Steve Smith Tuition: Physics Notes

Particle-opoly!

Contents

Prerequisites

None.

Notes

EXL
OCR-A
AQA-A

In order to try and give you an idea of what topics are required on which A-Level syllabi, I have put indicators in the margin by section headers. So, for example, if you see **this** in the margin, it is designed to indicate that the topic *is* required in the Edexcel syllabus (**green for required**), but *not* required in the OCR-A and AQA-A syllabi (**red for not required**).

The problem I've been having in writing this document, of course, is that in order to tell a coherent story, I've had to talk about things that aren't in any of the syllabi...

A more detailed breakdown of what topics are included on which syllabus can be found in Appendix A.

Another point I'd like to make is that in this document I have not mentioned anywhere anything to do with the history of particle physics. I've only presented a glimpse of the Standard Model as it currently stands. If you want to find out more about the history of particle physics, there are a number of very good books on the subject, such as (Close, 2004), (Hesketh, 2016), or (Ne'Eman et al., 1996).

Document History

Date	Version	Comments
5 May 2017	1.0	Initial creation of the document.

References

Close, F. (2004). *Particle Physics: A very Short Introduction*. OUP Oxford.

Hesketh, G. (2016). *The Particle Zoo*. Quercus.

Ne'Eman, Y., Kirsh, Y. et al. (1996). *The Particle Hunters*. Cambridge University Press.

Smith, S. (2017a). Particle Decays.

Smith, S. (2017b). Playing Particle-opoly!

1 Getting Ready to Play...

Before we start to learn how to play *Particle-opoly*, I have to mention a few really weird things that you need to know about. If you thought that opening a tin of baked beans with nothing but a banana was difficult, well, that's nothing to trying to understand this stuff. So hold on to your hat...

1.1 de Broglie's Formula

EXL
OCR-A
AQA-A

In 1905 Einstein published a paper that explained the observations from experiments on the photoelectric effect. Up until that point, light was considered to be *waves*. Unfortunately, Einstein showed that the only way of explaining the results of the photoelectric effect experiments was to consider light to be made of particles (which we now call *photons*), each carrying an energy given by

$$E = hf \tag{1}$$

h is a constant, with a value of $\approx 6.6 \times 10^{-34}$ J s.

This was the start of modern physics, as it was realised that sometimes things behave like particles, and sometimes they behave like waves. Light can be shown to act like particles (such as in the photoelectric effect experiments), and sometimes like waves (in Young's double-slit experiment, for example). Similarly, things we've always thought of as particles, like electrons, say, can exhibit wave behaviour too! Electrons were used in Young's double slit experiments, and yes, diffraction patterns resulted. So particles can behave like waves. Mad.

In 1923, de Broglie submitted a PhD thesis, which had one idea in it. That idea is, *what if*:

$$mv = \frac{h}{\lambda} \tag{2}$$

On the left of this equation we have *mass*, m and *velocity*, v (and when you multiply m and v you get a quantity called *momentum*). Standard particle-like stuff. On the right hand side of the equation is *wavelength*, λ. Now you can't get much more wave-y than a wavelength.

So essentially, de Broglie was saying that:

$$\text{a particle} \equiv \text{a wave}$$

and Equation (2) shows you how to convert information from one form of the thing to the other. h being the same constant as in Equation (1).

de Broglie gave no proof of Equation (2). There is is no derivation. No theory underpinning the equation. It just works, so we use it.

The significance of Equations (1) and (2) for us in this document is that *photons have energy, and photons have momentum*.

1.2 Einstein's Mass-Energy Equivalence Thingy

EXL
OCR-A
AQA-A

Particles have their own associated mass, which is measured in kg. Physicists seem to prefer to talk about the mass of particles in terms of energy, though. To do that you just use the $E = mc^2$ relationship that Einstein showed us meant that energy and mass were equivalent, and that c^2 is the conversion factor.

So, for example, the mass of a u quark (whatever that is) is often quoted as 2.3 MeV. Why?

The mass of a u quark is actually 4.09×10^{-30} kg. Now that's what I call a proper unit of mass. Kilograms. You can't argue with that!

But because of $E = mc^2$, this mass will have an energy equivalent of

$$\begin{aligned} E &= mc^2 \\ &= 4.09 \times 10^{-30} \cdot (3.0 \times 10^8)^2 \\ &= 3.68 \times 10^{-13}\ \text{J} \end{aligned}$$

Now since the *Joule* is such a big unit of energy for tiny sub-atomic particles, physicists have come up with another (profoundly non-metric!!) unit of energy: the *electron-volt* (symbol *eV*). What is an electron-volt? Well, the definition of an electron-volt is

$$1 \text{ eV} \equiv 1.6 \times 10^{-19} \text{ J}$$

So that means that the mass of our u quark would be

$$\begin{aligned} E &= 3.68 \times 10^{-13} \text{ J} \\ &= \frac{3.68 \times 10^{-13}}{1.6 \times 10^{-19}} \text{ eV} \\ &= 2300000 \text{ eV} \\ &= 2.3 \text{ MeV} \end{aligned}$$

or 2.3 million electron-volts, in energy units.

So 2.3 MeV is the *energy equivalent* of the mass of the u quark. Sometimes you see the mass of a thing expressed as 2.3 MeV/c^2 (so that it includes the mass→energy conversion constant). But the mass of something being written as 2.3 MeV and 2.3 MeV/c^2 mean the same thing. Physicists are just lazy when they say that the mass of a u quark is 2.3 MeV. Well, that's certainly not confusing at all, is it??

1.3 Particles and Anti-Particles

EXL
OCR-A
AQA-A

Before we can talk about particle annihilation and creation, we need a definition of an anti-particle.

Every particle has an anti-particle. Particles and their anti-particles have the same mass, but they have *opposite charges*. So, for example, and electron and a positron are anti-particles.

One thing that I didn't understand (until I learned about quarks) was that: by this definition of anti-matter, how on earth can there be an anti-neutron? I mean, if a particle has zero charge, how can it have an anti-particle?? This, I hope, will be answered later...

Some particles, like the photon, are their own anti-particles. That's quite interesting!

1.4 Particle Annihilation and Creation

EXL
OCR-A
AQA-A

After the discussion about particles and anti-particles, we can talk about particle annihilation. And you may have come across the idea of particle annihilation already: it's where you get two particles coming together, one a particle and the other its anti-particle, and when they meet, they destroy each other and completely convert their mass to energy (in the form of photons)[1]. The amount of energy the mass is converted into will be given by $E = mc^2$, of course.

For example, if we have an electron and a positron meeting,

$$e^- + e^+ \rightarrow 2\gamma$$

they can destroy each other to produce two γ photons, which carry away the energy-equivalent of the mass of the two particles.

The reverse of this process also occurs. If you have a photon of *exactly* the right energy, then this could happen:

$$\gamma \rightarrow e^- + e^+$$

The mass for the new particles coming from the energy of the photon, according to $E = mc^2$.

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[1] Interestingly, there are always *two* photons created in this process. That turns out to be in order to conserve the momentum of the "collision".

1.5 Heisenberg's Uncertainty Thingy

EXL
OCR-A
AQA-A

To be precise, this is actually called Heisenberg's Uncertainty *Principle*. But because no-one can be quite sure what it's called (because it's a bit uncertain), I'm going to call it Heisenberg's Uncertainty Thingy (or *HUT* for short).

So...what is *HUT*?

Well, as far as we are concerned in this document, *HUT* boils down to this kind-of-equation:

$$\Delta E \times \Delta t \approx \frac{h}{2\pi} \tag{3}$$

But what are all these symbols, and what does it all mean?

Well, as for the symbols: ΔE means *a change in energy*. Δ always means *change in* in physics and maths. So Δt means a change in time. h is known as Planck's constant, and has a value of 6.626×10^{-34} J s, which is pretty small. We've seen this h thing before, somewhere, haven't we? Now where was that...?

Now, what does this equation tell us?

Let's take an example. Let's say that at some point in space, there was currently *no energy*. Now what *HUT* tells us, via equation (3), is that it is possible to create a small amount of energy, *out of nothing*, if it was only to last a small amount of time.

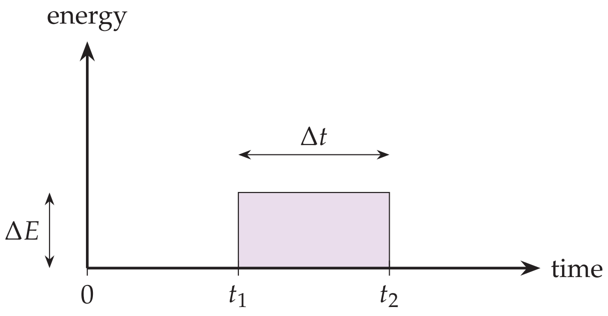

Figure 1: Heisenberg's Uncertainty Thingy

Check out Figure 1.

We start off, at $t = 0$, with no energy. Time rolls inexorably on, until we get to $t = t_1$.

Suddenly, an amount of energy appears! Wow! Out of nothing! Wow!! And it stays there until we get to $t = t_2$, where, just as suddenly, it disappears again! Wow!!!

Weird? Absolutely. This sort of thing can't possibly happen, can it? Absolutely. It does. All the time.

If you find that hard to swallow, how about this perfectly reasonable alternative explanation. How can you *not* understand this: at $t = t_1$, the small amount of energy ΔE is borrowed *from the future*, and then *paid back* when we get to $t = t_2$. Ah! that clears it all up.

And of course, because of equation (3), the more energy we borrow, the smaller the time we can borrow it for. For example, let's say that we wanted to borrow 80 GeV. That's 80 *giga* electron-volts. Yes: 80×10^9 electron-volts. How much time can we borrow this for?

Well, from (3)

$$\begin{aligned}\Delta t &\approx \frac{h}{2\pi\Delta E}\\ &\approx \frac{6.626 \times 10^{-34}}{2\pi \cdot 80 \times 10^9 \cdot 1.6 \times 10^{-19}} \text{ (converting the energy into Joules)}\\ &\approx 8 \times 10^{-27} \text{ s}\end{aligned}$$

Not very long.

The thing is though, now it is possible to borrow an amount of energy for a short while, what can we do with it? Well...

1.6 Spontaneous Particle Creation

EXL
OCR-A
AQA-A

Now because of *HUT*, there is another way to produce particles. Because of this borrowing-energy-out-of-nowhere thing, we can borrow a bit of energy, turn it into mass (using $E = mc^2$ of course) and make a particle out of it!

The only problem with this is that the particle won't be able to last very long.

Remember the example from earlier? Let's say that there was a particle that had a mass of 80 GeV. Let's call it a W^- boson. Stupid name, I know. But hey. Then if we wanted to create one of these things, we could just borrow the 80 GeV from the future, and create our own W^- boson! Out of nothing! Bargain!

The only problem is that we wouldn't have very long at all to play with it. We'll have to give it back after only 8×10^{-27} s. Hardly enough time to make friends...

1.7 Quantum Numbers

EXL
OCR-A
AQA-A

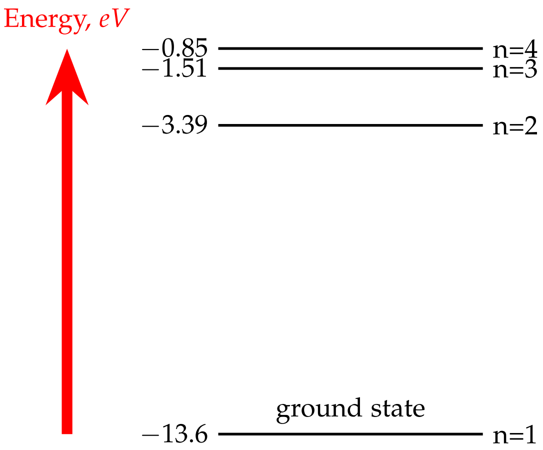

Figure 2: Electron Energy Levels in Atoms of Hydrogen

Quantum numbers are just important characteristics that particles have. Do you remember Bohr's idea that electrons can only exist in particular energy levels within atoms of Hydrogen (see Figure 2)?

Well, the values of n for the electrons (their energy level) is one of the quantum numbers that electrons can have when they're inside atoms.

There are others: charge, for example, is another. Particles can have different values of a set of quantum numbers. And these quantum numbers essentially tell you everything you want to know about a particle.

In fact, the big problem that physicists have had over the years is to discover what all the quantum numbers for particles were. This quest is essentially the same as discovering the rules of the game that we are playing here.

In this document we are concerned with particles in the nuclei of atoms, and not flying around the outside of the nucleus. It turns out that the set of quantum numbers that nuclear particles have that we are interested in are:

- charge, Q
- lepton number, L
- baryon number, B
- strangeness (!!), S
- colour (!!!), C

Don't worry abut what all these things are yet. I'll introduce them later.

1.8 Pauli's Exclusion Thingy

EXL
OCR-A
AQA-A

To be slightly less uncertain, this is actually called Pauli's Exclusion *Principle*, but I think *PET* sounds a bit better than *PEP*. It makes me think of something soft, warm and furry.

Wolfgang Pauli came up with this idea in 1925.

And here is the idea: In any system[2], no two particles can have the same set of quantum numbers.

It's a bit like the rule that at a party, no two women are allowed to have the same hair-do *and* the same dress.

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[2] Whatever that means!

2 ...The Game

Right. Now we have everything in place for me to be able to start to explain how to play *Particle-opoly*. And to do that, we have to learn what pieces we can move around the board, and what the rules of the game are. Let's start with the pieces.

2.1 The Pieces

2.1.1 The Leptons

EXL
OCR-A
AQA-A

Leptons[3] were the first elementary particles to be discovered. J. J. Thompson discovered the electron in 1897. That's before there was conclusive evidence for atoms!

Since then, further leptons have been discovered. It is now thought that there are six of them (and six corresponding anti-particles). Three of them are: the electron e^-, the muon, μ^- and the tauon, τ^-. These particles can all be thought of as just electrons.

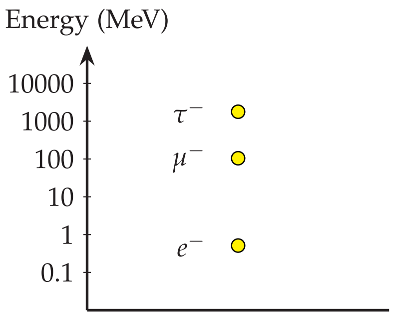

Figure 3: Electron Energies/Masses

The muon and the tauon are just electrons in higher energy levels (or alternatively: electrons with more mass, because that's the same thing, right?). See Figure 3. Note the logarithmic scale up the energy axis!

Associated with these electrons are three other particles called *neutrinos*[4]. Neutrinos have no charge and almost no mass. So, the neutrinos are: the electron-neutrino, ν_e, the muon-neutrino, ν_μ, and the tauon-neutrino, ν_τ.

And of course, just to jazz things up a bit, all these electrons and neutrinos have anti-particles. These are denoted by: e^+, μ^+, τ^+, $\bar{\nu}_e$, $\bar{\nu}_\mu$ and $\bar{\nu}_\tau$.

Table 1 shows all the leptons, together with their quantum numbers. We haven't talked about anything other than charge yet. That comes later. The columns that are greyed out correspond to quantum numbers that the particles don't have, so their values are zero.

Particle name, Symbol	Q	L	B	S	C	Mass (MeV)
Electron, e^-	-1	$+1$	0	0	0	0.5
Muon, μ^-	-1	$+1$	0	0	0	106
Tauon, τ^-	-1	$+1$	0	0	0	1777
Electron-neutrino, ν_e	0	$+1$	0	0	0	≈ 0
Muon-neutrino, ν_μ	0	$+1$	0	0	0	< 0.2
Tauon-neutrino, ν_τ	0	$+1$	0	0	0	< 16
Positron, e^+	$+1$	-1	0	0	0	0.5
Anti-muon, μ^+	$+1$	-1	0	0	0	106
Anti-tauon, τ^+	$+1$	-1	0	0	0	1777
Electron-antineutrino, $\overline{\nu_e}$	0	-1	0	0	0	≈ 0
Muon-antineutrino, $\overline{\nu_\mu}$	0	-1	0	0	0	< 0.2
Tauon-antineutrino, $\overline{\nu_\tau}$	0	-1	0	0	0	< 16

Table 1: Leptons and their Quantum Numbers

So here, as leptons aren't baryons, then they won't have a baryon number. Or, we could say that their baryon number is zero. Leptons don't have strangeness or colour, either (whatever they are).

Leptons are all fundamental particles: they can't be split up into anything smaller.

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[3] The name comes from the Greek word $\lambda\epsilon\pi\tau o\sigma$ (*leptos*), meaning "light ones". That was appropriate when the electron was discovered, but not any more!

[4] Named because they are electrically *neutral*, and that they have very little mass (*-ino* is often used to mean *small*.)

2.1.2 The Quarks

EXL
OCR-A
AQA-A

There are six quarks, called *up*, *down*, *strange*, *charm*, *top*, and *bottom*[5]. And then there are their anti-particles. So we also have *anti-up*, *anti-down*, *anti-strange*, *anti-charm*, *anti-top*, and *anti-bottom*. So there are twelve in all. These are all fundamental particles: they can't be split up into anything smaller.

The symbols used for the different quarks are: u, d, s, c, t, b for the quarks, respectively, and $\overline{u}$, $\overline{d}$, $\overline{s}$, $\overline{c}$, $\overline{t}$ and $\overline{b}$, respectively, for the anti-quarks.

These different types of quarks are called different *flavours* of quarks.

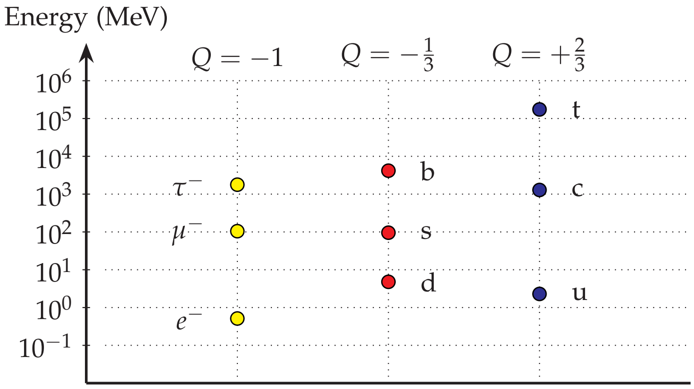

Figure 4: Electron and Quark Energies/Masses

So, bearing that in mind, Figure 4 is a chart showing the masses of the six different quarks (the respective anti-quarks have exactly the same masses as their normal matter twins). I've also included the electron masses for comparison. Note again the logarithmic energy-axis. Very important!!

Just as with the leptons, where we considered the muon and tauon as being electrons in a higher energy state (or electrons with more mass), well you can think of quarks in the same way. Because d, s and b quarks all have a charge of $-\frac{1}{3}$, you can think of s and b quarks as being d quarks in higher energy states; and because u, c and t quarks all have a charge of $+\frac{2}{3}$, you can think of c and t quarks as being u quarks in higher energy states.

Thinking of the electrons and quarks like this, we can group these particles in a different way: by *generation*. See Table 2.

Generation	Particles	Anti-particles
First	e^-, u, d	e^+, $\overline{u}$, $\overline{d}$
Second	μ^-, s, c	μ^+, $\overline{s}$, $\overline{c}$
Third	τ^-, b, t	τ^+, $\overline{b}$, $\overline{t}$

Table 2: Generations of Electrons and Quarks

So third generation particles have more energy (or mass) than second generation particles, and second generation particles have more energy (or mass) than first generation particles.

Table 3 lists all the quarks, and the anti-quarks, giving all their quantum numbers. As quarks aren't leptons, then their lepton number is zero.

Particle *flavour*, Symbol	Q	L	B	S	C	Mass (MeV)
Up, u	$+\frac{2}{3}$	0	$+\frac{1}{3}$	0	R, G or B	2.3
Down, d	$-\frac{1}{3}$	0	$+\frac{1}{3}$	0	R, G or B	4.8
Charm, c	$+\frac{2}{3}$	0	$+\frac{1}{3}$	0	R, G or B	1275
Strange, s	$-\frac{1}{3}$	0	$+\frac{1}{3}$	-1	R, G or B	95
Top, t	$+\frac{2}{3}$	0	$+\frac{1}{3}$	0	R, G or B	173210
Bottom, b	$-\frac{1}{3}$	0	$+\frac{1}{3}$	0	R, G or B	4180
Anti-up, $\overline{u}$	$-\frac{2}{3}$	0	$-\frac{1}{3}$	0	R, G or B	2.3
Anti-down, $\overline{d}$	$+\frac{1}{3}$	0	$-\frac{1}{3}$	0	R, G or B	4.8
Anti-charm, $\overline{c}$	$-\frac{2}{3}$	0	$-\frac{1}{3}$	0	R, G or B	1275
Anti-strange, $\overline{s}$	$+\frac{1}{3}$	0	$-\frac{1}{3}$	$+1$	R, G or B	95
Anti-top, $\overline{t}$	$-\frac{2}{3}$	0	$-\frac{1}{3}$	0	R, G or B	173210
Anti-bottom, $\overline{b}$	$+\frac{1}{3}$	0	$-\frac{1}{3}$	0	R, G or B	4180

Table 3: Quarks and their Quantum Numbers

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[5] These names don't mean anything. They're just words that are used to denote the different quarks, just so that we can talk about them behind their backs.

Table 3 also introduces a very strange quantum number indeed: *strangeness*. Only strange particles have strangeness. That's strange.

As a final couple of remarks about quarks, let me just say that the AQA-A and OCR-A syllabi teach that there are the six quarks: u, d, s, $\overline{u}$, $\overline{d}$, and $\overline{s}$. However, OCR-B (Advancing Physics) and Edexcel syllabi teach that there are all twelve. Also, OCR-B is the only syllabus to mention the *colour* quark quantum number, C.

2.1.3 The Bosons

EXL
OCR-A
AQA-A

Now here's a thing. In our Standard Model, there are particles and there are forces, and the forces act on the particles, causing them do do stuff. Right?

But in the current theory, there's a very big idea indeed: *the forces between particles are caused by the exchange of other particles*!!! So really, there aren't particles and forces, there are just particles. But some of those particles are purely responsible for giving the illusion that forces exist. Such particles are called *bosons*, and theories that use particles as force-carriers are called *gauge* theories (for some reason). So bosons are also called *gauge bosons*.

When Newton formulated his three laws of mechanics, his second law was written as

$$\text{force} = \text{rate of change of momentum}$$

so a change in a particle's momentum is equivalent to the particle experiencing a force. This means that we can view forces by the exchange of particles that carry momentum, so that the momentum of the interacting particles are both changed in the process: they both experience a force due to each other!

Force	Boson(s)	Mass (MeV)
Really strong nuclear (between quarks)	gluons	0
Strong nuclear (between nucleons)	π^+	140
	π^-	140
	π^0	135
Weak nuclear	W^+	80000
	W^-	80000
Electromagnetic	γ	0

Table 4: Forces and their Bosons

Table 4 shows all the exchange particles that we are interested in here, together with their masses.

One thing that's really confusing when you read books is that there seems to be something odd about the strong nuclear force. Sometimes you see that the bosons responsible for the strong force are gluons, and sometimes you see that pions are supposed to be responsible for it. So which is it? Gluons or pions?

Well, it turns out that it's *both*. There's more about this later, but for now, just think of it like this: gluons are the force-carriers between quarks (within a single baryon or meson), so gluons hold single hadrons together; pions are the force-carriers between nucleons in a nucleus, so pions provide the force that holds protons and neutrons together in a nucleus.

2.2 The Rules

The rules of the game are going to be built up in the next section. Can't wait, eh?

3 Build-Your-Own-Particle Kit

EXL
OCR-A
AQA-A

Now we know what all the fundamental matter particles[6] are (the leptons and quarks), how can we build bigger particles out of them? Here's where we start learning some of the rules of the game.

Rule 1: Particles can only be built using *quarks*

Rule 2: Particles can only have integer *charge*

Rule 3: Particles can only have integer *baryon number*

Now then: let's have a look at the consequences of these three rules.

These rules mean that we can never find a quark on its own. Since quarks have charges of $\pm\frac{1}{3}$ or $\pm\frac{2}{3}$, and baryon numbers of $\pm\frac{1}{3}$, then you can never get one without at least one mate to keep her company.

3.1 Particles Built from u, d, $\overline{u}$, and $\overline{d}$ Quarks

Because of **Rules 1-3**, it is only possible to build particles that have either two quarks in them (so they would have to have a baryon number of 0: these are called *mesons*), or three quarks, so that the baryon number is ± 1 or ± 2 (which are called *baryons*)[7].

3.1.1 Mesons

EXL
OCR-A
AQA-A

Let's have a look at the possible particles we could build out of two quarks. And to get a feel for the thing, let's start by only considering using u, d, $\overline{u}$, and $\overline{d}$ quarks, the *first generation* quarks, as our building blocks.

It makes some sense to do this: the first generation quarks are going to be the most stable, as they have the least energy. We'll learn later that more energetic quarks are unstable, and decay down to less energetic ones. You might expect this: the same sort of thing happens with electron energy levels in atoms.

u	d	$\overline{u}$	$\overline{d}$	Q	B	S	Name	Symbol	Mass (MeV)
uu				$\frac{4}{3}$	$\frac{2}{3}$	0			
u	d			$\frac{1}{3}$	$\frac{2}{3}$	0			
u		$\overline{u}$		0	0	0	Pion	π^0	135
u			$\overline{d}$	1	0	0	Pion	π^+	140
	dd			$-\frac{2}{3}$	$\frac{2}{3}$	0			
	d	$\overline{u}$		-1	0	0	Pion	π^-	140
	d		$\overline{d}$	0	0	0	Pion	π^0	135
		$\overline{uu}$		$-\frac{4}{3}$	$-\frac{2}{3}$	0			
		$\overline{u}$	$\overline{d}$	$-\frac{1}{3}$	$-\frac{2}{3}$	0			
			$\overline{dd}$	$\frac{2}{3}$	$-\frac{2}{3}$	0			

Table 5: All Possible Mesons Built From u, d, $\overline{u}$, and $\overline{d}$ Quarks

Table 5 shows all the possibilities using first generation quarks. The greyed rows indicate possibilities that violate **Rule 2** and/or **Rule 3**. The table shows that there are only four particles it is possible to make: these particles have been called *pions*.

Notice that the only possible particles that it is possible to make with two quarks are made of a quark-antiquark pair. This is because of the charges on the different types of quarks. This is an important result.

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[6] First off, there's a major difference between fundamental particles, the leptons and the quarks, and other non-fundamental particles that can be built from the fundamental ones, using them as building blocks. From now on, I'm going to call all non-fundamental particles just *particles*, and if I want to refer to leptons or quarks, I'll use those names.

[7] I'm slightly lying here. According to these first three rules, there's nothing to stop us building particles out of *four*, or *six* quarks, is there? Don't worry about doing this for A-Level, though!

Now there's one *very* interesting thing here: look at the *masses* of these pions. And then look at the masses of the quarks that make them up. What do you notice?

When you start building particles out of quarks, the masses of the particles are always greater (*much* greater), than the masses of the quarks that make them up. Why on earth is this? This is not at all easy to explain. I'm going to have a bash, but you'll have to wait until later!

3.1.2 Baryons

EXL
OCR-A
AQA-A

Now let's have a look at the possible particles we could build out of three quarks. And again I'm only going to use first generation quarks in the building process.

u	d	$\overline{u}$	$\overline{d}$	Q	B	S	Name	Symbol	Mass (MeV)
uuu				2	1	0	Delta	Δ^{++}	1232
uu	d			1	1	0	Proton	p^+	938
uu		$\overline{u}$		$\frac{2}{3}$	$\frac{1}{3}$	0			
uu			$\overline{d}$	$\frac{5}{3}$	$\frac{1}{3}$	0			
u	dd			0	1	0	Neutron	n^0	939
u	d	$\overline{u}$		$-\frac{1}{3}$	$\frac{1}{3}$	0			
u	d		$\overline{d}$	$\frac{2}{3}$	$\frac{1}{3}$	0			
u		$\overline{uu}$		$-\frac{2}{3}$	$-\frac{1}{3}$	0			
u		$\overline{u}$	$\overline{d}$	$\frac{1}{3}$	$-\frac{1}{3}$	0			
u			$\overline{dd}$	$\frac{4}{3}$	$-\frac{1}{3}$	0			
	ddd			-1	1	0	Delta	Δ^-	1232
	dd	$\overline{u}$		$-\frac{4}{3}$	$\frac{1}{3}$	0			
	dd		$\overline{d}$	$-\frac{1}{3}$	$\frac{1}{3}$	0			
	d	$\overline{uu}$		$-\frac{5}{3}$	$-\frac{1}{3}$	0			
	d	$\overline{u}$	$\overline{d}$	$-\frac{2}{3}$	$-\frac{1}{3}$	0			
	d		$\overline{dd}$	$\frac{1}{3}$	$-\frac{1}{3}$	0			
		$\overline{uuu}$		-2	-1	0	Delta	Δ^{--}	1232
		$\overline{uu}$	$\overline{d}$	-1	-1	0	Proton	p^-	938
		$\overline{u}$	$\overline{dd}$	0	-1	0	Neutron	n^0	939
			$\overline{ddd}$	1	-1	0	Delta	Δ^+	1232

Table 6: All Possible Baryons Built From u, d, $\overline{u}$, and $\overline{d}$ Quarks

Table 6 shows all the possibilities using first generation quarks. The greyed rows indicate possibilities that violate **Rule 2** and/or **Rule 3**. The table shows that there are only eight particles it is possible to make: and these particles have a variety of names!

This time notice that when we make baryons, particles made out of three quarks, it is only possible when either all three are quarks, or all three are anti-quarks. This is another important result.

And note also that the masses of these baryons, made of *three* quarks, are *much* greater than the masses of mesons, which are only made of *two* quarks. In fact, the proton, with a mass of around 938 MeV, is almost exactly *a hundred times* more massive than the quarks that make it up. Wow.

3.2 Particles Built from u, d, s, $\overline{u}$, $\overline{d}$, and $\bar{s}$ Quarks

3.2.1 Mesons

EXL
OCR-A
AQA-A

Now let's include the s and $\bar{s}$ quarks as building blocks. What can we make now?

This time, I'm only including particles that it is possible to make in our tables. That's because the numbers of possible particles is going up very fast! Including the s and $\bar{s}$ quarks gives us the *Kaon* mesons!

u	d	s	$\overline{u}$	$\overline{d}$	$\bar{s}$	Q	B	S	Name	Symbol	Mass ()MeV
u			$\overline{u}$			0	0	0	Pion	π^0	135
u				$\overline{d}$		1	0	0	Pion	π^+	140
u					$\bar{s}$	1	0	1	Kaon	K^+	494
	d		$\overline{u}$			−1	0	0	Pion	π^-	140
	d			$\overline{d}$		0	0	0	Pion	π^0	135
	d				$\bar{s}$	0	0	1	Kaon	K^0	498
		s	$\overline{u}$			−1	0	−1	Kaon	K^-	494
		s		$\overline{d}$		0	0	−1	Kaon	$\overline{K^0}$	498
		s			$\bar{s}$	0	0	0	Pion	π^0	548

Table 7: Mesons Built From u, d, s, $\overline{u}$, $\overline{d}$, and $\bar{s}$ Quarks

Notice how mesons made with second generation quarks are *much* more massive than mesons made with only first generation quarks.

3.2.2 Baryons

EXL
OCR-A
AQA-A

And including the s and $\bar{s}$ quarks gives us a whole host of new baryons.

u	d	s	$\overline{u}$	$\overline{d}$	$\bar{s}$	Q	B	S	Name	Symbol	Mass (MeV)
uuu						2	1	0	Delta	Δ^{++}	1232
uu	d					1	1	0	Proton	p^+	938
uu		s				1	1	−1	Sigma	$\sum^+$	1189
u	dd					0	1	0	Neutron	n^0	939
u	d	s				0	1	−1	Sigma	$\sum^0$	1193
u		ss				0	1	−2	Xi Cascade	Ξ^0	1315
	ddd					−1	1	0	Delta	Δ^-	1232
	dd	s				−1	1	−1	Sigma	$\sum^-$	1197
	d	ss				−1	1	−2	Xi Cascade	Ξ^-	1322
		sss				−1	1	−3	Omega	Ω^-	1672
			$\overline{uuu}$			−2	−1	0	Delta	Δ^{--}	1232
			$\overline{uu}$	$\overline{d}$		−1	−1	0	Proton	p^-	938
			$\overline{uu}$		$\bar{s}$	−1	−1	1	Sigma	$\sum^-$	1383
			$\overline{u}$	$\overline{dd}$		0	−1	0	Neutron	n^0	939
			$\overline{u}$	$\overline{d}$	$\bar{s}$	0	−1	1	Sigma	$\sum^0$	1384
			$\overline{u}$		$\overline{ss}$	0	−1	2	Xi Cascade	Ξ^0	1532
				$\overline{ddd}$		1	−1	0	Delta	Δ^+	1232
				$\overline{dd}$	$\bar{s}$	1	−1	1	Sigma	$\sum^+$	1197
				$\overline{d}$	$\overline{ss}$	1	−1	2	Xi Cascade	Ξ^+	1322
					$\overline{sss}$	1	−1	3	Omega	Ω^+	1672

Table 8: Baryons Built From u, d, s, $\overline{u}$, $\overline{d}$, and $\bar{s}$ Quarks

3.3 Particles Built from All the Quarks

EXL
OCR-A
AQA-A

There will be too many to list in table. In fact, if we worked out how many different particles you could make using **Rules 1-3**, you would find:

Quarks Used	Number of Mesons	Number of Baryons
$u, d, \overline{u}, \overline{d}$	4	8
$u, d, s, \overline{u}, \overline{d}, \overline{s}$	9	20
$u, d, s, c, \overline{u}, \overline{d}, \overline{s}, \overline{c}$	16	40
$u, d, s, c, b, \overline{u}, \overline{d}, \overline{s}, \overline{c}, \overline{b}$	25	70
$u, d, s, c, b, t, \overline{u}, \overline{d}, \overline{s}, \overline{c}, \overline{b}, \overline{t}$	36	112

Table 9: Numbers of Particles Made from Different Combinations of Quarks

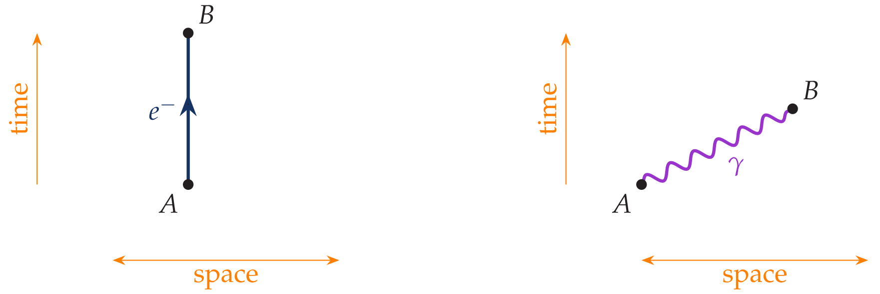
4 Forces

EXL
OCR-A
AQA-A

Right. Now let's start looking at all the forces. What we're interested in here is what effect the forces will have on different types of particles.

Now because we now know that there are two types of particles: matter particles (made of quarks and leptons), and force particles (the bosons), then what we're trying to do here is discover how the matter particles and force particles interact with themselves and each other.

To help with this, a famous physicist called Richard Feynman invented a way to draw pictures of the interactions of all these particles. They have become known, perhaps unsurprisingly, as Feynman diagrams. Here's a couple of examples:



(a) An electron stays in the same place as time passes.

(b) A photon travels from one place to another as time passes.

Figure 5: The Basic Feynman Diagram

There are two "axes" in a Feynman diagram. In my diagrams, the vertical y-axis will be *time*, with time increasing *up*[8]. The horizontal x-axis will be space. I'll always mark which is which in my diagrams to avoid confusion.

Check out Figure 5. In (a) we have an electron which stays in the same place as time passes. How do we know that it stays in the same place? Because its trajectory is vertically up. That means time will go by, but it's space coordinate will stay the same. [A particle will never actually stay in the same place in practice. This example is just to try and help you understand the diagrams!]

In (b) we have a photon which moves through space as time passes. How do we know that? Because during its trajectory, both the time and space coordinates change. Get the idea?

---

[8] Annoyingly, you will sometimes find that people draw Feynman diagrams with time along the x-axis, where time increases to the right. Watch out for this. The reason for this apparent absurdity that people draw Feynman diagrams in different ways, with the time axis going in different directions, is actually because one of the things that came out of Special Relativity theory is that space and time shouldn't be thought of as separate things. We should be combining them into what is now known as *spacetime*. Get this: that means we can do things like *rotate* Feynman Diagrams to see what consequences of interactions could be in different circumstances!!!!! Now, for example, particles can be found *going back in time...* My head hurts.

By the way: what would you say the points A and B represented in these diagrams? They're actually what physicists call *events*: that is: a point in both *space* and *time*.

Right. Now we know about Feynman diagrams, let's get started trying to understand forces. And the first one I'm going to choose is the electromagnetic force.

4.1 The Electromagnetic Force

4.1.1 Repulsive Forces

EXL
OCR-A
AQA-A

The electromagnetic force is the force that acts between charged particles. And if two particles have the same charge, the force pushes them apart, and if the two particles have opposite charges, then the force pulls them together.

In the Standard Model, the boson that's responsible for transmitting the electromagnetic force is the *photon*.

Let's see how this is done with the help of a Feynman diagram!

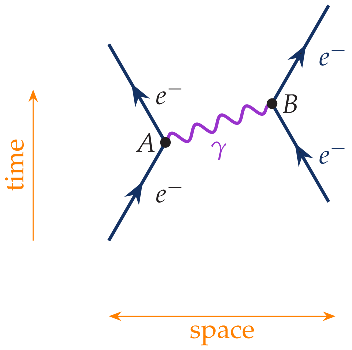


Figure 6: The Repulsive Electromagnetic Force

In Figure 6 we have a Feynman diagram of the repulsive force between two electrons. The electron on the left is travelling along, moving toward the electron on the right initially, until the event A occurs.

At A the left electron emits a photon. As photons have momentum (see Section 1.1), then the left electron's momentum will change, and its direction of motion will change (away from the right electron).

The photon travels toward the electron on the right, until at B the photon hits the right electron. This causes the momentum of the right electron to change too, and it moves away from the left electron.

So initially (toward the bottom of Figure 6) the two electrons are moving toward each other, and later (toward the top of Figure 6) the two electrons are moving away from each other. And the cause of the changes in directions of the electrons is the transmission and absorption of the photon.

4.1.2 Attractive Forces

It is much more difficult to explain the Feynman diagram for the attractive electromagnetic force (between a proton and an electron, say), so I'm going to avoid trying to do it.

At A-Level, you wouldn't be expected to be able to draw to the Feynman diagram for electromagnetic attraction.

So, after that nifty side-step, I'm going to move swiftly on to the weak nuclear force...

4.2 The Weak Nuclear Force

EXL
OCR-A
AQA-A

The weak nuclear force is a force that acts on quarks. It is transmitted via two bosons: the W^+ and the W^- (W for *w*eak) bosons. Only one of these bosons will be involved in any given interaction.

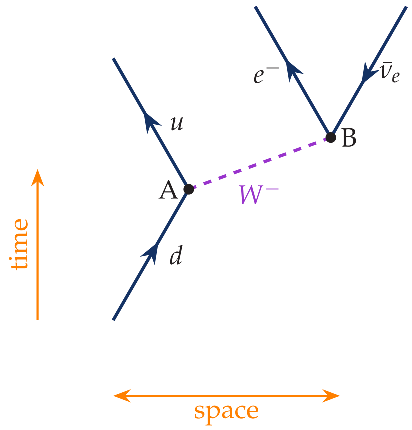


Figure 7: A Weak Interaction: β^- Decay

The weak nuclear force *changes the flavour of quarks*. That means, for example, that a d quark could change into a u quark during a weak interaction.

The weak interaction is the *only* force that can change the flavour of a quark. And to do that, the interaction has to use either the W^+ or W^- boson.

4.2.1 β^- Decay

Here's an example. In Figure 7 a d quark is going about its business quite happily, until at A, it spontaneously emits a W^- boson. Wow! W^- bosons have mass (and consequently momentum) and so the momentum of the quark will change.

W^- bosons also carry a negative charge of -1. That charge can only come from the d quark, and so the charge of the quark must change.

Talking about charge changing introduces us to another rule:

Rule 4: Charge is conserved in interactions.

In the interaction at A therefore, charge must be conserved. At A we must have an equation like this:

$$\begin{array}{cccccc} & d & \rightarrow & u & + & W^- \\ \text{Q:} & -\frac{1}{3} & \rightarrow & +\frac{2}{3} & + & -1 \end{array}$$

Since charge needs to be conserved, the total charge on each side has to be the same. This is the case: $(-\frac{1}{3}) = (+\frac{2}{3}) + (-1)$. That means that the quark that the d quark changes into must have a charge of $+\frac{2}{3}$. The best candidate for such a quark would be the u quark (since that's the quark with a charge of $+\frac{2}{3}$ with the least mass/energy, and so is easiest to make).

In the interaction at A (as in all interactions) baryon number must also be conserved.

Rule 5: Baryon number is conserved in interactions.

So at A our equation needs amending a bit:

$$\begin{array}{cccccc} & d & \rightarrow & u & + & W^- \\ \text{Q:} & -\frac{1}{3} & \rightarrow & +\frac{2}{3} & + & -1 \\ \text{B:} & +\frac{1}{3} & \rightarrow & +\frac{1}{3} & + & 0 \end{array}$$

At B the W^- quark decays. As it's carrying a charge of -1, the W^- particle decays into an electron. That's the particle with a charge of -1 that has the least mass/energy, and so is easiest to make. However, there's a problem.

Rule 6: Lepton Number is conserved in interactions.

An electron has a lepton number of $+1$. Since none of the stuff that participated in the interaction at A had a lepton number (because none of them are leptons!), then the interaction at B has no lepton number coming in. That means there has to be zero lepton number going out of B as well.

$$\begin{array}{cccccc} & W^- & \rightarrow & e^- & + & \bar{\nu}_e \\ \text{Q:} & -1 & \rightarrow & -1 & + & 0 \\ \text{L:} & 0 & \rightarrow & +1 & + & -1 \end{array}$$

That's the reason why you always get an electron antineutrino when you get an electron produced in this kind of interaction.

By the way, this particular interaction is known as β^- decay: this is the interaction responsible for β^- radiation in radioactivity.

It turns out that any of the negatively charged quarks can change into any of the positively charged quarks by emitting a W^- boson.

And huh! By symmetry, it turns out that any of the positively charged quarks can change into any of the negatively charged quarks by emitting a W^+ boson.

So you could sum up the weak interaction by:

$$\{u, c, t\} \longleftrightarrow \{d, s, b\}$$

This has an interesting consequence. If one of the quarks involved in the weak interaction was a strange quark, and the other one isn't, then strangeness won't be conserved in a weak interaction! But if that happens, it will only change by ± 1:

Rule 7: Strangeness changes by 0 or ± 1 in interactions.

And another interesting thing: I mentioned earlier that W bosons have mass. How much mass? Well, it turns out the the mass of the W bosons is around 80 GeV!! That's about 16000 times the mass of a d quark!! So, for the interaction at A in Figure 7, where did the energy come from to make the W^- boson? Well, Heisenberg's Uncertainty Thingy, of course.

And remember the calculation we did in Section 1.5? If we borrow 80 GeV of energy from the future, we can only have it for about 10^{-26} s before we have to pay it back. So these W^- bosons don't get very far before they decay into an electron and electron antineutrino. This is why the weak interaction is a *very short range* force.

4.2.2 β^+ Decay

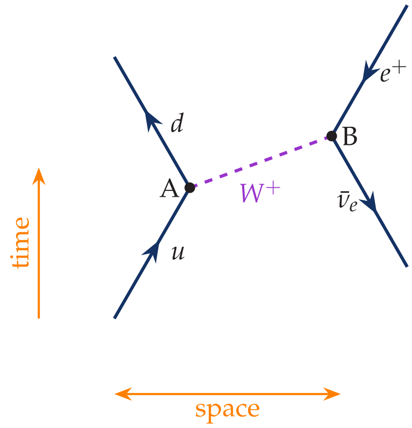


Figure 8: β^+ Decay

Here's another example of the weak nuclear force in action: β^+ decay.

This could be, for example, where a proton interacts with an anti-neutrino.

Figure 8 shows the Feynman diagram.

It is only one of the proton's u quarks that actually gets involved in this process: it emits a W^+ boson in the interaction at A, turning itself into a d quark:

$$\begin{array}{lccccc} & u & \rightarrow & d & + & W^+ \\ \text{Q:} & +\frac{2}{3} & \rightarrow & -\frac{1}{3} & + & +1 \\ \text{B:} & +\frac{1}{3} & \rightarrow & +\frac{1}{3} & + & 0 \end{array}$$

The W^+ boson then interacts with the anti-neutrino at B, turning themselves into a positron:

$$\begin{array}{lccccc} & W^+ & + & \bar{\nu}_e & \rightarrow & e^+ \\ \text{Q:} & +1 & + & 0 & \rightarrow & +1 \\ \text{L:} & 0 & + & -1 & \rightarrow & -1 \end{array}$$

4.2.3 Electron Capture

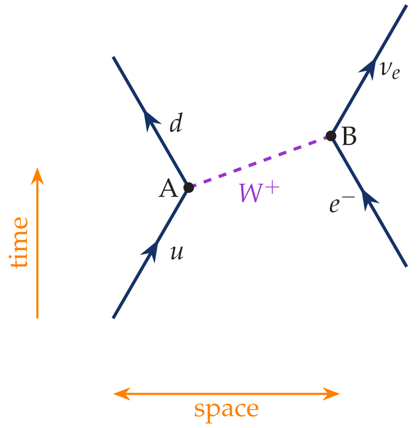


Figure 9: Electron Capture

Here's another example of the weak nuclear force in action: electron capture.

This is where an electron in an inner shell of an atom is drawn into the nucleus of the atom and interacts with a proton, turning the proton into a neutron and a neutrino in the process. It's actually a mechanism whereby an unstable nucleus can make itself more stable.

Figure 9 shows the Feynman diagram.

It is only one of the proton's u quarks that actually gets involved in this process: it emits a W^+ boson in the interaction at A, turning itself into a d quark:

$$\begin{array}{lccccc} & u & \rightarrow & d & + & W^+ \\ \text{Q:} & +\frac{2}{3} & \rightarrow & -\frac{1}{3} & + & +1 \\ \text{B:} & +\frac{1}{3} & \rightarrow & +\frac{1}{3} & + & 0 \end{array}$$

The W^+ boson then interacts with the electron at B, turning themselves into a neutrino:

$$\begin{array}{lccccc} & W^+ & + & e^- & \rightarrow & \nu_e \\ \text{Q:} & +1 & + & -1 & \rightarrow & 0 \\ \text{L:} & 0 & + & +1 & \rightarrow & +1 \end{array}$$

4.3 The Strong Nuclear Force

EXL
OCR-A
AQA-A

If the nucleus of an atom only has positively charged protons and neutral neutrons in it, how can it be stable?

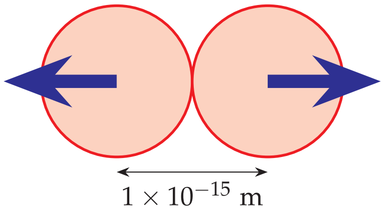


Figure 10: Two Adjacent Protons

A quick calculation of the (Coulomb) electromagnetic force between two adjacent protons in a nucleus, each of diameter 1×10^{-15} m and charge 1.6×10^{-19} C sitting next to each other yields

$$\begin{aligned} F &= \frac{qq}{4\pi\epsilon_0 r^2} \\ &= \frac{1.6 \times 10^{-19} \cdot 1.6 \times 10^{-19}}{4\pi \cdot 8.85 \times 10^{-12} \cdot (1 \times 10^{-15})^2} \\ &= 230 \text{ N} \end{aligned}$$

That's *two hundred and thirty newtons!!* Just to put that in perspective, a typical apple has a weight of about a newton. So the force pushing two adjacent protons apart in a nucleus is equivalent to several bags of *very* heavy shopping. And that's acting on two particles that have a diameter of 1×10^{-15} m!! And most nuclei have more than two protons in them...

How can protons possibly stay together under that amount of repulsive force?

There must be some other, *even stronger*, force acting, pulling the protons together!

And another thing: how do the quarks stay together inside baryons and mesons?

Drum roll...enter the *Strong Nuclear Force*. And here's an interesting twist: the strong nuclear force needs to be thought of in *two* ways. Firstly as a *really, REALLY* strong force (acting on the quarks within a hadron), and secondly as a *not quite such a* strong force acting between hadrons (especially in a nucleus of an atom).

You couldn't make this stuff up, could you?

4.3.1 The Strong Nuclear Force Within a Hadron

EXL
OCR-A
AQA-A

The strong nuclear force acts between quarks within a hadron. It keeps the quarks together. Now the electromagnetic force acts between objects that have *charge*; the weak force acts between objects that have *flavour*; what property of an object makes it susceptible to the strong nuclear force? It's an object's *colour*.

Why do we need this new colour quantum number? Well, remember Pauli's Exclusion Thingy? Imagine that you had a proton. A proton consists of two u quarks and a d quark. Up to now, the two u quarks would be identitcal - they would have the same set of quantum numbers: the same charge $\left(+\frac{2}{3}\right)$, lepton number (0), baryon number $\left(+\frac{1}{3}\right)$ and strangeness (0). But *PET* tell us that no two quarks in the same hadron can have the same set of quantum numbers. So we need another quantum number to distinguish them. Hence the need for quark colour.

Colour is absolutely nothing to do with what we think of as colour. It's just a name that physicists have given to a property of a quark, that can be in one of *three* possible states. They could have called the property "Gibb", and the three states "Barry", "Maurice" and "Robin". Or "Spice", with the states given by "Scary", "Sporty" and "Baby". But they didn't. Possibly because there were actually *five* Spice girls. Everyone forgets "Ginger", don't they? And who's the other one?

Anyway, the powers that be chose "colour" as the name of the property, and the three states that an object with this property can be in are "red", "blue" and "green". Any given quark has to have one of these colours, and it can only have one of them at any one time.

Oh - and anti-quarks have the colours of anti-red, anti-blue or anti-green, of course!

So in a proton, one of the u quarks could be red, and the other one could be blue. Then we can tell them apart! They would obey the *PET*.

Right. The strong nuclear force acts between objects that have colour. Of the particles we have come across so far, only quarks have colour, so this is a force that acts between quarks.

The particle that transmits the force is called a *gluon*. And what the gluon does when it leaves one quark, or hits another, is to change the quark's colour.

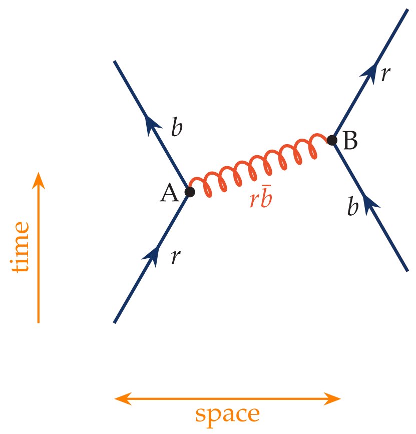


Figure 11: A Strong Interaction

Figure 11 is an example of a Feynman diagram showing how this happens. At A a red quark emits a gluon and turns into a blue quark. At B that gluon hits a blue quark and turns it red.

How does it do this? *Gluons also have colour*! But in a really weird way! Gluons have both a colour *and an anti-colour*!! So when the red quark turns blue, it does this by creating and emitting a red/anti-blue gluon, thereby *conserving total colour* in the interaction!

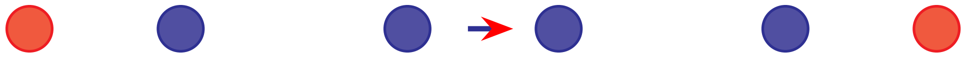
And when the red/anti-blue gluon hits the blue quark in the interaction at B, it changes the quark's colour from blue to red, again *conserving total colour* in the interaction!

So we have another rule:

Rule 8: Colour is conserved in interactions.

Another way of looking at this transmission and reception of the red/anti-blue gluon between the red and blue quarks is shown in Figure 12. The big balls represent the quarks, each one having it's own colour. For this process, we don't care what flavour the quarks are (u, d, etc.), as the strong force doesn't care what flavour the quarks are, only their colour. The arrow, →, represents the gluon. The head of the arrow represents the colour of the gluon, the tail the anti-colour.

So, in picture (a), we are in a state immediately prior to the transmission of the gluon. We have two quarks, one red, the other blue. Total colour: $r + b$.



(a) Two quarks: one red, the other blue.

(b) The red quark emits a red/anti-blue gluon, turning blue in the process.

(c) The gluon hits the other blue quark and turns it red.

Figure 12: Transmission and Reception of a Gluon

In (b) the red quark has emitted the $r\bar{b}$ gluon, turning blue in the process. Total colour of quarks and gluons: $b + r\bar{b} + b = r + b$ (as one of the bs and the $\bar{b}$ cancel out!).

In (c) the gluon hits the other blue quark, turning it red. Total colour: $r + b$. Colour has been conserved throughout!

Now, how can different combinations of colour exist within hadrons? It turns out that free particles can only have quarks whose colours add up to *white*. How does that work? Well:

$$\begin{aligned} \text{red} + \text{blue} + \text{green} &= \text{white} \\ \text{red} + \text{anti-red} &= \text{white} \\ \text{blue} + \text{anti-blue} &= \text{white} \\ \text{green} + \text{anti-green} &= \text{white} \end{aligned}$$

Another rule:

Rule 9: Free particles can only be white.

So that means we can't ever get a quark outside of a hadron (as it has colour), and we can't get gluons outside of hadrons either (as they have colour).

4.3.2 Gluons Can Create Quarks!

EXL
OCR-A
AQA-A

It is also possible for gluons to create quarks. Check out Figure 13.

(a) A red quark.

(b) The red quark emits a red/anti-blue gluon, turning blue in the process.

(c) The gluon doesn't hit anything: it creates a red/anti-blue quark pair.

Figure 13: Gluons Creating Quarks

In (a) we have a red quark. Total colour: r.

In (b) the red quark has emitted a red/anti-blue gluon, turning the quark blue. Total colour: $b + r\bar{b} = r$.

In (c), the gluon *decays* before hitting another quark. The gluon has decayed into a quark/anti-quark pair (which would have to have corresponding flavours: e.g. $u\bar{u}$, $d\bar{d}$, etc), converting the gluon colours into the quark colours. The quark would take the gluon colour, and the anti-quark would take the gluon anti-colour. Total colour: $b + r\bar{b} = r$.

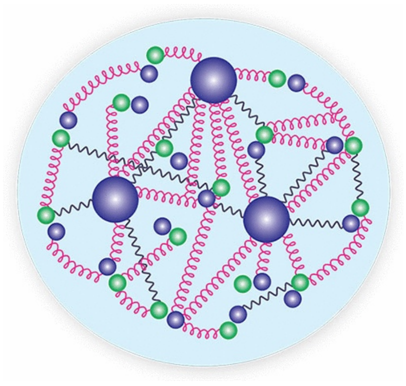


Figure 14: The Sea of Quarks Within a Proton

Just a minute: gluons don't have mass. So how can they possibly create a meson (quark/anti-quark pair) that does have mass? Oh stupid me! Heisenberg's Uncertainty Thingy.

Imagine that the red quark in (a) is in a proton. *HUT* tells us that the meson in (c) won't be around for very long. But it will be around long enough for the proton to have significantly more mass than before the meson was created! That's because the proton now has, temporarily, *five* quarks in it!!

And it gets worse: mesons are being created within a hadron by the decay of gluons like crazy, thereby increasing the numbers of quarks in the hadron enormously. If, at any one instant, instead of there being not *three* quarks, but *three hundred* quarks in a proton, that would explain where all that extra mass of the proton comes from, compared to the mass of the three component quarks!!!

Check out Figure 14[9] This picture is designed to illustrate the mayhem that's going on inside a baryon. The three particle quarks (the large purple balls) are surrounded by a sea of gluons (the springs), photons (the wavey lines - we get photons exchanged between charged particles, remember!) and mesons (the small green and purple balls). If I had drawn this picture, I would have coloured the quarks properly: either red, green or blue. But I hope you get the idea.

4.3.3 Annihilation Can Create Gluons!

EXL
OCR-A
AQA-A

It is also possible for quark/anti-quark pairs to annihilate to create gluons. Check out Figure 15.

(a) A $d\bar{d}$ pair. (b) The pair annihilate... (c) ...producing a $g\bar{r}$ gluon.

Figure 15: Annihilation Creating Gluons

Again, colour has to be conserved (**Rule 8**). And this sort of thing is happenning continually inside all hadrons (see Figure 14 again).

4.3.4 The Strong Nuclear Force Within a Nucleus

EXL
OCR-A
AQA-A

We now have everything we need to understand how two nucleons are attracted together by the strong nuclear force. Or to put it another way, how two nucleons can exchange particles that cause an attraction between them. Check out Figure 16 as an example of this inter-nucleon particle exchange process.

[By the way: in order to try and keep this as simple as I can, I have omitted all the gluons that are continually flying about between the quarks within the proton and the neutron in the diagrams.]

In (a) we have a proton, consisting of *uud* quarks down in the bottom left, and a neutron, consisting of *udd* quarks, in the upper right. For both particles we have one red, one green and one blue quark, according to **Rule 9**.

In (b) the blue *d* quark in the proton has emmitted a blue/anti-green gluon. This turns the blue quark green.

In (c) the gluon explodes! No it doesn't. But it does cease to exist, and...

...in (d) the gluon turns into a quark/anti-quark pair, using pair-production (see Section 4.3.2). This pair have to be a quark/anti-quark pair: in this case, they happen to be a $d\bar{d}$ pair. And their colours have to come from the gluon (colour conservation in the interaction: **Rule 8**). So the *d* quark takes the gluon colour, and the anti-*d* quark takes the gluon anti-colour. This quark/anti-quark pair forms a *pion*, and leaves the proton. As this pion has colour, it can't leave the nucleus.

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[9] Which is a picture I've shamelessly nicked from the Physics Today website.

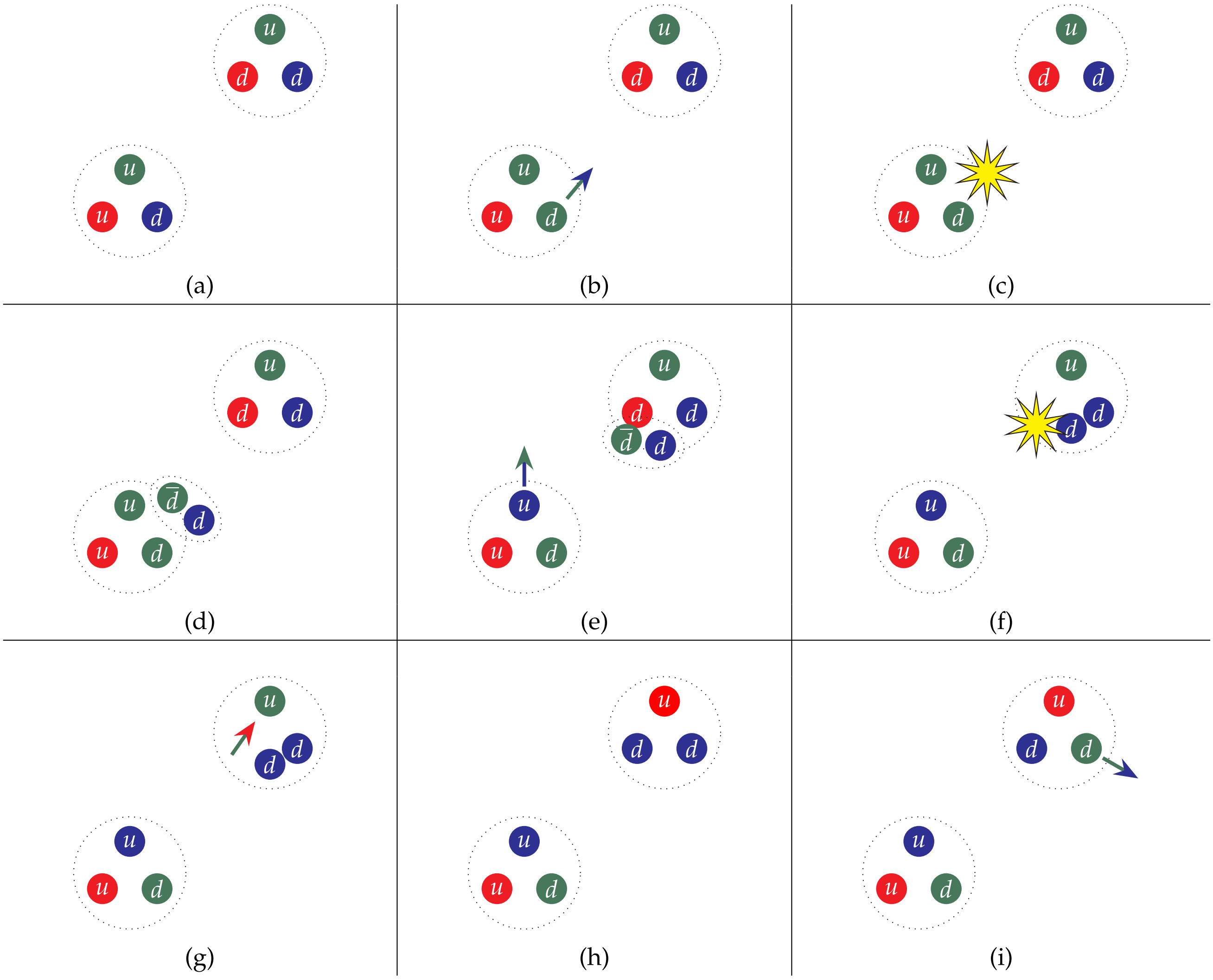

Figure 16: Force Acting Between Two Nucleons

In (e) the pion emitted by the proton arrives at the neutron. Meanwhile, back at the proton, the green u quark emits a green/anti-blue gluon. This turns the quark blue. This gluon would then form another pion by pair production which would fly off somewhere. But to keep Figure 16 as simple as possible, I'm not going to follow that one through...

In (f) something interesting happens! The anti-green $\overline{d}$ quark in the pion annihilates with the red d quark in the neutron...

...which creates a red/anti-green gluon (colour has to be conserved, **Rule 8**) in (g).

In (h) the gluon hits the green u quark in the neutron, turning it red.

In (i) one of the blue d quarks in the neutron emits a gluon, turning the quark green, so that the neutron as a whole turns white (**Rule 9**). This will then form a pion which will fly off and hit another nucleon...

4.4 So - How Do You Know If an Interaction is Strong, or Weak?

EXL
OCR-A
AQA-A

Well,

- if an interaction involves a W as the exchange particle, changes the flavour of a quark, and/or produces a pair of leptons, it's *weak*;
- if an interaction involves a gluon (or a pion) as the exchange particle, conserves the flavour of quarks, and produces no leptons, it's *strong*.

5 Summary of Particle Forces

EXL
OCR-A
AQA-A

Force	**Boson(s)**	**Property**
Really strong nuclear (between quarks)	gluons	quark colour
Strong nuclear (between nucleons)	π^+, π^-, π^0	quark colour
Weak nuclear	W^+, W^-	quark flavour
Electromagnetic	γ	charge

Table 10: Summary of Particle Forces

6 Summary of the Rules

EXL
OCR-A
AQA-A

Rule 1: Particles can only be built using *quarks*

Rule 2: Particles can only have integer *charge*

Rule 3: Particles can only have integer *baryon number*

Rule 4: Charge is conserved in interactions.

Rule 5: Baryon Number is conserved in interactions.

Rule 6: Lepton Number is conserved in interactions.

Rule 7: Strangeness changes by 0 or ±1 in interactions.

EXL
OCR-A
AQA-A

Rule 8: Colour is conserved in interactions.

Rule 9: Free particles can only be white.

A Required Particle Knowledge by Exam Board and Syllabus

Matter and Antimatter	**AQA**	**Edexcel**	**OCR**
de Broglie's formula and wave-particle duality	Yes	Yes	Yes
Heisenberg's uncertainty principle	No	No	No
Annihilation and pair-production	Yes	Yes	Yes
Spontaneous particle creation	No	No	No
Every particle has its own anti-particle	Yes	Yes	Yes
Leptons and their antiparticles	Yes	Yes	Yes
Is knowledge of $E = mc^2$ required?	Yes	Yes	Yes
Is $E = mc^2$ required in calculations?	No	Yes	Yes
The anti-particles of the electron, proton, neutron and neutrino	Yes	Yes	Yes
Two classes of hadrons: baryons and mesons	Yes	Yes	Yes
Comparison of particle and anti-particle masses in GeV	Yes	Yes	No
Which Quarks?	u, d, s	All	u, d, s
Quarks combine in threes to make baryons	Yes	Yes	Yes
Quarks combine in twos to make mesons	Yes	Yes	No
Nucleon (mass) number and proton (atomic) number	Yes	Yes	Yes

Table 11: Matter and Antimatter

Particle Interactions	**AQA**	**Edexcel**	**OCR**
Knowledge of the four interaction types: gravity, electromagnetic, weak, strong	Yes	Yes	Yes
Exchange particles are used to explain forces	Yes	Yes	No
Knowledge of the gluon, Z^0 and graviton	No	Yes	No
Virtual photons are the exchange particle for the electromagnetic force	Yes	Yes	No
Hadrons are subject to strong interactions	Yes	Yes	Yes
Pions are the exchange particles for the strong nuclear force	Yes	No	No
Weak interaction limited to β^- and β^+ decay, electron capture and electron-proton collisions	Yes	Yes	Yes
W^- and W^+ particles are the exchange particles for the weak interaction	Yes	Yes	No
Conservation of energy and momentum in interactions	Yes	Yes	Yes
Strange particles are created via the strong interaction and decay via the weak interaction	Yes	No	No
Quark types change in weak interactions	Yes	No	No

Table 12: Particle Interactions

Particle Decay	**AQA**	**Edexcel**	**OCR**
Kaons can decay into pions	Yes	No	No
Proton is the only stable baryon	Yes	No	No
Feynman Diagrams	Yes	No	No
Decay of a neutron into a proton	Yes	No	No

Table 13: Particle Decay

Quantum Numbers	**AQA**	**Edexcel**	**OCR**
Pauli's exclusion principle	No	No	No
Baryon number as a quantum number	Yes	Yes	No
Conservation of baryon number in interactions	Yes	Yes	No
Lepton number as a quantum number	Yes	Yes	No
Conservation of lepton number in interactions	Yes	Yes	No
Strangeness as a quantum number	Yes	Yes	No
Conservation of strangeness in strong interactions	Yes	Yes	No
Strangeness changes by 0 or ± in weak interactions	Yes	Yes	No
Application of conservation laws of Q, B and L	Yes	Yes	No
Application of conservation law of S	Yes	Yes	No
Quark properties of charge and baryon number	Yes	Yes	Yes
Quark property of strangeness	Yes	Yes	No

Table 14: Quantum Numbers

B Playing the Game

To play Particle-opoly!, you must visit a companion document to this one, called..."Playing Particle-opoly!". See Smith (2017b).

Basically, this document explains how to do some past paper particle physics questions from the different exam boards and syllabi.

C Particle Decays

There is another companion document to this one, that shows Feynman diagrams of lots of particle decays. See (Smith, 2017a).

D Things I've Left Out

Amongst the many and varied treats I've left out of the story are such diverse things as...

D.1 The Z^0 Boson

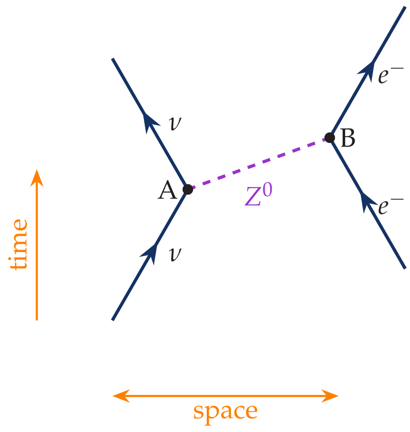

Figure 17: A Z^0 Interaction

There are actually *three* bosons that act as exchange particles in the weak interaction. The other one is called a Z^0 boson.

So: what about the Z^0-boson? What does that do? Well, here's an example.

Since the Z^0 boson has no charge, then it must leave the quark that emitted it with the same charge. So you might think that the Z-boson could transform any of the positively charged quarks into any other positively charged quark (and the same for the negatively charged ones).

Unfortunately, that *doesn't* happen!! Instead, for the purposes of this document, let's think of the Z^0-boson as a boson that leaves the particles it interacts with unchanged, apart from transferring momentum from one to the other. See Figure 17.

At A-Level, we're not interested in Z^0 bosons.

D.2 *W* Boson Decays

W bosons can decay into quarks, as well as leptons. So, for example,

$$W^+ \to u + \bar{d}$$

happens. The charges are conserved; energy level is reduced.

This means that there are considerably more ways that particles could decay. For example,

$$K^+ \to \pi^+ + \pi^0$$

(See Figure 18.)

As another example, the Σ^+ particle decays by one of the following two processes:

$$\begin{aligned} \Sigma^+ &\to p^+ + \pi^0 \\ \Sigma^+ &\to n^0 + \pi^+ \end{aligned}$$

with similar Feynman diagrams to 18. See if you can come up with them yourself!

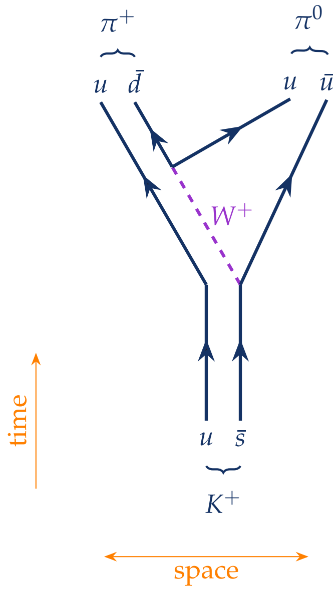

Figure 18: Another Kaon Decay

D.3 Other Quantum Numbers

- charm,
- topness,
- bottomness,
- different types of lepton numbers,
- spin

D.4 Wave-Particle Duality Stuff

To be written.

D.5 Group Theory Stuff

To be written.