	$\frac{1}{2}$	$+\frac{1}{3}$	$\bar{c}$	$-\frac{2}{3}$	$\frac{1}{2}$	$-\frac{1}{3}$
3 <sup>rd</sup> generation	Bottom	b	$-\frac{1}{3}$	$\frac{1}{2}$	$+\frac{1}{3}$	$\bar{b}$	$+\frac{1}{3}$	$\frac{1}{2}$	$-\frac{1}{3}$
	Top	t	$+\frac{2}{3}$	$\frac{1}{2}$	$+\frac{1}{3}$	$\bar{t}$	$-\frac{2}{3}$	$\frac{1}{2}$	$-\frac{1}{3}$

\* the c, b and t flavours are discussed below

### Example 1

The proton consists of two up quarks and one down quark (uud). The neutron consists of one up quark and two down quarks (udd). For both baryons show that the sum of their baryon numbers, charges and spins add up to their observed properties.

For the proton:

$$\begin{aligned}\text{baryon number: } & \frac{1}{3} + \frac{1}{3} + \frac{1}{3} = 1 \\ \text{charge: } & (+\frac{2}{3}) + (+\frac{2}{3}) + (-\frac{1}{3}) = +1 \\ \text{spin } & (+\frac{1}{2}) + (-\frac{1}{2}) + (+\frac{1}{2}) = \frac{1}{2}\end{aligned}$$

For the neutron:

$$\begin{aligned}\text{baryon number: } & \frac{1}{3} + \frac{1}{3} + \frac{1}{3} = 1 \\ \text{charge: } & (+\frac{2}{3}) + (-\frac{1}{3}) + (-\frac{1}{3}) = 0 \\ \text{spin } & (+\frac{1}{2}) + (-\frac{1}{2}) + (+\frac{1}{2}) = \frac{1}{2}\end{aligned}$$

The table to the right shows the quark combinations that form a number of hadrons.

Using the quark model, not only did Gell-Mann accurately predict the existence of the omega ( $\Omega^-$ ) particle, he showed how to produce the particle. The model also accurately predicted key aspects of electron-positron interactions. However, the quark model was not easily accepted. The property of fractional charges was just too weird and many physicists had trouble accepting this radical concept. No such charges had ever been seen before and they still have not been directly observed to the present day.

The quark composition of several hadrons

Mesons		Baryons	
$\pi^0$	$u\bar{u}, d\bar{d}$ mix	p	uud
$\pi^+$	$u\bar{d}$	n	udd
$\pi^-$	$\bar{u}d$	$\Delta^0$	udd
$\eta$	$d\bar{d}, u\bar{u}$ mix	$\Delta^{++}$	uuu
$\eta'$	$s\bar{s}$	$\Delta^+$	uud
$K^0$	$d\bar{s}$	$\Delta^-$	ddd
$\bar{K}^0$	$\bar{d}s$	$\Sigma^+$	uus
$K^+$	$u\bar{s}$	$\Sigma^-$	dds
$K^-$	$\bar{u}s$	$\Sigma^0$	uds
$J/\psi$	$c\bar{c}$	$\Xi^0$	uss
$\Upsilon$	$b\bar{b}$	$\Xi^-$	dss
		$\Lambda^0$	uds
		$\Omega^-$	sss

In 1969, Friedman, Kendall, and Taylor at the Stanford Linear Accelerator Center (SLAC) in California, determined a way to “see” the quarks within the nucleus. The experiment was very similar to the experiment of Ernest Rutherford (Lesson 27), but this time the targets were protons and neutrons and the beam consisted of electrons accelerated to energies a thousand times higher than Rutherford's beam of alpha particles. If the proton was a fundamental particle without any internal structure, then electrons fired at it would be deflected by small angles. However, since the proton does have internal structure, electrons fired at it were deflected by large angles. Again, like Rutherford, the angles of the scattered particles revealed a new level of matter. Deep inside protons and neutrons, they found physical evidence of three point-like charges.

A few years later, physicists at CERN scattered neutrinos off protons and neutrons. Neutrinos are extremely light particles that have weak force interactions but not electromagnetic interactions with matter. The comparison of the rate for neutrino scattering versus that for electron scattering, provided strong evidence for fractional charge.

As fate would have it, quark theory, which was none too popular in the 1960s and early 70s, was revived by a chance discovery. In 1974, two teams of scientists – one at

Brookhaven National Laboratory under Sam Ting, and the other at SLAC under Bernie Richter – almost simultaneously discovered a new hadron, called  $J/\psi$  by one and  $\psi$  (psi) by the other. The  $J/\psi$  meson was three times more massive than the proton and, remarkably, lived for  $10^{-20}$  s before decaying – 1000 times longer than is normal for a hadron of that mass. The quark theory as it stood at that time was no help – it was all filled up, there were no more particles that could be accounted for with three quarks.

The difficulty was soon settled by appealing to an idea, suggested by a Danish-American physicist named Sheldon L. Glashow, that had been around for some time but had found little support. Because there were then four known leptons, it had been proposed (on the grounds of natural symmetry among elementary particles) that there ought to be four quarks. The new addition had already been named **charm** (c), though up until the discovery of  $J/\psi$  there was no reason to take it seriously. It is now accepted that  $J/\psi$  corresponds to the two-quark bound state ( $c\bar{c}$ ). A whole clutch of very massive mesons and baryons containing the heavy charm quark have since been discovered.

This story played itself out again in 1975 when the tau ( $\tau$ ) lepton was discovered. Like the electron and muon with their partner neutrinos, the  $\tau$ -neutrino was theorised in 1975 but it was not observed until 2000 at Fermilab. There were now six leptons. Based again on natural symmetry between leptons and fermions, a third generation of quark flavours **bottom**, or beauty, (b) and **top**, or truth, (t) were theorised. By 1977, a new massive meson, the upsilon ( $\Upsilon$ ), was observed and was recognized to be ( $b\bar{b}$ ). The mesons (bd) and (bu) were found in 1983. The sixth heavy quark flavour top was confirmed in 1995 at Fermilab.

Will there be a fourth generation of quarks and leptons? Experiments in 1990 strongly suggest that nature probably cannot accommodate more than three kinds of neutrinos, and therefore there will be a total of six leptons and presumably no more than six quark flavours forming three generations of elementary particles.

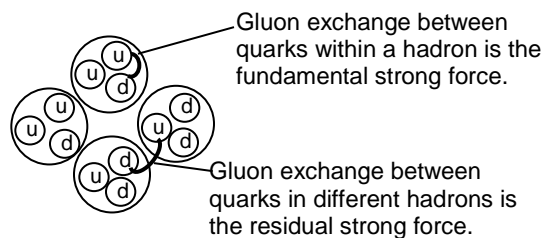
## II. “Color” charge and the strong force (optional)

Another theoretical objection to the quark model was raised in the early 1960s. According to the Pauli Exclusion Principle, two identical particles with identical sets of quantum numbers cannot occur together in the same atomic or subatomic system. For example, the  $\Delta^{++}$  baryon corresponds to uuu, three u-quarks (three fermions in the same quantum state is a no no no). A way out of the quark quandary or quagmire developed that has since proven to be remarkably fruitful for a number of reasons. Glashow proposed that each flavour of quark actually came in three varieties, or “colors”: red, green, and blue. He further proposed that the three quarks that make up baryons all have a different “color”. Thus, the u-quarks in  $\Delta^{++}$  – namely ( $u_R u_G u_B$ ) – were not really identical and therefore there is no problem with the Exclusion Principle. This mix of colors results in baryons being “color” neutral (red, green, and blue add together to form white or neutral color). If this were not true, there could be 10 different varieties of each baryon, which is not the case.

It is very important to understand what is meant by “color” charge. Just as electric charge is an intrinsic property of electrons or positrons that responds to electromagnetic

fields, **color** charge is an intrinsic property of quarks and antiquarks that feels and responds to **strong force** fields. Since hadrons are color charge neutral it follows that color is an internal characteristic. This means that either the total amount of each color is zero (as with mesons that are color-anticolor pairs  $q_R \bar{q}_R$ ), or that all the colors are present in equal amounts (as with baryons,  $q_R q_B q_G$ ). This scheme demands that no observable particle be composed of either two ( $qq$ ) or four ( $qqqq$ ) quarks, nor can free quarks exist. Quarks only form “color” neutral composites, which is why only  $qqq$  and  $q\bar{q}$  are seen.

But the idea of color-charge is far more than a way to appease the Exclusion Principle. Glashow believed that the quark color had to do with the strong nuclear force and that quarks had exchange particles called **gluons**. According to the theory, the exchange of gluons of color in the interactions between quarks was the real source of the strong force, not the mesons, as originally proposed by Yukawa. However, in the more modern view, there is a problem. The strong force is only supposed to affect particles with “color” charge, and protons and neutrons are “color” neutral. Physicists realized that baryons such as neutrons and protons in the nucleus can overlap. So while the “color” neutral protons and neutrons do not interact with each other, their quarks do. Therefore, there are two categories of strong force. While the **fundamental** strong force acts within hadrons to hold the quarks together, the **residual** strong force occurs through the exchange of gluons between quarks in different protons and neutrons. This residual interaction “glues” the nucleus together. It is similar to how neutral atoms bind together to make molecules. The diagram to the right represents the exchange of gluons that take place between quarks within a helium nucleus consisting of 2 protons and 2 neutrons.



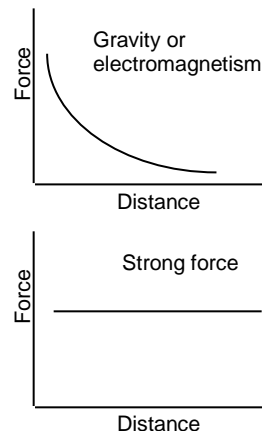
Thus, there are three kinds of **charge**. The first is **electromagnetic** charge which manifests as (+) and (–) and is mediated by photons. The second is **color** charge which manifests as eight types of gluons that mediate the strong force. The third is **weak** charge that manifests in the weak nuclear force and is mediated by  $W^+$ ,  $W^-$  and  $Z^0$  bosons.

### III. No individual quarks (optional)

One might expect that blasting two protons together would produce a shower of quarks – they ought to be easy to generate and easy to identify, and yet their shyness proved a continuing impediment to the acceptance of the theory. No free quark has ever been observed. Accordingly, theoreticians have made a case for **quark confinement**. If a quark is somehow pulled away from its neighbours, the field of the strong force “stretches” between the quarks. Like a rubber band being stretched, more and more energy goes into the field as the quarks are pulled apart. When there is enough energy in the field, the energy will be converted into a new quark-antiquark pair – i.e. a meson emerges. Energy is still conserved because the energy in the field was converted into the mass of the new quarks. In addition, the field of the strong force has returned to its ground state. Thus, quarks cannot exist individually. The contention that free quarks cannot exist is not entirely convincing (it certainly wasn't in the early 1970s).

Quark confinement demonstrates the equivalence of mass and energy discovered by Einstein. The mass of a particle made of quarks not only comes from the mass of the individual quarks, but also from their kinetic energy. In a proton, only 1.3% of its mass comes from the mass of the three quarks. (This is quite different from the mass deficit idea where a nucleus has less mass than its constituents.) Since the quarks in a proton or neutron have plenty of available kinetic energy, how are they bound? How come they cannot escape the proton?

For gravity and electromagnetism, as masses or charges are pulled apart the force between them decreases as the square of the distance. Less and less work needs to be done to separate the masses or charges as they are pulled further apart.



Since the strong force (unlike gravity and electromagnetism) remains constant as quarks within a proton separate, more and more work must be done. Thus, a quark can never get free.

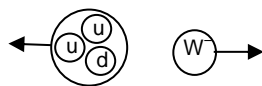
## IV. Neutron decay revisited

In scientific progress, old ideas are seldom completely replaced, but their range of applicability is seen to be restricted. Such was the case with the idea of neutron decay. As we saw in Lesson 36, a neutron can decay into a proton, electron, and electron antineutrino. But when physicists determined that the neutron is composed of quarks, one up quark and two down quarks, they realised that the neutron itself was not decaying, but rather one of the quarks was decaying. Neutron beta decay is when a neutron (udd) decays into a proton (uud), an electron, and an electron antineutrino.

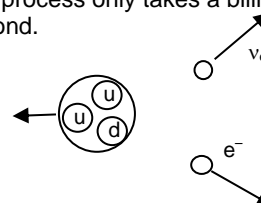
The neutron is a chargeless particle composed of one up quark and two down quarks.



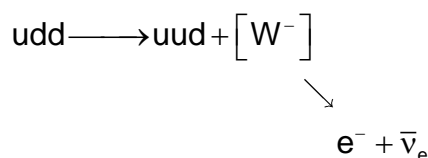
When the decay occurs, one of the down quarks transforms into an up quark. Since the down quark has a charge of  $-1/3$  and the up quark has a charge of  $+2/3$ , charge must be conserved. This is done through the release of a virtual  $W^-$  boson.



The neutron has now become a proton. As the virtual  $W^-$  particle rebounds away from the proton, it transforms into an electron and electron antineutrino. The proton, electron, and antineutrino all move away from one another. In reality, this entire process only takes a billionth of a billionth of a second.



The decay of a neutron can also be represented as a quark decay:



Refer to Pearson pages 845 to 849.



## V. To quark or not to quark? (optional)

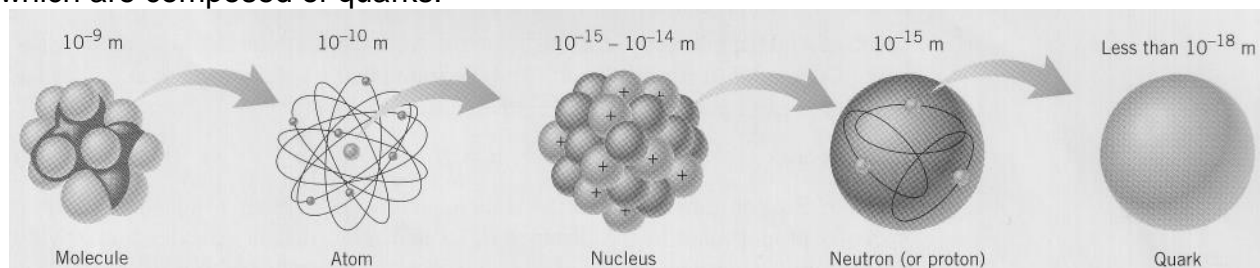
Are quarks fundamental? With the current generation of accelerators, we have found no evidence for structure or constituents within quarks. One way to look is to collide protons head-on at extremely high energies. If quarks had smaller constituents inside them, the resulting particles would more often fly out at larger angles. So far, the study of these collisions establishes that the quark is fundamental to a tiny scale,  $10^{-19}$  m. But one does not know if quarks are fundamental. Only future investigations through experiments at new, more energetic colliders like the Large Hadron Collider will reveal this secret of nature.

In the 1970s and early 1980s, scientists found that the fundamental particles are the quarks and the leptons. Of the former fundamental triad – proton, neutron, and electron – only the electron survives as fundamental. The question arises, "What importance do quarks have to the materials we use in the everyday world?" The only leptons we need are the electron and its companion neutrino, to explain the weak interactions. The up and down quarks are needed to form the protons and neutrons in atomic nuclei. The muon and its neutrino, and the strange quark, only appear in the high-energy world of cosmic rays, high above the Earth; they have no role in the ordinary world at the Earth's surface. Similarly, the charm, top and bottom quarks only appear in the explorations of particle accelerators. And so it seems that the quarks do not have much relevance for us.

## VI. The standard model (optional)

The various elementary particles that have been discovered can interact via one or more of the four fundamental forces: the gravitational force, the strong nuclear force, the weak nuclear force, and the electromagnetic force. In particle physics, the phrase "the standard model" refers to the currently accepted explanation for the strong nuclear force, the weak nuclear force, and the electromagnetic force. In this model, the strong nuclear force between quarks is described in terms of the concept of color charge, the theory being referred to as quantum chromodynamics. And according to the standard model, the weak nuclear force and the electromagnetic force are separate manifestations of a single even more fundamental interaction, referred to as the **electroweak interaction**.

In the standard model, our understanding of the building blocks of matter follows the pattern illustrated in the figure below. Molecules, such as water ( $\text{H}_2\text{O}$ ) and glucose ( $\text{C}_6\text{H}_{12}\text{O}_6$ ), are composed of atoms. Each atom consists of a nucleus that is surrounded by a cloud of electrons. The nucleus, in turn, is made up of protons and neutrons, which are composed of quarks.



## VII. Hand-In Assignment

1. In the early 1900s, which three subatomic particles were thought to be the fundamental building blocks of matter? Which of these particles is still thought to be fundamental?
2. Why was the quark theory first proposed? Outline the experimental evidence that supports this theory. Explain why the standard model now includes six quarks instead of the three originally suggested by Gell-Mann and Zweig.
3. Identify a major difference that distinguishes
  - (a) leptons from hadrons
  - (b) mesons from baryons
  - (c) fermions and bosons
4. What experimental evidence suggests that the proton contains three smaller particles?
5. Why do physicists require extremely high energy particles for studying the structure of nucleons?
6. Why is it probably impossible to observe an individual quark on its own?
7. Compare the quark composition of a proton to that of a neutron.
8. Describe the difference between mesons and baryons in terms of quarks.
9. Using quark theory, write an equation for the beta decay of a neutron. Show that charge is conserved in this decay process.
10. Is the beta decay  $\mu^+ \longrightarrow e^- + \nu_e + \bar{\nu}_\mu$  possible? Justify your answer.
11. What is the advantage of using units of  $\text{MeV}/c^2$  to express the mass of subatomic particles?
12. Describe an experiment that provided evidence for the existence of quarks.
13. Why did physicists suspect that there might be a sixth quark? What is the name of this sixth quark? Why was a huge accelerator necessary for the discovery of this quark?
14. Determine the charge on a particle having the quark composition uus.