background sheet

The Standard Model 2: Interactions and forces

Force

The Australian Curriculum refers to fundamental forces, force-carrying particles and reactions between particles. However in this resource we have chosen to use a terminology used by contemporary particle physicists, that of interactions.

The difference between 'force' and 'interaction' is subtle, but significant. Understanding it helps make sense of this complex study area.

Students were probably introduced to the topic of force through 'pushes and pulls'. They learnt that changes to an object's motion didn't happen spontaneously, but were the result of some external action: a push or a pull.

Later on these ideas were codified in Newton's laws of motion. Together with Newton's universal law of gravitation, and Coulomb's law of electrostatic interaction, changes in motion of objects could be seen as a consequence of force-pairs (action and reaction) acting between two objects. Examples include the attractive force between Earth and a tennis ball in motion, and repulsion between two similarly charged objects.

In these cases the classical view is that a force acts between two objects, and this force is transmitted through a field. Thus a gravitational force acts through the gravitational field surrounding Earth and the tennis ball; and electromagnetic force acts through the electromagnetic field surrounding charged objects.

Whilst this model works well on a macroscopic scale it really doesn't work at all on the subatomic scale. Nuclear forces that bind protons and neutrons in atomic nuclei do not behave in the same way as gravity and electromagnetism. An alternative view, derived from quantum mechanics, works at these scales. This is based on the concept of particle interactions.

Interactions

In any closed system a number of properties are conserved. These include energy, momentum and charge. Although the totals of each property are conserved, their distribution amongst components of a system can change. Whenever energy (or momentum, charge or any other conserved property) is redistributed amongst components of a system then an interaction has taken place. In other words, interactions lead to redistribution of energy, momentum and charge.

In Figure 1 two particles change their motion as they approach. There has been an exchange of energy and momentum between them, so an interaction has taken place. In this case the interaction is a consequence of these particles having charge, so the interaction is described as electromagnetic.

Physicists recognise four fundamental interactions:

- gravitational interaction
- electromagnetic interaction
- strong interaction
- weak interaction

Whenever energy, momentum, charge or one of the other conserved properties is redistributed amongst the components of a system, one or more of these interactions has taken place. We 'see' or 'feel' this interaction as a force.

When a proton decays into a neutron, electron and electron antineutrino (radioactive beta-decay) there has been a redistribution of energy, momentum and charge. This is, therefore, an interaction — specifically a weak interaction. It's difficult to make sense of this as a force as there's only one particle involved initially (a proton). However, in the sense that an interaction is defined as a redistribution of energy and momentum, it is very to understand that this is an interaction.

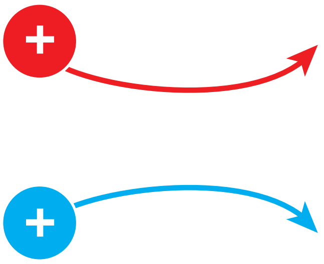

Figure 1.

Interacting particles exchange energy and momentum.

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How do interactions occur?

Classically, the transfer of energy and momentum involved in an interaction is described in terms of fields: electromagnetic fields transfer energy and momentum in electromagnetic interactions; and gravitational fields transfer energy and momentum in gravitational interactions. In both cases, the resulting behavior of particles (attraction or repulsion) is attributed to the action of forces, but at a more fundamental level it's transfer of energy and momentum that results in changes in particle trajectories.

In the Standard Model interactions are explained through exchange of particles called gauge bosons. The Australian Curriculum refers to these as force-carrying particles, but this terminology is problematic. Gauge bosons can't 'carry' force — force isn't something that any particle can carry. Particles carry energy, momentum, charge and so on, and gauge bosons are no different.

Gauge bosons have been exchanged between the interacting particles in Figure 1. This exchange has effected a net exchange of energy and momentum between the two particles. Because this is an example of an electromagnetic interaction, the gauge bosons concerned are photons. These photons 'exist' for a fleeting instant — for this reason they are referred to as virtual photons. As with many concepts in quantum mechanics it makes little sense to ask whether they actually exist. Photons can of course exist for long periods of time. These 'real' photons are familiar as light.

Similar gauge bosons are involved in (or 'mediate') the strong interaction (gluons) and weak interaction (W and Z bosons). A quantum theory of gravity, involving the hypothetical graviton boson, is yet to be developed.

Why do interactions occur?

Consider the particles shown in Figure 2a and 2b. What would happen if they didn't move apart as a result of electromagnetic interaction, as shown in Figure 2b?

It's certainly possible for two charged particles to move closer together in this way. Some kinetic energy of the moving particles is transformed into potential energy whilst keeping the total energy of the system constant.

However the laws of nature always seem to operate to minimise potential energy.

A ball rolls down a slope under the influence of gravity for the same reason: energy is conserved, but there's less potential energy (in this case gravitational potential energy) in the system when the ball is at the bottom of the slope than when it's at the top.

Any interaction between particles favours the outcome with minimum potential energy. For this reason particles move apart (as in Figure 2a), because for particles with like charges, increasing their separation reduces electrostatic potential energy. Energy and momentum are still conserved, but this outcome has lower potential energy.

For particles with opposite charges, electrostatic potential energy reduces when particles move closer to each other. This appears as an attractive force between particles with opposite charge.

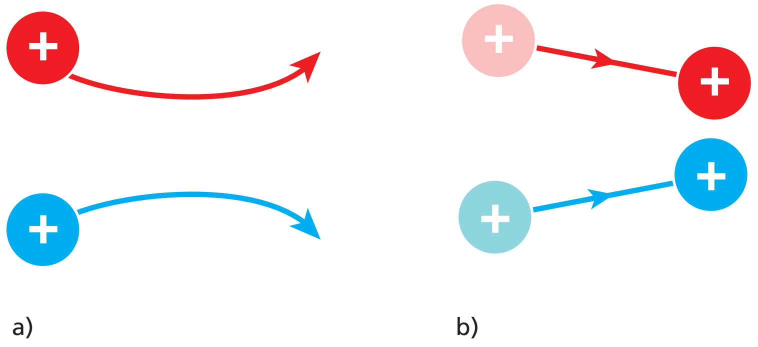

Figure 2.

Interacting particles — compare the energy distribution if similarly charged particles: a) move apart; or b) move closer together.

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