Year 2 Particles and Nuclei – Lecture 2 (+3?)

Particles and Forces

In the last lecture we introduced the idea that the fundamental constituents of matter (as far as we know) are quarks and electrons (and other particles like these). Now we are going to look at their properties.

Some of their most important properties concern how they interact with each other, and moreover our ability to study these particles depends on these same interactions. So a crucial part of understanding these particles is understanding the forces by which they interact.

Quantised Forces:

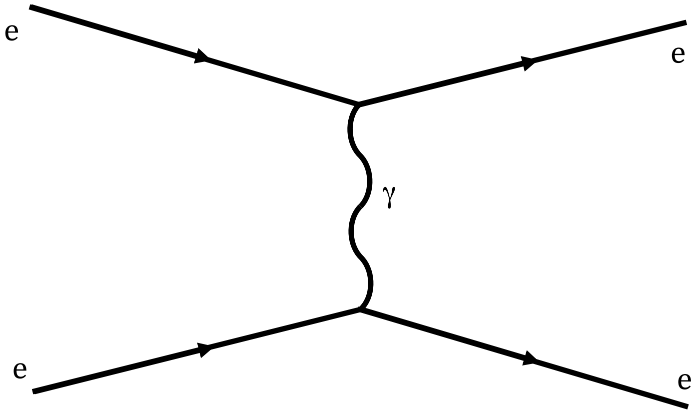
The best theoretical description of sub-atomic physics comes from relativistic quantum field theory. And one important way in which these theories differ from the Schrödinger equation which most of you are studying in Quantum Mechanics 2 is in how forces are treated. In the Schrödinger picture we describe forces in terms of classical fields, of potential energy as a function of position (and, sometimes, of time), e.g.

$$\frac{-\hbar^2}{2m}\nabla^2\psi + V(r)\psi = E\psi$$

In Quantum Field Theory the forces themselves are quantised – rather than a potential energy which varies continuously with position, there are discrete exchanges of energy and momentum between particles, carried by “quanta” (particles) of the fields.

Electromagnetic force:

To give an example, let’s consider the scattering of one electron by another. The electrons interact via the electromagnetic force, and the quantum of this force is the photon – the “particle of light”. So in Quantum Electrodynamics we would represent this interaction by:



The photon transfers energy and momentum between the two particles. The classical definition of a force is F = -dp/dt, so this change in momentum would be consistent with that definition of a force. You could view the classical force as the result of many, low-momentum transfers of this sort (equivalence principle).

This is an example of a Feynman diagram.

In this diagram the horizontal axis represents time and the vertical axis represents space. So we have 2 particles which start off approaching each other, exchange momentum via the electromagnetic field, and end up moving apart.

While we will use these diagrams simply to illustrate reactions, they actually have a more serious purpose in Quantum Field Theory (QFT). They are in fact a tool for constructing the mathematical expressions used to calculate the probabilities or rates of reactions in QFT. Each element represents a part of the expression:

- The straight lines describe matter particles travelling through space and time
- The curly line represents the force quantum travelling through space and time

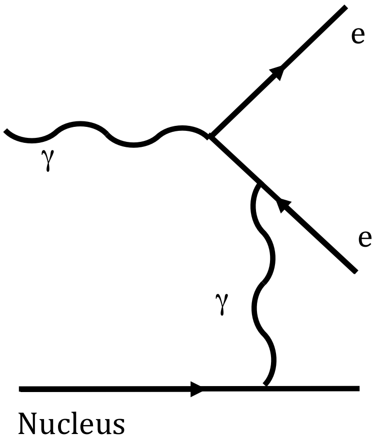
The expressions these terms represent are collectively known as "propagators".

In addition, at each vertex (where the photons are emitted or absorbed by the electrons) there is a "coupling constant" factor, representing the charge of the particle.

Squaring and integrating the expressions constructed this way allows us to calculate the rates of reactions.

Let's use another diagram to illustrate other properties of these diagrams.

One way in which high-energy photons interact with matter is pair production, γ → e+ e-. We would represent this by:



- The positron is an anti-electron. This is represented by an electron line with the arrow reversed – an electron that's propagating backwards in time! For our purposes this is just a convention for how we represent antiparticles in these diagrams.

- The other thing to note is that charge is conserved at each vertex, i.e. the net charges of the incoming and outgoing particles are the same.

Since the electromagnetic force is carried by the photon, its properties are related to those of the particle which carries it:

- Coupling: the photon only "couples to" (can be emitted or absorbed by) particles which carry an electric charge.
- The photon itself is neutral. Hence photons to not interact (directly) with other photons, i.e. do not experience the EM force that they carry.
- The photon is a massless, which means that the electromagnetic force has infinite range (will discuss this further shortly).

However, as soon as we discovered that the nucleus was composite it was clear that additional forces were needed to explain the properties and structure of matter.

Nuclear force:

While electrons are held within atoms by electromagnetic forces, these cannot hold the nucleus together: the nucleus consists of protons (positive) and neutrons (neutral), and so the electromagnetic interactions are all repulsive! And since $F_{EM} \propto 1/r^2$, and protons inside nuclei are separated by ~1fm, the repulsion is very strong: the repulsive potential energy between a pair of protons separated by 1fm is ~1.4 MeV. Yet many nuclei are stable, with binding energies (the energy needed to separate a nucleon from the nucleus) several times this size. So the attractive force which binds the nucleus together is clearly significantly stronger than the electromagnetic repulsion.

This strong nuclear force also has a short range. To see this, consider what would happen to the Rutherford scattering experiment if this attractive force had a range much larger than the size of the nucleus: rather than being scattered back, the alpha particles would have been captured by the nuclei they approached closely. In fact the range of this attractive force is ~1fm.

In 1934 Hideki Yukawa proposed that this short range was because the force was due to the exchange of massive particles. A simple version of the argument goes like this:

> Creating a massive exchange particle (mass > energy transferred) would violate energy conservation. But according to the uncertainty principle, if a system only exists in some state for a finite time interval there is an uncertainty in the energy of the system:
>
> $$\Delta E \Delta t \geq \hbar$$
>
> So if the time during which the exchange occurs is short enough, the uncertainty will be large enough to allow the temporary creation of a massive exchange particle.

Since nothing can travel faster than light, this allows us to estimate the maximum range of a force carried by a particle of mass M:

$$\Delta t \geq \frac{\hbar}{\Delta E} = \frac{\hbar}{Mc^2}$$

$$\therefore \text{range} < c\Delta t = \frac{\hbar}{Mc}$$

So a force with a range of 1-2fm would imply an exchange particle with a mass of 100-200 MeV/c^2.

(The converse of this argument is that the maximum range of the EM force is infinite).

Yukawa called this particle the "meson", because its mass was intermediate between the light particle (or "lepton"), the electron, and the heavy particles ("baryons"), the proton and neutron. Shortly after he proposed this, observations of cosmic ray interactions revealed the existence of a new particle with a mass of just over 100 MeV/c^2. This was originally thought to be Yukawa's meson, but it did not interact strongly with nuclear matter – in fact it turned out to be a heavy version of the electron, now known as the muon. The lightest particle you can make from quarks, the pion, is in fact the best analogue of Yukawa's meson, and pion exchange still provides a reasonable working model for the nuclear force, even if it is no longer thought to be the real truth.

Strong force:

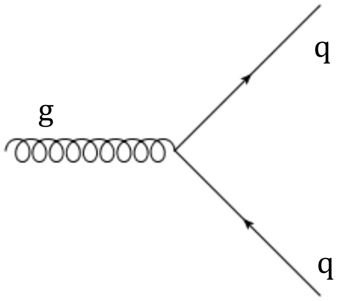
In fact this strong nuclear force is no longer thought of as a fundamental force in its own right. Rather it is a relatively weak "spill-over" of the true strong force, which binds quarks together to form protons and neutrons.

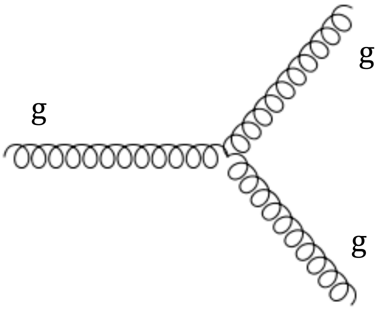
The strong force is considerable stronger than the EM: 100-1000 times stronger in low-energy interactions (such as those which bind quarks together into protons and neutrons).

Only quarks experience the strong force. The evidence (which we'll discuss later) suggests that unlike electric charge, which has only one type, there are three types of strong charge. These are referred to as "colours", with the three different types being labelled "red", "green" and "blue", with the three together forming a "colourless" (neutral) object. In addition there are "anti-colours" (anti-red, anti-green, anti-blue), with colour and anti-colour being analogous to positive and negative electric charges.

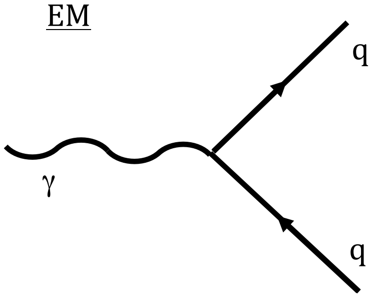
The carriers of the strong force are called "gluons". Like the photons, these are massless. Unlike the photons, the gluons themselves carry colour charges, and so couple to other gluons and experience the strong interaction themselves.

Strong





EM



No equivalent in EM interactions

Each gluon carries a colour and an anti-colour, e.g. red-antigreen. As with EM charges, colour charges must also be conserved during interactions (i.e. at the vertices of Feynman diagrams). So if in the top-left diagram above the gluon is red+anti-green, the outgoing quark will be red and the anti-quark anti-green.

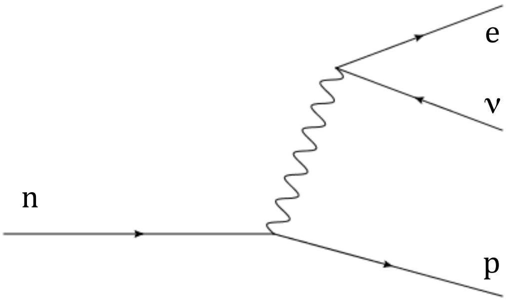
> There are actually 8 distinct gluon states, but to discuss that you need to think about group theory and the way that quantum states are superposed. So for the moment let's just note that there are 8 independent combinations of colour states for the gluons.

The strength of the strong interaction, and the fact that the gluons themselves also experience the strong force, is understood to be the real reason for the short range of the strong force. In the same way that quarks are unable to leave the proton because they are held in by the strong force, so will any gluons that try to travel any distance from the proton be.

Only quarks and gluons carry the colour charges, so only particles made from these experience the strong force.

Weak interaction:

Some reactions are observed which cannot be due to either of these forces. The simplest example is beta decay: $n \rightarrow p\ e^- \overline{\nu}_e$



The neutrino is a very light, neutral partner of the electron.

This decay could not be caused by either the strong or EM forces because:

- The reaction changes the charge of the nucleon (n →p), so the exchange particle must be electrically charged, which neither photon nor gluon is.
- It cannot be caused by the strong interaction because an electron is produced, which does not interact strongly.
- It cannot be cause by the EM interaction because the neutrino has no charge, so doesn't couple to the photon

Hence a different force is needed to mediate this decay.

In addition, processes like this occur much more slowly than those mediated by the strong or EM interactions. Hence this new force was labelled "weak".

Since the exchange particle in this reaction is carrying the weak force, and has a negative charge, it is called the W^-. There are also reactions with the opposite charge, implying a W^+. Much later it was predicted that there would be a neutral version too, and so a third particle, the Z^0, was added.

At low energies, typical of nuclear reactions, the weak interaction has a strength < 10^{-5} that of the strong force. But in high energy processes (> 100 GeV) its strength is similar to the electromagnetic interaction. It also has an extremely short range, and these two facts have the same cause.

Whereas the photon and gluon are massless, the carriers of the weak interaction are not:

$W^\pm$: mass = 80.385 ± 0.015 GeV/^{2}

Z^0: mass = 91.1876 ± 0.0021 GeV/c^2

If we use the same uncertainty principle calculation that we used for Yukawa's meson, we would estimate the range of a weak force carried by the W to be $\text{range} < c\Delta t = \frac{\hbar}{Mc} = \frac{197}{80{,}000} \approx 2\times 10^{-3}\,\text{fm}$.

This also explains the weakness of the force: the reactions are suppressed by the mass of the exchange particle. For energies >> the W mass this is no longer a problem, and so weak interactions are able to proceed much more easily.

Gravity:

We are going to ignore gravity completely. This is primarily because it is absurdly weak – more than 30 orders of magnitude weaker than the strong interaction – and so has no observable effect in subatomic physics.

Also, we do not have a working quantum theory of gravity. There's still an opportunity there for anyone who fancies a challenge ☺

Summary:

All of the interactions of sub-atomic particles can be described in terms of 3 forces:

- Strong: strength ~1; range ~1fm; carriers = gluons (massless); couples to quarks and gluons.
- Electromagnetic: strength ~0.01; range = infinite; carrier = photon (massless); couples to charged particles.
- Weak: strength ~ 10^{-5}; range ~0.001fm; carriers = W, Z (massive); couples to all matter particles.

Next we can look at the properties of the matter particles.