Course Title: **Radiological Control Technician**
Module Title: **Nuclear Physics**
Module Number: **1.04**

Objectives:

1.04.01 Identify the definitions of the following terms:
a. Nucleon
b. Nuclide
c. Isotope

1.04.02 Identify the basic principles of the mass-energy equivalence concept.

1.04.03 Identify the definitions of the following terms:
a. Mass defect
b. Binding energy
c. Binding energy per nucleon

1.04.04 Identify the definitions of the following terms:
a. Fission
b. Criticality
c. Fusion

References:

1. "Nuclear Chemistry"; Harvey, B. G.
2. "Physics of the Atom"; Wehr, M. R. and Richards, J. A. Jr.
3. "Introduction to Atomic and Nuclear Physics"; Oldenburg, O. and Holladay, W. G.
4. "Health Physics Fundamentals"; General Physics Corp.
5. "Basic Radiation Protection Technology"; Gollnick, Daniel; Pacific Radiation Press; 1994.
6. "Fundamental Manual Vol. 1"; Defense Reactor Training Program, Entry Level Training Program.
7. "Introduction to Health Physics"; Cember, Herman; 2nd ed.; Pergamon Press; 1983.
8. ANL-88-26 (1988) "Operational Health Physics Training"; Moe, Harold; Argonne National Laboratory, Chicago.
9. NAVPERS 10786 (1958) "Basic Nuclear Physics"; Bureau of Naval Personnel.

Instructional Aids:

1. Overheads
2. Overhead projector and screen
3. Chalkboard/whiteboard
4. Lessons Learned

I. MODULE INTRODUCTION

A. Self-Introduction

1. Name
2. Phone number
3. Background
4. Emergency procedure review

B. Motivation

This lesson is designed to provide an understanding of the forces present withing an atom.

C. Overview of Lesson

1. Nucleon
2. Nuclide
3. Isotope
4. Mass-Energy Equivalence
5. Mass Defect
6. Binding Energy
7. Fission
8. Criticality
9. Fusion

D. Introduce Objectives — O.H.: Objectives

II. MODULE OUTLINE

A. Nuclear Terminology — Objective 1.04.01

1. Nucleon - a constituent particle of the nucleus, either a proton or a neutron

2. Nuclide

   a. Atoms with a specific combination of neutrons and protons

   b. Nuclides have individual blocks on the Chart of the Nuclides

3. Isotope

   a. Have the same number of protons but different number of neutrons

   b. Same atomic number but different atomic mass number

   c. Isotopes of Hydrogen have one proton; however, the atomic mass number is different

   d. Protium (^1H) has A=1, deuterium (^2H) has A=2, tritium (^3H) has A=3

B. Mass - Energy Equivalence — Objective 1.04.02

1. Theory on Relativity developed by Albert Einstein in 1905

2. Equation: — Write equation on board

   $E = mc^2$

   where:

   E = Energy

   m = mass

   c = speed of light

3. Mass may be transformed to energy and vice versa

4. Mass and energy are interchangeable

5. The mass of an object depends on its speed

6. Matter contains energy by virtue of its mass

7. Energy/Mass cannot be created or destroyed, only converted

8. Pair Annihilation (Mass to Energy example) — Information only

   a. When a positron and electron collide, both particles are annihilated and their mass is converted to energy

   b. Mass of electron/positron is 0.00054858026 amu, annihilation energy will be: — (1 amu = 931.478 MeV)

$$\frac{2(0.00054858026\, amu)}{1} \times \frac{931.478\, MeV}{amu} = 1.022\, MeV$$

C. Mass Defect/Binding Energy — Objective 1.04.03

1. Mass Defect — See Fig. 1 "Atomic Scale"

   a. Difference between the sum of the protons and neutrons and the actual mass of a nuclide

   b. Equation:

$$\delta = (Z)(M_p) + (Z)(M_e) + (A\text{-}Z)(M_n) - M_a$$

Where:

δ = mass defect

Z = atomic number

M_p = mass of a proton (1.00728 amu)

M_e = mass of a electron (0.000548 amu)

A = mass number

M_n = mass of a neutron (1.00867 amu)

M_a = atomic mass (from Chart of the Nuclides)

   c. Example for ${}^{7}_{3}Li$: — Work example on board

   1) A = 7
      Z = 3
      M = 7.01600 amu

   2) Therefore:

$$\delta = (3)(1.00728) + (3)(0.000548) + (7\text{-}3)(1.00867) - (7.01600)$$
$$\delta = (3.02184) + (0.001644) + (4.03468) - (7.01600)$$

δ = (7.058164) - (7.01600)
δ = 0.042164 amu

2. Binding energy

    a. The energy equivalent of mass defect

    b. Example for $^{7}_{3}Li$:

Work example on board
(1 amu = 931.478 MeV)

$$BE = \frac{0.042164\ amu}{1} \times \frac{931.478\ MeV}{amu} = 39.27\ MeV$$

3. Binding energy of a neutron

    a. Energy added to a nucleus by adding the mass of a single neutron

    b. Must be calculated for each isotope to determine value

    c. Example for ^{235}U:

Work example on board

Δm = $(m_n + m_{U235}) - m_{U236}$
Δm = (1.00867 + 235.0439) - 236.0456
Δm = 0.0070 amu
0.0070 amu × 931.5 MeV/amu = 6.52 MeV

4. Binding energy per nucleon

See Fig. 2 "Binding Energy vs. Mass Number"

    a. Calculated by dividing the total binding energy of an isotope by its mass number

    b. Example for $^{7}_{3}Li$:

Work example on board

$$\frac{39.27\ MeV}{7\ nucleons} = 5.61\ MeV\ per\ nucleon$$

    c. Peaks at about 8.5 MeV for mass numbers 40 - 120

5. Nuclear Transformation Equations (Q Value)

    Example alpha decay for ^{226}Ra:

$$^{226}_{88}Ra \rightarrow\rightarrow\rightarrow\ ^{222}_{86}Rn + ^{4}_{2}\alpha + Q$$

D. Terminology

Objective 1.04.04

1. Fission

a. Splitting of a nucleus into at least two other nuclei with the release of energy

b. Two or three neutrons are generally released

c. Liquid drop model

See Fig. 3 "Liquid Drop Model of Fission"

1) Equates the nucleus with a drop of water

2) Each contains cohesive forces

3) When forces are overcome, the water drop/atom will split/fission

d. Fissile nuclei

1) Neutron binding energy must exceed critical energy for fission

2) Critical energy for fission (E_c): The energy required to drive the nucleus to the point of separation.

3) No kinetic energy required by the neutron

4) Fissile nuclei: ^{235}U, ^{233}U, ^{239}Pu

See Fig. 4 "^{235}U Fission Process"

e. Fissionable nuclei

1) Neutron binding energy not enough to exceed critical energy for fission

2) Kinetic energy required to cause fission

3) ^{238}U, ^{232}Th

f. Energy released

1) Makes two smaller nuclei from one large nucleus

2) Binding energy per nucleon increases

3) Approximately 200 Mev released per fission (for ^{235}U)

g. Fission products

1) Created during fission

2) Normally unstable - N/P ratio too high

3) Will undergo radioactive decay until stable - May take less than a second to several hundred years to reach stability

See Fig. 5 "Chain Reaction"

2. Criticality

a. Criticality is the condition in which the number of neutrons produced by fission is equal to the number of neutrons produced in the previous generation

b. The effective multiplication constant or K_{eff} is defined as the ratio of the number of neutrons in the reactor in one generation to the number of neutrons in the previous generation.

See Table 1 - "The Effective Multiplication Constant"

1) Subcritical - $K_{eff} < 1$

2) Critical - $K_{eff} = 1$

3) Supercritical - $K_{eff} > 1$

3. Fusion

a. Fusion builds atoms

b. The process of fusing nuclei into a larger nucleus with an accompanying release of energy

c. Change of mass

d. Energy released

III. SUMMARY

A. Review major topics

1. Nucleon
2. Nuclide
3. Isotope
4. Mass-Energy Equivalence
5. Mass Defect
6. Binding Energy
7. Fission
8. Criticality
9. Fusion

B. Review learning objectives

IV. EVALUATION

Evaluation should consist of a written examination comprised of multiple choice questions. 80% should be the minimum passing criteria for the examination.