Basic Physics of Radiation Physical

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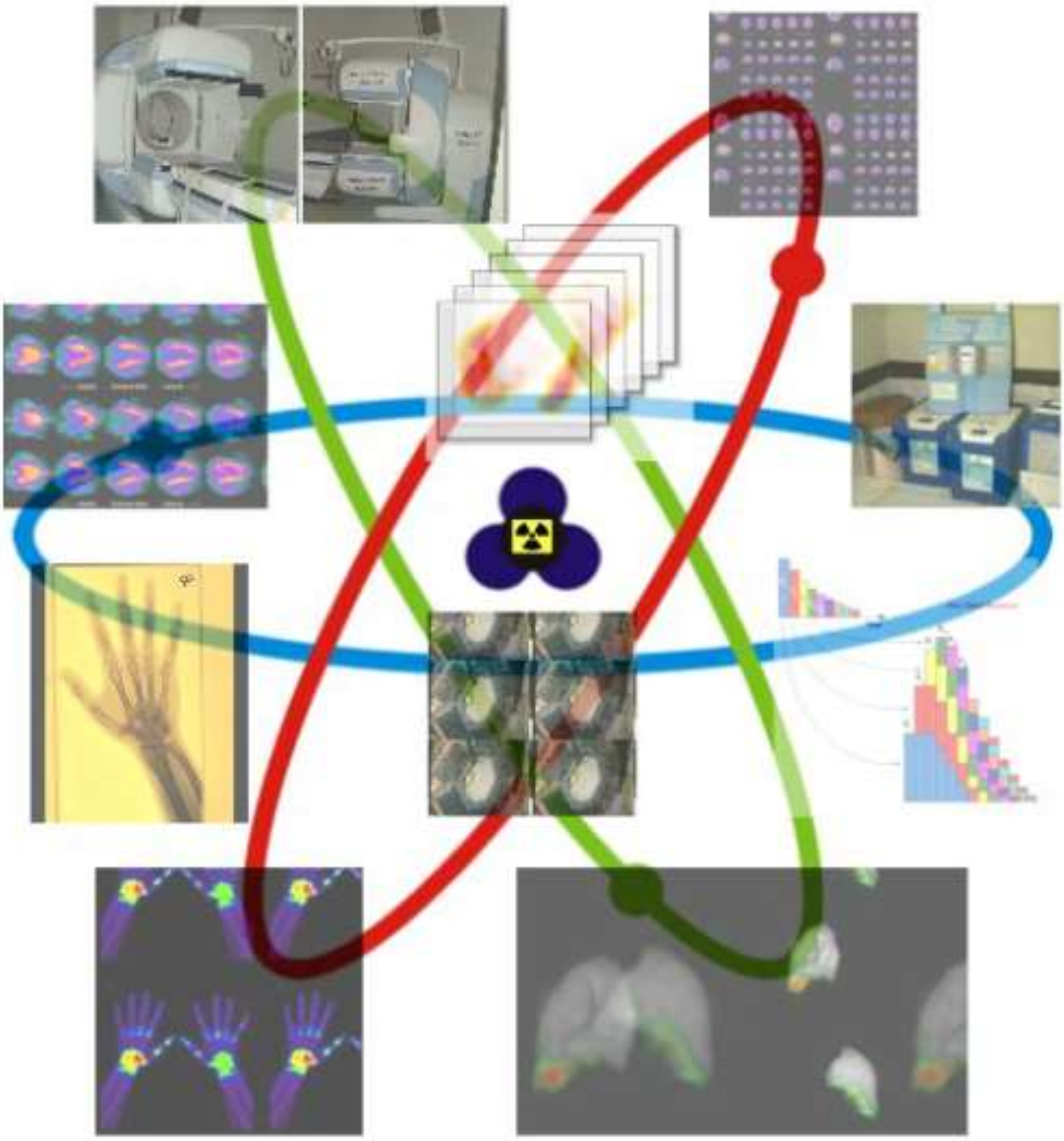


CHAPTER 1 ATOMIC & NUCLEAR STRUCTURE

Introduction

You will have encountered much of what we will cover here in your high school physics. We are going to review this material again below so as to set the context for subsequent chapters. This chapter will also provide you with an opportunity to check your understanding of this topic.

The chapter covers atomic structure, nuclear structure, the classification of nuclei, binding energy and nuclear stability.

Atomic Structure

The atom is considered to be the basic building block of all matter. A simple theory of the atom tells us that it consists of two components: a nucleus surrounded by an electron cloud. The situation can be considered as being similar in some respects to planets orbiting the sun.

From an electrical point of view, the nucleus is said to be positively charged and the electrons negatively charged.

From a size point of view, the radius of an atom is about 10-10 m while the radius of a nucleus is about 10-14 m, i.e. about ten thousand times smaller. The situation could be viewed as something like a cricket ball, representing the nucleus, in the middle of a sporting arena with the electrons orbiting somewhere around where the spectators would sit. This perspective tells us that the atom should be composed mainly of empty space. However, the situation is far more complex than this simple picture portrays in that we must also take into account the physical forces which bind the atom together.

Chemical phenomena can be thought of as interactions between the electrons of individual atoms.

Radioactivity on the other hand can be thought of as changes which occur within the nuclei of atoms.

The Nucleus

A simple description of the nucleus tells us that it is composed of protons and neutrons. These two particle types are collectively called **nucleons**, i.e. particles which inhabit the nucleus.

From a mass point of view the mass of a proton is roughly equal to the mass of a neutron and each of these is about 2,000 times the mass of an electron. So most of the mass of an atom is concentrated in the small region at its core.

From an electrical point of view the proton is positively charged and the neutron has no charge. An atom all on its own (if that were possible to achieve!) is electrically neutral. The number of protons in the nucleus of such an atom must therefore equal the number of electrons orbiting that atom.

Classification of Nuclei

The term **Atomic Number** is defined in nuclear physics as the number of protons in a nucleus and is given the symbol Z. From your chemistry you will remember that this number also defines the position of an element in the Periodic Table of Elements.

The term **Mass Number** is defined as the number of nucleons in a nucleus, that is the number of protons plus the number of neutrons, and is given the symbol A.

Note that the symbols here are a bit odd, in that it would prevent some confusion if the Atomic Number were given the symbol A, and the Mass Number were given another symbol, such as M, but its not a simple world!

It is possible for nuclei of a given element to have the same number of protons but differing numbers of neutrons, that is to have the same Atomic Number but different Mass Numbers. Such nuclei are referred to as Isotopes. All elements have isotopes and the number ranges from three for hydrogen to over 30 for elements such as caesium and barium.

Chemistry has a relatively simple way of classifying the different elements by the use of symbols such as H for hydrogen, He for helium and so on. The classification scheme used to identify different isotopes is based on this approach with the use of a superscript before the chemical symbol to denote the Mass Number along with a subscript before the chemical symbol to denote the Atomic Number. In other words an isotope is identified as:

$${}_{Z}^{A}\mathbf{X}$$

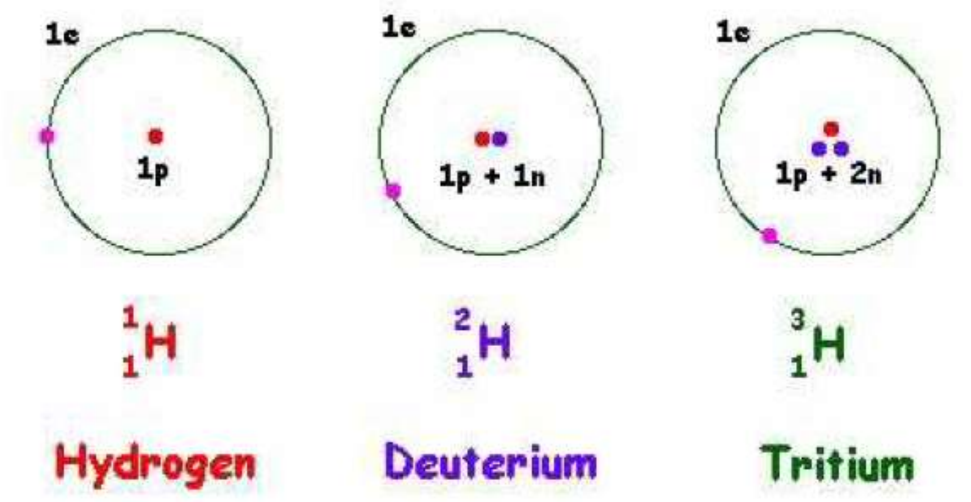
where X is the chemical symbol of the element.

Let us take the case of hydrogen as an example. It has three isotopes:

- the most common one consisting of a single proton orbited by one electron.
- a second isotope consisting of a nucleus containing a proton and a neutron orbited by one electron.

- a third whose nucleus consists of one proton and two neutrons, again orbited by a single electron.

A simple illustration of these isotopes is shown below. Remember though that this is a simplified illustration given what we noted earlier about the size of a nucleus compared with that of an atom. But the illustration is nevertheless useful for showing how isotopes are classified.



Click HERE for an animated version of this figure.

The first isotope commonly called **hydrogen** has a Mass Number of 1, an Atomic Number of 1 and hence is identified as:

$$^{1}_{1}\mathbf{H}$$

The second isotope commonly called **deuterium** has a Mass Number of 2, an Atomic Number of 1 and is identified as:

$$^{2}_{1}\mathbf{H}$$

The third isotope commonly called tritium is identified as:

$$^{3}_{1}\mathbf{H}$$

The same classification scheme is used for all isotopes. For example, you should now be able to figure out that the uranium isotope, $^{236}_{92}\mathbf{U}$, contains 92 protons and 144 neutrons.

A final point on classification is that we can also refer to individual isotopes by giving the name of the element followed by the Mass Number. For example, we can refer to deuterium as hydrogen-2 and we can refer to

$$^{236}_{92}\mathbf{U}$$

as uranium-236.

Before we leave this classification scheme let us further consider the difference between chemistry and nuclear physics. You will remember that the water molecule is made up of two hydrogen atoms bonded with an oxygen atom. Theoretically if we were to combine atoms of hydrogen and oxygen in this manner many, many of billions of times we could make a glass of water. We could also make our glass of water using deuterium instead of hydrogen. This second glass of water would theoretically be very similar from a chemical perspective. However, from a physics perspective our second glass would be heavier than the first since each deuterium nucleus is about twice the mass of each hydrogen nucleus. Indeed water made in this fashion is called **heavy water**.

Atomic Mass Unit

The conventional unit of mass, the gram, is rather large for use in describing characteristics of nuclei. For this reason, a special unit called the Atomic Mass Unit (amu) is often used. This unit is sometimes defined as 1/12th of the mass of the stable most commonly occurring isotope of carbon, i.e. ^{12}C. In terms of grams, 1 amu is equal to 1.66×10^{-24} g, that is, just over one million, million, million millionth of a gram.

The masses of the proton, m_p and neutron, m_n on this basis are:

$$m_p = 1.00783 \text{ amu}$$

and

$$m_n = 1.00866 \text{ amu}$$

while that of the electron is just 0.00055 amu.

Binding Energy

We are now in a position to consider the subject of nuclear stability. From what we have covered so far, we have seen that the nucleus is a tiny region in the centre of an atom and that it is composed of neutrally and positively charged particles. So, in a large nucleus such as that of uranium (Z=92) we have a large number of positively charged protons concentrated into a tiny region in the centre of the atom. An obvious question which arises is that with all these positive charges in close proximity, how come the nucleus does not fly apart? How can a nucleus remain as an entity with such electrostatic repulsion between the components? Should the orbiting negatively-charged electrons not attract the protons away from the nucleus?

Let us take the case of the helium-4 nucleus as an example. This nucleus contains two protons and two neutrons so that in terms of amu we can figure out from what we covered earlier that the

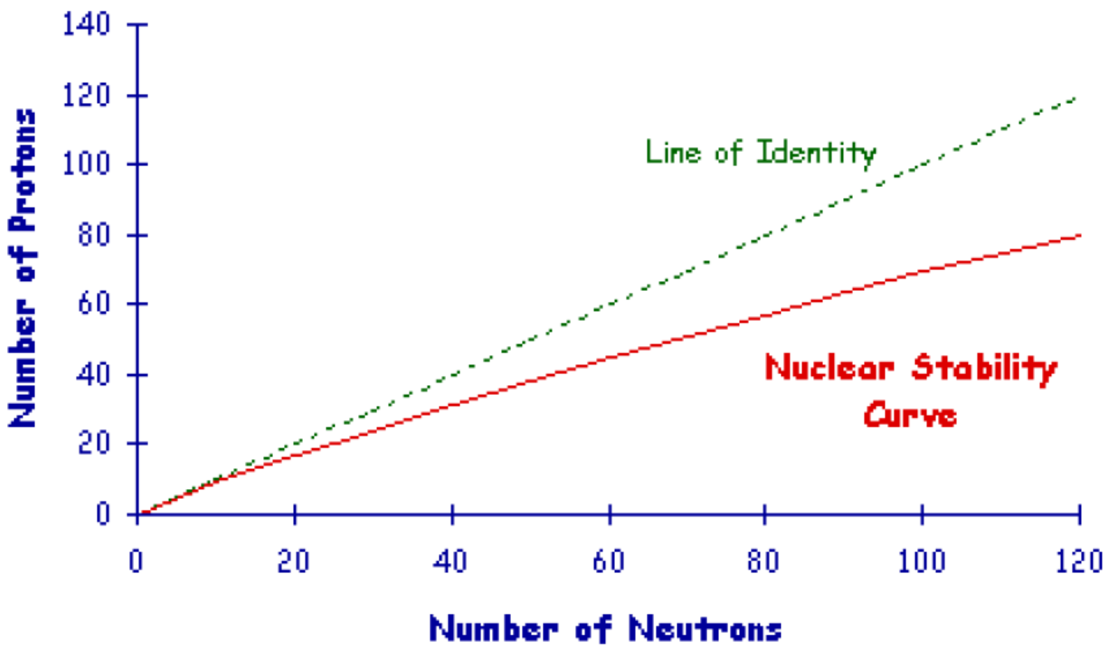
mass of 2 protons = 2.01566 amu,

and the

mass of 2 neutrons = 2.01732 amu.

Therefore we would expect the total mass of the nucleus to be 4.03298 mu.

The experimentally determined mass of a helium-4 nucleus is a bit less - just 4.00260 amu. In other words, there is a difference of 0.03038 amu between what we might expect as the mass of this



Note that the number of protons equals the number of neutrons for small nuclei. But notice also that the number of neutrons increases more rapidly than the number of protons as the size of the nucleus gets bigger so as to maintain the stability of the nucleus. In other words more neutrons need to be there to contribute to the binding energy used to counteract the electrostatic repulsion between the protons.

Radioactivity

There are about 2,450 known isotopes of the one hundred odd elements in the Periodic Table. You can imagine the size of a table of isotopes relative to that of the Periodic Table! The unstable isotopes lie above or below the Nuclear Stability Curve. These unstable isotopes attempt to reach the stability curve by splitting into fragments, in a process called Fission, or by emitting particles and/or energy in the form of radiation. This latter process is called **Radioactivity**.

It is useful to dwell for a few moments on the term radioactivity. For example, what has nuclear stability to do with radio? From a historical perspective remember that when these radiations were discovered about 100 years ago we did not know exactly what we were dealing with. When people like Henri Becquerel and Marie Curie were working initially on these strange emanations from certain natural materials it was thought that the radiations were somehow related to another phenomenon which also was not well understood at the time - that of radio communication. It seems reasonable on this basis to appreciate that some people considered that the two phenomena were somehow related and hence that the materials which emitted radiation were termed *radio-active*.

We know today that the two phenomena are not directly related but we nevertheless hold onto the term radioactivity for historical purposes. But it should be quite clear to you having reached this stage of this chapter that the term radioactive refers to the emission of particles and/or energy from unstable isotopes. Unstable isotopes for instance those that have too many protons to remain a stable entity are called radioactive isotopes - and called radioisotopes for short. The term radionuclide is also sometimes used.

Finally about 300 of the 2,450-odd isotopes mentioned above are found in nature. The rest are man-made (or person-made!), that is they are produced artificially. These 2,150 or so artificial isotopes have been made during the last 100 years or so with most having been made since the second world war. Click HERE to access an interactive webpage which gives details of elements in the Periodic Table and of radioisotopes used in medicine.

We will return to the production of radioisotopes in the last chapter of this wikibook and will proceed for the time being with a description of the types of radiation emitted by radioisotopes.