Section 15 - Particle Physics

"Forsan et haec olim meminisse iuvabit?"

Virgil, Aeneid

From your grade school education, you may have come away with the notion that there are three types of particles: protons, neutron, and electrons. At the moment, it is thought that there are thirty-eight *fundamental particles*,[1] and the proton and neutron are actually not among them. There are over a hundred *composite particles*, those composed of combinations of fundamental particles. Particles can be classified in a number of ways, such as by charge or spin or mass, but also by a number of properties that are inferred from the possibility (or impossibility) of particular reactions. Obviously, particle physics is a very complicated field, but at this stage in your education, it is to some degree an exercise in accounting. As we have seen before, there are certain quantities that are conserved in closed systems, such as charge or momentum. In this section, we'll see that there are many such rules. And, just like many of the rules we've discussed for these three semesters, you'll eventually find out that there are exceptions.

Anti-matter

Yes, there really is such a thing. In 1932, the *anti-electron*[2] was discovered, a particle virtually identical to the electron except positively charged. Discoveries of the *anti-proton* and *anti-neutron* followed in the 1950s. As was hinted earlier in these notes, a collision of a particle with one of its anti-particles results in *annihilation* of both and the release of high energy gamma rays to carry away the particles' energies and momentums, including their relativistic rest masses. Similarly, high energy gamma rays may sometimes spontaneously create a pair of particles. [3]

One of the mysteries of modern physics is why there seems to be more matter in our universe than anti-matter.

Beta Decay

Beta rays were discovered at the turn of the last century as an emission from radioactive material, and were quickly shown to be electrons. This process *transmutes* the nucleus into one with about the same mass but with the next higher value of Z. We might say naïvely that a nuclear neutron changes into a nuclear proton and an electron (e- or β-), which then escaped:

$$\mathrm{n}^0 \rightarrow \mathrm{p}^{+1} + \mathrm{e}^{-1} \ .$$

Later, an analogous process was discovered that reduces the atomic number by one with the release of an anti-electron (e+ or β+):

$$\mathrm{p}^{+1} \rightarrow \mathrm{n}^0 + \mathrm{e}^{+1} \quad .$$

[1] One of these has not actually been observed yet. And, there may actually be more to come!
[2] The anti-electron is more usually called a *positron*.
[3] A bar over the symbol of a particle indicates that it is an 'anti-particle.'

The latter reaction <u>does</u> require that additional energy be supplied; put very simplistically, there must be enough to create an anti-electron plus enough to provide the small increase of the mass of the neutron over that of the proton and electron.

$$E_{REQUIRED} = 939.565415 + 0.510999 - 938.272088 = 1.804 \text{ MeV} \ .$$

DISCUSSION 15-1

Which of these two decay processes is more likely to occur spontaneously? Is your response consistent with known decay lifetimes?

Particle	Half-life
Free Proton	$>5.3\times10^{41}$ seconds
Free Neutron	880 seconds

HOMEWORK 15-1

At approximately what temperature would there be enough thermal energy to effect transmutation of a proton into a neutron? This was the temperature of the universe about one second after the Big Bang (well, give or take a bit).

DISCUSSION 15-2

So it seems that today, at a temperature of about 290K, we should never observe the decay of an isolated proton. Yet, we <u>do</u> see proton β+ decay when that proton is within a nucleus. What provides that 1.8 MeV of energy? Should we see a similar restriction for β- decay?

Let's examine beta decay a bit more, but with a different goal in mind.

EXAMPLE 15-1

Bismuth 210 undergoes β- decay to become polonium 210. That is, overall, a neutron converts to a proton and an electron is released. There are a number of problems with this scenario. First, let's consider the energy available to the electron as it exits.

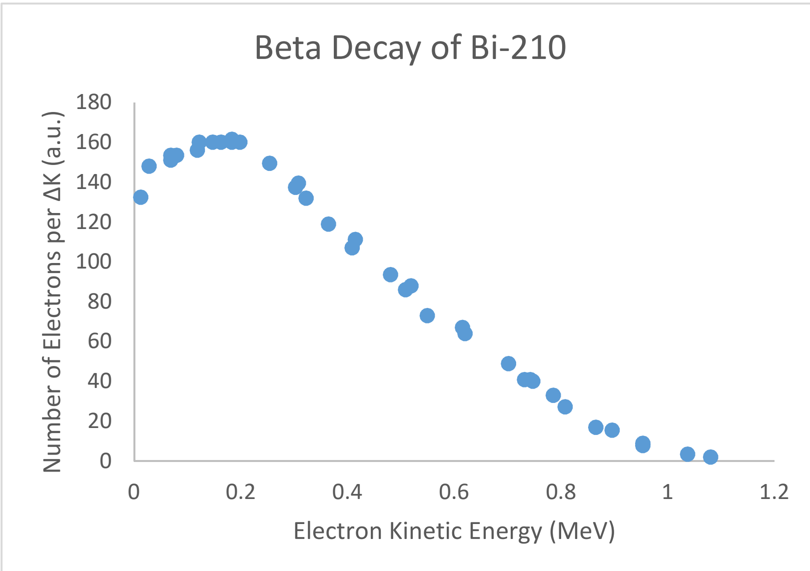
We'll need to look up the nuclear masses of Bi-210 and Po-210.

	Atomic Mass (Da)	Subtract Electrons	Nuclear Mass (Da)
Bi-210	209.9841204	$- 83 \times 0.00054858$	= 209.938588
Po-210	209.9828737	$- 84 \times 0.00054858$	= 209.936793

$$\Delta mc^2 = (209.938588 - 209.936793 - 0.00054858) * 931.5 = 1.1611 \text{ MeV}$$

This energy gets split unevenly between the polonium and the electron. Since this energy is larger than the rest energy of the electron (1.8 MeV > 0.511 MeV), we should count its motion as relativistic. On the other hand, since the mass of the polonium is several hundred thousand times the mass of the electron, I'm going to go out on a limb here and say that almost all of this energy should go into the electron.

Our prediction, then, is that every electron emitted as beta radiation from a Bi-210 nucleus should have energy ~ 1.16 MeV, similar to the case for alpha particles. Here's what actually happens: [4]



While the very fastest electrons have a kinetic energy of about 1.16 MeV, the majority do not. Although the data are not presented here, the electrons also do not exhibit the predicted momentum characteristic either. This implies that there is at least one more particle created in this process.

We can deduce some of the properties of this new particle. Clearly, it must have no charge. Its mass must be small, or possibly even zero.[5] And, it must have spin ½. This last, of course, is necessary to counter the newly created electron's spin.

The Neutrino

In 1930, Wolfgang Pauli suggested the existence of a new particle, now called the *neutrino*, which would account for the differences between expectations and observations.

$$n^0 \rightarrow p^{+1} + e^{-1} + \bar{\nu}_e \qquad p^{+1} \rightarrow n^0 + e^{+1} + \nu_e \quad .$$

They are very difficult, but not impossible, to detect. The *electron neutrino* wasn't detected experimentally until 1956.

In a previous section, we mentioned the *muon*. Muons are similar to electrons, but with much more mass, and they decay into smaller particles, usually electrons. In 1962, a different type of neutrino was observed associated with this process:

$$\mu^- \rightarrow e^{-1} + \nu_\mu + \bar{\nu}_e \quad .$$

On the other hand, this process is never observed:

[4] INSERT REFERENCE
[5] Current thinking is that the neutrino must have some mass to account for some freaky observations.

$$\mu^{-} \rightarrow e^{-1} + n\,\gamma^{0} \quad .$$

The *mu-neutrinos* are a necessary part of the process.

In 1975, a third type of particle similar to the electron, the *tauon* or *tau particle*, was discovered, along with its associated neutrino. The decay processes of the tau particle are more complicated; because it is so massive, there are more ways in which it can decay.

Let's try to put this all into some type of framework.

Leptons – The Electron's Family.

Let's define a set of particles called *leptons,*[6] which are classified by *generation*. The first is the physicist's friend, the electron, which has charge -1e and is thought to be stable against decay into smaller particles. This seems to be due to the simple fact that there is no known particle less massive than the electron. We've also briefly discussed the muon, with a charge of -1e, more mass than the electron, but with a short lifetime (it decays into particles smaller than itself). Lastly, there is the tau particle, with charge -1e and a very large mass (and correspondingly shorter lifetime). Each such particle has an *anti-particle*, identical except for having positive charge. To complicate matters, each such particle is associated with its proper *neutrino*, a light, neutral particle. Each type of neutrino is distinct, but it is now believed that they may occasionally convert from one type to another.[7]

Generation	Lepton		Neutrino	
1st	electron (e-)	anti-electron (e+)	electron neutrino (ν_e)	electron anti-neutrino ($\bar{\nu}_e$)
2nd	muon (μ-)	anti muon (μ+)	muon neutrino (ν_μ)	muon anti-neutrino ($\bar{\nu}_\mu$)
3rd	tauon (τ-)	anti-tauon (τ+)	tau neutrino (ν_τ)	tau anti-neutrino ($\bar{\nu}_\tau$)

The idea here is that we are going to develop some rules based on what reactions are observed and what reactions are not observed so that we may be able to make some predictions. Each generation of lepton has some property that, from observation, we assume must be conserved in a reaction. These properties are called *lepton number*, and there are three kinds: *electron lepton number*, L_e, *muon lepton number*, L_μ, and of course, *tau lepton number*, L_τ. Each lepton and its associated neutrino has a value of +1 for its own number, and zeros for the other two. Anti-particles have corresponding values of -1. Explicitly:

Lepton	L_e	L_μ	L_τ		mass	half-life
e-	+1	0	0		9.11×10^{-31} kg	$> 2.1\times10^{+36}$ s[8]
e+	-1	0	0		9.11×10^{-31} kg	$> 2.1\times10^{+36}$ s
μ-	0	+1	0		1.88×10^{-28} kg	2.2×10^{-6} s
μ+	0	-1	0		1.88×10^{-28} kg	2.2×10^{-6} s

[6] The word comes from the Greek for 'small' or 'light' in terms of their masses.
[7] We're going to ignore that fact.
[8] So, maybe forever?

τ-	0	0	+1		3.16×10^{-27} kg	2.9×10^{-13} s
τ+	0	0	-1		3.16×10^{-27} kg	2.9×10^{-13} s
ν_e	+1	0	0		$< 1.25\times10^{-37}$ kg	
$\bar{\nu}_e$	-1	0	0		$< 1.25\times10^{-37}$ kg	
ν_μ	0	+1	0		$< 1.25\times10^{-37}$ kg	
$\bar{\nu}_\mu$	0	-1	0		$< 1.25\times10^{-37}$ kg	
ν_τ	0	0	+1		$< 1.25\times10^{-37}$ kg	
$\bar{\nu}_\tau$	0	0	-1		$< 1.25\times10^{-37}$ kg	

Note that the negatively charged particles have positive lepton number values.

EXAMPLE 15-2

Electrons are long lived due to the fact that there are no lighter particles into which it can decay. The tau particle however can decay in any of a large number of ways. Consider the process whereby the tau decays into an electron. What other particles are created?

$$\tau^- \to e^- + ?$$

The left side of the equation has charge -1 and $L_\tau = +1$. We need a particle on the right that also has $L_\tau = +1$ with q = 0, and the candidate is ν_τ. At the same time, L_e is zero on the left but +1 on the right, so we need another neutrino to take care of that.

$$\tau^- \to e^- + \nu_\tau + \bar{\nu}_e \quad .$$

Or, maybe a bit more organized,

	τ^-		e^-	ν_τ	$\bar{\nu}_e$
Q	-1		-1	0	0
L_e	0		+1	0	-1
L_μ	0		0	0	0
L_τ	+1		0	+1	0

The idea is to get all conserved quantities to balance on each side of the reaction, a bit like stoichiometry problems in Chemistry.

HOMEWORK 15-2

Consider an anti-tau particle that decays to an anti-muon. Find the other particles produced.

The Mesons

It has been suggested that that electromagnetic interactions between charges are actually due to exchanges of short-lived photons between the charges. Since photons have no mass, they would be capable of transmitting electrical forces over large distances. This is the basis of what is now called *quantum electrodynamics* (QED).

Yukawa suggested that the nuclear force that causes nucleons to attract each other may also be carried by a then unknown intermediate particle. These have retroactively been named *mesons*. Let's investigate.

We know that the nuclear force does not extend far outside of the nucleus itself from the Geiger-Müller alpha-scattering experiment. This implies that the meson has some mass, otherwise the range of the nuclear force would be much larger, as for photons. We should be able to make a rough estimate of the mass.

EXAMPLE 15-3

Estimate the mass of a meson carrying the nuclear force. We'll make use of the Heisenberg uncertainty principle,

$$\delta E \, \delta t \geq \frac{\hbar}{2} \ .$$

When a nucleon emits a meson, it creates mass, and therefor a surplus energy of $m_M c^2$. This is normally not allowed, of course, but the uncertainty principle suggest that it might be possible if the meson exists for a short enough time. Let's set $\delta E = m_{Meson} c^2$. Next, let's estimate the necessary lifetime of the meson. In the last Section, we estimated the distance between adjacent nucleons' centers to be about 1.2 fm. We also assumed that the nuclear force has a range short enough so that only nearest neighbors attract. If we assume that mesons travel at or near the speed of light, the shortest possible time a meson could make the trip from one nucleon to its neighbor would be on the order of

$$t > \frac{d}{c} = \frac{1.2 \times 10^{-15}}{3 \times 10^{8}} = 4 \times 10^{-24} \text{ seconds} \, .$$

The time could of course be longer, so we will use this as the minimum uncertainty in the time, δt.

Then,[9]

$$\delta E_{\text{Meson}} \, \delta t = (m_M c^2)\left(\frac{d}{c}\right) < \frac{\hbar}{2} \quad \rightarrow \quad m_M < \frac{\hbar}{2dc} = \frac{1.055 \times 10^{-3}}{2(1.2 \times 10^{-15})(3 \times 10^{8})}$$
$$= 2 \times 10^{-28} \text{ kg} \ .$$

This corresponds to a rest energy of about 100 MeV. Remembering that the rest energy of an electron is about 0.5 MeV and that of a nucleon is 933 MeV, the meaning of the name becomes clear; it is an intermediate mass particle.[10] Oddly, the experimental search for this particle did not find it, but instead found the muon with a mass of about the same value. It was not until the late 1940s that charged mesons were discovered in cosmic rays, and a neutral meson was created in a

[9] The inequality sign reverses because we don't want to be able to detect these events. We want them within the uncertainty.

[10] 'Meso-' is a Greek-root prefix meaning 'intermediate,' in this case in terms again of mass.

laboratory in the early 1950s, with approximately the predicted masses. These particular mesons are now called *pions*:

Particle	Mass	Half-life
π^+	140 MeV	2.6×10^{-8} seconds
π^-	140 MeV	2.6×10^{-8} seconds
π^0	135 MeV	9×10^{-17} seconds

The 'mu-meson' it turns out is not actually a meson, and so no one calls it that anymore.

There are other types of mesons as well. Here are a few:

Particle	Mass	Half-life
K^0	497.6 MeV	
K^+	493.7 MeV	1.2×10^{-8} seconds
η	548.8 MeV	$<10^{-18}$ seconds

The Baryons

Let's return to beta decay for a moment. We discussed a mechanism by which a nuclear neutron can convert to a nuclear proton, and a similar process for the reverse. When a neutron is studied by itself outside of the nucleus, the same reaction is observed. The only such decay ever observed is

$$n^0 \rightarrow p^{+1} + e^{-1} + \bar{\nu}_e \ ,$$

that is, a proton is always produced. This reaction, which we may well think meets our conservation rules, is never observed:

$$n^0 \rightarrow \pi^{+1} + e^{-1} + \bar{\nu}_e \ .$$

We postulate then, that there is another conservation rule that must be followed, satisfied by a proton but not by a +pion. After studying a number of reactions, we conclude that neutrons, protons, *lambda particles*, *sigma particles*, and a quite a number of other particles behave similarly. Since these particles are relatively heavy, we call then *baryons*. Like the generations of leptons, we will assign a *baryon number* to the particles, which must be conserved in any reaction.[11]

Particle	Baryon Number B	Mass	Half-life
Proton p^+	+1	938.3 MeV	$>10^{41}$ seconds
Neutron n^0	+1	939.6 MeV	930 seconds
Lambda particle Λ^0	+1	1116 MeV	2.5×10^{-10} seconds
Sigma plus particle Σ^+	+1	1189 MeV	8×10^{-11} seconds
Sigma particle Σ^0	+1	1192 MeV	$<10^{-14}$ seconds

[11] Let's be clear. This is to say that if a reaction occurs, we assign baryon numbers so that the total is conserved, and if a reaction does not take place, we assign values so that the total is not conserved.

Sigma minus particle Σ^-	+1	1197 MeV	1.5×10^{-10} seconds

Anti-particles have a baryon number of -1. Non-baryons, such as leptons, photons, and mesons, have a baryon number of zero.

Let's re-examine the two previous reactions:

	n^0		p^+	e^{-1}	$\bar{\nu}_e$	
Q	0		+1	-1	0	Balanced
L_e	0		0	+1	-1	Balanced
L_μ	0		0	0	0	Balanced
L_τ	0		0	0	0	Balanced
B	+1		+1	0	0	Balanced

	n^0		π^+	e^{-1}	$\bar{\nu}_e$	
Q	0		+1	-1	0	Balanced
L_e	0		0	+1	-1	Balanced
L_μ	0		0	0	0	Balanced
L_τ	0		0	0	0	Balanced
B	+1		0	0	0	Unbalanced

HOMEWORK 15-3

Generate a table similar to the ones above to confirm that the following reaction is possible:

$$\pi^- \rightarrow \mu^- + \bar{\nu}_\mu \quad .$$

HOMEWORK 15-4

In a nucleus, a proton can change to a neutron through this reaction:

$$\mathrm{p}^{+1} \rightarrow \mathrm{n}^0 + \mathrm{e}^{+1} + \nu_e \, .$$

However, isolated protons do not decay (there are no lighter particles into which it could decay). Why is there a difference between the proton being solitary or within a nucleus?

What?! Another Rule?

The following reaction happens:

$$\pi^- + \mathrm{p}^+ \rightarrow \mathrm{K}^0 + \Lambda^0 \; .$$

This one does not:

$$\pi^- + \mathrm{p}^+ \rightarrow \mathrm{K}^0 + \mathrm{n}^0 \; .$$

HOMEWORK 15-5

Generate a table for each of these reactions to confirm that they <u>should</u> be possible.

Since charge, baryon number, and the three lepton numbers are conserved in both of the reactions above, there must be yet another rule we haven't sussed out yet, some property that some of these particles possess that others don't. We will call this property *strangeness*, S.[12] Let's assign a value of S = +1 to the K^0 and S = -1 to the Λ^0. Then,

	π^-	p^+		K^0	Λ^0	
S	0	0		+1	-1	Balanced

	π^-	p^+		K^0	n^0	
S	0	0		+1	0	Unbalanced

Of course, we would need to justify this assumption by examining many, many different reactions and test for consistency. Leptons apparently do not possess strangeness; the property is restricted to baryons and mesons.

Particle	Strangeness
Λ^0, Σ^0, Σ^+, Σ^-	-1
p^+, n^0, π^0, π^-, π^+, Δ^0	0
K^0	+1

Strangeness of anti-particles is of course reversed.

As more and more particles were discovered, several more such properties were developed to account for the viability or non-viability of various reactions. We won't cover those.[13]

HOMEWORK 15-6

Which of the following reactions are possible and which are not? If the reaction is not allowed, which conservation rule or rules does it violate?

A) $p^+ + p^+ \rightarrow p^+ + p^+ + \pi^0$

B) $\Lambda^0 \rightarrow p^+ + \pi^-$

C) $p^+ + p^+ \rightarrow n^0 + \Sigma^+ + K^0 + \pi^+$

The Quark Model

It appears that, with the possible exception of the leptons, all of our particles are composite, that is, their inner bits can be exchanged with those of other particles to make new particles. In the example above, a meson and a baryon combine to produce a different meson and a different baryon: $\pi^- + p^+ \rightarrow K^0 + \Lambda^0$. The model that is often applied to mesons and baryons is the

[12] Don't confuse this with spin, $\vec{S}$. In older textbooks, this property is called 'sideways.' Baryons that possess strangeness are called *hyperons*.

[13] These properties are named *charm*, *truth*, and *beauty*, although the latter two are usually referred to as top and bottom.

quark model. Appropriate combinations of these quarks should account for the properties of charge, baryon number, strangeness, and spin, as well as a few others we are omitting.

Consider three types of quarks, called *flavors*,[14] called *up*, *down*, and *strange*. They possess the following properties:

	u	d	s
Q	+2/3	-1/3	-1/3
B	+1/3	+1/3	1/3
S	0	0	-1
spin	1/2	1/2	1/2

Anti-quarks (anti-up, anti-down, and anti-strange)[15] have opposite values.

Spin is a little tricky, but we've discussed how nucleons would like to align antiparallel if possible, so a combination of three quarks would be usually be expected to have spins +½ – ½ + ½ = +½.

EXAMPLE 15-4

Let's find the quark composition of a proton. The proton has Q = +1, B = +1, S = 0 and spin = ½.

Try uud.

	u	u	d		p+
Q	+2/3	+2/3	-1/3		+1
B	+1/3	+1/3	+1/3		+1
S	0	0	0		0
spin	1/2	(-)1/2	1/2		1/2

EXAMPLE 15-5

Find the quark composition of the anti-sigma minus particle, $\bar{\Sigma}^-$ with properties Q = +1, B = -1, and S = +1.[16] If you can't work it out by sight, you can do this more mathematically.

$\bar{\Sigma}^-$ = Xu + Yd + Zs, where X, Y, and Z are the number of each type of quark.

$X(^2/_3) + Y(^{-1}/_3) + Z(^{-1}/_3) = +1$ Charge

$X(^1/_3) + Y(^1/_3) + Z(^1/_3) = -1$ Baryon Number

$X(0) + Y(0) + Z(-1) = +1$ Strangeness

The third equation clearly indicates that Z = -1, *i.e.*, there is one anti-strange quark.

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[14] In the end, there are six flavors. The other three are *charm*, *truth*, and *beauty*.
[15] Anti-up is not down and anti-down is not up. Up and down are completely different particles.
[16] The Σ^- and Σ^+ are not each others' anti-particles.

The other two equations then become

$X(^2/_3) + Y(^{-1}/_3) = +\,^2/_3$ Charge

$X(^1/_3) + Y(^1/_3) = -\,^2/_3$ Baryon Number

Adding these equations results in X = 0, so there are no up quarks.

Then,

$Y(^{-1}/_3) = +\,^2/_3$

tells that Y = -2, there are two anti-down quarks, so the quark composition is $\bar{d}\bar{d}\bar{s}$.[17]

HOMEWORK 15-7

Find the quark composition of the neutron.

Now, back to the mesons. When we introduced strangeness, we assigned values to the K^0 meson and the Λ^0 baryon. And, since we've ascribed strangeness to the existence of the strange quark, we might assume that mesons are also composed of quarks. Since mesons are NOT baryons, there must be an even number of quarks so that their B values cancel to zero. Specifically, then, there must be a quark and an anti-quark to meet this condition. Here is a very short list of mesons.

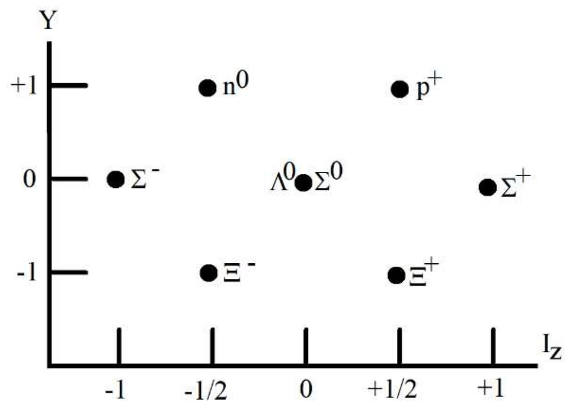
Meson	Composition
π^-	$u\bar{d}$
π^+	$\bar{u}d$
K^0	$d\bar{s}$
K^+	$u\bar{s}$
K^-	$\bar{u}s$

Fun with Graphs

Particle physicists often make use of quantities we have not mentioned that are more useful in the study of quarks. For example, the *hypercharge* Y of a particle is the sum of its baryon number and strangeness:

$$Y = B + S \quad .$$

[17] Unfortunately, this doesn't always work in reverse; knowing the quark composition does not necessarily mean we know the particle. Some particles are 'excited' states of other particles with the same composition.

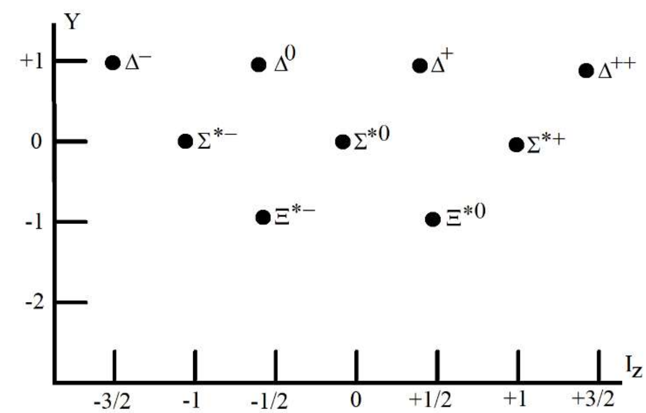


The *isospin* is given by

$$I_z = Q - \frac{Y}{2} = \frac{2Q - B - S}{2} \ .$$

The reason I bring this up is that, when these values are plotted for spin ½ baryons, an interesting pattern emerges. A similar pattern appears when plotting spin zero mesons.

Let's plot spin 3/2 baryons and see what may emerge.



You might notice that something is missing. This particle's existence was predicted in 1961 from nothing other than this graph and the particle itself was observed in 1965.

HOMEWORK 15-8

Determine the baryon number, charge, and strangeness of this 'missing particle.' What is the quark composition?

A Colorful End and Yet Another 'Number'

Our last topic wraps up a lingering problem. Quarks are spin ½ particles, and as such must obey the Pauli exclusion principle, the same rule that dictates that only two electrons can inhabit any one orbital in an atom. A proton would be no problem:

$$u\uparrow \ u\downarrow \ d\uparrow \ .$$

The two up quarks are in different spin states and the net spin is ½ as expected, while the d quark is an entirely different particle.[18] Problems arise with other particles, however, such as the Ω^-, the Δ^-, and the Δ++, which are each spin $^3/_2$ particles. In those cases, all three quark spins must be in the same direction, and since the Δ^- is composed of three down quarks, they must presumably all be in the same state:

$$d\uparrow d\uparrow d\uparrow \ .$$

[18] Think protons and neutrons in the nucleus. A neutron can be in the same state as a proton.

The solution to this conceptual problem is to differentiate the three possible states for baryon quarks with a new quantum 'number,' as was done for orbital electrons. However, the three states are labeled with an analogy to color: *red*, *green*, and *blue*.[19]

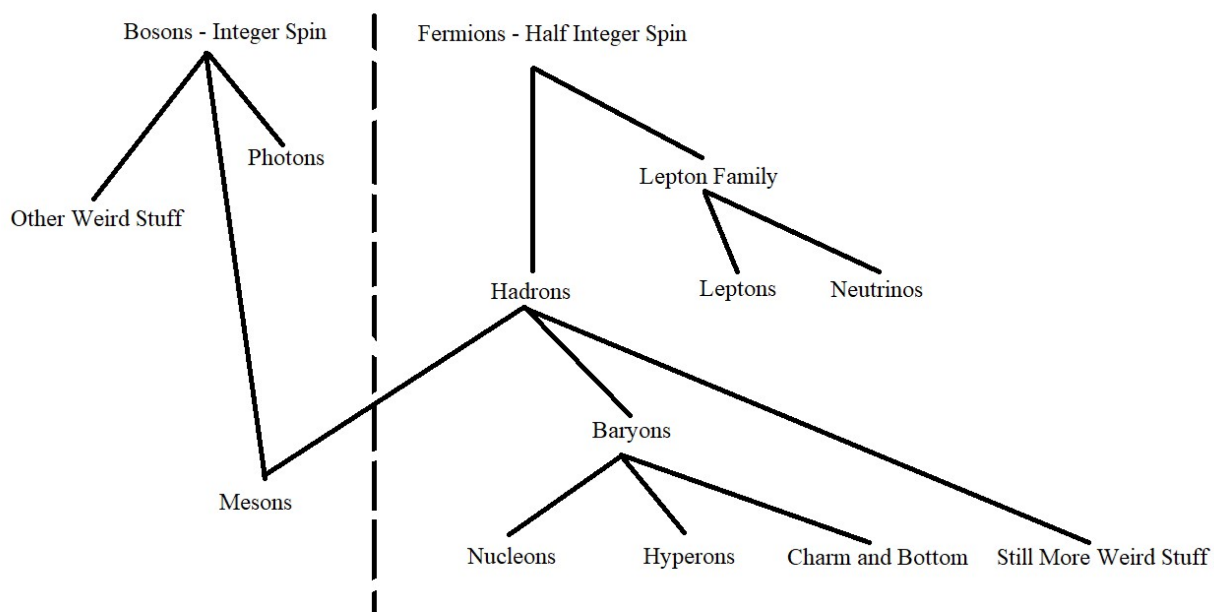
$$d\uparrow d\uparrow d\uparrow \;.$$

These are referred to as the *color charge* of the quarks. Their complementary states are anti-red, anti-green, and anti-blue. The requirement is that any combination of quarks must be 'white.' For baryons, that means either R-G-B or aR-aG-aB. For mesons, the quark states must be R-aR, G-aG, or B-aB.

HOMEWORK 15-9

What is the quark composition of the Δ^{++} baryon?

And, finally, the current thinking is that this color force that binds the quarks together is what we called the nuclear force in previous chapters. As a vague analogy, think of the force leaking out of each nucleon, exerting a small attraction on the quarks in any neighboring nucleons. There are a number of ideas of how this works.



[19] The choice of color as a parameter is not to imply that there are actual colors involved. The choice may as well have been sweet, sour, and bitter, or Coke, Pepsi, and RC, or Kurt, Krist, and Dave.