Lancaster Particle Pamphlets

Number 5 Interactions of Particles

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Interactions of Particles Contents

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Introduction

In P4 we outlined the discoveries of the three families of quarks and leptons. There is symmetry between the quark and lepton families in that they appear in pairs, the members of a pair differing in electric charge by one unit. In this pamphlet, we develop ideas on how the elementary particles interact with each other. The basis of the quark lepton symmetry then becomes clearer.

Knowledge of the interactions between the quarks and leptons leads to an understanding of how quarks can join together to form the familiar protons and neutrons. Protons and neutrons are the constituents of atomic nuclei. It also allows us to form a deeper understanding of radioactive decay processes.

There are four fundamental interactions involving quarks and leptons. They are listed in order of decreasing strength:

- **Strong**
- **Electromagnetic**
- **Weak**
- **Gravitation**

You will be familiar with the electromagnetic interaction that manifests itself on the human scale as electric and magnetic fields. You will also remember that the production of electromagnetic radiation (light) is described by the emission of single *photons* by atoms. The interaction of electrically charged quarks and leptons is also described by the emission of single photons. The theory has been fully developed over the past seventy years and is called “Quantum Electrodynamics” or QED for short! Fortunately, you need know nothing of the complex mathematics of this theory, the essentials can be understood using *Feynman diagrams*. We can draw one here to illustrate the electromagnetic interaction between an electron and a positron: Each arrow represents a particle entering or leaving the point of interaction. The wiggly line represents a single photon. The time arrow tells us that an electron and positron exist before and after the interaction.

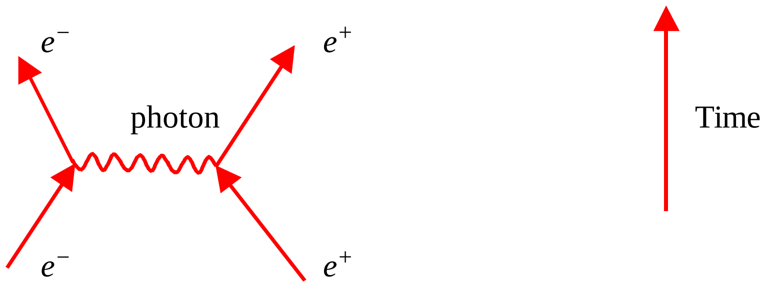

Fig. 1 The basic electromagnetic interaction $e^- + e^+ \rightarrow e^- + e^+$.

Here the electron and positron *exchange* a single photon. This is the basis of the electromagnetic interaction, taking place on the sub-nuclear scale. The interaction is written as: $e^- + e^+ \rightarrow e^- + e^+$.

The other fundamental interactions are also described by the emission of single "force particles" and can be illustrated by Feynman diagrams.

The Electromagnetic Interaction

We can now discuss the electromagnetic interaction in a bit more detail. The important fact is that the interaction takes place only between particles that possess *electrical charge*. The electrical charge is a kind of focus for the interaction. One can imagine the charged particle continuously emitting photons and then reabsorbing them. If another charged particle is nearby then the photon can be absorbed by it. The exchanged photon transfers both *energy* and *momentum* from one charged particle to another. This is the basis of the electromagnetic interaction and, taken to large-scale limit, reproduces the familiar electrostatic inverse square law of force and the laws of electromagnetism.

The photons familiar to you from the photoelectric effect (and those you see with!) have an important characteristic. They have *zero mass*. However, an application of the relativistic equations given in P1 to each electron photon vertex in Fig 1 shows that the *exchanged photons cannot have zero mass*! For this reason, they are called **virtual photons**. Virtual photons cannot exist as free particles but must soon be absorbed. In Feynman diagrams the virtual photon is given the greek symbol g (gamma).

The strength of the electromagnetic interaction between two charged particles depends on the magnitude of the charges. It follows that the electromagnetic interaction between two quarks is weaker than the interaction between two electrons. There can be no electromagnetic interaction between two neutrinos, which have zero charge, or between a neutrino and an electron.

Virtual photons have spin quantum number 1 (remember leptons and quarks have spin quantum number ½). All particles with integer or zero spin are called *bosons* in honour of the Indian physicist J C Bose. Virtual photons are the **exchanged bosons** that mediate the electromagnetic force**.** Exchanged bosons are often called "**gauge bosons**" because of the nature of the underlying theory.

Sir J.C. Bose,
physiologist an
physicist. (185
1937)

Fun with Feynman

The Feynman diagram representing the basic interaction between an electron and positron is shown in Fig 1. Note that electrical charge is *conserved* at each vertex. The net charge into the vertex is exactly equal to net charge out. If we turn the diagram on its side and reverse the direction of one of the arrows then we have a picture of electron-positron annihilation followed by pair creation! Notice again that charge is conserved at each vertex. This is an example of matter and antimatter annihilating to produce energy in the form of the virtual photon. The virtual photon cannot last long and materialises into any lepton antilepton pair or any quark antiquark pair provided the initial particles have sufficient energy. This interaction is written: $e^+ + e^- \rightarrow g \rightarrow e^+ + e^-$

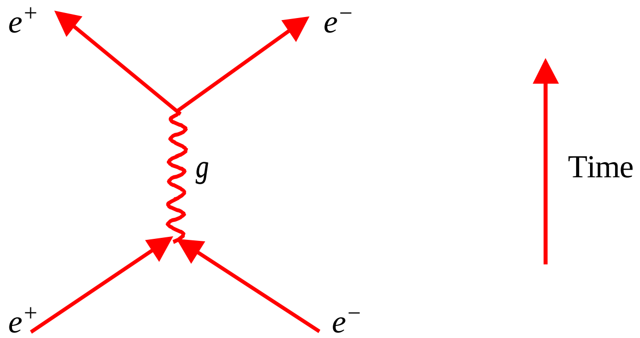

Fig. 2a Electron positron annihilation followed by pair creation $e^+ + e^- \rightarrow g \rightarrow e^+ + e^-$

We will play many similar games with Feynman diagrams, all legitimate and all illustrating possible interactions. The next illustration represents an electron and positron annihilating to form a virtual photon that materialises as an up quark and anti up quark pair $e^+ + e^- \rightarrow u + \bar{u}$.

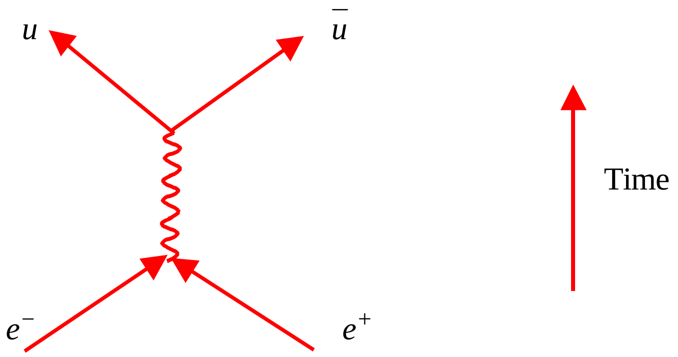

Fig. 2b Electron and positron annihilate followed by quark antiquark pair creation $e^+ + e^- \to u + \bar{u}$.

The Weak Interaction

Photons are not the only kind of boson particle associated with interactions between quarks and leptons. Closely related to the photon but very different in mass are the W^+, W^-, and Z^0 bosons. These particles possess electrical charge as indicated by the superscripts. Leptons and quarks continually emit and absorb virtual W and Z particles but one could be absorbed by a nearby lepton or quark. This exchange is illustrated in Fig 3a, b, c.

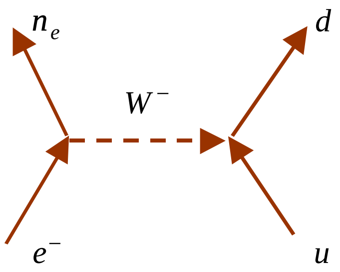

Fig 3a. This represents an electron interacting with an up quark to produce a neutrino and a down quark. $e^- + u \to n_e + d$. A virtual W^- is exchanged.

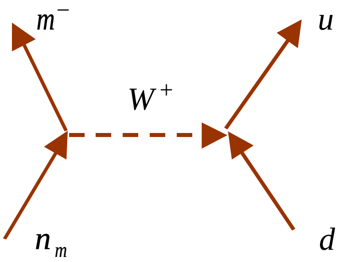

Fig 3b. This represents a muon neutrino interacting with a down quark to produce a negative muon and an up quark. A virtual W^+ is exchanged.

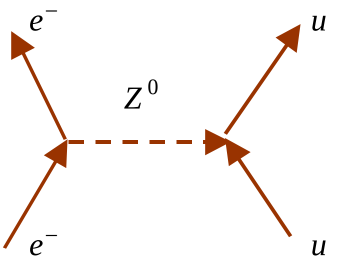

Fig 3c. This represents an electron interacting with and scattering from an up quark. A virtual Z^0 is exchanged.

Notice that electrical charge must be conserved at *each* vertex. This means that when a charged *W* particle is involved the lepton or quark must change charge. For example, an electron can change into an electron neutrino, a muon into a muon neutrino or a tau into a tau neutrino. Similarly, a down quark can change to an up quark, a strange quark to a charm quark and a bottom quark to a top quark. **This is precisely why we grouped the leptons and quarks into families.**

There is one important modification to this rule; there is a small chance that a quark can change family when a charged *W* is involved. For example, a strange quark can change into an up quark when a W^- is emitted. When the Z^0 is involved the leptons or quarks do not change electrical charge nor do they change family.

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The exchanged virtual *W* and Z^0 particles behave in a manner very similar indeed to an exchanged virtual photon in the electromagnetic interaction. There is however one major difference, the real *W* and Z^0 have masses almost two orders of magnitude greater than a single proton! The effect of this is to make the interactions between quarks and leptons involving *W* and *Z* particles very much *weaker* than the electromagnetic interaction when the interacting particles have low energies. For this reason, the interaction involving *W* and *Z* bosons is called the *weak interaction.* However, when the energies of the particles are equal to

The mass of
$W^{\pm}$ is 82
GeV/c^2. The
mass of the
is 92 GeV/c

or greater than the rest mass energies of the W and Z, the weak interaction and the electromagnetic interaction have similar strength. Also the virtual W and Z particles can exist for times of order 10^{-25} s and the range of the force is only 10^{-17} m.

Of course, we can play games with W and Z bosons using Feynman diagrams. Take Fig 3a, rotate it by 90° and turn round the d quark so it becomes an antiquark $\bar{d}$. The diagram can now represents an up quark interacting with a down antiquark to make a real W particle, which then materialises into a positron and an electron antineutrino (Figure 4).

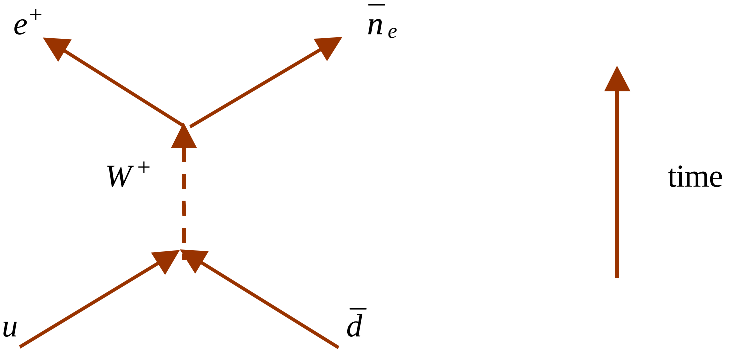

Fig. 4 Energetic u and $\bar{d}$ quarks interact to make a real W^+. The W^+ decays into a positron and an anti electron neutrino $u+\bar{d}\rightarrow W^+\rightarrow e^+ + \bar{n}_e$.

This is more than a game because it is the process by which the *real* W particles were discovered at CERN in 1981. Using the proton antiproton colliding beam machine operating at 270 GeV, teams were able to create real W and Z particles. The created particles could be positively identified via their decay into high-energy electrons or muons. The u and $\bar{d}$ quarks were contained within the colliding proton and antiproton.

Note that the neutrino interacts only via W or Z exchange. If a neutrino or antineutrino is involved in an interaction you know *for sure* that the weak interaction is involved.

The Electroweak Interaction

In recent years, the fundamental theory of electromagnetism has been combined with the weak interaction theory to make a *unified* **electroweak** theory. This unification is comparable in importance with the unification of theories of electricity and magnetism by Maxwell in the late nineteenth century. Maxwell's electromagnetic theory led directly to radio waves and it was a crucial starting point for Einstein's relativity theory. No one knows what practical applications, if any, will spring from electroweak theory but they may radically change science and technology in the next century.

The Strong Interaction

The electromagnetic interaction takes place between particles possessing electrical charge. The strong interaction takes place between particles having a different kind of charge. The focus of the strong interaction is called the *colour charge*. The colour charge has **nothing to do with real colours** but it is given that name for interesting reasons. First, the colour charge comes in *three* different kinds, which we label *red*, *green* and *blue*. In contrast, the electrical charge comes in *two* kinds, which we named *positive* and *negative*. Second, we find that particles with the same colour charge repel each other and those with different colour charge attract each other. Third, the combination of three particles with red, green and blue colour charges forms a colour neutral object. Here is the **analogy** with real colours: red, green and blue added together make neutral white. Just as the stable hydrogen atom is an electrically neutral combination of a positive nucleus and negative electron, we will see in P6 that a proton is a colour neutral combination of three quarks.

The six quarks identified in P4 possess the colour charge in any one of the three forms, red, green or blue. Therefore, they can interact with each other via the strong force. Two red quarks will repel each other whilst a red quark and a blue quark will attract each other. The antiquarks possess colour charges anti-red, anti-green and anti-blue. This allows the analogy with real colour to be taken further. The anti-colour charge behaves like a complementary colour, a red quark can combine with an anti-red quark to make a colour neutral object. Again, in P6 we will see how pi mesons can be made from quark and antiquark pairs. As its name suggests the strong force can easily overcome the repulsion between quarks with opposite electrical charge.

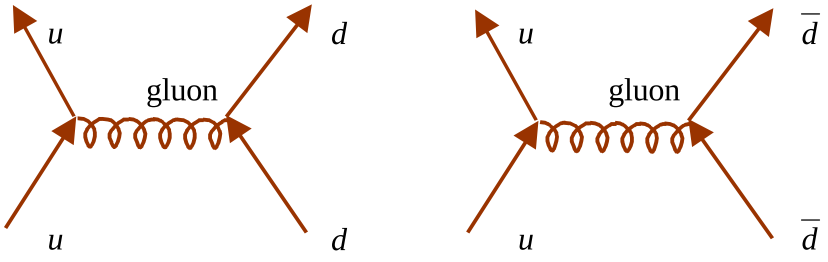

Fig. 5 Two examples of the strong interaction.

Each fundamental interaction has an exchanged virtual boson or gauge boson. The strong interaction is mediated by the exchange of a *gluon*. The name “gluon” eloquently expresses its function: it can stick quarks together! The gluon is similar to a photon in some respects, it has zero mass and it has spin quantum number 1. However, it behaves differently in that the strong force between quarks *increases* as the distance between them increases. Elastic bands or springs also have this property and for this reason, the gluon is usually drawn as a coiled spring in Feynman diagrams. Figure 5 shows two typical strong interactions.

Only the quarks possess the colour charges and the antiquarks the anti-colour charges. *The leptons do not have the colour charge*. In consequence, the leptons do not interact via the strong force. It is most important to note that the gluon cannot change one flavour of quark into another flavour, in other words the strong interaction preserves the flavour of each quark.

The Gravitational Interaction

The gravitational potential energy between two particles is given by the formula $E_G = Gm_1m_2/r$. Inside a proton the quarks are typically 10^{-15} m apart and have masses roughly 0.3 GeV/c^2. Putting these numbers into the formula gives $E_G = 10^{-40}$ GeV. This energy is very much smaller than anything we are likely to encounter in particle physics. We are justified in neglecting gravitation in comparison with the strong, electromagnetic and weak interactions between individual quarks and leptons. Gravitation is important at distances of order 10^{-35} m or when matter is large clumps.

Introduction to Conservation Laws

We can readily account for the conservation of electrical charge in a Feynman diagram by adding up the net charge flowing into each vertex. The procedure is similar to Kirchoff’s law in circuit theory. To conserve charge the net flow in or out of each vertex must be zero. Similarly, we can codify other aspects of the behaviour of quarks and leptons when they interact by the strong, electromagnetic or weak interactions. In P7, the concepts of *lepton number* conservation and *baryon number* conservation will be introduced. At this stage, the following facts can be noted.

- Counting quarks as +1 and antiquarks as –1, the total number of quarks before any interaction is equal to the number after.

- Similarly, the total number of leptons is the same before and after any interaction.
- The electromagnetic interaction cannot change the type of lepton at a vertex, nor can it change the flavour of a quark.
- The strong interaction cannot change the flavour of a quark.
- The weak interaction can change the flavour of a quark provided the quark charge also changes.

Summary of the four fundamental forces

The properties of the four forces are summarised in Table 1. The relative strengths of the forces acting between two quarks when the energy is 1GeV are given. Note that the relative strengths of the interactions change as the energy changes. As the energy increases the strengths of the forces become progressively closer to each other. It is possible that at 10^{19} GeV all four forces have the same strength and may well be indistinguishable! This is the so called unification energy and may correspond to conditions in the earliest moments of the “big bang”

Table 1

Force	**Gauge boson**	**Relative Strength at 1 GeV**	**Particles involved**	**Comment**
Strong	Gluon	1	Quarks (colour charge)	Short range*
Electromagnetic	Photon (*g*)	1/137= .007	Quarks and leptons (with electric charge)	Long range
Weak	W^+, W^-, Z^0	10^{-5}	Quarks and leptons	Very short range
Gravity	graviton	10^{-42}	Quarks and leptons	Long range