The nature of force in particle physics

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The interaction between particles can be pictured as an exchange of virtual particles, but this view creates doubts in many people. Feynman diagrams can help in this but a consideration of fields is important.

Increasingly these days teachers are having to present ideas that really need quantum mechanics without the luxury of being able to teach quantum mechanics as a subject. I am thinking especially of the rise of particle physics either as an optional course or in some cases as part of the compulsory section of A-level syllabuses (at least the pre-Dearing ones). The biggest worry I have found, in my experience of workshops for teachers wishing to present particle physics courses, is how to explain the modern view of forces. Often the ideas involved have been developed since the teacher took his or her degree.

In preparing to teach the subject teachers have consulted some of the popular books on quantum mechanics, relativity and particle physics. Such books generally describe forces as arising from the exchange of objects called *gauge bosons* (an intimidating name at best, I shall stick to *exchange particles*[†]). To go along with this a picture such as that in figure 1 is drawn.

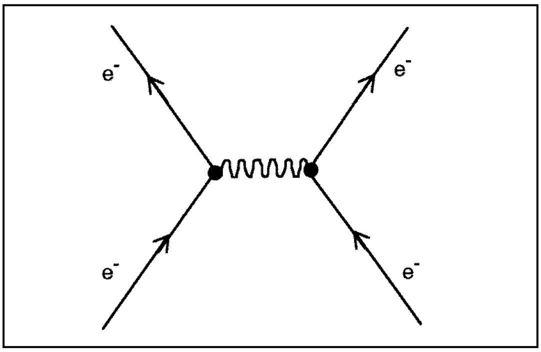

Figure 1. *A Feynman diagram showing how a photon can be exchanged between two electrons.*

It is well known that there are four fundamental forces: electromagnetism, the weak force, the strong force and gravity (even though the weak and electromagnetic forces have been brought together under one theoretical framework, we still tend to talk about four forces). Each is described in terms of different exchange particles: the photon, the Ws and Z, the gluon and the graviton respectively. The whole picture seems quite elegant and simple. However, there are nagging doubts that most teachers experience:

- what do Feynman diagrams tell us about what is actually happening in an interaction?
- how can an exchange particle know before it is emitted how much energy it must 'borrow' to reach the particle that absorbs it?
- how can the exchange of a particle give rise to an attractive force as well as a repulsion?
- how can a force which is an interaction between two or more particles give rise to the decay of a single particle?

All of these questions arise from stressing the exchange *particle* too much and ignoring the *field* of force that underlies the interaction.

In this article I shall attempt to develop a better picture and point out how some of the problems of understanding can be avoided.

[†] The only danger with using this term instead of *gauge boson* is that some exchange particles are not fundamental. In the theory of the strong nuclear force between protons and neutrons in the nucleus, pions act as exchange particles – but they are not fundamental field excitations. In this article I shall always mean fundamental field excitations when I say exchange particles.

What is a Feynman diagram?

The prototype of all forces is the electromagnetic force that exists between charged particles. Students are introduced to the idea that this force arises because a photon is exchanged between the two charged particles (see figure 1).

There is no convention among popular books as to the way in which such diagrams should be drawn. Some insist that they are space-time diagrams and that there is an implied time axis (vertical in this case) and an implied one-dimensional spatial axis (horizontal). Others make no comment about space-time and regard the diagram as a 'doodle' that provides a picture of what is going on.

Feynman originally invented his diagrams to help provide a framework for calculations. The various elements of the diagram correspond to terms in an integral. The power of the method lies in the way it helps construct integrals systematically. His diagrams were never intended as space-time pictures – the mathematical terms that they stand for are expressed in terms of the momentum and energy of the particle, not its position and velocity.

There *are* such things as space-time diagrams (or time-ordered diagrams), but they are *not* Feynman diagrams.

One of Feynman's great contributions to the subject was to realize that the two diagrams drawn in figure 2 were equivalent. The order of emission and absorption of the photon can be dependent on the frame of reference from which the event is viewed (spatially separated events in relativity have no fixed time ordering). Furthermore, Feynman's system extends to include the possibility that the exchange particle may move backwards in time!

Feynman realized that this sort of diagram was equivalent to a diagram in which an antiparticle moved forwards in time (that is what we 'really' see). Of course an antiphoton is identical to a photon, so for electromagnetism it does not make much difference.

Every Feynman diagram is relativistically invariant, that is to say it represents a *process*[†] that is taking place. The details of the process such as the time ordering, who emitted what, who received it, whether it was a particle or an antiparticle that was exchanged, etc are irrelevant.

Think about this in the same terms as you do electric and magnetic fields. We are used to thinking about relativity in such contexts. If you move a wire through a magnetic field, then the magnetic force on the charge carriers within the wire causes an EMF, resulting in a current flow. Viewed from the perspective of someone sitting on the wire, the EMF is due to an electric field along the wire. The physical result is the same – a current flow. A Feynman diagram is a process diagram that covers all the possibilities that can be mapped into the process by a Lorentz transformation.

How much of this can be introduced to pupils? It is probably best not to get into problems in the first place. In my experience pupils are quite happy with the idea of the Feynman diagram as being a

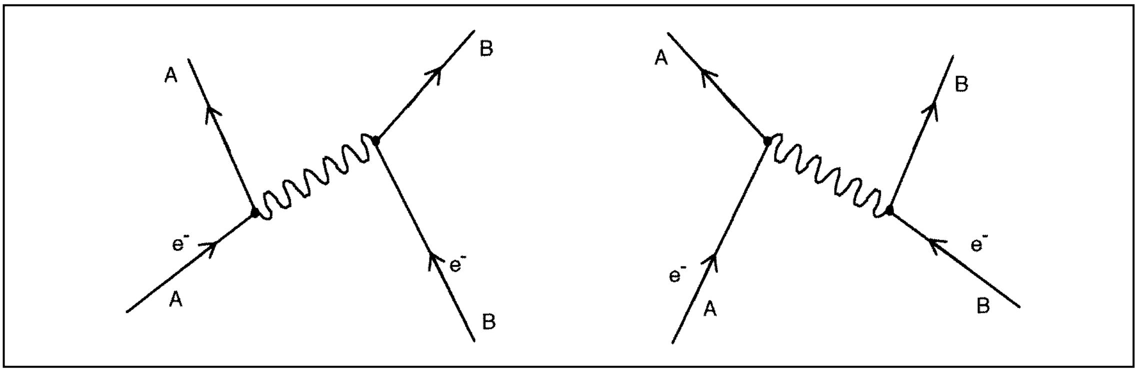

Figure 2. *If Feynman diagrams had a vertical time axis, then these two diagrams would represent different time orderings of the events. The Feynman diagram of figure 1 is relativistically invariant and so covers both these diagrams.*

[†] Strictly they are a means of calculating the amplitude for a process. The probability of the process is found by summing the amplitudes and squaring.

'doodle' and they will never try to think of it as a space-time diagram unless you suggest it!

What is a virtual particle?

We tell students that the carriers of the weak force (the W^+, the W^- and the Z^0) are particles with masses of the order of 80–90 GeV/c^2 (or about 80–90 proton masses). Then we will go on to describe the process of neutron decay as one of the d quarks (clearly much lighter than the neutron) inside the neutron emitting a W^- (about 80 proton masses). The next stage is to sit back and await the inevitable question: 'how can it do that, where does it get the energy from?'.

In the context of neutron decay we are dealing with a double problem. How can the quark emit an object that is more massive than it is, and how can forces give rise to decays? Putting the latter to one side for the moment, the picture can be made slightly clearer by considering a reaction such as neutrino–quark scattering:

$$\nu_e + d \rightarrow u + e^-$$

which may not seem a very important reaction, but it is the principal way by which neutrinos from the sun are detected.

The most common way of explaining how a particle can emit another object that is more massive is to resort to the uncertainty principle. (Whenever a physicist turns to the uncertainty principle to explain anything I start to get deeply worried. A fudge is about to be perpetrated.)

If there is an uncertainty relationship $\Delta x\ \Delta p \geq h/2\pi$ for position and momentum, then it is reasonable to believe that a similar relationship exists between energy and time: $\Delta E\ \Delta t \geq h/2\pi$.

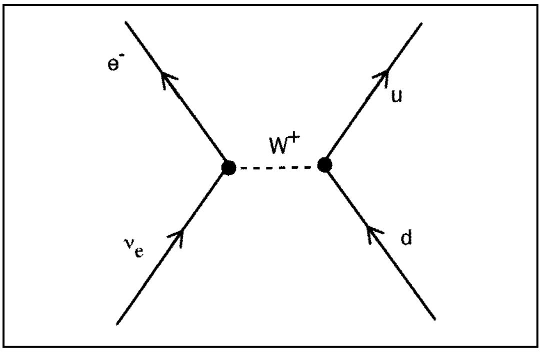

Figure 3. *A Feynman diagram representing neutrino–quark scattering.*

By exploiting this relationship the exchange particle is able to pop into existence by borrowing enough energy (ΔE) to be produced (in this case nearly 80 proton masses worth). However, this energy has to be paid back within a certain time span ($\Delta t \leq h/2\pi\Delta E$). Any energy that is borrowed over that needed to produce the particle is the kinetic energy needed to travel between the emitting particle and the target.

The time limit on the loan gives the force a range that depends on the mass of the exchange particle. The more massive the particle the greater the amount of energy that needs to be borrowed and the shorter the loan time – hence the particle cannot go very far before it has to be paid back. The force has a short range. The exchange particle is living on borrowed time (literally). It has no right to be regarded as a real particle, and so it is called a virtual particle. Its presence in the interaction is impossible to detect directly.

The problem with this explanation is that it is very difficult to believe that the exchange particle knows how far away the intended target is before it is emitted. If this is the case, how does it know how much energy it needs to borrow *before it sets off*? Where does it borrow the energy from anyway?

In the Feynman diagram picture there is no borrowing and paying back of energy. Energy is conserved at the point of emission and the point of absorption. However, the particle that is travelling *is off mass shell*. This rather daunting expression simply means that the W that is exchanged (for example) is not necessarily 80 proton masses.

The key to understanding this is to realize that the emission and absorption of exchange particles *are not independent events*. Feynman diagrams hide the fact that there is already 'contact' between the two particles before the exchange takes place. The Feynman diagram does not show the field that underlies the process. Understanding this is vital to feeling comfortable about the whole Feynman approach.

When two charged particles approach each other there is an electromagnetic field in the volume of space surrounding them. The total field is composed of a superposition of the fields of the separate objects. If the particles are moving, then the field is in a state of change. As the particles interact with one another the field undergoes a very complicated dynamic process that can result in the exchange of energy and momentum between the particles. The amount of exchanged energy and momentum depends on the state of motion of *each* particle. They are both important in determining the dynamics of the electromagnetic field.

When we draw a single Feynman diagram we are simplifying the process tremendously. The wavy line that we draw (in the case of a photon) represents a disturbance in a field that extends invisibly across the whole diagram. Think of a ruck in a carpet. That is a photon in an electromagnetic field. We can make the ruck move by whipping one end of the carpet, but the tension in the carpet and the distribution of furniture round the room all influence the motion because they are setting up the background conditions in which the motion is taking place. The photon is a disturbance in the field connecting the two particles and its creation is as much to do with the motion of the absorber as it is of the emitter.

In the context of the weak force, the d quark and the neutrino both have weak fields that interact as the particles get closer together. The closer they are, the greater the energy that exists in the field (the greater the disturbance that is set up). The more energy there is in the field, the more likely it is that a W will be *formed* (note the use of formed, not emitted – this terminology emphasizes the true nature of the interaction). The W can be formed at any energy, but the further the energy in the field is from the 'mass' of the W, the less likely it is to appear. This is why massive exchange particles give rise to a range for a force. The more massive the exchange particle, the greater the energy there has to be in the field to make the formation of the particle reasonably likely. The nearer it is to being 'on mass shell', the more likely it is to appear.

In my experience students are reasonably happy with this way of looking at things. It makes a link between Feynman diagrams and the ideas of fields of force that they have already studied. They have seen how the field of two charged objects differs from the field of an isolated charge, so they can imagine that as particles move about changes take place in the field between them. The carpet analogy works quite well and they see the sense in saying that the more energy there is in the field, the more likely the exchange particle is to be formed.

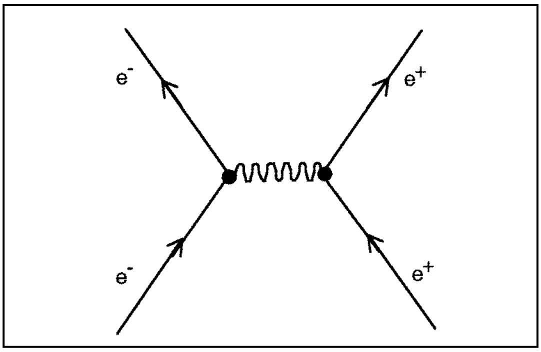

Figure 4. *The first-order diagram for electron–positron scattering looks exactly like that for electron–electron scattering. This often leads to confusion if this is regarded as the only diagram that is taking place.*

How do you get attraction and repulsion from particle exchange?

This is a perennial problem that has attracted a series of quite absurd fudges in an attempt to resolve the issue. It is quite easy to visualize how exchanging objects can give rise to a repulsion. The standard analogy is to imagine two people cycling side by side. One throws a medicine ball to the other. Understandably the thrower recoils away at the moment of release. The victim, or target, recoils at the moment of impact. Viewed from above this does seem very similar to a Feynman diagram.

However, if you draw a diagram for the interaction of particles with opposite charge, say an electron and a positron, then it looks exactly the same!

The most absurd way of explaining this that I have seen is to accuse the exchange particle of being like a boomerang that curves away from the emitter in the opposite direction to what one would expect. It then whips round behind the target and knocks it towards the emitter.

Of course, nothing of the sort happens. The simple diagrams for attraction and repulsion not only look the same, they are the same! If we only had to include the 'first order' diagrams (like figures 1 and 4) then there would be no difference between the interactions of charged particles of the same sign and of the opposite sign. But that is not all that is going on. As mentioned in the previous section, the dynamic changes in the field are extremely complicated and the simple diagram is the most basic approximation to the process. Just like the terms in an expansion for a mathematical formula, there are many more Feynman diagrams that must be considered for each interaction.

Some of the other diagrams that must be considered to get the full picture are the same for both sorts of interaction, but some are not. One example of this is the annihilation diagrams can only take place when the particles have opposite sign.

It is the difference in the total picture that one gets when other diagrams are considered that gives rise to attraction and repulsion.

The drawback to this is that the student starts to wonder which diagram is 'actually' taking place. How can particles be exchanging one photon, or two or more at the same time? The mathematically inclined seem quite happy with the idea that the different diagrams are 'terms' in an expansion series and that none of them represent what is happening on their own. The less mathematical can be won over by a simple demonstration. A mass suspended from a spring can be set into vertical oscillations. A pendulum of the same length with an equal mass can be set moving next to the spring. Ask the students to imagine that we had glued up the spring so that the coils could not move. Then the pendulum motion of the spring would look very similar to that of the actual pendulum. Set the spring in motion by pulling it to one side and releasing. Part of the time the motion will look to be simple vertical oscillations. Part of the time it will look like simple pendulum motion. Most of the time it will be a complex mixture of the two. The vertical oscillation and the pendulum motion are 'Feynman diagrams' that represent different aspects of the more complex motion that is taking place. This does have the benefit of making the point that no single diagram is happening – they are all involved.

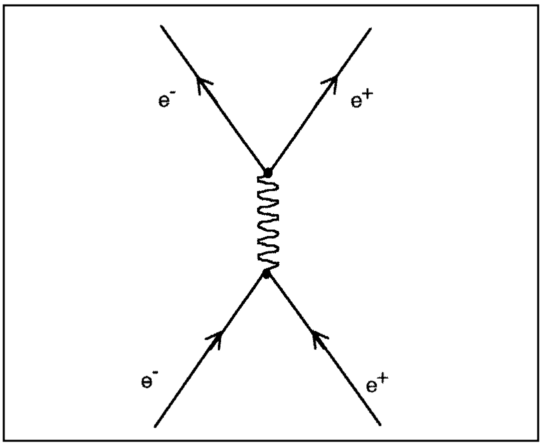

Figure 5. *This annihilation diagram (and others like it) is not possible in electron–electron scattering. Diagrams like these help to distinguish between attraction and repulsion.*

How do forces give rise to decays?

At A-level a force is a simple push or pull. In particle physics forces are much more than that. Interactions are more subtle and the forces that we see are only part of the whole picture. If we pursue the idea that Feynman diagrams give us pictures of disturbances that take place in fields, then we are forced to consider the idea that every particle is surrounded by a force field. In fact a quark is surrounded by electro-weak fields, a strong field and a gravitational field. When the fields of different particles overlap, interactions can take place resulting in the formation of exchange particles and giving rise to forces. When the particle is sitting on its own, then it can get rid of excess energy by dumping it into its field. This sets up a disturbance in the field that propagates away. The particle has decayed. What links forces and decays together is the underlying field that exists.

In the case of the neutron decay discussed earlier, the d quark has dumped energy into a W^+ and has turned into a u quark (the W has carried away charge, so the d cannot just become a lower energy d). The W^+ moves away from the quark. It is a localized region of high energy within the weak field. Within a short time, the energy is used to create new particles – in this case an electron and an antielectron neutrino.

Summary

The picture that I have been presenting provides a coherent view of the nature of interactions in particle physics. It draws on some of the ideas to do with fields developed in the A-level core. It can be summarized in the following statements:

- Particles are surrounded by fields: quarks have electro-weak, gravitational and strong fields;

leptons have all but strong fields.

- When particles interact their fields become intermeshed and start to develop in a complex and dynamic manner. As a result of this interaction, energy and momentum can be exchanged between the particles. We picture this as the formation of excitations, or vibrations, in the field and visualize them as field particles that move across the interaction.
- We draw Feynman diagrams as a means of organizing the results of such interactions. For any interaction an infinite number of diagrams can be drawn. No one diagram represents the truth.
- Some exchange particles have mass. This represents the amount of energy that needs to exist in the field to make the formation of the particle most likely. They can be formed at lower energy than this, and at higher energy, but the probability of formation decreases as the energy moves away from the 'correct' amount.
- Exchange particles also form a means by which a particle can 'dump' energy into one of its fields and so decay into a lighter particle.

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Further reading

Allday J 1997 *Quarks, Leptons and The Big Bang* (Bristol: Institute of Physics Publishing) at press

Close F 1983 *The Cosmic Onion* (London: Heinemann Educational)

Particle Physics: a new course for schools and colleges available from Institute of Physics, London