**The Standard Model – Advice for Teaching**

There are four key areas for students to demonstrate knowledge and understanding in this sub-topic, most of which has depth in the conceptual understanding of the Standard Model. In general, students are required to:

* demonstrate a conceptual understanding of the Standard Model
* use the model and its conservation laws to make predictions
* apply the conservation laws to composite particles and nuclear reactions
* use the mass-energy equivalence relation.

**Conceptual understanding**

The students need to be able to describe each of the fundamental particles and explain how they are interconnected within the Standard Model. From the subject outline, this means students must be able to:

* describe the electromagnetic, weak nuclear, and strong nuclear forces in terms of gauge bosons
* distinguish between the three types of fundamental particles (gauge bosons, leptons, and quarks)

Examples of the kinds of questions that students need to answer could include:

* *Stating the fundamental particles and providing an example of each.*
* *Differentiate between quarks and leptons in terms of the forces affect each type of particle.*
* *Describe the relationship between the fundamental forces and their gauge bosons.*
* *Use the Standard Model to explain some physical interactions.*

The strong nuclear, electromagnetic and gravitational forces are well known, and students should be to provide contexts to discuss each of these forces. However, the weak force is likely to be outside of student experience. It might be worthwhile discussing some situations where the weak force is relevant. For example,

* The weak force can turn one type of quark into another.
* Beta decay is a result of the weak force changing quarks
* Particle/anti-particle pair production

*It is worthwhile discussing that the weak force is difficult to measure as the electromagnetic force has a greater effect on particles by a factor of ten billion.*

A good teaching strategy for the conceptual aspects of the Standard Model is to get students to construct a visual representation the model. Students should construct their own representation that shows that interconnection of the particles and forces which can be used for the remainder of their learning for this subtopic. Their representation may be adapted as new content is taught.

At the end of this document is a diagram which provides a general overview of the Standard Model.

***Sample questions***

**Q**: Name the four fundamental forces and their gauge bosons.

**A**: *Strong nuclear force – mediated by gluons*

*Electromagnetic force – mediated by photons*

*Weak nuclear force – mediated by W and Z bosons*

*Gravitational force – mediated by gravitons (not yet observed)*

**Q:** The electromagnetic force is mediated by a photon. For two particles with the same sign charge, this force is repulsive. Use the conservation of momentum to explain how the emission and absorption of a photon results in a repulsive force for two positively charged particles.

**A:** *As the two particles approach each other, a photon is emitted from each. These photons are emitted with momentum, p, which is transferred to the other particle as the photons are absorbed. Therefore, both particles experiences a change in momentum away each other. The net result is a repulsive force acting on the particles as .*

**Q**: Describe two differences between quarks and leptons

**A**: *Leptons are single particles, but quarks cannot be isolated – they are only found in combination. Leptons and quarks differ in terms of their charges. Leptons can be positively or negatively charged, or have no charge. Quarks are different in they are fractionally charged.*

*Leptons and quarks also differ in terms of the forces that affect them. Both types of particles are affected by the weak nuclear force, gravitational force, and electromagnetic forces but only quarks are affected by the strong nuclear force.*

**Q**: Beta minus decay is a type of radioactive decay where an electron (*e-*) and an anti-neutrino () are emitted from a nucleus within which a neutron (*n*) transforms into a proton (*p*). The decay is the result of one of the nuclear forces affecting all particles in the decay.

The electron is a lepton and the anti-neutrino is an anti-lepton.

Use the Standard Model to suggest why beta minus decay is the result of the weak nuclear force and not the strong nuclear force

**A***: Beta decay involves the emission of electrons as a result of nuclear forces within the nucleus. Electrons are leptons, which means that they are not affected by the strong nuclear force. This implies that if beta minus decay is the result of a nuclear force, it must be the weak nuclear force.*

*Alternatively, the strong nuclear force cannot be responsible for the decay as the electron is emitted at high speeds. The strong nuclear force is an attractive force that acts over short distances – therefore if the strong force was responsible then an electron would not be emitted.*

**Conservation laws**

In comparison to the conceptual challenges, the conservation laws are fairly straightforward – given a particular reaction/decay, students need to determine if charge, lepton number and baryon number are conserved. The subject outline states that students:

* Use the conservation laws to determine the baryon number, lepton number, and charge of particles in reactions.
* Given a reaction between particles, demonstrate that baryon number, lepton number, and charge are conserved.

Students may find it challenging to remember what values are assigned to each type of particle.

If students can incorporate the baryon and lepton numbers into their visual representations it may aid their recall and understanding.

Questions involving conservation laws may be given greater depth by giving a reaction with an unknown particle, then asking students to predict properties of that particle.

***Sample Questions***

**Q**: Mesons are particles which are composed of quark/anti-quark pairs. A pion is a meson that can be positively charged (), negatively charged () or neutral ().

Pions are often involved in interactions with baryons such as protons () or neutrons (); leptons such as muons () or neutrinos (); or antileptons such as anti-muons ().

Use conservation laws to determine if the following interactions can occur:

1. 
2. 
3. 
4. 

**A**:

1. 

*No.*

*Baryon number - LHS: 1, RHS: 0 + 0 = 0. Conservation of Baryon number does not hold.*

*Lepton number - LHS: 0, RHS: 0 + 0 = 0. Conservation of Lepton number holds.*

*Charge - LHS: +1, RHS: +1 + 0 = +1. Conservation of charge holds.*

1. 

*No.*

*Baryon number - LHS: 0, RHS: 0 + 0 = 0. Conservation of Baryon number holds.*

*Lepton number - LHS: +1, RHS: +1 + 1 = +2. Conservation of Lepton number does not hold.*

*Charge - LHS: -1, RHS: -1 + 0 = -1. Conservation of charge holds.*

1. 

*Yes.*

*Baryon number - LHS: 0, RHS: 0 + 0 = 0. Conservation of Baryon number holds.*

*Lepton number - LHS: 0, RHS: -1 + 1 = 0. Conservation of Lepton number holds.*

*Charge - LHS: +1, RHS: +1 + 0 = +1. Conservation of charge holds.*

1. 

*No.*

*Baryon number - LHS: 0, RHS: 0 + 0 = 0. Conservation of Baryon number holds.*

*Lepton number - LHS: 0, RHS: -1 + 0 = -1. Conservation of Lepton number does not hold.*

*Charge - LHS: +1, RHS: +1 + 0 = +1. Conservation of charge holds.*

**Q**: A negative pion () is a negatively charged meson that is often formed in the upper atmosphere. The following reaction shows a pion decaying into a negative muon () and an unknown particle,.



Determine if  is a neutrino or an anti-neutrino. Justify your answer.

**A***: The lepton number of a meson is L = 0 as it is not a lepton. To conserve lepton number in this reaction, a particle on the right-hand side must be formed such that the sum of the lepton numbers also equals 0. Therefore, the particle must have a lepton number of L = -1 since a muon has L = +1. Therefore, since an anti-neutrino is an anti-particle, it has lepton number -1 and must be the missing particle.*

**Q**: A single interaction between particles may require the conservation of two or more different types of lepton numbers. The electronic lepton number,, applies to electrons, electron neutrinos (), and their anti-particles. Similarly, the muonic lepton number,, applies to muons (), muon-neutrinos ($ν\_{μ}$), and their anti-particles.

Explain if each lepton number is conserved in the following decays.

1. 
2. 
3. 

**A**:

1. 

*- LHS: 0 RHS: +1 + 1+ 0 = +2. The electronic lepton number is not conserved.*

* - LHS: +1 RHS: 0 + 0 + -1 = -1. The muonic lepton number is not conserved.*

1. 

*- LHS: 0 + 0 +1 = +1 RHS: +1 + 0 + 0= +1. The electronic lepton number is conserved.*

* - LHS: -1 + 0 + 0= -1 RHS: 0 + -1 + 0 = -1. The muonic lepton number is conserved.*

1. 

*- LHS: 0 + 0 +1 = +1 RHS: +2 + -1 + 0= +1. The electronic lepton number is conserved.*

* - LHS: -1 + 0 + 0 = -1 RHS: 0 + 0 + -1 = -1. The muonic lepton number is conserved.*

**Particle Composition**

Students need to demonstrate an understanding of how composite particles such as baryons and mesons are formed from quarks and anti-quarks. From the subject outline:

* Describe how protons, neutrons, and other baryons may be formed from different combinations of quarks

Much of the content for this part of the subtopic draws on the use of the law of conservation of baryon number and the law of the conservation of charge. Each of these may be shown to apply to a particular baryon, or to predict a missing quark. This concept may be probed at an even greater depth and unfamiliarity to students by applying the laws to mesons.

***Sample Questions***

**Q**: A proton is a particle composed of two up quarks and a down quark. Show that this combination of quarks is consistent with the conservation of baryon number and charge.

**A**: *A proton is composed of three quarks: uud. It is known that proton has a charge of +1e, therefore the sum of the charges of the quarks should also be +1e.*

*We have  and , therefore for charge, *

*Similarly, since the proton is a baryon, it has a baryon number of +1. Each quark has a baryon number of . Therefore, the sum of the baryon numbers of the quarks is given by: . Thus, the conservation of baryon number holds.*

**Q**: A particular Sigma particle (**) has a quark combination of *xxs*, where *x* is an unknown quark.

1. Use the conservation laws to explain why the Sigma particle could be uus or dds.

The same quark, x, can also be combined with an anti-quark, *,* to form the neutral kaon meson (**).

1. Explain if *x* is an up or down quark and hence determine the charge of the Sigma particle.

**A**: (a) *The up quark has a charge of  and the down quark has a charge of , therefore, in both of these combinations dds and uus, the baryon number and charge result in integer values.*

*Charge:  and *

*Baryon number:  and *

*(b) Since the kaon particle formed is neutral, the quark x must have the opposite charge to* *. Since the anti-strange particle has a charge of* *, quark x must have a charge of* *. Therefore, it must be down quark. The charge of the Sigma particle is thus -1e.*

**Q:** Using the baryon number and charge, explain if it is possible to have a meson composed of an up quark and an anti-down quark.

**A:**

*Yes, it is possible. The charge of the of the up quark is and the charge of an anti-down quark is , giving a total charge of .*

*Similarly, the baryon number of an up quark is and the baryon number of an anti-down quark is, giving a total baryon number of . This is consistent with the conservation of baryon number, as the baryon number of a meson is 0.*

**Mass-energy equivalence relation**

Here, students need to be able to demonstrate the use of the formula **in the context of a particle/anti-particle annihilation event. The subject outline states that:

When a particle and its antiparticle collide, they annihilate, releasing energy according to the mass-energy equivalence formula: *.*

This relation may be used in conjunction with other aspects of the course. For example, if two particles annihilate, students may be asked to:

* Calculate the energy released in joules or electron volts.
* If the energy is converted into photons, calculate the energy of each photon.
* Calculate the frequency of the photons released.

***Sample questions***:

**Q**: Calculate the energy released, in electron volts, when an electron and positron annihilate.

**A**: *The total mass is converted to energy, therefore:*

**

*In electron volts, this becomes *

**Q**: A muon and an anti-muon, both of mass *kg ,* annihilate to form two photons. Calculate the energy and frequency of each photon. Assume that both particles were at rest during the annihilation event.

**A**: *The total mass is converted to energy, therefore:*

**

*Each photon has energy: *

*Therefore, the frequency is given by: *

**

***Standard Model Visual Representation Summary***

