teacher guide

The Standard Model 2: Structure of matter

Components

	NAME	DESCRIPTION	AUDIENCE
	Structure of matter teacher guide	This guide contains notes for teachers on three presentations related to the fundamental structure of matter.	teachers
	Interactions and forces background sheet	This background sheet for teachers explains why this resource package uses the term ‘fundamental interaction’ rather than ‘fundamental force’.	teachers
	Thoughts on fields video	Professor Ian McArthur, physicist at The University of Western Australia, introduces some advanced ideas about the nature of fields.	students
	Particle physics presentation	This presentation relates the scale of subatomic particles to the observable world. Methods of study are introduced.	students
	Quarks presentation	This presentation describes how quarks interact to make protons and neutrons.	students
	Fundamental interactions presentation	A presentation introduces the four fundamental interactions: gravity; electromagnetism; weak and strong nuclear interactions.	students
	Glossary fact sheet	Particle physics introduces many new terms. This glossary will help students keep track of them.	students

Purpose

Students **Explore** aspects of the fundamental structure of matter through a series of presentations.

Outcomes

Students understand:

- how scientists study the fundamental structure of matter;
- why high energies are required to study fundamental particles;
- basic concepts of the Standard Model, including how quarks, leptons and bosons explain matter and forces.

Activity summary

ACTIVITY	POSSIBLE STRATEGY
Students watch video, *Thoughts on fields*.	whole class
Teacher steps through presentation, *Particle physics*.	class discussion
Teacher steps through presentation, *Quarks*.	class discussion
Teacher steps through presentation, *Fundamental interactions*.	class discussion
Students construct concept map of particle physics using glossary.	individual activity

Teacher notes

Thoughts on fields

This video presents an advanced view of how electric fields are produced by charged particles. Einstein's theory of relativity is used to explain how fields that surround charged particles exchange energy when they interact.

It is a useful introduction to the presentation in this package, *Fundamental interactions*.

A more detailed explanation of a quantum view of interactions and forces is included in *The Standard Model 4: Quantum approach.*

Particle physics

This presentation introduces students to the scale of subatomic particles and techniques scientists use to study them.

SLIDES	CONTENT
1 – 3	Introduction
4	A logarithmic scale displays 20 orders of magnitude, from 1 m to 10^{-20} m. This includes units for: millimetre (mm); micrometre (μm); nanometre (nm); picometre (pm); femtometre (fm); and attometre (am). It shows the size limit where scientists currently work: a factor of 10^{-5} smaller than a proton. *The Scale of the Universe 2* is an excellent animation that puts microscopic (and macroscopic) dimensions into perspective of everyday objects. It can be found at http://htwins.net/scale2/
5 – 6	Scattering experiments are a key to studying properties of the world around us. Just looking at an object relies on scattering: the eye detects light (electromagnetic radiation) that is reflected or emitted from an object. Characteristics of this light provide information to the observer. In physics experiments probe particles may be: photons (light and other invisible radiation); electrons; or other simple and complex particles. The detector may be: the eye (observing a sample through a microscope for example); a camera; or some electronic device. The ATLAS detector in the Large Hadron Collider is 46 m long, 25 m diameter and weighs 7000 t.
7 – 9	These slides explore limits to magnification. Why can't we simply build microscopes with unlimited powers of magnification? The key concept is that the wavelength of light used to study an object has to be substantially smaller than the object under study. A post in the ocean will have no effect on waves that pass it (diameter of the post is much smaller than the waves' wavelength). A rocky outcrop will have an effect of waves (they refract around it) if the outcrop's width is larger than the wavelength. Visible light has a wavelength of a few hundred nanometres, so it will never be possible to see atoms with an optical microscope as atoms are fractions of a nanometre in diameter. Using electromagnetic radiation with shorter wavelength than visible light allows some progress towards smaller objects, but nowhere near the size range of subatomic particles.
10 – 12	To study subatomic particles scientists use the principle of particle-wave duality. Every particle has an equivalent wavelength (the De Broglie wavelength) that is inversely proportional to its momentum. Accelerating particles to very high velocities gives them large momentum and hence small wavelength. This is the basis of electron microscopes, which resolve structures down to 10^{-11} m. The Large Hadron Collider accelerates more massive particles (protons) to 99.9999% of the speed of light in order to resolve structures down to 10^{-19} m.

SLIDES	CONTENT
13	The idea that matter is made of fundamental particles (particles that are indivisible) has been around a long time. However progress through the 20th century often showed that particles once thought to be indivisible were actually made of smaller, apparently fundamental, particles. Thus atoms were found to have a nucleus; the nucleus contained nucleons (protons and neutrons); and nucleons themselves contained quarks and other particles binding quarks (gauge bosons). At this time electrons and quarks appear to be fundamental particles, but it is expected that they have internal structure. (Note: protons are accelerated in the LHC to an energy of 4 TeV. They are placed in two beams circulating in opposite directions, giving collisions at 8 TeV. From 2015 the LHC will collide beams of 7 TeV protons to give collision energy of 14 TeV.)
14 – 16	During the first half of the 20th century a large number of particles were discovered, seemingly without any organising principles. The Standard Model imposed an order on this, mainly by proposing that many particles previously regarded as fundamental were in fact made up of combinations of quarks. The Standard Model divides particles into two major groups: fermions and bosons. Fermions make up the matter around us; bosons are responsible for interactions that hold matter together. Bosons also make up light and other forms of electromagnetic radiation. Fermions are themselves divided into two groups: quarks (fundamental particles that bind to form composite particles such as protons, neutrons and mesons, collectively called hadrons); and leptons (apparently fundamental particles that include electrons and neutrinos).
17 – 18	A tabular summary of the Standard Model shows leptons and quarks both come in three 'generations'. In everyday life only generation one is important. Higher generations only come into play at high energy levels (such as those seen in the LHC and in the early Universe). The Standard Model isn't a complete picture of the world however. Gravity does not currently fit into it, nor do dark matter or dark energy. These will require extensions to the Standard Model.
19	Common matter particles, such as protons and neutrons, do not appear in the Standard Model table of fundamental particles. They are composite particles containing quarks in bound states.

Quarks

This presentation explores how quarks are assembled into hadrons.

SLIDES	CONTENT
1 – 2	Introduction
3 – 4	These slides examine some basic properties of the two most common quarks: up and down (and their antimatter partners, anti-up and anti-down). Hadrons are either composed of three quarks (baryons: protons and neutrons) or a quark-antiquark pair (mesons). Quarks have a fractional charge of: +2/3 (up); -2/3 (anti-up); -1/3 (down); and +1/3 (anti-down). The net charge on a proton or neutron is given by summing the charges on its component quarks. Thus the charge on a proton (up / up / down) is (+2/3) + (+2/3) + (-1/3) = +1.
5	Scientists have never observed a quark in isolation (that is, outside a baryon). The energy to pull a quark out of a baryon is so large that more quarks are created from this energy that bind with any isolated quark.
6	Up and down quarks and electrons make up most of the visible universe. They do so by forming various bound states. Exactly how these bound states are formed is the topic of the next presentation in this series, *Fundamental interactions*. Up and down quarks bind to form protons and neutrons, which bind to form atomic nuclei. Atomic nuclei and electrons bind to form atoms, and atoms bind to form molecules and crystals. Molecules and crystals make up the matter around us: planets, stars, galaxies and the visible universe. Things not made of quarks and electrons include light (photons) and, presumably, dark matter, the nature of which remains a mystery.
7 – 8	In 1969, Murray Gell-Mann proposed a mathematical model in which the quark is the basic building block of protons and neutrons, which make up nuclei. Until 1968, there was little evidence for the existence of quarks. Since then, all six flavours of quark have been observed in experiments. The top quark, the heaviest (with a mass almost equal to that of a gold atom), was the last to be discovered in 1995.

Fundamental interactions

This presentation provides a brief introduction to the four fundamental interactions: electromagnetism; gravity; and weak and strong interactions.

SLIDES	CONTENT
1 – 2	Introduction
3 – 4	Our visible world (matter, light and what happens around us) is governed by two fundamental interactions: gravity and electromagnetism. The other two fundamental interactions (strong and weak) are crucial in the subatomic world but their effects are less obvious. Electromagnetic force, which results from electromagnetic interactions, is behind most common forces, such as tension in spring, friction and elastic rebound of a tennis ball. Gravity is familiar as the force that keeps the Earth-Moon system together as well as the broad structure of the Universe.
5 – 8	A key feature of an interaction is that energy and momentum are redistributed amongst components of a system. In the absence of an interaction momentum and energy of all particles remain unchanged. Where there is no change to number and type of particles involved in an interaction then changes to energy and momentum can also be viewed as the consequence of forces. Examples of this include two electrons repelling each other, or an electron and positron attracting. However when the number of nature of particles changes it's no longer possible to view this as a force. For example, decay of a neutron to a proton, electron and antineutrino involves redistribution of a neutron's energy and momentum amongst the decay products. This is an interaction (weak interaction) but the redistribution cannot be interpreted as a consequence of a force acting.
9 – 10	Different interactions affect different particles, depending on their properties. For example, only charged particles are affected by electromagnetic interactions — uncharged (neutral) particles are not affected by electromagnetic interactions. Another way of putting this is that charged particles participate in electromagnetic interactions; uncharged particles do not. What about magnets? They aren't electrically charged, but they undergo electromagnetic interactions. The magnetic field around a magnet is a consequence of the presence of charged particles (electrons) within the magnet. Particles with mass interact through gravity. What about light? Photons are usually said to have no mass, yet a black hole's gravity prevents photons from escaping. Gravity around a black hole warps space-time. Photons follow warped paths through space-time created by gravity.
11	Picking up pieces of paper with a charged rod is a simple demonstration of the relative strength of electromagnetic and gravitational interactions. A feeble electrostatic interaction can overcome 6×10^{24} kg of Earth pulling on a piece of paper. Electromagnetism is much stronger than gravity. Both interactions follow inverse square laws. Newton's law of universal gravitation: $F = G\frac{m_1 m_2}{r^2}$ Coulomb's law: $F = k_e \frac{q_1 q_2}{r^2}$ If gravity is such a feeble interaction how does it shape the Universe? Gravity only comes in one form (attractive, never repulsive) so builds up cumulatively as greater volumes of space are considered. Electromagnetism comes in two forms (positive and negative) that cancel each other out over large volumes. The three types of colour charge in the strong interaction cancel each other out in a similar way to leave neutral colour charge.
12	The strong interaction is stronger again, but only operates over distances of around one femtometre. It is reponsible for binding quarks together.
13	Particles that participate in the strong interaction are said to have 'colour charge'. This term has nothing to do with colour in its popular sense. It's just a property of some particles that comes in three values (conventionally said to be 'red', 'blue' and 'green'). The table summarising properties of the fundamental interactions shows one reason why leptons don't form composite particles in the way that quarks form hadrons. They don't have colour charge, so can't interact via the strong interaction.

SLIDES	CONTENT
14 – 15	Although water molecules are electrically neutral, electromagnetic effects are responsible for 'sticking' water molecules together. This may be called residual electromagnetic interaction. Quarks in protons and neutrons interact through their colour charge and the strong interaction. Although protons and neutrons are colour charge neutral overall, residual strong interaction is responsible for binding protons and neutrons together in an atomic nucleus.
16	64 N is a very large force between two tiny particles. Therefore there must be a considerably greater attractive force that overcomes the electromagnetic force of repulsion. This is the residual strong interaction. Note that residual strong interaction applies to both protons and neutrons, whereas Coulomb repulsion applies only to protons in a nucleus.
17	Binding of quarks and electrons introduced in the presentation, *Quarks*, can now be seen in terms of the various fundamental interactions.
18	The weak interaction is not a binding interaction. It does not 'stick' particles together. However it does fit the definition that interactions cause exchange of energy and momentum. The weak interaction is explained further in *The Standard Model 4: Quantum approach*.
19	Interactions, forces and fields are intimately connected. If you push the North poles of two magnets together it's hard to believe there isn't 'something' between them. However the magnetic field that surrounds a magnet (one manifestation of an electromagnetic field), and the gravitational field that surrounds a mass, are mathematical constructs. They can be used to calculate the force experienced by a charged (or massive) object as it interacts with the field. An alternative view describes fields in terms of particles, known as virtual gauge bosons. Each interaction (or field) is carried by one or more gauge bosons. • photon for electromagnetic interaction • gluon for strong nuclear interaction • W and Z bosons for weak nuclear interaction • graviton (yet to be verified) for gravity Some of these ideas are explored further in *The Standard Model 4: Quantum approach*. The Higgs boson is the particle form of the Higgs field that was introduced in Professor Brian Cox's TED talk (*The Standard Model 1: Big physics*). Concepts about the Higgs boson and field are rather too advanced for this audience — to know more enrol in a university physics degree! Although the Standard Model is a very successful theory that explains much of the physical world, it has some shortcomings: the theory is incompatible with some aspects of general relativity, so gravity is not successfully explained, and dark matter and dark energy do not fit into the Standard Model.

Glossary

A glossary of terms in particle physics is included as a separate fact sheet in this resource as this topic introduces a large number of terms that students may find confusing. A useful summative exercise for students may be to construct a concept or mind map for particle physics, using this glossary and other resources of their choice

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Technical requirements

The teacher guide requires Adobe Reader (version 5 or later), which is a free download from www.adobe.com. The presentations are in Microsoft PowerPoint format. They are also available in PDF format. A modern browser (eg Internet Explorer 9 or later, Google Chrome, Safari 5.0+, Opera or Firefox) is required to view the video. A high quality MP4 version of the video is available by download from the SPICE website.

SPICE resources and copyright

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Quarks

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'Murray Gell-Mann ' photo by Jurvetson (flickr)

Associated SPICE resources

The Standard Model 2: Structure of matter may be used in conjunction with related SPICE resources to teach the topic of the Standard Model.

DESCRIPTION	LEARNING PURPOSE
The Standard Model (overview) This learning pathway shows how a number of SPICE resources can be used in teaching students about the Standard Model.	
The Standard Model 1: Big physics Students watch a TED talk on the Large Hadron Collider. What do scientists hope to discover with this machine?	**Engage**
The Standard Model 2: Structure of matter A series of presentations guide discussion of the fundamental building blocks of the Universe.	**Explore**
The Standard Model 3: Particle calculations Students perform calculations using properties of fundamental particles.	**Explain**
The Standard Model 4: Quantum approach A presentation introduces a quantum view of particle interactions.	**Elaborate**