MODULE 3 RADIOACTIVITY AND BINDING ENERGY OF NUCLEI

UNIT 1 NUCLEAR STRUCTURE

CONTENTS

1.0 INTRODUCTION

In we will treat the properties of nucleus, such as mass, radius, binding energy, mass defect, binding energy per nucleon, and angular momentum.

2.0 A OBJECTIVEs

By the end of this unit you will be able to:

- determine the Bohr's radius and the speed of an electron in an orbit;
- determine the mass defect of any nuclei; and
- determine the binding energy of the nucleus and binding energy per nucleon.

2.0 B How to Study this Unit:

1. You are expected to read carefully through this unit twice before attempting to answer the activity questions. Do not look at the solution or guides provided at the end of the unit until you are satisfied that you have done your best to get all the answers.
2. Share your difficulties in understanding the unit with your mates, facilitators and

by consulting other relevant materials or internet.

3. Ensure that you only check correct answers to the activities as a way of confirming what you have done.
4. Note that if you follow these instructions strictly, you will feel fulfilled at the end that you have achieved your aim and could stimulate you to do more.

3.0 MAIN CONTENT

3.1 Properties of the nucleus

The key properties of any nucleus include mass, radius, binding energy, mass defect, binding energy per nucleon, and angular momentum.

The orbital radii (or radius of the orbit) in the Bohr model is : $r_n = \frac{\varepsilon_0 n^2 h^2}{\pi m e^2}$ and the orbital speed in Bohr's model is : $V_n = \frac{e^2}{\varepsilon_0 2nh}$ where all symbols maintained their usual meanings as has been defined.

3.2 Binding Energy: Is the energy needed to add to the nucleus to separate it into individual protons and neutrons (or nucleons).

i.e Binding energy E_B = [(Mass of protons + Neutron) – Mass of ${}^{N+Z}_{Z}X$]c2 or Binding energy $(E_B = ZM_H + NM_n - {}^{A}_{Z}M)c^2$, where is the mass defect and c is the speed of light.

3.3 Binding energy per nucleon

Binding energy per nucleon is the binding energy divided by the total number of protons and neutrons.

i.e binding energy per nucleon = $\frac{binding\ energy}{total\ number\ of\ protons\ and\ neutrons}$.

The total mass of separated neutrons and protons is greater than the mass of the nucleus

3.4 Mass defect

It is the difference in mass between the total mass of individual protons and neutrons and the mass of the nucleus.

Mass and energy are related by $E = mc^2$ where E = mass, c = speed of light = $3 X 10^8$ m/s. The unit of mass is atomic mass unit (amu).

1 amu = $1.66 X 10^{-27}$ Kg. The unit of energy in modern physics is Megaelectonvolt (MeV). 1 MeV = electronic charge X 10^6 Joules.

$= 1.6 \times 10^{-19} \times 10^{6}$

$= 1.6 \times 10^{-13}$ J

1 amu $= 1.65 \times 10^{-27} \times (3 \times 10^{8})^{2}$

$= 1.49 \times 10^{-10}$ J.

= 931 MeV

3.5 Solved examples

1. Calculate the binding energy of $^{7}_{3}Li$ in (i) Joules and (ii) in electronvolt. (take the atomic mass of $^{7}_{3}Li$ = 7. 01600u, mass of proton = 1.00783u, mass of neutron = 1.00867u, unified atomic mass unit (amu), u = 931MeV, 1 eV = 1.6 X 1^{-19} J).

Solution
Number of protons = 3
Number of neutrons = 4
Total mass of protons = 3 X 1.00783u = 3.02349u
Total mass of neutrons = 4 X 1.00867u = 4.03468u
Total mass of neutrons + protons (or nucleons) = 7.05817u
Mass difference (or mass defect) = total mass of nucleons – mass of $^{7}_{3}Li$

= 7.05817u – 7.01600u

= 0.04217u

i. Binding energy = 0.04217 X 1u

= 0.04217 X 931MeV
= 39.26027 MeV

ii. Binding energy in Joules = 39.26027 X 10^{6} X 1 eV
$= 39.26027 \times 10^{6} \times 1.6 \times 10^{-19}$
$= 6.2816432 \times 10^{-12}$ J

2. Calculate the binding energy of $^{59}_{27}Co$ in (i) electronvolt and (ii) Joules. (take the atomic mass of $^{59}_{27}Co$ 5 8 . 9332u, mass of proton = 1.00783u, mass of neutron = 1.00867u, 1 amu = 931 MeV, 1 eV = 1.6 X 10^{-19} J.)

Solution
Number of neutrons = 32
Number of protons = 27
Total mass of neutrons = 27 X 1.00783u = 27.211410u
Total mass of protons = 32 X 1.00867u = 32.27744u
Total mass of protons + neutrons = 59.48885u
Mass difference = (Total mass of protons + neutrons) – mass of $^{59}_{27}Co$

= 59.48885u – 58.9332u

= 0.55565u

i. Binding energy in electronvolt = 0.55565 X 1u

= 0.55565 X 921 MeV
= 517.31015 MeV

ii. Binding energy in joules = 517.31015 X 10^6 X 1.6^{-19} J
= 8.2769624 J

4.0 CONCLUSION

In this unit you have learnt to:

- Determine the mass defect of the nucleus.
- Calculate the binding energy of the nucleus in joules and in electronvolts.

5.0 SUMMARY

What you have in this unit are:

- Binding energy
- Mass defect
- Atomic mass unit (amu)
- Binding energy per nucleon.

6.0 TUTORS MARKED ASSIGNMENT

1. Calculate the binding energy of (i) ${}^{20}_{10}Ne$ ii. ${}^{235}_{92}U$ in electronvolt and in Joules. (take the atomic mass of ${}^{20}_{10}Ne = 19.9925u$ *and that of* ${}^{235}_{92}U = 235.0439u$ Mass of proton =1.0078u, mass of neutron = 1.0087u, 1amu = 931 Mev, 1eV = 1.6 X 10^{-19} J).
2. Calculate the binding energy of ${}^{4}_{2}He$ *and* ${}^{3}_{2}He$ in electronvolt and in Joules (take the atomic mass of ${}^{4}_{2}He = 4.00387u$ ${}^{3}_{2}He = 3.01664u$, mass of proton = 1.0078u, mass of neutron = 1.00867u, 1u = 931 Mev, 1eV =1.6 X 10^{-19} J.)

7.0 REFERENCES/FURTHER READING

Ronald Gautreau and William Savin, (1978), Theory and problems of modern Physics. Schaum's Outline Series.

Tom Duncan (2000), Advanced Physics (5Th Edition). Hodder Murray.

UNIT 2 NUCLEAR STABILITY

CONTENTS

1.0 INTRODUCTION

In this unit you will learn about what makes the nucleus to be stable or unstable.

2.0 A OBJECTIVES

By the end of this unit, you will be able to know what is meant by stability of the nucleus.

2.0 B How to Study this Unit

1. You are expected to read carefully through this unit twice before attempting to answer the activity questions. Do not look at the solution or guides provided at the end of the unit until you are satisfied that you have done your best to get all the answers.
2. Share your difficulties in understanding the unit with your mates, facilitators and by consulting other relevant materials or internet.
3. Ensure that you only check correct answers to the activities as a way of confirming what you have done.
4. Note that if you follow these instructions strictly, you will feel fulfilled at the end that you have achieved your aim and could stimulate you to do more.

3.0 MAIN CONTENT

3.1 Nuclear Stability

The stability of the atom depends on both the number of protons and neutrons in the atom. For stable nuclides the following points emerge.

i. The lightest nuclides have almost equal number of protons and protons.
ii. The heaviest nuclides require more neutrons than protons, the heaviest having about 50% more.

iii. Most nuclides have both an even number of protons and neutron. This implies that and alpha particle which has two protons and two neutrons ^4_2He or $^4_2\alpha$) very stable and so also oxygen ($^{16}_8O$) , Silicon($^{28}_{14}Si$),Iron($^{56}_{28}Fe$) etc.

For unstable nuclides, the following can be noted.

i. They continue to disintegrate until new stable nuclides is formed.

ii. An unstable nuclide nuclear can undergo β^{-1} decay so as to give an increase of proton number (in which a neutron changes to a proton and an electron). Its neutron – to – proton ratio is thereby decreased.

iii. A n unstable nuclide can undergo a decay so that its proton number decreases and its neutron – to – proton ratio increases. In heavy nuclides, it occurs by emission of alpha particles (i.e ^4_2He or $^4_2\alpha$)

Nuclear Stability

Binding Energy is used it to explain why fusion in stars can only result in elements to iron. The energy that holds the protons and neutrons in the nucleus increases with each particle up to iron. Nickel and iron isotopes have nuclear particles most tightly bound and adding more protons or neutrons to them won't release energy but will require energy. The amount of energy required to add each nuclear particle to a nucleus increases with the atomic mass number. Therefore if a heavy nucleus breaks apart into smaller pieces or loses nuclear particles, energy will be released.

iv. Is it possible to predict which isotopes of elements are stable with respect to radioactive decay? Any isotope with 84 or more protons in the nucleus will be unstable. Isotopes of the lighest elements are stable when the ratio of protons to neutrons is about 1. For elements in the middle range, isotopes are most stable when the ratio of neutrons to protons is somewhat greater than one, 1:2 to 1:5 neutrons to protons.

4.0 CONCLUSION

In this unit you have learnt what makes the nucleus to be stable and unstable.

5.0 SUMMARY

In this unit, you have learnt about:

- Stable nuclei
- Unstable nuclei

6.0 TUTORS MARKED ASSIGNMENT

1. List the properties of stable and unstable nuclei.
2. How do nuclei acquire stability?

7.0 REFERENCES/FURTHER READING

Bueche, F. J. & Hecht, E. (2006). *College physics*. Schaum's Outline Series. New York: McGraw-Hill.

Duncan, T. (1982). *Physics. A textbook for Advanced Level Students*

Duncan, T. (2000), Advanced physics (5^{Th} edition). Hodder Murray.

Gautreau, R. & Savin, W. (1978). Theory and problems of modern Physics. Schaum's Outline Series.

Geddes, S. M. (1981). *Advanced physics*. London: Macmillan Education Ltd.

Gibbs, K (2011). *Advanced physics, 2^{nd} ed*. Cambridge: Cambridge University Pres

Halladay, Resnick & Walker, (2003), Fundamentals of Physics. Enhanced problems version (6^{TH} ed.).

http://web.sahra.arizona.edu/programs/isotopes/types/radioactive.html

IGNOU (2005). *Electricity and Magnetism Physics* PHE-07, New Delhi, India.

McKenzie, A. E. E (1973). *A second course of electricity*. Cambridge: The University Press.

Philip, M. (1992), Advanced chemistry. Cambridge Low Price Editions.

Raymond A. S, Robert, J. B (2000), Physics For scientists and Engineers (5^{TH} edition),.Saunders College Publishing.

Vuille, C., Serway, R. A. & Faughn, J. S. (2009). *College physics*, 8^{th} ed. Belmont, USA: Brooks/Cole.

UNIT 3 RADIOACTIVITY

CONTENTS

1.0 INTRODUCTION

In this unit, we would treat radioactivity, the fundamental law of radioactivity, and half – life.

2.0 A OBJECTIVES

At the end of this unit, you would be able to:

- Explain what is meant by radioactivity
- State the fundamental radioactive law
- Explain what is half – life
- Calculate half – life of radioactive elements

2.0 B How to Study this Unit

1. You are expected to read carefully through this unit twice before attempting to answer the activity questions. Do not look at the solution or guides provided at the end of the unit until you are satisfied that you have done your best to get all the answers.
2. Share your difficulties in understanding the unit with your mates, facilitators and by consulting other relevant materials or internet.
3. Ensure that you only check correct answers to the activities as a way of confirming what you have done.
4. Note that if you follow these instructions strictly, you will feel fulfilled at the end that you have achieved your aim and could stimulate you to do more.

3.0 MAIN CONTENT

3.1 Radioactive decay

The nucleus of an unstable isotope can lose one of several particles:

1. Neutron (n) Loss of a neutron gives a different isotope of the same element. The atomic number (number of protons, determining the element) remains the same but the atomic mass reduces by about 1 amu. 2. Alpha particle (α) An alpha particle is a helium nucleus, 2 protons and 2 neutrons, loss of an alpha particle give a new element with an atomic number 2 less than the original isotope and an atomic mass that is lower by about 4 amu.
3. Beta minus particle (β) This is an electron. An electron can be lost from the nucleus when one of the neutrons in that nucleus splits into a proton and an electron. Beta decay forms a new isotope with an atomic mass greater by 1 than the original isotope but the atomic mass is nearly unchanged.
4. Beta plus particle (β+) This is a positron and it results from a proton in the nucleus splitting into a positron and a neutron. When the positron leaves the nucleus it always collides with an electron, annialating both in a burst of gamma radiation. Loss of a beta plus particle gives a new element with an atomic number 1 less than the original isotope and an atomic mass that is nearly unchanged. Chemistry 102 Prof. Shapley page 2 Examples Radioactive decay through loss of an alpha particle: The newly formed nucleus has a lower atomic mass by 4 units and a lower atomic number by 2 units. Plutonium-239 is converted into helium-4 and uranium-235. Radioactive decay through loss of an electron: A neutron is converted to a proton and an electron. The product has one additional proton in the nucleus and the same mass number. Carbon-14 is converted to nitrogen-14. Chemistry 102 Prof. Shapley page 3 Radioactive decay through loss of a positron: A proton is converted to a neutron and a positron. The product has one fewer proton in the nucleus and the same mass number. Helium-2 is converted to hydrogen-2. Nuclear Fission Heavy nuclei can also decompose by breaking apart into 2 or more nuclei in a process called nuclear fission. For example, the uranium-236 nucleus can break apart to give an isotope of barium, an isotope of kripton, and 3 neutrons. The uranium-236 nucleus results from the capture of a free neutron by uranium-235.

Hyperphysics

There are many other possible fission products from the decay of urnaium-236. These include about 200 isotopes of 35 elements. We have seen that many isotopes of the elements are unstable with respect to loss of a neutron, alpha particle, or beta particle. All of the heavy elements are thermodynamically less stable than their constituent particles and can undergo fission. The amount of time it takes for 1/2 of the sample to decompose is called the half-life. This varies considerably from isotope to isotope. The mode of radioactive decay also varies. For example, plutonium-239 emits alpha particles and plutonium-242 emits beta particles. Both isotopes also produce gamma rays. Kinetics of Radioactive Decay The rate of nuclear reaction depends only on the isotope and the quantity of material present. Lets call the number of nuclei of a particular type N. The rate of decay of this isotope can be represented by $-\Delta N/\Delta t$, or the change in the number of this kind of nuclei per change in time. It has a negative sign because the number of nuclei of the isotope will decrease over time. The rate of

decay is equal to the number of the nuclei multiplied by a proportionality constant that depends on the exact isotope
Radioactivity is the spontaneous emission of α, β, and γ by unstable nuclides to become stable.

Radioactive decay law: The law states that ‘’the rate of disintegration of a given nuclide at anytime t is directly proportional to the number of nuclei N of the nuclide present at that time”.

Mathematically, the law is

$$-\frac{dN}{dt}\alpha\ N$$

The negative (-ve) sign indicates that N decreases (or is decaying) as time t increases.

$$\frac{dN}{dt}=-\lambda N \qquad (1)$$

Where λ is the radioactive decay constant and is the proportionality constant. The unit of λ is disintegration per second.

Integrating equation (1) above

$$\frac{dN}{N}=-\lambda dt$$

$$\int_{N_0}^{N}\frac{dN}{N}=-\lambda\int_{0}^{t}dt$$

Where N_0 = number of undecayed nuclei at time t = 0 , N = number of undecayed nuclei at present time t.

$$[\ln N]_{N_0}^{N}=-\lambda t$$

$$\ln N-\ln N_0=-\lambda t$$

$$\ln\left(\frac{N}{N_0}\right)=-\lambda t$$

$$\frac{N}{N_0}=e^{-\lambda t}$$

$$N=N_0e^{-\lambda t} \qquad (2)$$

Equation (2) is called the decay law, which states that a radioactive substance decays exponentially with time.

3.2 Half – life

Is the time taken for radioactive nuclei to decay by half its original (or initial) quantity. Half – life is denoted by $T_{½}$.

From equation (2), if $N=\frac{N_0}{2},\ then\ t=T_{½}$ and equation (2) becomes:

$$\frac{N_0}{2} = N_0 e^{-\lambda T_{1/2}}$$
$$\frac{1}{2} = e^{-\lambda T_{1/2}}$$
take $\log_e$ *of both sides*
$$\ln\left(\frac{1}{2}\right) = -\lambda T_{1/2}$$
$$\ln 1 - \ln 2 = -\lambda T_{1/2}$$
$$0 - \ln 2 = -\lambda T_{1/2}$$
$$-\ln 2 = -\lambda T_{1/2}$$
$$T_{1/2} = \frac{\ln 2}{\lambda}$$
$$T_{1/2} = 0.693 \qquad (3)$$

3.3 Solved examples

1. In 24 days a radioactive isotope decreases from 64g to 2g. What is the half life of the radioactive material?

Solution

Using $N = N_0 e^{-\lambda t}$

$$N = 2\,g \;,\; N_0 = 64\,g \;,\; t = 24\,days$$
$$2 = 64e^{-24\lambda}$$
$$\frac{2}{64} = e^{-24\lambda}$$
$$\ln\left(\frac{2}{64}\right) = -24\lambda$$
$$\lambda = \frac{\ln\left(\frac{2}{64}\right)}{-24}$$
$$\lambda = \frac{5\ln 2}{24}$$
$$but \;\; T_{1/2} = \frac{\ln 2}{\lambda}$$
$$T_{1/2} = \frac{\ln 2}{5\ln 2/24}$$
$$T_{1/2} = 4.8\; days$$

2. The half – life of a radioactive substance is 5.2 years. How long does it take for 60% of a given mass of the material to disintegrate?

Solution

$$N = N_0 e^{-\lambda t}$$
$$N = \frac{40}{100} N_0 \quad t = T_{1/2} = 5.2\,yrs.$$
$$\frac{40}{100} N_0 = N_0 e^{-\lambda t}$$
$$\frac{2}{5} = e^{-\lambda t}$$
$$\ln\left(\frac{2}{5}\right) = -\lambda t$$
$$t = \frac{\ln(0.4)}{-\lambda}$$
$$but\ \lambda = \frac{\ln 2}{T_{1/2}} = \frac{\ln 2}{5.2} = 0.1333$$
$$t = \frac{\ln(0.4)}{-0.1333}$$
$$t = 6.9\ yrs.$$

4.0 CONCLUSION

In this unit, you have learnt:

- Radioactivity
- Fundamental law of radioactivity
- Half – life
- How to calculate the half – life of radioactive materials.

5.0 Summary

What you have learnt in this unit are:

- Radioactivity
- Radioactivity
- Radioactive decay law, $N = N_0 e^{-\lambda t}$
- Half – life, $T_{1/2} = \frac{\ln 2}{\lambda} = \frac{0.693}{\lambda}$

6.0 TUTORS MARKED ASSIGNMENT

1. A sample of thorium was kept in an open chamber. Calculate the time taken for 10% of the sample to disintegrate. Assume the half – life of thorium to be 1.4 X 10^{10} years.
2. The half – life of a radioactive element is 40 days. Calculate the time taken for the activity to decay to 30% of its initial value.

7.0 REFERENCES/FURTHER READING

Bueche, F. J. & Hecht, E. (2006). *College physics*. Schaum's Outline Series. New York: McGraw-Hill.

Duncan, T. (1982). *Physics. A textbook for Advanced Level Students*

Duncan, T. (2000), Advanced physics (5^{Th} edition). Hodder Murray.

Gautreau, R. & Savin, W. (1978). Theory and problems of modern Physics. Schaum's Outline Series.

Geddes, S. M. (1981). *Advanced physics*. London: Macmillan Education Ltd.

Gibbs, K (2011). *Advanced physics, 2^{nd} ed*. Cambridge: Cambridge University Pres

Halladay, Resnick & Walker, (2003), Fundamentals of Physics. Enhanced problems version (6^{TH} ed.).

http://web.sahra.arizona.edu/programs/isotopes/types/radioactive.html

IGNOU (2005). *Electricity and Magnetism Physics* PHE-07, New Delhi, India.

McKenzie, A. E. E (1973). *A second course of electricity*. Cambridge: The University Press.

Philip, M. (1992), Advanced chemistry. Cambridge Low Price Editions.

Raymond A. S, Robert, J. B (2000), Physics For scientists and Engineers (5^{TH} edition),.Saunders College Publishing.

Vuille, C., Serway, R. A. & Faughn, J. S. (2009). *College physics*, 8^{th} ed. Belmont, USA: Brooks/Cole.

UNIT 4 RADIOACTIVE SERIES

CONTENT

1.0 INTRODUCTION

In this unit you will study the continuous disintegration of unstable nuclei until when a stable nucleus is attained. This particles emitted are alpha, beta, gamma, protons, or electrons etc.

2.0 A OBJECTIVES

At the end of this unit you will be able to:

- Know the unstable nuclei
- Know the particle to emit to attain stability

2.0 B How to Study this Unit

1. You are expected to read carefully through this unit twice before attempting to answer the activity questions. Do not look at the solution or guides provided at the end of the unit until you are satisfied that you have done your best to get all the answers.
2. Share your difficulties in understanding the unit with your mates, facilitators and by consulting other relevant materials or internet.
3. Ensure that you only check correct answers to the activities as a way of confirming what you have done.
4. Note that if you follow these instructions strictly, you will feel fulfilled at the end that you have achieved your aim and could stimulate you to do more.

3.0 MAIN CONTENT

3.1 Radioactive Decay: History

All the elements and isotopes we encounter on Earth, with the exceptions of hydrogen, deuterium, helium, helium-3, and perhaps trace amounts of stable lithium and beryllium isotopes which were created in the Big Bang, were created by the s-process or the r-process in stars, and for those to be today a part of the Earth, must have been created not later than 4.5 billion years ago. All the elements created more than 4.5 billion years ago are termed *primordial*, meaning they were generated by the universe's stellar processes. At the time when they were created, those that were unstable began decaying immediately. All the isotopes which have half-lives less than 100 million years have been reduced to 0.0000000000028% (2.8×10^{-12}%) or less of whatever original amounts were created and captured by Earth's accretion; they are of trace quantity today, or have decayed away altogether. There are only two other methods to create isotopes: *artificially*, inside a man-made (or perhaps a natural) reactor, or through decay of a parent isotopic species, the process known as the *decay chain*.

Unstable isotopes are in a continual struggle to become more stable; the ultimate goal is becoming one of the 200 or so stable isotopes in the universe. Stable isotopes have ratios of neutrons to protons in their nucleus that start out at 1 in stable helium-4 and smoothly rise to ~1.5 for lead (there is no complete stability for anything heavier than lead-208). The elements heavier than that have to shed weight to achieve stability, most usually as alpha decay. The other common method for isotopes of the proper weight but high n/p ratio is beta decay, in which the nuclide changes elemental identity while keeping the same weight and lowering its n/p ratio. Also there is an inverse beta decay, which assists isotopes too light in neutrons to approach the ideal; however, since fission almost always produces products which are neutron heavy, positron emission is relatively rare compared to beta emission. There are many relatively short beta decay chains, at least two (a heavy, beta decay and a light, positron decay) for every discrete weight up to around 207 and some beyond, but for the higher weight elements (often referred to as "transuranics", but actually used for all isotopes heavier than lead) there are only four pathways in which all are represented. This fact is made inevitable by the two decay methods possible: alpha radiation, which reduces the weight by 4 AMUs, and beta, which does not change the weight at all (just the atomic number and the p/n ratio). The four paths are termed 4n, 4n + 1, 4n + 2, and 4n + 3; the remainder of the atomic weight divided by four gives the chain the isotope will use to decay. There are other decay modes, but they invariably occur at a lower probability than alpha or beta decay.

Three of those chains have a long-lived isotope near the top; they are bottlenecks in the process through which the chain flows very slowly, and keep the chain below them "alive" with flow. The three materials are uranium-238 (half-life=4.5 billion years), uranium-235 (half-life=700 million years) and thorium-232 (half-life=14 billion years). The fourth chain has no such long lasting bottleneck isotope, so almost all of the isotopes in that chain have long since decayed down to very near the stability at the bottom. Near the end of that chain is bismuth-209, which was long thought to be stable. Recently, however, Bi-209 was found to be unstable with a half-life of 19 billion billion years; it is the last step before stable thallium-205. In the far past, around the time that the solar system formed, there were more kinds of unstable high-weight isotopes available, and the four chains were longer with isotopes that have since decayed away. Today we have manufactured extinct isotopes, which again take their places: plutonium-239, the nuclear bomb fuel, as the major example has a half-life of "only" 24,500 years, and decays by alpha emission into uranium-235.

3.2 Radioactive Series

Radioactive series is a sequence of nuclides, each of which transforms by radioactive disintegration into the next, until a stable nuclide is reached. It is also known as decay series or disintegration series.

i. Thorium-232 ($^{232}_{90}Th$) $\xrightarrow{\alpha}$ Radium-228 ($^{228}_{88}Ra$) $\xrightarrow{\beta^{-1}}$ Actinium-228 ($^{228}_{89}Ac$) $\xrightarrow{\beta^{-1}}$ Thorium-228 ($^{228}_{90}Th$) $\xrightarrow{\alpha}$ Radium-224 ($^{224}_{88}Ra$) $\xrightarrow{\alpha}$ Radon-220 ($^{220}_{86}Rn$) $\xrightarrow{\alpha}$ Polomium-216 ($^{216}_{84}(P_0)$ $\xrightarrow{\alpha}$ Lead-212 ($^{212}_{82}P_b$)

ii. Uranium-228($^{238}_{92}U$) $\xrightarrow{\alpha}$ Thorium-234($^{234}_{90}Th$) $\xrightarrow{\beta^{-1}}$ Protactinium-234 ($^{234}_{91}Pa$) $\xrightarrow{\beta^{-1}}$ Uranium-234($^{234}_{92}U$)

4.0 CONCLUSION

In this unit you have learnt:

- The radioactive decay series
- The types of particles that are emitted to attain stability

5.0 SUMMARY

You have learnt:

- Radioactive decay series
- Why nuclei undergo radioactivity.
- The types of particles emitted in radioactivity

6.0 TUTORS MARKED ASSIGNMENTS

Part of the Uranium decay series is shown below:

$^{238}_{92}U \longrightarrow ^{234}_{90}Th \longrightarrow ^{234}_{91}Pa \longrightarrow ^{238}_{92}U \longrightarrow ^{220}_{90}Th \longrightarrow ^{226}_{88}Ra$

(a) What particle is emitted at each decay?

(b) How many pairs of isotopes are there?

7.0 REFERENCES/FURTHER READING

Bueche, F. J. & Hecht, E. (2006). *College physics*. Schaum's Outline Series. New York: McGraw-Hill.

Duncan, T. (1982). *Physics. A textbook for Advanced Level Students*

Duncan, T. (2000), Advanced physics (5Th edition). Hodder Murray.

Gautreau, R. & Savin, W. (1978). Theory and problems of modern Physics. Schaum's Outline Series.

Geddes, S. M. (1981). *Advanced physics*. London: Macmillan Education Ltd.

Gibbs, K (2011). *Advanced physics, 2nd ed*. Cambridge: Cambridge University Pres

Halladay, Resnick & Walker, (2003), Fundamentals of Physics. Enhanced problems version (6TH ed.).

http://web.sahra.arizona.edu/programs/isotopes/types/radioactive.html

IGNOU (2005). *Electricity and Magnetism Physics* PHE-07, New Delhi, India.

McKenzie, A.E.E (1973). *A second course of electricity*. Cambridge: The University Press.

Philip, M. (1992), Advanced chemistry. Cambridge Low Price Editions.

Radioactive Decay Series: Introduction." *Boundless Physics*. Boundless, 21 Jul. 2015. Retrieved 14 Jan. 2016 from https://www.boundless.com/physics/textbooks/boundless-physics-textbook/nuclear-physics-and-radioactivity-30/radioactivity-190/radioactive-decay-series-introduction-708-1301

Raymond A. S, Robert, J. B (2000), Physics For scientists and Engineers (5TH edition),.Saunders College Publishing.

Vuille, C., Serway, R. A. & Faughn, J. S. (2009). *College physics*, 8th ed. Belmont, USA: Brooks/Cole.

UNIT 5 ACCELERATORS AND DETECTORS

CONTENTS

1.0 INTRODUCTION

In this unit, you will learn about accelerators and detectors.

2.0 A OBJECTIVES

At the end of this unit, you should be able to:

1. state what are accelerators and detectors and the principle upon which they operate; and
2. discuss 5 types of detectors.

How to Study this Unit:

1.You are expected to read carefully through this unit twice before attempting to answer the activity questions. Do not look at the solution or guides provided at the end of the unit until you are satisfied that you have done your best to get all the answers.

2.Share your difficulties in understanding the unit with your mates, facilitators and by consulting other relevant materials or internet.

3.Ensure that you only check correct answers to the activities as a way of confirming what you have done.

4.Note that if you follow these instructions strictly, you will feel fulfilled at the end that you have achieved your aim and could stimulate you to do more.

3.0 MAIN CONTENT

Accelerators are machines built to accelerate charge particles such as protons to high speed by means of potential differences of hundreds of thousands of volts for nuclear physicists' experiments.

3.1 Types of accelerators

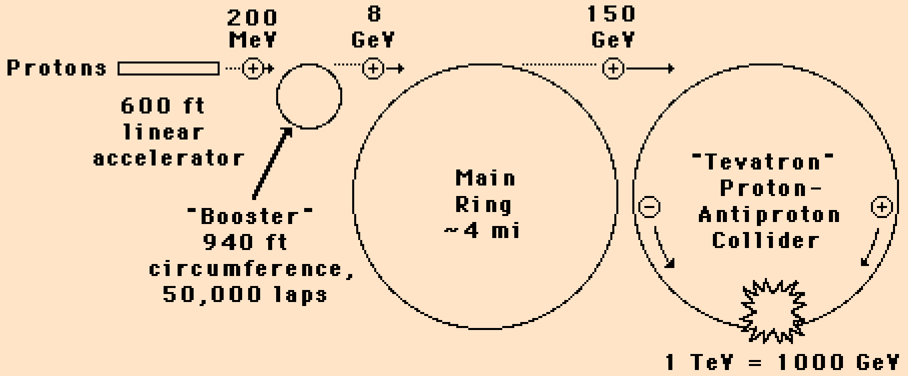
1. Van de Graff generator
2. Linear accelerator
3. Cyclotron
4. Synchrotron

Acceleration Devices for Energy Physics

The major accelerator facilities make use of several types of devices to build up the energy of the particles. Some of the types of apparatus used are:

- Cockroft-Walton accelerators: high DC voltage device which accelerates ions through steps of voltage created by a voltage divider.
- van de Graaf accelerators: charge is transported by an insulating belt to a conductor which builds in voltage as a result of charge collection.
- Cyclotrons: An oscillating electric field repetitively accelerates charged particles across the gap between semicircular magnetic field regions.
- Synchrocyclotrons: cyclotrons with variable-frequency accelerating voltages to track relativistic effects.
- Betatrons: electron accelerators in a circular geometry with acceleration achieved by magnetic flux increase.
- Synchrotrons: large ring accelerators where the particles move in an evacuated tube at constant radius, accelerated by radio frequency applications with synchronous magnetic field increases to maintain the constant radius.
- Linear Accelerators: linear arrays of radio frequency acceleration cells.

The Fermi National Accelerator Laboratory near Chicago has the most powerful proton-antiproton collider, designed to reach 1 TeV. It is the only current facility which seems to have the power to produce evidence for the last of the quarks, the top quark.



-

- Protons from the Main Ring in bunches of a quadrillion are smashed into a metal target to make antiprotons. About 10 billion are made and extracted into a triangular magnet array called an accumulator. Once a sufficient "stack" of antiprotons is accumulated, they are injected into the Tevatron. Six bunches of each type of particle, each bunch 2 ft long and thinner than a pencil, are accelerated in opposite directions around the ring to collide in a "shot" in the collider detector (Trefil,Discover Dec89, p56).
- The Fermilab facility houses the Main Injector, a proton synchrotronaccelerator. Beneath it in the same tunnel is another synchrotron, a superconducting magnetic ring called the Tevatron which boosts the energy to 1 TeV. There is an antiproton storage ring which achieves collision energies of about 1.8 TeV.
- Before entering the Main Injector, protons are accelerated to about 750 keV by a Cockroft-Walton accelerator, then to about 400 MeV by a linear accelerator. They are raised to 8 GeV by a comparatively small booster accelerator and then up to 150 GeV by the Main Injector.

3.2 Detectors

Detectors are sensing devices which sense the presence of charges or changes in something such as radiation or pressure.
In a nuclear radiation detector energy is transform from the radiation to atoms of the detector and may cause:

i. Ionization of a gas in the ionization chamber e.g Geiger Muller tube, a cloud or bubble chamber.
ii. Exposure of a photographic emulsion.
iii. Fluorescence of a phosphor as in a scintillation counter.
iv. Mobile charge carriers in a semiconductor solid state detector.

The radiation is thus detected by the effect it produces.

3.3 Types of detectors

1. Ionization Chamber
2. Geiger Muller tube
3. Cloud Chamber
4. Bubble Chamber
5. Scintillation counter
6. Solid state detector.

Geiger counter

The Geiger counter is one of the oldest and simplest of the many particle detectors. German nuclear physicist Hans Geiger (1882–1945) and German-American physicist

Erwin Wilhelm Müller (1911–1977) developed the counter in the early part of the twentieth century, shortly after the discovery of radioactivity. A schematic diagram of a Geiger counter is shown in Figure 1.

A wire electrode runs along the center line of a cylinder having conducting walls. The tube is usually filled with a monatomic gas such as argon at a pressure of about 0.1 atmosphere. A high voltage, slightly less than that required to produce a discharge in the gas, is applied between the walls and the central electrode. A rapidly moving charged particle that

gets into the tube will ionize some of the gas molecules in the tube, triggering a discharge. The result of each ionizing event is an electrical pulse that can be amplified to activate ear phones or a loud speaker, making the counter useful in searches for radioactive minerals or in surveys to check for radioactive contamination. The counter provides very little information about the particles that trigger it because the signal from it is the same size no matter how it is triggered. However, one can learn quite a bit about the source of radiation by inserting various amounts of shielding between source and counter to see how the radiation is attenuated.

Scintillation detector

Scintillation counters are made from materials that emit light when charged particles move through them. To detect these events and to gain information about the radiation, some means of detecting the light must be used. One of the first scintillation detectors was a glass screen coated with zinc sulfide. This sort of detector was used by New Zealand-British physicist Ernest Rutherford (1871–1937) in the early versions of his classic experiment in which he discovered the nucleus of the atom by scattering alpha particles from heavy atoms such as gold. The scattered alpha particles hit the scintillating screen. Experimenters in a darkened room using only the human eye observed the small flashes that were produced.

The modern scintillation counter usually uses what is called a photo multiplier tube to detect the light. Light incident on the photocathode of such a tube is converted into an electrical signal and amplified millions of times after which it can be sent to appropriate counters. Physicists working at particle accelerators often use transparent plastic materials like Lucite or plexiglass to which are added materials to make them scintillate. These plastic scintillators can be cut to convenient shapes, mounted on a photomultipler tube and placed in particle beams to provide a very fast signal when charged particles pass through them.

A very useful scintillation detector, particularly for the measurement of gamma rays, utilizes a transparent crystal of NaI (sodium iodide) mounted on a photomultiplier tube. These crystals are particularly useful because charged particles produce in them an amount of light directly proportional to their energy over a wide range. A schematic diagram of a gamma ray scintillation spectrometer is shown in Figure 2.

Gamma rays have no charge and, thus, no detector is sensitive to them directly. Fortunately, gamma rays interact with matter and produce charged particles—usually electrons. For the measurement of gamma ray energies, the two most important interactions are the photoelectric effect and the Compton effect. These two processes can combine to produce energetic electrons in the crystal, which scintillates to produce an amount of light directly proportional to the gamma ray energy. These light pulses are converted to electrical pulses in the photomultiplier tube. These are amplified and sent to a pulse height analyze, which sorts out the pulses and displays a pulse height spectrum. A particular gamma ray shows up as a fairly sharp peak in this pulse height distribution.

Solid state detectors

Similar results with much improved energy resolution, the sharpness of the peaks in the pulse height distribution, can be obtained using solid state detectors made from semiconducting materials such as silicon or germanium. When properly constructed, the electrical charges released in the material by the passage of charged particles can be collected directly producing a short electrical pulse that can be amplified and analyzed. Germanium detectors made for use with gamma rays can have peaks in the pulse height distribution almost 100 times narrower than the peaks from a sodium iodide detector. To obtain this improved resolution these detectors must be cooled to the temperature of liquid nitrogen: 77K (-320.8°F; -196°C).

Smaller solid state detectors, usually made from silicon, are also used for measuring the energy of alpha particles, beta rays (electrons) from radioactive materials and x rays.

Neutron detectors

Since neutrons are uncharged, their detection must depend on an interaction with matter that produces energetic charged particles. There are several nuclear reactions initiated by neutrons that result in charged particles. One of the most useful for slow neutrons is the reaction in which a neutron is incident on a boron nucleus. This reaction produces a lithium nucleus and an alpha particle, both of which are rapidly moving. Note that it is the boron isotope of mass 10, with a natural abundance of about 20%, that is required for this reaction and that the alpha particle is simply the nucleus of the helium atom. The boron is usually incorporated in the gas molecule BF^3(boron trifluoride) that can be used as the gas in a proportional counter, which is much like a Geiger counter. The difference is simply that the voltages used are lower so that the discharge does not spread disruptively along the entire central electrode with the result that the electrical signal coming from the tube is proportional to the number of ions produced. The signals are much smaller than from a Geiger tube and require more amplification but the signal produced by the lithium nucleus and alpha particle, both of which are heavily ionizing, is relatively large and easily distinguishable. For fast neutrons, the probability of this boron reaction becomes very low so that other methods are required. A useful technique is to use a proportional counter filled with hydrogen. Fast neutrons colliding with the protons in hydrogen produce energetic protons that produce a signal from the counter.

Cerenkov detectors

When a charged particle moves through a transparent material with a velocity v, greater than the

speed of light c in that material, it radiates light in the forward direction at an angle whose cosine is equal to c/vn, where n is the index of refraction of the material. This light is called Cerenkov radiation and can be detected with photomultiplier tubes, as was the case with scintillation detectors (Figure 3).

It is named after Russian physicist Soviet physicist Pavel Alekseyevich Cerenkov (1904–1990) who discovered it in 1934. The special theory of relativity limits particle velocities to values less than c, the speed of light in a vacuum. Cerenkov detectors can be of two types. A threshold detector merely detects the fact that light is emitted and indicates that the velocity of the particle passing through it is greater than c/n. Other more complicated detectors can actually determine the velocity v by measuring the angle at which light is emitted.

Cloud chambers and bubble chambers

A cloud chamber utilizes an enclosed volume of clean air saturated with water vapor. If this volume of air is enclosed in a cylinder with a piston, and the volume is suddenly expanded, the temperature of the air falls, causing the mixture to become supersaturated. If a charged particle passes through the volume at this time the vapor tends to condense on the ions produced, leaving a trail of water droplets on the path of the charged particle. With proper illumination and timing, these trails can be photographed. If a magnetic field is applied, the radius of curvature of these tracks can be measured. This information, combined with the density of droplets along the trail, can be used to measure the energy of the particle. The cloud chamber was first used by Scottish physicist Charles Thomson Rees (C.T.R.) Wilson (1869–1959) around the beginning of the twentieth century, and was useful in the early days of nuclear physics. However, it suffered from several disadvantages such as the long time required to recycle and the low density of air. In 1932, American experimental physicist Carl David Anderson (1905–1991) discovered the positron, the antiparticle of the electron while using a cloud chamber to observe cosmic rays.

A rather similar device called the bubble chamber was developed using liquids rather than a gas. Liquefied gases such as hydrogen, xenon, and helium have been used. Pressure is applied to the liquid to keep it a liquid above its normal boiling point at atmospheric pressure. If the pressure is suddenly reduced, the liquid is superheated but will not boil spontaneously, at least for a short time. In order to boil, the liquid must have small irregularities on which bubbles of vapor form and they can be provided in the bubble chamber by the ions left by charged particles passing through the chamber. Thus, tiny bubbles form along the tracks of particles passing through the chamber just after the pressure has been reduced. The bubbles grow very quickly but if the tracks are photographed at just the right time after expansion, they are revealed as a thin trail of tiny bubbles.

Bubble chambers work very well with particle accelerators that are pulsed. The expansion of the chamber can be timed so that particles from the accelerator pass through just after the chamber is expanded. As with the cloud chamber, application of a magnetic field permits measurement of the curvature of the tracks and when this information is combined with the density of bubbles along the track the energy, momentum, charge (sign), and mass of the particle can be determined. The bubble chamber was invented in 1953 by American physicist and neurobiologist Donald Arthur Glaser (1926–) who used a small glass device containing about 30 cubic centimeters of diethyl ether. The use and size of bubble chambers grew during the following decades culminating in the discovery of the omega minus particle in the 80 in (203 cm) bubble chamber at Brookhaven National Laboratory in 1964; and the construction of the 3168 gal (12,000 l) Gargamelle chamber at the CERN (European Organization for Nuclear Research) laboratory in Geneva,Switzerland, in the early 1970s. In recognition of the great importance of this device to particle physics research, Glaser was awarded the Nobel Prize for physics in 1960.

Wire chambers

In many nuclear and particle physics experiments, beam lines are constructed along which secondary particles of interest, produced by an accelerator, are maintained in a beam by a series of focusing and

KEY TERMS

Anti-proton —The anti-particle of the proton. Identical to the proton except that its charge is opposite in sign.

Gamma ray —Energetic electromagnetic radiation emitted by radioactive nuclei, produced by particle accelerators and present also in cosmic rays.

Mesons and baryons —Sub-atomic particles, usually with very short lifetimes, believed to be composed of quarks in various combinations.

Omega minus particle —A short lived baryon believed to be made up of three quarks called strange quarks.

Photomultiplier tube —An electronic tube, sensitive to very small amounts of light. The tube converts a light signal into an electrical signal of useful size.

Positron —The anti-particle of the electron. Identical to the electron except that its charge is opposite in sign.

Quarks —Believed to be the most fundamental units of protons and neutrons.

bending magnets. Wire chambers are used along these beam lines to actually track individual particles as they move along the beam line. The chambers are similar in a general way to the Geiger counter since they are gas counters. Instead of one wire, the chambers have many parallel wires spaced at distances of a few millimeters. The position of charged particles passing through the chamber can be measured with uncertainties even less than the wire spacing, using fast timing circuits. These chamber measurements facilitate identification of the particle and the measurement of its momentum.

Large layered detectors

The ultimate in particle detectors are probably those being used and constructed at large national and international laboratories such as Fermilab (Fermi National Accelerator Laboratory) in Batavia, Illinois, and CERN in Geneva, Switzerland. At these locations, colliding beam accelerators have been built that produce collisions of fundamental particles, such as electrons and positrons at CERN, and protons and anti-protons at Fermilab. At various points around these large circular accelerators, the counter rotating beams cross, and head-on collisions can take place making large amounts of energy available for the production of other particles. Huge detectors costing millions of dollars and requiring hundreds of physicists to run them are constructed surrounding these collision points.

At Fermilab, two of these large devices, one called CDF (Collider Detector) and the other DZero (D0 Experiment), have recently reconstructed events, produced in these collisions, which provide strong evidence for the existence of the long sought top quark. To do this, the detectors are designed to detect as many of the millions of particles produced in these collisions as possible. At DZero, about 400,000 proton-anti-proton collisions occur per second. The detectors, weighing thousands of tons, are constructed in layers and surround the collision points. They utilize most of the detection techniques discussed above including scintillators, solid-state detectors and devices similar to wire chambers that provide much improved performance. These are called silicon micro-strip detectors. They are made up of closely spaced strips of silicon detectors that give very fast position measurements of particles accurate to about 0.01 mm. The thousands of individual detectors and detector systems are connected to computers which help select the very special events that might involve the top quark from the millions that do not.

4.0 CONCLUSION

In this unit, you have learnt:

- Accelerators e.g. Van de Graff generators, linear accelerator, Cyclotron and synchrotron.
- Detectors e.g. Ionization chamber, Geiger – Muller tube, Cloud chamber, Bubble Chamber, Scintillation counter, Solid state detector.

A detector works on the principle that the radiation produces an effect on it.

5.0 SUMMARY

What you have learnt in this unit are:

- Accelerators, which combines both electric and magnetic fields to accelerate charged particles.
- Detectors, which operates on the principle that the radiation produce an effect on the detector.

6.0 TUTORS MARKED ASSIGNMENT

1. State the principle of radiation of a nuclear detector.
2. What are accelerators? State one important use of accelerators.
3. Discuss any five types of detectors

7.0 REFERENCES/FURTHER READING

Bueche, F. J. & Hecht, E. (2006). *College physics*. Schaum's Outline Series. New York: McGraw-Hill.

Duncan, T. (1982). *Physics. A textbook for Advanced Level Students*

Duncan, T. (2000), Advanced physics (5Th edition). Hodder Murray.

Gautreau, R. & Savin, W. (1978). Theory and problems of modern Physics. Schaum's Outline Series.

Geddes, S. M. (1981). *Advanced physics*. London: Macmillan Education Ltd.

Gibbs, K (2011). *Advanced physics, 2nd ed*. Cambridge: Cambridge University Pres

Halladay, Resnick & Walker, (2003), Fundamentals of Physics. Enhanced problems version (6TH ed.).

http://web.sahra.arizona.edu/programs/isotopes/types/radioactive.html IGNOU (2005). *Electricity and Magnetism Physics* PHE-07, New Delhi, India.

McKenzie, A. E. E (1973). *A second course of electricity*. Cambridge: The University Press.

Philip, M. (1992), Advanced chemistry. Cambridge Low Price Editions.

Raymond A. S, Robert, J. B (2000), Physics For scientists and Engineers (5TH edition),.Saunders College Publishing.

Vuille, C., Serway, R. A. & Faughn, J. S. (2009). *College physics*, 8th ed. Belmont, USA: Brooks/Cole.