teachers guide

Matter and relativity 1: Quarks

Components

	NAME	DESCRIPTION	AUDIENCE
	Quarks teachers guide	This guide provides suggestions and strategies for using the presentation, *The story of quarks*.	teachers
	The story of quarks presentation	This presentation engages students in a conversation about atomic structure, using slides as stimulus materials. It includes presenter's notes, suggested discussion points and answers.	teachers and students
	The Large Hadron Collider fact sheet	This fact sheet provides information on the location, design and purpose of the Large Hadron Collider (LHC).	students

Purpose

To extend and update students' understanding of subatomic particles, including neutrinos and quarks.

Outcomes

Students:

- describe the evolutionary nature of scientific knowledge,
- explain that quarks and leptons are fundamental particles, and
- explain how particle colliders and detectors are used to investigate atomic structure.

Activity summary

ACTIVITY	POSSIBLE STRATEGY
Teacher introduces the presentation, *The story of quarks*, and shows the introductory slides and four images of the Large Hadron Collider.	teacher and students
Students read and discuss the fact sheet, *The Large Hadron Collider*.	think, pair, share
Teacher resumes the presentation, pausing it for students to discuss questions that appear on screen.	think, pair, share
Teacher introduces discussion points, as indicated in the notes, as appropriate for their students.	teacher-led discussion

Technical requirements

The presentation is provided in Microsoft PowerPoint and Adobe PDF formats. The guide and fact sheet require Adobe Reader (version 5 or later), which is a free download from adobe.com.

Teacher notes

The following notes accompany the presentation, *The story of quarks*.

SLIDE	NOTES
1. The story of quarks	The presentation describes discoveries about atomic structure, from Rutherford's early discoveries, through the standard model of fundamental particles and force, to use of the Large Hadron Collider (LHC) to search for the elusive Higgs boson. The fact sheet, *The Large Hadron Collider*, provides students with information about the LHC: what it is; where it is located; what it does; and what physicists hope to learn from using it.
3. The Large Hadron Collider	The images on this slide illustrate the LHC ring, superimposed on countryside. Following slides show tunnels and detectors inside the LHC.
5. Atlas detector	The Atlas detector is about 45 m long, more than 25 m tall, and weighs about 7000 tonnes. It is about half as big as Notre Dame Cathedral in Paris, and weighs the same as the Eiffel Tower. Atlas is one of the LHC's general purpose detectors used in the search for the elusive Higgs boson.
7. 'New' particles	Students read through fact sheet, *The Large Hadron Collider.* **Question**: Why is it likely that 'new' particles will be discovered in the LHC? **Answer**: Collisions in the LHC release energy, which is converted into mass according to Einstein's equation, $E = mc^2$. This results in the formation of particles, some of which decay into other particles. Heavier particles can be produced only when large amounts of energy are involved. Discussion point: The LHC announced the discovery of a new particle – the Higgs boson, with a mass of 125 GeV on 4 July 2012. Interaction with the Higgs field is responsible for giving particles such as protons and neutrons their mass. The idea of a Higgs boson has been around since 1964 (proposed by Peter Higgs) but it took the large energies possible in the LHC to find the particle experimentally. In 2013, Peter Higgs and Francois Englert won the Nobel Prize in Physics for their work on the Higgs boson. (Note that the particle masses are expressed in energy units.)
8. Rutherford's experiment	Physicists today still use similar research methods to Rutherford's experiment conducted almost 100 years ago – namely firing sub-atomic particles at target atoms to investigate the nature of matter. **Question**: What conclusions did Rutherford draw from this experiment? **Answer**: Rutherford concluded that: • an atom is mostly open space, • an atomic nucleus is very small and positively charged, and • electrons orbit the nucleus like planets around a star.
9. Rutherford's model of the atom	**Question**: Why did many scientists object to Rutherford's model at that time? **Answer**: Rutherford's contemporaries knew that accelerating charges radiate energy, so electrons should lose energy and spiral into the nucleus, meaning that Rutherford's atom would be unstable (particles moving in a circular orbits are accelerating). The model couldn't explain the observed line emission spectra of elements, such as hydrogen. Rutherford's atom would emit a continuous spectrum ('smear') as electrons spiralled into the nucleus.
10. The Bohr-Rutherford atom	In 1913, Bohr introduced a quantum mechanical approach to the Rutherford atom, suggesting that electrons orbit in discrete energy levels (shells) in which they do not radiate energy. Bohr's major success with this model was its ability to explain the spectral emission lines of hydrogen, as described by the Rydberg formula. **Question**: What do we now know is wrong with this model? **Answer**: The neutron is missing (it was not discovered until 1932). The model isn't able to explain atomic mass or the existence of isotopes.

SLIDE	NOTES
11. The neutron	In 1930 the German physicists Bothe and Becker bombarded beryllium with alpha particles and noticed that a very penetrating form of radiation was emitted. The radiation was non-ionising and they assumed it to be gamma rays. In 1932 Irène and Frédéric Joliot-Curie investigated the radiation. They aimed the radiation at a block of paraffin wax and found it caused the wax to emit protons. When they measured the speeds of the protons they found that gamma rays would need to have an unrealistic amount of energy to release protons from wax. Chadwick reported the experiment to Rutherford, who didn't believe that gamma rays could cause the wax to emit protons. They were convinced that beryllium was emitting neutrons. Chadwick studied the radiation using an ionisation counter and a cloud chamber. Within a month he had conclusive proof of the existence of the neutron. He published his findings in the journal, *Nature*, on February 27, 1932. More information: http://www-outreach.phy.cam.ac.uk/camphy/neutron/neutron4_1.htm **Question**: Does this now complete the picture of atomic structure? **Answer**: At that time, the model successfully explained many observations about the atom, including atomic mass and the existence of isotopes.
12. More recent discoveries	Positrons have the same mass as electrons, but a positive charge. Pions (pi-meson): three types of meson have zero spin and either a positive, negative or zero charge (π^+, π^- and π^0). They are important for explaining low-energy properties of the strong force. Muons are elementary particles (leptons) similar to the electron and neutrinos. Strange particles, or kaons (K-mesons). In addition, the existence of neutrinos was postulated. **Question**: What impact did these new discoveries have on the existing theories and model of atomic structure? **Answer**: Where necessary, existing theories needed to be modified or discarded. If discarded, new theories were needed to account for the new discoveries.
13. Particle accelerators and detectors	Discussion points: • Particle accelerators use electric fields to accelerate charged particles, and magnetic fields to control their direction. • Particle detectors include photographic plates, calorimeters, cloud chambers, bubble chambers and streamer chambers.
16. Detectors	Discussion point: Physicists can determine the charge and mass of particles by studying their motion in electric and magnetic fields: • charged particles are deflected by an electric field (positive charges are attracted to negative electrodes …), • magnetic fields cause charged particles to move in circular paths, and • uncharged particles are not deflected by electric or magnetic fields.
18. Quarks	Discussion point: • 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. The initial model described two quarks (up and down) with properties such as mass, charge, colour charge and spin (up has a charge of +⅔; down has -⅓). According to the model: • protons are made up of three quarks (u, u, d) with an overall charge of +1 (+⅔, +⅔ and -⅓), and • neutrons have three quarks (u, d, d) with zero overall charge (+⅔, -⅓ and -⅓). Quarks have the following properties: • mass, so they interact via gravity; • electromagnetic charge (+⅓, +⅔, -⅓ or -⅔), so they interact via electromagnetism; • colour charge (red, green, blue, anti-red, anti-green or anti-blue), so they interact via the strong force; and • spin. Strong force is the strongest interaction between particles. It is the force that holds quarks together in protons and neutrons. Quarks are never found in isolation because the amount of energy required to break the strong force ends up creating new particles (mass-energy equivalence).

SLIDE	NOTES
19. … and more quarks	Discussion/teaching point: • Physicists agree that there are six flavours of quarks, known as: up, down, charm, strange, top and bottom. Evidence to support the quark model: 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. Up and down quarks have the lowest masses of all quarks. Heavier quarks rapidly change into up and down quarks through a process of particle decay. Up and down quarks are generally stable and are the most common in the universe.
20. The standard model	Discussion points: • The electron and neutrinos are the best-known leptons. The term ‘lepton’ literally means ‘thin’ or ‘small mass’. The standard model proposes that forces are carried by particles: • photons carry the electromagnetic force that holds protons and electrons together, • gluons carry the strong force that holds quarks together, and • W and Z bosons carry the weak force that is responsible for nuclear decay. The standard model incorporates electromagnetic, strong and weak forces, but not the fourth fundamental force, gravitation. Physicists are still working towards a unified theory that brings together all four fundamental forces.
25. A question of mass	Mass of an up quark is 0.002 GeV/c^2 (3.56×10^{-30} kg). Mass of a down quark is 0.005 GeV/c^2 (8.90×10^{-30} kg). Mass of a proton is 0.938 GeV/c^2 (1.67×10^{-27} kg). **Question**: Why don’t the masses of the quarks add up to the mass of the proton? **Answer**: The difference in mass is due to the energy holding the quarks together in the proton ($E = mc^2$).
26. A question of charge	**Question**: What can you deduce about the magnitude of the strong force? **Answer**: The strong force is much stronger than the electromagnetic force. **Colour charge and the strong force** • In addition to electromagnetic charge, quarks have a different kind of charge called colour charge. • Colour charge is related to the interactions of quarks and gluons via the strong force. • The strong force is much stronger than the electromagnetic force, but has almost no effect at distances above the size of an atomic nucleus. • The strong force binds quarks together into particles, such as protons and neutrons.
27. The Higgs boson	The LHC creates extremely high-energy collisions in which energy is converted into mass according to $E = mc^2$. Particles with large mass, such as the Higgs boson, are produced only when very large amounts of energy are converted to mass. The LHC has cast new light on the standard model and other recent theories, including supersymmetry and string theory. **Question**: Can you suggest why the Higgs boson took so long to be discovered? **Answer**: Until the LHC, particle accelerators have not released enough energy to create particles as massive as the Higgs boson (now known to be around 125 GeV/c^2). The LHC has the potential to produce particles with masses up to several hundreds of GeV/c^2.
28. Naming the quark	This slide describes the origin of the term, quark, and reveals something about humour in physics.

Glossary

The following glossary explains some of the terms used in particle physics.

TERM	MEANING
antimatter	At the instant of the Big Bang, scientists believe that equal amounts of matter and antimatter were produced, with every type of matter particle having a corresponding antimatter particle. The observable universe, however, appears to be almost entirely made up of matter. Scientists speculate about whether there are other places that are almost entirely made up of antimatter. When matter and antimatter particles meet, they annihilate into pure energy.

TERM	MEANING
antiparticle	Antiparticles (antimatter particles) look and behave exactly like their corresponding matter particles, except they have opposite charge. For example, the positron, which is the electron's antiparticle, has the same mass as an electron but carries a positive charge. Electrically neutral particles also have antiparticles. For example, an antineutron is made of antiquarks.
baryon	Baryons are composite particles made of three quarks. Protons and neutrons are baryons.
boson	Bosons are particles that transmit force: • photons transmit the electromagnetic force, • W and Z bosons transmit the weak force, and • gluons transmit the strong force.
composite particle	Composite particles are made of smaller particles. Baryons and mesons are composite particles, both made of quarks.
elementary particle	Elementary (or fundamental) particles are the basic building blocks of the Universe from which all other particles are made. In the standard model, quarks, leptons and some bosons are elementary particles.
fermion	Fermions are particles that have certain defined spin characteristics. They include leptons, quarks, and baryons.
gluon	Gluons are responsible for transmitting the strong force. There are eight types or 'colours' of gluon.
hadron	Hadrons are particles that are made of quarks. They include baryons, such as protons and neutrons which are made of three quarks; and mesons which are made of a quark and antiquark.
Higgs boson	The particle that provides evidence of the existence of the Higgs field.
Higgs field	In the standard model, the Higgs field is responsible for giving other particles their mass.
lepton	Leptons are elementary particles that interact through the electromagnetic force, weak force and gravitational force, but are not affected by the strong force. There are 12 leptons, including electrons, muons, tau particles, and their respective neutrinos.
meson	Mesons are composite particles made up of one quark and one antiquark. Pions and kaons are mesons.
neutrino	Neutrinos ('small neutral ones') are elementary particles that often travel at close to the speed of light. They are able to pass through matter almost undisturbed as they are electrically neutral. They have a minuscule mass and are extremely difficult to detect. Neutrinos are created in certain types of radioactive decay or nuclear reactions, such as those that take place in the sun, in nuclear reactors, or when cosmic rays hit atoms. There are three types, or 'flavours', of neutrinos: electron neutrinos, muon neutrinos and tau neutrinos.
neutron	Neutrons are subatomic particles with no net electric charge and a mass slightly larger than that of a proton. They are made up of three quarks (up, down and down). Neutrons are found in the atomic nucleus.
photon	Photons are responsible for transmitting the electromagnetic force. They also make up electromagnetic radiation.
proton	Protons are subatomic particles with a positive electric charge and a mass slightly less than that of a neutron. They are made up of three quarks (up, up and down). Protons are found in the atomic nucleus.
quark	Quarks are elementary particles that combine to form composite particles called hadrons, the most stable of which are protons and neutrons. They are only ever found within hadrons — never in isolation. Quarks carry an electric charge of either +⅔ or -⅓. There are six types of quark (up, down, charm, strange, top and bottom) and each type of quark has a corresponding antiparticle (an antiquark) which has opposite charge. Each of the six quarks and six antiquarks comes in three colours, to make a total of 36 quarks.
standard model	The standard model is a theory that brings together the elementary particles of matter and three of the four known fundamental forces that exist in the Universe. The model falls short of being a comprehensive theory of fundamental interactions because it does not include the gravitational force.
W and Z bosons	The two W bosons and single Z boson are responsible for transmitting the weak force.

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Email: spice@uwa.edu.au
Phone: (08) 6488 3917

Centre for Learning Technology (M016)
The University of Western Australia
35 Stirling Highway
Crawley WA 6009