**Worksheet on Deep Inside the Atom**

1. By the mid-1930’s, it was believed that all atoms were composed of protons, neutrons and electrons and that these particles were the fundamental constituents of matter. Provide an analysis of the evidence that suggests that the proton and the neutron are not fundamental particles.
2. The Standard Model asserts that matter can be grouped into three families: **bosons, quarks and leptons**. Describe how the Standard Model accounts for the transmission of the four fundamental forces of nature.
3. Quarks are matter particles with charges that are sub-multiples of the electronic charge. They are considered fundamental particles, since they have no known components. Provide three other distinct features of quarks.
4. Define the term hadron. Identify and briefly describe the two distinct groups into which hadrons can be classified.
5. Define the term lepton. Identify and briefly describe the two distinct groups into which leptons can be classified.
6. Particle accelerators are used to accelerate sub-atomic particles to very high energies for the purpose of probing the structure of matter. Explain why high-energy particles are useful for probing matter.
7. Particle accelerators are used to obtain evidence that tests and/or validates aspects of theories, including the Standard Model of matter. Provide two examples of evidence gained from particle accelerators in support of theories of matter.

**Answers**

1. The evidence that suggests that the proton and the neutron are not fundamental particles came originally from two main sources:

(i) the discovery, starting in the mid-1930’s, of a multitude of other particles with masses less than that of the proton and neutron; for example Anderson’s discovery of the **positron (positive electron)** in cosmic rays; Anderson & Neddermeyer’s discovery of the **u-meson** **(muon)**; Powell & Occhialini’s discovery of a particle predicted by Yukawa called the **-meson** **(pion)**. By the 1950’s & 1960’s many new types of particles similar to the neutron and proton had been discovered, as well as mesons whose masses were mostly less than nucleon masses but more than the electron mass. It became difficult to defend the proton and neutron as fundamental when there were so many similar particles and many particles with masses smaller than those of the proton and neutron.
(ii) direct experimental evidence that when high-energy electron beams are used to probe the proton or neutron, three distinct scattering centres are found inside each particle, suggesting the presence of three smaller, more fundamental particles, inside the proton and neutron. In 1964, Murray Gell-Mann and, independently, George Zweig, proposed a model which explained how protons and neutrons were composed of these smaller particles, which Gell-Mann named **quarks**. The existence of the quark was confirmed by deep inelastic scattering experiments at SLAC in 1968 and experiments have since provided evidence for all six flavours of quark — up, down, strange, charm, bottom and top. This effectively ended any argument over whether protons and neutrons were fundamental particles. Clearly, based on experimental evidence, they were not. Today **quarks and leptons** are considered the fundamental particles in nature rather than protons and neutrons.
2. In the Standard Model, the four fundamental forces of nature are transmitted by **gauge bosons**. These are **force-carrying particles**. Each of the four fundamental forces in nature is carried between particles by a **gauge boson**, as described below.

	* The **gravitational force** – a long-range force acting on all masses in the universe. It is the weakest of all the forces. It is believed to be carried by the **graviton**, which has not yet been observed experimentally.
	* The **electromagnetic force** – a long-range force that acts on all charges in the universe. It holds atoms and molecules together. It is carried by the **photon**.
	* The **strong nuclear force** – holds protons and neutrons together in the nucleus. It is a short-range force operating at nuclear distances (10-15 m). In the standard model, it also binds quarks together and is carried by the **gluon**.
	* The **weak nuclear force** – interacts with particles such as electrons to change them into other forms of particle. It is short-ranged (10-17 m). In the standard model it also transforms one quark type into another and is carried by the **W and Z bosons**.
3. There is a variety of answers to this question. Any three of the following will do:
	* Quarks come in six flavours – up, down, charm, strange, top & bottom.
	* Quarks combine to form composite particles called hadrons, the most stable of which are protons and neutrons, the components of atomic nuclei.
	* Quarks have various intrinsic properties, including electric charge, mass, colour charge and spin.
	* The up and down quarks have the lowest masses of all quarks.
	* Quarks have electric charge of either (+2/3) e or (-1/3) e, where e = charge on electron.
	* Quarks are the only known particles whose electric charges are not integer multiples of the electronic charge.
	* Quarks are the only elementary particles in the Standard Model to experience all four fundamental interactions, also known as fundamental forces.
	* All commonly observable matter is composed of up quarks, down quarks and electrons.
	* Quarks are never found in isolation; they can be found only within hadrons. (This is because the strong force that binds quarks together is such that it increases in strength with increasing distance.)
	* Quarks are held together by colour charge. (Colour charge is the source of the powerful forces that bind quarks together and build up the baryons and mesons.)
	* The heavier quarks rapidly change into up and down quarks through a process of particle decay.
	* Quarks get their masses from a process connected to the Higgs boson.
	* For every quark flavour there exists a corresponding antiquark.
4. A hadron is any particle composed of quarks. Hadrons can be divided into two groups:

	* Baryons – 3 quark combinations. The most well-known, lightest and most stable baryons are the proton and neutron. The proton is composed of two up quarks and one down quark (uud) and has a net charge of +1 e. The neutron is composed of one up quark and two down quarks (udd) and is therefore neutral. Many other baryons exist (lambda, sigma, xi, omega). All baryons interact through the strong force.
	* Mesons – 2 quark combinations. Mesons consist of a quark and an antiquark. They are unstable and decay in millionths of a second to produce other particles such as photons, electrons and neutrinos. Examples of mesons are pions, kaons and eta-mesons. For example, a + meson is composed of an up quark and a down anti-quark , giving a total charge of +1e. All mesons interact through the strong force.
5. Leptons are matter particles with little or no mass and half-integer spin (spin ½ ). They do not experience the strong force and interact through the weak force (and the electromagnetic force if they are charged). Leptons are considered fundamental particles since they have no known components. One group of leptons has the same size negative charge as the electron and distinct masses. This group consists of three flavours – electron, muon and tau particles. The other group has zero charge and extremely small mass and consists of the three flavours – electron-neutrino, muon-neutrino and tau-neutrino. For every lepton there is a corresponding anti-lepton. Unlike quarks, individual leptons can be found in isolation.
6. Beams of very high-energy particles are useful matter probes for two main reasons. Firstly, the higher the energy (and therefore velocity) of a particle, the smaller the de Broglie wavelength. The smaller the de Broglie wavelength, the smaller the detail the particle can “see” – ie the better the resolving power of a beam of such particles. Secondly, the higher the energy of a probe particle colliding with a target particle, the more massive are the possible product particles, since in every reaction, some of the energy of the probe particle is converted into mass according to E = mc2. This means effectively that physicists can re-create and study in the laboratory, conditions that may have existed in the early stages of the creation of the universe. This enables physicists to test and validate aspects of theories, such as theories of the early history of the universe and especially aspects of the Standard Model of matter itself.
7. The existence of the quark was confirmed by deep inelastic scattering experiments at the Stanford Linear Accelerator Centre (SLAC) in 1968. These experiments used high-energy electron beams to probe the proton and discovered three distinct scattering centres inside the proton, suggesting the proton was composed of three quarks. This confirmed that the proton was not a fundamental particle.

Since 1964, a much sought-after particle in the Standard Model of matter was the Higgs boson, the essential particle in a proposed mechanism to explain why some particles have mass. In 2012, a subatomic particle with the expected properties was discovered by the ATLAS and CMS experiments at the Large Hadron Collider (LHC) at CERN, in Switzerland. The new particle was subsequently confirmed to match the expected properties of a Higgs boson. This evidence confirmed a prediction of the model that such a particle should exist and therefore provided support for the model.