17.2: A Brief History of Nuclear Physics

Fundamental Particles

The idea that everything is made of tiny pieces of 'stuff' dates back to ancient Greece and India. In fact, the word atom comes from the ancient Greek word *atomos*, which means "uncuttable" or indivisible. The idea that there was some smallest piece of matter was supported by the work of John Dalton (1766-1844). He collected data on the weights of chemical compounds and found that they could be explained if the smallest piece of each element had a different weight. He decided to call these smallest pieces 'atoms'. For about 100 years afterwards, everyone thought these were the smallest, most fundamental pieces of matter.

In 1897, a physicist named J.J. Thomson was able to show that atoms were *not* indivisible by discovering electrons and showing that the electrons weigh much less than atoms. He found that they have a negative charge, and the movement of these electrons was an electric current. Since atoms are usually neutral (uncharged), that meant that the electrons' negative charge had to be balanced by some positive charge somewhere in the atom. The atom would be held together by the attractive Coulomb force between oppositely charged objects. Thomson thought that the positive and negative charges were evenly blended throughout the atom, but that model was not supported by experimental evidence.

The Atomic Model

A trio of physicists (Ernest Rutherford, Hans Geiger and Ernest Marsden) performed experiments between 1908 and 1913 that showed that the positive charges in the atom were packed into a tiny space at the center of the atom. This space was called the *nucleus* and the experimental evidence suggested that most of the atomic mass was located in the nucleus. Furthermore, the experiments showed that the nucleus was thousands of times smaller than the atom.

This meant that most of the atom was empty space and another physicist, Niels Bohr, developed a model of the atom that had the negative electrons orbiting around the positive center at certain fixed distances, much like the planets orbit the sun in our solar system. That line of thought eventually led to the development of quantum mechanics, a subject beyond the scope of this text.

Rutherford deduced that the hydrogen atom is the simplest atom, made of a single electron and a positive nucleus. He named the positive charge of the hydrogen nucleus the *proton*. The proton has the same amount of charge as the electron, but it has the opposite sign. Since protons and electrons have the same amount of charge, in order for an atom to be electrically neutral, the number of protons have to equal the number of electrons.

The Nuclear Model

Rutherford was also able to show that the mass of many elements was larger than the mass of the protons and the electrons combined. To explain the missing mass, he hypothesized a neutral particle of about the same mass as the proton, a *neutron*, that was also part of the nucleus. In 1932, James Chadwick's experiments confirmed the existence of the neutron. For the lighter elements, the number of protons and neutrons are roughly the same, but for the heavier elements there were typically more neutrons than protons.

The nucleus was now thought to be a collection of protons and neutrons, giving it a positive charge and accounting for most of the mass of the atom. There was a problem. The same Coulomb force that caused the electrons and protons to be attracted also would make the protons repel each other. How could a collection of positively charged protons and uncharged neutrons be packed into the nucleus? The Coulomb force trying to push the protons apart would be immense at those tiny distances!

Physicists hypothesized that there must be an attractive force between the protons and neutrons, and that it had to be stronger than the Coulomb force to keep the nucleus from flying apart. This new force was called the *strong force* and it could only act at very small distances, to keep the nucleus intact. Now the nucleus is modeled by two different forces. The strong force that keeps the nucleus together and the Coulomb force that exists between the protons that tries to tear the nucleus apart.

Radioactivity, Quarks and the Standard Model

Some elements spontaneously transform into different elements through a process that is called *radioactive decay*. It seems that some nuclei are unstable. The strong force is just barely large enough to keep the nucleus together, so sometimes it falls apart. Trying to understand that process led to the discovery that neutrons and protons are not truly fundamental particles.

Although we once thought atoms were fundamental, we learned that an atom is composed of smaller objects: protons, neutrons and electrons. In a similar way, we thought that protons and neutrons are fundamental particles but we've learned that the nucleons are made up of even smaller objects, called *quarks.*

It currently appears at though quarks are truly fundamental particles. Trying to understand how quarks behave has led to the development of the *Standard Model of Particle Physics* as a way to understand the universe. This framework is well-supported by many experimental results but is known to be incomplete.