NATIONAL QUALIFICATIONS CURRICULUM SUPPORT

Physics

The Standard Model

Teacher's Notes

[HIGHER]

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Introduction

These notes supplement the National Qualifications Arrangements for Higher Physics. The content tables within the Arrangements define the content of the course and these include a column indicating the assessable material. These teacher notes provide guidance to teachers and lecturers that will be useful in considering the order of teaching and the depth to which each topic may be taken. They cover more than the minimum required for assessment. Sometimes extra background knowledge is desirable to avoid unexpected difficulties, see the π mesons below. Suitable comments regarding assessable material is included.

In physics we develop theories and laws but these must agree with observations otherwise our theories require modification or rejection, hence the emphasis on appreciation of relevant current experiments to investigate situations, measure quantities or verify relationships.

The Standard Model

All respectable theorizing about the elementary particles is carried out within the framework of quantum field theory which includes both the standard model and superstring theory. Quantum field theory is based on three fundamental assumptions: the validity of quantum mechanics, the validity of Einstein's relativity principles (special relativity when gravitation is not included, and general relativity otherwise), and locality (meaning that all fundamental forces arise from local processes and not by means of action at a distance). Those local processes involve the emission and absorption of particles.

The Quark and the Jaguar by Murray Gell-Mann

Without involving quantum field theory, we can introduce the Standard Model as a successful model for classifying sub-nuclear particles and their interactions.

Newtonian mechanics provides accurate results for most of our everyday situations. For high speeds (>10%c) we require Einstein's relativity equations. For situations involving atomic, nuclear and sub-nuclear 'particles' we find that neither Newtonian nor relativity equations give results that agree with experiment. Quantum mechanics, which involves another set of equations and additional mathematics, gives excellent agreement between theory and experiment in this realm. Relativity has been included at this subatomic level to give relativistic quantum mechanics. Although quantum mechanics was discovered in the 1920s, its interpretation can still provoke discussion. Many misconceptions abound to prevent understanding. Details of quantum mechanics are *not* required for Higher Physics but the photoelectric effect and wave/particle duality are in this unit.

The fundamental building blocks of matter were first thought to be atoms (from the Greek 'indivisible' or 'un-cuttable'). Early in the twentieth century, physicists expected that protons, neutrons and electrons, the particles appearing to make up all atoms, would be the fundamental building blocks. However, during the last century an enormous array (hundreds) of sub-nuclear particles emerged!

Perhaps these particles were made up of smaller, more fundamental building blocks? Were there any 'fundamental' particles? If so how many?

Orders of magnitude

Before introducing subatomic models, let us consider the range of orders of magnitude from the very small (sub-nuclear) to the very large (intergalactic distances). Our own 'macro' world has an order of magnitude of length near the middle of this range, a full grown human being is about 1.5 to 2 m tall, which is an order of magnitude of 10^0 m.

The tables below show the range of orders of magnitude of length from the smallest sub-nuclear particles to the largest celestial distances. Students are not required to recall specific details of the size of particles or distances to astronomical objects, but they are required to make correct selections from data of relative size.

Relative order of magnitude size of some important particles and objects

Smaller than a human being (~10^0 m)

Particle or object	Neutrino	Proton	Hydrogen atom	Dust	Human being
Order of magnitude	~10^{-24} m	10^{-15} m	10^{-10} m	10^{-4} m	10^0 m

(Note that the size of the neutrino is not known with certainty.)

Larger than a human being (~10^0 m)

Particle or object	Earth	Sun	Solar system	Nearest star	Galaxy	Distance to a quasar
Order of magnitude	10^7 m	10^9 m	10^{13} m	10^{17} m	10^{21} m	10^{26} m

The fact that structures such as the atom and the solar system are mostly empty space can be inferred from the data.

Quantum mechanics, which is the theory required for nuclear particles, suggests that the 'smallest' length is the Planck length of ~10^{-35} m. At the other extreme, light takes a finite time to travel (3×10^8 m s^{-1}), hence we can only 'see' objects if the time taken for the light to reach us is less than the age of the universe!

(Distance = age of universe (in seconds) × speed of light
= $13.7 \times 10^9 \times 365 \times 24 \times 60 \times 60 \times 3 \times 10^8 = 1.3 \times 10^{26}$ m = ~10^{26} m)

Since we use the SI unit of the metre for the very large to the very small, it is worth glancing at the current list of prefixes, http://physics.nist.gov/cuu/Units/prefixes.html.
At the time of writing there is a petition for 10^{27} to be called the Hella.

An aside

The website http://en.wikipedia.org/wiki/Category:Units_of_length gives an interesting list of length units from the Scandinavian Alen to the Indian Yojana with the Scots mile (1.1 miles or 1.8 km) being mentioned.

Attention could be drawn to commonly used units:

(i) The Bohr radius, used by atomic physicists as one of the 'atomic units', since it can be defined in terms of electronic mass, electronic charge and the Planck constant.
(ii) Light year and parsec are used in cosmology.

Mass/energy units (SQA will use SI units in assessments)

This is a useful place to mention the mass, or energy, of particles. Mass and energy are related by Einstein's equation $E = mc^2$. In particle physics the unit electron-volt (eV) is commonly used. Its definition and use, both for energy and to compare the masses of different particles, are widespread. One electron volt is the energy acquired by an electron accelerated from rest through a potential difference of 1 V. A more common unit is the GeV, which is 10^9 eV or one billion electron volts.

Thus 1 eV = $1.6 \times 10^{-19} \times 1$ J and 1 GeV = $1.6 \times 10^{-19} \times 10^9 = 1.6 \times 10^{-10}$ J (0.16 nJ).

Using $E = mc^2$ the corresponding unit of mass is GeV/c^2. (1 GeV/c^2 = 1.8×10^{-27} kg)

For example:

mass of an electron = $9.1 \times 10^{-31} \times (3 \times 10^8)^2 / (1.6 \times 10^{-19} \times 10^9)$ = ~5×10^{-4} GeV/c^2
mass of proton or neutron = ~ 1 GeV/c^2 (mass of a proton = 0.938 GeV/c^2)

(Since the mass of a proton is ~1 GeV/c^2 these notes will indicate masses in terms of the mass of a proton. Teachers can then easily relate to other published units.)

Students may be aware that the energies of operation of the Large Hadron Collider at CERN in Switzerland are quoted in GeV or Tev (T = terra is the prefix for $\times 10^{12}$). At full power protons could be accelerated to 7 TeV, giving a head -on collision of 14 TeV, a very high energy.

The Standard Model of Fundamental Particles and Interactions

Students are expected to have pre-knowledge of the model of the atom, in terms of protons, neutrons and electrons. For example, the carbon atom consists of six protons and six neutrons in the nucleus with six electrons 'in orbit' around the nucleus. The size of the nucleus is tiny compared to the size of the atom, most of the atom being empty space. The chemical properties of an atom depend on the number of protons in the nucleus. The 'outer' electron interactions produce molecules.

The Geiger and Marsden experiment that led Rutherford to this model should be reviewed. Prior to the experiment the atom was thought to be a 'ball' or 'pudding', of about the consistency of candy floss, filling the atomic space with the electrons embedded inside. This experiment is relevant, bringing out two important points:

(i) the atom is mainly empty space because most of the alpha particles pass through the gold foil
(ii) the occasional deflection backwards suggests the atom has structure – a central nucleus and 'outer electrons'.

'Scattering' experiments play an important role in investigating nuclear structure.

There are various resources describing this experiment on the websites Talkphysics or Glow (or at http://mrhood.net/sputnik).
The Rutherford model 'fits' the experimental data – we cannot 'see' the atom directly.

Production of sub-nuclear particles

In a particle accelerator a small particle, eg an electron, can be accelerated by electric and magnetic fields to a very high speed. Being a light particle, speeds near to the speed of light may be achieved. When these particles collide with a stationary target, or other fast-moving particles, a substantial amount of energy is released in a small space. Some of this energy may be converted into mass ($E = mc^2$), producing showers of nuclear particles. By passing these particles through a magnetic field and observing the deflection their mass and charge can be measured. For example, an electron with low mass will be more easily deflected than its heavier cousin, the muon. A positive particle will be deflected in the opposite direction to a negative particle. Cosmic rays from outer space also contain particles, which can be studied in a similar manner.

The Large Hadron Collider is a 27 km ring under the Swiss/French border near Geneva that is used to accelerate particles, eg protons, to very high speeds (see www.lhc.ac.uk and http://public.web.cern.ch/public/en/LHC/LHC-en.html). Relativity considerations indicate that very large energies are required to increase the speed of the particles as the speeds approach the speed of light. Hence the particles require to be sent round the ring many times before they acquire enough energy.

For information on current research see http://lhc-webcast.web.cern.ch.

After the initial collision, many of the particles produced decay into other particles.

Over the years a multitude of particles have been ‘identified’. Where were the building blocks in this multitude of particles? Did any patterns or classifications emerge? Before considering models or classifications in general let us turn to some specific results.

Antimatter

Analysis of the properties of particles produced in particle accelerators has revealed that *every particle has an antimatter equivalent* that has the same mass but the opposite charge. For example, a positron has the same mass as an electron, but a positive charge. Dirac’s relativistic equation for the electron, published in 1928, predicted the positron, but it was not discovered experimentally until 1932 by Carl Anderson at Calthec and Patrick Blackett at Cambridge.

Some (not all) electrically neutral particles, like the photon, are their own antiparticle.

A particle and its antimatter particle *annihilate* when they meet: they ‘disappear’ and their kinetic plus rest mass energy is converted into other particles ($E = mc^2$). For example, when an electron and a positron annihilate, two gamma rays are produced. These gamma rays go off in opposite directions because both energy and momentum must be conserved. Notice that two gamma rays must be produced in order for momentum to be conserved.

The annihilation of positrons is the basis of positron emission tomography (PET). A tracer, which emits positrons, is introduced into the body. The positrons decay to give gamma rays, and detectors produce three-dimensional images. This aids the accurate location of tumours and the design of treatment plans (http://www.patient.co.uk/health/PET-Scan.htm).

Matter and antimatter seem essentially identical but there appears to be very little antimatter in our universe. (On a local level we are not surrounded by antimatter or we would have been annihilated long ago!) This conclusion is partly based on the low observed abundance of antimatter in cosmic rays, which constantly rain down on us from outer space. All of the antimatter present in cosmic rays can be accounted for by radioactive decays or nuclear reactions involving ordinary matter. Also we do not see the signatures of electron-positron annihilation or proton-antiproton annihilation coming from the edges of galaxies, or from places where two galaxies are near each other. As a result, we believe that essentially all of the objects we see in the universe are made of matter not antimatter.

The general way to denote an antiparticle is by adding a bar over the particle's symbol. For example, a proton and its antiproton are denoted as p and $\bar{p}$ respectively. Another convention, particularly for 'common' particles is to distinguish particles by their electric charge. Thus, the electron and positron are denoted simply as e^- and e^+ respectively. Students should be familiar with both notations.

Beta decay and the neutrino

Students should already have met beta decay. At Higher level, the process is considered in more detail, including the emission of a neutrino.

During beta decay, a proton changes to a neutron within the nucleus of an atom and a beta particle is emitted. (It is not required to explain this by consideration of the conversion of a quark by weak interaction.) Beta particles are high-energy electrons or their antimatter equivalent, positrons. The nuclear equation below shows a positron ejected in beta decay.

$^{64}_{29}\mathrm{Cu} \rightarrow {}^{64}_{28}\mathrm{Ni} + \bar{\mathrm{e}}$ (A copper atom decays to nickel and a positron, $\bar{e}$ is e^+.)

Students should be familiar with the terminology of nuclear equations and be able to use them to state the number of protons and neutrons in a nucleus.

Study of beta decays show that the recoil of the nucleus is not in the direction opposite to the momentum of the beta particle. It appears that momentum is not conserved. It was proposed that this anomaly was caused by the emission of another particle. Enrico Fermi called this particle the neutrino ('small one'). (Consideration of the continuous energy spectrum of beta particles as evidence for neutrino emission is not required at Higher level.) Measurement of the masses in these decays indicated that the mass of the neutrino was either zero or very, very small. Neutrinos have no charge and almost zero mass, hence are hard to detect. However, in 1956 the experimental detection of the neutrino was achieved (no details required).

For symmetry reasons, the particle emitted with the electron from nuclei is the anti- neutrino $\bar{\nu}$ and the emission of a positron is accompanied by a neutrino ν. (Although the neutrino is uncharged it is *not* its own anti particle.)

Thus the full nuclear equation showing beta emission (positron) from a copper nucleus, including the neutrino is:

$$^{64}_{29}\mathrm{Cu} \rightarrow {}^{64}_{28}\mathrm{Ni} + \bar{\mathrm{e}} + \nu$$

Another beta decay is that of cobalt, Co, which emits an electron and anti neutrino:

$$^{60}_{27}\mathrm{Co} \rightarrow {}^{60}_{28}\mathrm{Ni} + \mathrm{e} + \bar{\nu}$$

Classification of particles

By the 1960s hundreds of particles had been identified and physicists began to classify them into groups depending how they reacted and decayed. For example, electrons and their heavier cousins, the muon and tau, were involved in beta decay -type reactions with anti-neutrinos, together with the anti matter equivalent reactions. But the neutrinos did not seem to feature in proton, neutron and the somewhat heavier sub-nuclear particles interactions, for example a delta, Δ^{++}, decays into a proton, p^+, and a pion, π^+. In addition it was observed in high- energy collisions that the proton and neutron appeared to have an internal 'structure'. When high-energy electrons are 'bounced off' protons and neutrons the scattering angle is characteristic of internal point-like 'particles' existing inside the nucleons. It was proposed that many of the 'heavier' sub-nuclear particles could be built from a few fundamental particles, leading to the Standard Model. (Students do not require any of the history of the development of the theory.)

Fermions and bosons

All particles are classified as either fermions or bosons.

(Fermions are named after Enrico Fermi, pronounced fermi'ons, and bosons are named after Satyendra Nath Bose, pronounced bose'ons.)

Fermions include the more familiar matter particles electrons, protons and neutrons and their antimatter equivalents. All matter is made from these particles.

(All fermions obey Pauli's exclusion principle: no two particles can occupy the same quantum state at the same time. Quantum mechanics provides a natural unit for the spin angular momentum, abbreviated to just 'spin'. In terms of this unit, all fermions have an half integral spin, eg $\frac{1}{2}$, $\frac{3}{2}$, $\frac{5}{2}$ ….
In the Standard Model all the elementary fermions have a spin of $\frac{1}{2}$.)

All force- mediating particles are bosons. The most familiar force-mediating boson is the photon. Some bosons do have mass. (All bosons obey the anti-exclusion principle: particles like to be in the same quantum state, eg in a laser, photons in a given state stimulate the emission of more photons in the same state. Bosons have an integral spin, 0, 1, 2....)

The classification of fermions and bosons according to the exclusion principle or spin is not required at Higher level. However, care is needed when discussing the classification into fermions and bosons since the mesons are bosons, see below.

Fermions – quarks

While electrons appear to be truly fundamental, the standard model holds that protons and neutrons are made from even smaller particles called **quarks**.

Gell-Mann assigned the name, without the spelling, thinking it might be spelt 'kwork'. He then came across the phrase 'Three quarks for Muster Mark' in *Finnegans Wake* by James Joyce. This would give 'kwark' to rhyme with 'Mark'. Gell-Mann later noted that the number 'three' in this quotation fitted well with the number of 'families' of quarks in nature.

There are six types of quark: up, down, charmed, strange, top and bottom, which are denoted by u, d, c, s, t and b. The quarks have a non-integral charge (see the table below for their properties). There are six corresponding anti-quarks with charges of opposite sign.

Individual quarks have not been isolated. All the particles we observe are made of combinations of quarks to give particles with whole numbers of charge, eg –1, 0, +1, +2, … (in terms of the electronic charge). Particles with fractions of charge *e* do not exist. The force holding the quarks together appears to increase with distance (over its short range). Hence, attempting to pull quarks apart would strongly increase the force between them, forcing them back together.

Fermions – leptons

The electron appears to be a fundamental particle and with its heavier ‘cousins’ the muon and tau, together with the associated neutrinos, comprise the six leptons.

Again there are the six corresponding antiparticles. In any beta-type decay a lepton is always accompanied with its associated anti-neutrino.

The *fundamental fermions* can be summarised in the following table. There are three ‘families’ of fundamental particles, as shown in the table. Experimental evidence suggests that there are only three families.

Family	**Quarks**		**(Charge)**	**~Mass**	**Leptons**		**~ Mass**
First	Up	u	(+2/3)	0.004	Electron	e	5×10^{-4}
	Down	d	(–1/3)	0.008	Electron neutrino	ν_e	$<10^{-8}$
Second	Charm	c	(+2/3)	1.5	Muon	μ	0.1
	Strange	s	(–1/3)	0.15	Muon neutrino	ν_μ	$<10^{-4}$
Third	Top	t	(+2/3)	176	Tau	τ	1.8
	Bottom	b	(–1/3)	4.7	Tau neutrino	ν_τ	$<10^{-2}$

(Details of charge and mass are not required for Higher and are given for teachers’ background information only.

Charge values are relative to the magnitude of the charge on an electron, *e*.

Masses are given relative to the mass of a proton, ~1 GeV/c^2. The quark ‘mass’ is a value that gives a good fit both for scattering experiments and ratio to other particle masses. Its numerical value should not be taken too seriously. A quark cannot be isolated. We can’t ‘put a quark’ on scales!

Combinations of quarks – hadrons

Hadrons are matter particles made up of combinations of quarks. As mentioned above quarks only exist in combinations.

Hadrons are subdivided into baryons and mesons.

Baryons are made up of three quarks. Their antiparticles are made up of three anti-quarks. Protons and neutrons are baryons and each contain up and down quarks.

The proton is uud (+2/3, +2/3, –1/3 = 1) and the neutron is udd (+2/3, –1/3, –1.3 = 0).

(For interest one could calculate the mass of the three quarks uud and note that this is ~0.02 × the mass of a proton. The majority of the proton mass comes from the energy of the strong interaction holding the quarks together, see below.)

All baryons, made up of three quarks – an odd number – are fermions.

Mesons are made from two quarks, a quark and anti-quark.

The pion, π^+, is $u\bar{d}$ with charge (+2/3, +1/3). Recall that the antiparticle $\bar{d}$ has opposite charge to d. The negative pion π^- is $\bar{u}d$. There is also a neutral pion.

All mesons, made up of two quarks – an even number – are bosons.

(For interest only: Mesons have integral spin, being a combination of two half-integral spin particles. In 1935 Hideki Yukawa predicted from theoretical considerations that a particle of mass between the electron and proton should exist. This particle, the π meson or pion, was discovered in 1947. Yukawa postulated that the pion 'transmitted' the nuclear force as an exchange particle being emitted and absorbed over short distances. The pion π^- can be considered to 'transform' a proton inside a nucleus into a neutron, or vice versa, for example π^- ($\bar{u}d$) + ${}^{A}_{Z}N \rightarrow$ n (udd) + ${}^{A-1}_{Z-1}N$.

A glance at the list of mesons on Wikipedia indicates the complexity of this group of particles (http://uk.ask.com/wiki/List_of_mesons). In particular notice the composition of the neutral pion π^0 as $\frac{1}{\sqrt{2}}(u\bar{u} + d\bar{d})$, which can be difficult to explain at this level.

The **gluons**, which act between the quarks, are now considered to be the fundamental force-mediating particles for the strong force, see below.)

Student recall of precise details, eg mass or exact composition, is not required but an appreciation of overall classification is expected, see chart below.

Students should note that composite particles made of an **even** number of fermions (eg mesons made of **two** quarks) are bosons, but composite particles made of an **odd** number of fermions (eg protons and neutrons made of **three** quarks) are themselves fermions, as shown below.

To summarise: matter particles

Matter

- **Hadrons** (composite particles of quarks or anti-quarks)
  - ***Baryons*** (made up of three quarks) composite fermions
    (can be stable, eg protons and neutrons*)
  - ***Mesons*** (made up of one quark and one anti-quark) composite bosons
    (unstable)
- **Leptons** (fundamental particles) fermions
  (can be stable, eg electron)

*A neutron is only stable within the nucleus; a ‘free’ neutron decays with a mean lifetime of ~15 minutes.

The fundamental forces

All interactions between matter are governed by forces. Forces supply the means through which particles interact and exchange momentum, attracting or repelling one another depending on their properties. According to our present understanding, only four fundamental forces operate under ordinary conditions in the universe. Gravity and electromagnetism are the most familiar of the four. The other two are the strong and weak nuclear forces.

The strong and weak forces act only on extremely short distance scales – so short that these forces can only be felt within atomic nuclei. These forces fall off to zero outside the nucleus. Except for hydrogen, nuclei contain more than one proton, all of which are positively charged. Thus the electromagnetic force pushes protons apart inside the nucleus. With just the electromagnetic force all atomic nuclei would fly apart! The strong force, so-called because it is strong enough to overcome electromagnetic repulsion, is the force holding nuclei together. All particles made from quarks feel the strong force.

The weak force is important in nuclear reactions and *radioactive decay*. Neutrinos feel the weak force only.

Both the electromagnetic and gravitational forces act over an *infinite* range. The strength of the force is proportional to $1/r^2$. Hence the force decreases with distance in a uniform manner. This is not the case for either the strong or the weak forces.

According to the Standard Model, each force is transmitted by an *exchange* particle that transfers momentum between two interacting particles. For example, photons are the exchange particle for the electromagnetic force.

Fundamental force mediating particles – bosons

The force-mediating particles are all bosons and each is associated with a fundamental force.

The **photon** is associated with the *electromagnetic* force. The photon has zero mass.

Gauge bosons W^+, W^- and Z^0 are responsible for the transfer of the weak nuclear force. (Masses are ~80 × proton mass for W and ~90 × proton mass for Z.)

Gluons are associated with the *strong* nuclear force that acts between quarks, holding nucleons together (there are eight gluons).

The Higgs particle is a massive particle, predicted by the standard model but not yet observed. Experimental detection of the Higgs could help to explain the mass of particles.

(Gravitons are thought to carry the gravitational force through the universe. Gravitons have not yet been detected but are thought to have zero mass.)

Some further details of the fundamental forces are provided in the following table.

Force	Relative strength within nucleus	Relative strength beyond nucleus	Exchange particle (all bosons)	Major role
Strong	100	0	Gluons	Nucleon binding
Electromagnetic	1	1	Photon	Chemistry and biology
Weak	10^{-5}	0	Weak bosons W^+, W^- and Z^0	Nuclear reactions Radioactive decay
Gravity	10^{-43}	10^{-43}	Graviton	Large-scale structure

(Exact details of strength values do not need to be memorised.)

To summarise: fundamental forces – properties and exchange particles

Fundamental forces

- **Nuclear forces** (very short range, almost zero outside the nucleus)
  - ***Strong*** (holds nucleons together, nuclear reactions)
    exchange particles are gluons – bosons
    (gluons act between quarks, strong force 'felt' by hadrons only)
  - ***Weak*** (radioactive decay and nuclear reactions)
    exchange particles are W^+, W^- and Z^0 – gauge bosons
    (weak force felt by leptons and hadrons)
- **Forces with infinite range** (these forces have $F \alpha 1/r^2$)
  - ***Electromagnetic*** (all electrical and magnetic phenomena)
    exchange particle is photon – boson
    (electromagnetic force is 'felt' by all charged particles)
  - ***Gravitational*** (all masses*)
    exchange particle is graviton – a boson not yet detected
    (gravitational force is 'felt' by all masses*)

* Einstein's mass/energy equivalence $E = mc^2$ implies that gravitational effects are 'felt' by all mass/energy. A gravitational field, eg a sun, can bend light, that is photons. This was observed in 1919 during an eclipse of the Sun and provided experimental evidence for the General Theory of Relativity. This is not required for Higher Physics.)

Other useful websites

The following interesting sites show the range of orders of magnitude.
http://www.nikon.com/about/feelnikon/universcale/index.htm
http://primaxstudio.com/stuff/scale_of_universe/

Wikipedia has a chart showing the fundamental particles and force-mediating particles.
http://en.wikipedia.org/wiki/File:Particle_overview.svg

The CERN educational website provides some good background material.
http://education.web.cern.ch/education (select Teaching Resources)

The following websites provide a glossary of terms:
http://www.interactions.org/cms/?pid=1002289 (this site also has some educational material)

http://www.lbl.gov/abc/wallchart/glossary/glossary.html

http://www2.slac.stanford.edu/vvc/glossary.html