

Course: NUCLEAR PHYSICS

Lesson: NUCLEAR STABILITY CONCEPTS

TABLE OF CONTENTS

	INTRODUCTION
	OBJECTIVES
1.0	NUCLEAR STABILITY
2.0	TYPES OF RADIATION
2.1	ALPHA PARTICLES
2.2	BETA PARTICLES
2.3	GAMMA RAYS
2.4	NEUTRONS
3.0	MASS ENERGY EQUIVALENCE
3.1	MASS DEFECT
3.2	BINDING ENERGY
4.0	SUMMARY

INTRODUCTION

It is known that the neutron to proton ratio within the nucleus is a major factor in the stability of a nucleus. If a nucleus is unstable, it undergoes radioactive decay.

In this lesson we will examine why a nucleus may be unstable and the types of radiation it can emit. Also, the concept of Einstein's equation for mass-energy equivalence will be presented. A thorough knowledge of mass defect and binding energy is important in understanding nuclear reactions and decay processes.

OBJECTIVES

TERMINAL OBJECTIVE

The Contractor Health Physics Technician will describe the characteristics of each type of radiation. The Contractor Health Physics Technician will also describe the concepts of range, specific ionization, and radiological thickness.

ENABLING OBJECTIVES

Upon completion of this lesson, the Contractor Health Physics Technician will be able to:

- ❖ Define radiation.
- ❖ Describe the difference between atomic radiation and nuclear radiation.
- ❖ Distinguish between electromagnetic and particulate radiation.
- ❖ Recognize the units of energy such as erg and electron volt.

1.0 NUCLEAR STABILITY

As mentioned in Lesson 1, the predominant factor in nuclear stability is the neutron to proton ratio. A physical explanation of this phenomenon can become very complex. The n/p ratio is important to stability because of the tendency of protons to repel each other even though bound into a nucleus by nuclear forces. Figure NP-2-1 represents a picture of the nucleus and each nucleon's sphere of action.

Because of their like charges, the protons will tend to separate. To take up the nuclear space, neutrons will be required since neutrons will provide nuclear force without charge repulsion. Protons on opposite sides of the nucleus will experience no direct nuclear force, but will exert electrostatic repulsion on each other. This electrostatic repulsion is not sufficient to expel the protons since they are bound by the nuclear forces of internal nucleons.

When comparing the ratio of neutrons to protons in stable nuclei, a definite pattern is evident. Figure NP-2-2 plots n/p ratios for stable isotopes.

Isotopes, which either have too low or too high a n/p ratio, fall outside the "line of stability" and will undergo radioactive decay in order to adjust their n/p ratio.

2.0 TYPES OF RADIATION

Radioactivity is defined as the spontaneous decay or disintegration of an excited nucleus. An excited nucleus is one that is unstable due to its n/p ratio being too high or too low. The decay of radioactive nuclei is accompanied by the emission of energy in the form of energetic particles and/or electromagnetic waves (or photons). The particles and photons, which are emitted from an unstable nucleus, are referred to as radiation. Atomic Radiation refers to the emanation of electromagnetic waves from the electron shells of the atom. Nuclear Radiation refers to the emanation of those energetic particles and/or electromagnetic waves from the nucleus of the atom. In any case, the purpose of any radiation protection program is the subsequent protection and dose assessment of plant personnel from the collective radiation, both atomic and nuclear in origin.

It is important to realize that there are several different manners in which radioactive nuclides can decay. In this lesson we will examine four types of radiation: alpha particles, beta particles, neutron and gamma rays. Each radioactive nuclide normally decays by emission of one or more of these types of radiation. Because radioactive nuclides have characteristic types and energies of emissions, they can often be identified by the radiation they emit.

The unit for energy in nuclear reactions is the electron volt (eV). One eV is the amount of energy gained by an electron when accelerated through a potential difference of one volt.

The electron volt is usually too small a unit to conveniently use to describe the energies of nuclear reactions. For this reason, the unit of a million electron volts (Mev) is normally used. $\text{Mev} = 1 \times 10^6 \text{ eV}$

$$1 \text{ Mev} = 1.6 \times 10^{-13} \text{ joules}$$

2.1 ALPHA PARTICLES

The symbol α is used to denote an alpha particle. Alpha particles consist of two protons and two neutrons ($Z=2$, $A=4$). An alpha particle is essentially a helium nucleus.

Each alpha particle emitting nuclide will normally emit alphas at a distinct or characteristic energy. These energies range from about 2 Mev to 12 Mev. While these are relatively high energies, the penetrating power of alphas is minimal because of their large mass and +2 charge. An alpha particle will travel only a few centimeters in air and will be stopped by a sheet of paper.

2.2 BETA PARTICLES

The symbol β is used to denote beta particles. A beta particle is an electron emitted from the nucleus of a radioactive isotope. Beta particles can be either positively or negatively charged (+1 or -1). Positively charged betas are called positrons or beta plus particles. Negatively charged betas are called beta minus particles. Beta minus decay is the more common of the two. The mass of a beta particle is $1/1838$ AMU, the mass of an electron.

2.3 GAMMA RAYS

The symbol γ is used to denote a gamma ray. As the word "ray" implies, gamma radiation is not particulate in nature. Gamma radiation involves the emission of photons (electromagnetic rays) from the nucleus. Gamma rays are very similar to X-rays. In fact, gamma rays differ from X-rays only in their energy level. Since X-rays are usually associated with electronic energy transition and gamma rays are nuclear energy transition, gamma rays possess more energy. Visible light is a form of electromagnetic radiation (photons) of a much lower energy than either X or gamma radiation. Gamma rays have no mass and no charge.

Since all nuclides, which decay by gamma emission, have distinct energy gammas, measuring the energy of the gamma radiation emitted can identify the specific radioisotope in question.

2.4 NEUTRONS

The symbol n denotes a neutron. Direct emission of neutrons by radioactive nuclides is rare, it occurs in nuclei, which are a result of fission (the fission process will be covered in detail in a later lesson). These highly excited nuclides formed from fission have much too high a n/p ratio for stability and often emit neutrons immediately after their formation. Other sources of neutron radiation include the neutron sources installed in nuclear reactor cores used for reactor startup and instrumentation testing.

Neutron radiation is very high in the core of an operating nuclear reactor, it is the particle which initiates (and sustains) the fission chain reaction.

3.0 MASS-ENERGY EQUIVALENCE

Of primary concern in nuclear reactions is the question of whether a particular reaction is possible and if so, how much energy is required to initiate the reaction and how much energy is released as a result of the reaction. The answer to these questions lies in the equivalence of mass and energy.

Albert Einstein discovered that mass can be transformed into energy and vice-versa. The equation which relates the two is $E = mc^2$.

See Figure NP-2-3.

Where energy is in ergs, mass is in grams and c represents the speed of light in cm/sec, (3×10^{10} cm/sec).

In any nuclear reaction, whether it is radioactive decay or fission, the total mass energy is conserved. This is of particular importance in calculating the energies of the various types of radiation, which accompany the decay of nuclei. In the fission process the mass energy equivalence allows the calculation of the energy released during the fission reaction.

3.1 MASS DEFECT

When a nucleus is assembled from its constituent parts, i.e., protons and neutrons, it is found that the mass of the nucleus is less than the sum of the masses of the protons and neutrons. This difference of mass is known as the mass defect.

See Figure NP-2-4

To calculate mass defect one must add up the masses of the constituent particles then subtract the known mass of that atom.

Particle	Mass (AMU)	Symbol
Neutron	1.00866	M_n
Proton	1.00727	M_p
Electron	0.00055	M_e

If we designate M to equal the mass of the atom, the mass defect equation is:

$$\text{Mass defect} = [Z(M_p + M_e) + (A-Z) M_n] - M$$

recall: Z = atomic number (number of protons or electrons).
 A = atomic mass number (number of protons and neutrons).
 $(A - Z)$ = number of neutrons.

This equation can be simplified somewhat by combining the mass of the proton and electron which becomes equivalent to the mass of a hydrogen atom and is equal to 1.00782 AMU.

$$\therefore \text{Mass defect} = ZM_H + (A-Z) M_n - M$$

Example: Calculate the mass defect of ^{235}U . The mass of U-235 is 235.0439 AMU.

$$Z = 92$$

$$A = 235$$

$$(A - Z) = 143$$

$$\begin{aligned} \text{Mass defect} &= [(Z)M_H + (A-Z) M_n] - M \\ &= 92 (1.00782) + 143 (1.00866) - 235.0439 \\ &= (92.71944 + 144.23838) - 235.0439 \\ &= 236.95782 - 235.0439 \\ &= 1.91392 \text{ AMU} \end{aligned}$$

3.2 BINDING ENERGY

An atom's mass defect is not mass which just disappears; that is contrary to the laws of conservation. The missing mass was converted to energy when the nucleus was formed. Binding energy of a nucleus is the energy equivalent of its mass defect. That is, binding energy is the amount of energy liberated when a nucleus is formed from its constituent parts. Conversely, binding energy is the amount of energy which would have to be provided to a nucleus in order to break it apart into separate protons and it is found that 1 AMU of mass is equivalent to 931 Mev of energy.

$$E=mc^2$$

Recall: $1 \text{ AMU} = 1.6605 \times 10^{-24} \text{ gm}$

$$E \text{ (ergs)} = (1.6605 \times 10^{-24} \text{ gm}) (3 \times 10^{10} \text{ cm/sec})^2$$

$$E \text{ (ergs)} = 1.495 \times 10^{-3} \text{ ergs}$$

Converting to Mev:

$$1.495 \times 10^{-3} \text{ ergs} \left(\frac{1 \text{ Joule}}{1 \times 10^7 \text{ ergs}} \right) \left(\frac{1 \text{ Mev}}{1.6 \times 10^{-13} \text{ Joule}} \right) = 931 \text{ Mev}$$

The binding energy of a nucleus can thus be found by multiplying the mass defect by 931 Mev / AMU

4.0 SUMMARY

The reader has been presented material describing the concept of nuclear stability and its relationship to the neutron to proton ratio. In addition, the types of radiation emitted by an unstable nucleus were discussed. The type and energy of radiation emitted can be used to determine the isotope(s) present in a sample of radioactive material.

The concept of mass energy equivalence according to Einstein's equation was introduced and applied to the nucleus. The mass defect and binding energy of nuclei was presented and the student should be able to