THEORETICAL CALCULATION OF EXCITATION FUNCTION FOR PARTICLE INDUCED REACTIONS ON STABLE IODINE-127

BY

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DECEMBER 2019

DECLARATION

I hereby declare that this work is the product of my research efforts undertaken under the supervision of Dr. Idris Ahmad and has not been presented anywhere for the award of a degree or certificate. All sources have been duly acknowledged.

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CERTIFICATION

This is to certify that the research work for this dissertation and the subsequent write up Zubaida Gali Habib (SPS/16/MPY/00073) were carried out under my supervision.

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APPROVAL

This dissertation has been examined and approved for the award of Masters in (Nuclear Physics).

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All beautiful praises be to Allah (S.W.T.), The Creator and Sustainer of mankind, the universe and all other creatures, Who initiated creation without copying its plan, pattern or style from anybody or from anywhere. Peace and blessings of Allah (S.W.T.) be upon the last and best of His Prophets, The savior of mankind, the comforter and intercessor on behalf of all creation – Prophet Muhammad (S.A.W), may Allah bless his companions and members of His household, Ameen.

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Zubaida Gali Habib
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DEDICATION

This work is dedicated to my father, Alhaji Gali Habib, my husband, Yahya M. Khalil, my children Muhammad, Gali, Asma'u, Fatima, Mahmoud, Khalil and Hassan and to the loving memory of my late mother, HajiyaHassanaGali. May her gentle soul rest in everlastingabode of peace and blessing. Ameen.

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ABSTRACT

Investigation on nuclear reactions data for production of radioactive nuclei plays a crucial role in many areas of Science and Technology. This research investigates the Excitation function for the production of radioisotopes through particle Induced reaction on Iodine-127, using EXIFON code. The threshold energy, maximum cross-section and energy that provide the highest cross-section were obtained for the formation of ^{123,124,125}Sb; ^{123,124,125,126,127}Te; ^{125,126,128,129}I; ^{125,126,127,128,129}Xe and ^{128,129,130,131}Cs isotopes. The results obtained were compared with the available experimental data (EXFOR database) and evaluated nuclear data files (ENDF) and they are in good agreement. This research has generated nuclear data for reactions not worked upon before for some radionuclides of Caesium, Xenon and Iodine.

CHAPTER ONE
(INTRODUCTION)

1 GENERAL OVERVIEW

Nuclear physics is the study that deals with the atomic nucleus, its transformation and its interaction with other nuclei and particles. The main characteristics of a stable nucleus include its charge, radius, mass, spin, magnetic moment, electric quadrupole moment and parity. Radioactive nuclei are also characterized by such parameters as the type of radioactive transformation (alpha or beta decay, spontaneous fission, etc.), the half life and the emitted particles energies(Mukhin, 1970).

Among the applications of nuclear physics include its contributions in the production of electricity via nuclear power plant; improve quality and productivity of agricultural products, modern industries, and in the world of medicine (Walter, 2003).

Production of radioisotopes for medical applications is one of the most important directions of nuclear physics. It plays an important role in terms of beneficial applications in both diagnosis and therapy(Saied, 2013). Treatment of thyroid disorder with radioiodine is one of the examples of therapy using radioisotopes. The diagnosis entails the introduction of a short-lived radionuclide, attached to a suitable pharmaceutical into the patient. Followed by measurement of accumulation and movement of activity from outside (Qaim, 2001). Using external detectors to capture and form images from the radiation emitted by the radiopharmaceutical. This process is called emission tomography and involves single photon emission computed tomography (SPECT) and positron emission tomography (PET).

Nuclear diagnostics are now routinely employed throughout the developed world and in many developing countries to detect anomalies in the heart, brain, kidneys, lungs, liver, breast and glands(Kenneth Shultis & Faw, 2010). Also benefitting directly from the routine use of radionuclides are bone and joint disorders along with spinal disorders. The primary principle in all diagnostic studies is that the radiation dose to the patient is kept as low as possible to avoid damage to underlying tissues(Alonso, 2001).

However, with the expanding of radioisotopes in medical diagnosis and treatment, there is vulnerability to some sort of supply crisis if anything hitches the availability of radioisotopes(Oliveira, Santos, Ferreira, Coelho, & Veiga, 2006). This was experienced due to shortages of some important radionuclides such as Technetium-99 (Qaim, 2001). This was apparently caused by Reactor stoppages, due to aging infrastructureleading to a shortage of Molybdenum-99 from which Technetium is produced. Many medical procedures were canceled leading to delays in diagnoses and use of inferior procedures(Ruth, 2014). These problems have the potential of halting the use of radionuclide in diagnoses and therapy, if alternative routes of production are not utilized to produce the radionuclide.

In view of the current increase in population, and the rising morbidity of various types some of which require nuclear procedural services , a medical isotope crisis is sure to cause untold hardship and fatalities if the supply of radionuclides becomes compromised(E. E. Kim et al., 2012). This forms the basis behind exploring the various alternative routes of radionuclide production. including inducement with particles (such as neutrons, proton and alpha), use of cyclotrons and accelerators and low enrichment to mention a few (Saied, 2013).

1.1 NUCLEAR DATA

The nuclear data is a fundamental data base for nuclear science and technology. It has played a crucial role in the course of nuclear energy development of fission and fusion reactors. . Nuclear data are commonly categorized in two main groups: nuclear reaction data, describing the interactions of various projectiles such as neutrons, protons or photons with target nuclei; and nuclear structure and decay data, describing nuclear levels, half-lives and radioactive decay radiations. For both groups, the type of information given can be experimental data (EXFOR) and evaluated data (ENDF).Nuclear reactions data are becoming more important for various reasons such as optimizing radionuclide production as per reaction channels, analysis of impurities and radionuclide purification, as well as prediction of most suitable radionuclide production method with high efficiency (Iwamoto, 2007).

Nuclear theory, using quantum mechanics, is used to predict the probability that a specific nuclear process will occur under certain conditions (Hibstie, Mathuthu, & Derso, 2018). The quantitative measure of this prediction is the cross-section of the process. This cross-section may be measured in the laboratory using experimental techniques that have been strongly developed in the last decades, investigating nuclear reactions involving radioactive nuclei and playing a crucial role in many areas of basic and applied nuclear sciences.

The need for this research emanates from the requisition of nuclear data as the most important prelude for medical radioisotope production. Nuclear cross-section and excitation function data helps in optimizing production routes such that shortage of radioisotopes is prevented.(any shortage of radionuclides may make procedures vulnerable to delay or halt) (Ruth, 2014).

The mainobjectives of this research are to obtain the relevant nuclear data for optimal production of some medical radionuclides with efficiency and reliability.

1.2 RADIOISOTOPES PRODUCTION METHODS

There are basically three main methods of producing radioisotopes. These areNuclear reactor, particle accelerator(e.g. cyclotron) and radioisotope generator.

1.2.1 Nuclear Reactor

In spontaneous fission; heavy nucleus can break into a number of fragments. Thisdisintegration process can be induced to occur when certain heavy nuclei absorb neutrons. Following absorption of a neutron such nuclei break into smaller fragments with atomic numbers between about 30 and 65. Some of these new nuclei are of value to nuclear medicine and can be separated from other fission fragments using chemical processes. The fission process is controlled inside a nuclear reactor. These reactor based radionuclides include ^{14}C, ^{24}Na, ^{32}P, ^{42}K, ^{51}Cr, ^{59}Fe, ^{75}Se, ^{125}I and ^{131}I etc.

1.2.2 Cyclotron

In this method of radioisotope production charged particles are accelerated up to very high energies and caused to collide into a target material. Examples of such charged particles are protons, alpha particles and deuterons. New nuclei can be formed when these particles collide with nuclei in the target material. Some of these nuclei are of value to nuclear medicine. An example of this method is the production of ^{22}Na where a target of ^{24}Mg is bombarded with deuterons, that is: $^{24}Mg + {}^{2}H \rightarrow {}^{22}Na + {}^{4}He$.

A deuteron (^{2}H), when it collides with a ^{24}Mg nucleus a ^{22}Na nucleus plus an alpha particle is produced. The target is exposed to the deuterons for a period of time and is subsequently processed chemically in order to separate out the ^{22}Na nuclei.

The device commonly used for this method of radioisotope production is called a cyclotron. It consists of an ion gun for producing the charged particles, electrodes for accelerating them to high energies and a magnet for steering them towards the target material. All arranged in a circular structure. Cyclotron based radioisotopes include, ^{14}C, ^{13}N, ^{15}O, ^{18}F, ^{22}Na, ^{43}K, ^{67}Ga, ^{111}In, ^{123}I and ^{201}Ti.

1.2.3 Radioisotope Generator

This method is widely used to produce certain short-lived radioisotopes in a hospital or clinic. It involves obtaining a relatively long-lived radioisotope which decays into the short-lived isotope of interest.A good example is ^{99m}Tc which is the most widely used radioisotope in nuclear medicine today. This isotope has a half-life of six hours which is rather short if we wish to have it delivered directly from a nuclear facility. Instead the nuclear facility supplies the isotope ^{99}Mo which decays into ^{99m}Tc with a half life of about 2.75 days. The ^{99}Mo is called the "parent" isotope and ^{99m}Tc is called the "daughter" isotope. Thus, the nuclear facility produces the parent isotope which decays relatively slowly into the daughter isotope and the daughter is separated chemically from the parent at the hospital/clinic. The chemical separation device is called,Generator. Examples of such radioisotopes include ^{68}Ga, ^{82}Rb, ^{87m}Sr and^{99m}Tc.

1.3 STATEMENT OF THE PROBLEM

With increasing population and commensurate rise in medical cases requiring the use of radioisotopes for imaging and therapy, any shortage of radionuclides may make nuclear medical procedures vulnerable to delay or halt. Radioisotope shortage occurred in Europe in 2008 due to failure of Petten Nuclear Reactor (The Netherlands) and affected some 25 countries including Germany, France and United Kingdom. Further, it also happened in Canada in 1995 when flight personnel went on strike, affecting radioisotope shipments from world's largest producer. This scenario may bring rancor, acrimony or even fatalities not to mention the socioeconomic effect on hospitals. Hence there is need for finding other alternative routes of production of radionuclides to take care of any eventual shortages.

1.4 AIM AND OBJECTIVES

The aim of this research is to investigate the reaction cross-section of particle induced reactions on stable I-127 for the production of medical radioisotopes.

The main objectives of this research work are to

1. Select the target and the incident particles for the reactions.
2. Obtain cross-section for the reaction.
3. Obtain the excitation function.
4. Obtain the threshold energy required to initiate the nuclear reaction.
5. Obtain the maximum cross-section for the reaction
6. Obtain the energy for the maximum cross-section

1.5 SCOPE OF THE RESEARCH

This study encompasses subjecting target nucleus (Iodine -127) through inducement reactions using neutrons, protons and alpha particles only with a view to analyze optimal energy, reaction cross-section and excitation function for the production of medically important radioisotopes.

CHAPTER TWO
(LITERATURE REVIEW)

2 INTRODUCTION

In nuclear physics, a nuclear reaction is semantically considered to be the process in which two nuclei, or else a nucleus of an atom and a subatomic particle (such as a proton, neutron) from outside the atom, collide to produce one or more nuclides that are different from the nuclide(s) that began the process. Thus, a nuclear reaction must cause a transformation of at least one nuclide to another (Hamidatou, Slamene, Akhal, & Zourane, 2013). If a nucleus interacts with another nucleus or particle and they then separate without changing the nature of any nuclide, the process is simply referred to as a type of nuclear scattering, rather than a nuclear reaction(Barrell & Silbergeld, 2007).

Computer codes are programs used to calculate numerically the statistical weights of nuclear interactions and the interaction products which are the results of reaction mechanisms using modified and improved models on time that verifies the theoretical predictions and fit the experimental data. The computer codes are thus designed to simplify the complicated numerical analyses of nuclear reactions at different stages of interaction and decay processes. ALICE-91, ACT, EXIFON, etc are some of the computer codes which are designed for the prediction and analyses of the excitation functions energy spectrum of reaction products of different type at different stages. In this research, EXIFON code is used to obtain the prediction of excitation functions for the particle induced reactions on Iodine-127. The theoretical calculations for the reactions have been performed in the energy range 1-20 MeV following statistical multistep direct and statistical multistep compound reaction model

2.1 REVIEW OF PREVIOUS WORK

The most used radioisotopes were discovered before World War II using the early cyclotrons of Ernest Lawrence, with the initial applications to medicine being developed by John Lawrence(Jeremiah, Suchiang, & Jyrwa, 2013). Some of the most well known radioisotopes, discovered by Glenn Seaborg and his coworkers, are ^{60}Co discovered in 1937, ^{131}I discovered in 1938,^{99mTc} in 1938, and ^{137}Cs in 1941(Goriely, Hilaire, Koning, Sin, & Capote, 2009). By 1970, 90 percent of radioisotopes administrations per year utilized ^{131}I, ^{60}Co, or ^{99m}Tc. Today, ^{99m}Tc, with a half-life of 6 hours, is the workhorse of nuclear medicine(Ruth, 2014).

Nuclear reaction cross-sections for (n,na) reaction on ^{127}I were calculated by Bormann for production of ^{123}Sb with the results in agreement with theoretical expectation(Bormann, 1962).

Cross-section for (n,g) reaction with natural ^{127}I were calculated with the results agreeing with experimental data files by Prasad et al(Prasad, Sarkar, & Khurana, 1966).

The cross-sections for neutron induced reactions on stable ^{127}I were measured by Barral with the results exhibiting theoretically expected trend(Barrall & Holmes, 1969).

The study of nuclear cross-sections by Paans for the production of ^{125}I via (p,5n) reaction on stable ^{127}I. The results gave the theoretically expected shape but earlier measurements showed a steep decline of the cross-section with increasing proton energy(Paans , Vaalsburg & Van Herk, 1974).

Cross-sections for high energy alpha particle induced reaction on Aluminium and Magnesium were measured for the production of ^{28}Mg, the only isotope of Magnesium used

as a radiotracer and found results in agreement with measurements carried out under 103MeV(Probst & Qaim, 1974).

Kondo measured cross-sections for the Te(p,2n)^{123}I and Te(p,n)^{124}I reactions and the effect of target enrichment on radionuclide purity. The results exhibited the expected trend for (p,n) and (p,2n) reactions(Kondo, 1977).

Nuclear cross-sections for (p,n) reactions on ^{127}I were measured by West for ^{127}Xe production and results generated exhibit the trend of experimental evaluations(West , Nuckoll & Hudson, 1993)

^{127}I (n,3n)reactioncross-section were measured for the production of ^{125}I, ^{127}I(p,3n) reaction cross-sections were also investigated by Takacs, leading to the production of ^{125}Xe.(Takacs & Tarkanyl, 2005).

Further in 2011, cross-sections were measured for (p,na), (p,a), (n,2n), (a.2np) and (p,p) nuclear reactions and the findings were in agreement with theoretical data(Koning , 2011).

Alharbi measured reaction cross-sections for proton induced reactions using natural copper with energies up to 50MeV using ALICE-IPPE code. The results generally agree with measured data at low energies up to 11MeV, whereas it underestimated the cross-section values in the range between 11 and 23MeV(Alharbi, 2012).

Nuclearcross-sections of (n,p), (n,a) and (n,2n) were measured for stable isotopes of ^{50,60,61}Ni from threshold to 20MeV and generally the measurements were in good agreement with experimental data (EXFOR) and ENDF data files(Yamoah & Asamoah, 2013).

16 cross-sections were evaluated for neutron induced reactions on ^{127}I for different exit channels in the energy range of 1 – 30MeV in the production of ^{123,124126}Sb and ^{125,126,127}Te and $^{125,126,127.128}$I(Ahmad & Koki, 2017) .

A number of Tellurium radioisotopes are useful as targets for production of important isotopes such as I-123, and I-124 which are PET isotopes. I-125 radioiodine is important in nuclear therapy as well as biological labeling(Kenneth Shultis & Faw, 2010), I-126 serves as target nucleus for radioisotope production, while I-128 is useful in Scintigraphy and therapy (in radiopharmaceutical Lobenguane, it is used to image or treat neural tissue tumors)(Volkert, 2003). Radioiodine I-129 is used as tracer and in dating applications because of its long half life(Saied, 2013). Xenon radioisotopes Xe-125 is useful as nuclear reaction target nucleus, Xe-126 is nuclear target for production of radioactive Barium 128 which is used in study of gastric ailments well as in tracing gas migration in geological studies(Waltar, 2003).

Xe-127 is useful in the study of blood flow through the brain, and flow of air through the lungs(Oliveira et al., 2006) while Xe-129 is important in Magnetic resonance imaging of gas flows in lungs(Volkert, 2003). Caesium radioisotopes are usually useful as targets except Cs-131 which is useful in Brachytherapy (Bass, 2013), and some of the Antimony radioisotopes produced are useful as biotracers (Alonso, 2001).

Nuclear data is importantfor the purposes of optimization of the production route of medical radionuclides, provision of higher yield and purity. Hence the need for evaluating and maintaining nuclear data on nuclear reaction cross-section, excitation function, reaction energetic, angular distribution, etc (IAEA-TECDOC, 2001). This forms the basis for the collation, compilation and review of nuclear data. The International Atomic Energy Agency (IAEA) has been conducting this task for about five decades and which is made accessible online via the IAEA nuclear data services website. For the purpose of research, innovation(Parker & Patrocinio,2012), dissemination and development and further, through

such data, the evaluation of reaction cross-section and other calculations are validated through comparison.

2.2 THEORETICAL BACKGROUND

When a projectile such as proton, neutron, alpha particle, deuteron, etc come close enough to interact with the target nucleus either elastic or inelastic scattering may take place or one or more nucleons which are altogether different may be knocked out of the nucleus or the incident nucleon may have been captured and a gamma ray emitted. When the mass number and /or atomic number of the target nuclei change after the bombardment, we say that a nuclear reaction has taken place.

The probability of processes as a function of energy of the incident particle$a$, in the energy and direction of the outgoing particles is usually interested in the whole set of reactions(Dzysiuk, Koning, Rochman, & Fischer, 2017).

$$a + \mathrm{X} = \begin{cases} X + a \\ \mathrm{X}^{*} + a \\ Y + b \\ Z + c \\ etc \end{cases} \qquad (2.1)$$

The first two reactions in Equation 2.1 are distinguished by the fact that the projectile re-emerges after the reaction. The first of these represents elastic scattering: the projectile leaves with the same energy and the target nucleus X is left in its initial state. The second reaction represents inelastic scattering. The target nucleus X is forced into an excited state X*, and the projectile a re-emerges but with energy lower than its initial one by the amount of excitation energy given to the target nucleus.

The interaction takes place with very small portion of the target nucleus (just outside the closedShell) and it takes very small time for the process in the order of 10^{-22} -10^{-23} sec. these type of reaction is called Direct reaction.

2.2.1 Nuclear Reaction Mechanism

Nuclear reaction mechanism may be classified as direct reaction, compound nuclear reaction, and pre-equilibrium reaction.

Direct reaction

The main characteristics of direct reactions are:

1. The presence of large number of high energy emitted particles in the spectrum.

2. Large number of forward peaked particles (small value of scattering angle inthe order of 0-7^0)

3.Monotonic change of cross-section with energy for the given channel without distinct resonance, i.e. as the threshold energy of a certain reaction is reached the cross-section decreases and this continues.Exchange of nucleonis the typical feature of direct reactionsas in the case of stripping and pick up reaction.

The direct reactions mainly include elastic scattering ((p,p) and (n,n) reactions), inelastic scattering ((n, n′) reactions), Stripping reaction ((d, n) and (d, p) reactions) and pickup reaction ((n,d and (n,t) reactions).

Scattering reaction

Scattering reactions include elastic and inelastic scattering, as described in the first two reactions from Equation (2.1) respectively.

Pick up and Stripping Reaction

Both pick up and stripping reactions are direct reaction because the nucleons involved in the reaction process enter or leave the target nucleus without disturbing the other nucleons of the target nucleus. Interaction with only surface nucleons takes place, not with the nucleus as a whole.

When the projectile and the target nucleus exchange nucleons and the projectile gains nucleons from the target the reaction is said to be pick up reactions. While if the projectile losses nucleons (the target gains nucleons) the reaction is called stripping reactions such as in the third reaction of Equation (2.1).Since both processes involve nucleons exchange between the target and the projectile the reaction also called nucleon transfer reactions.

Pre-equilibrium reaction

It can happen that a particle is neither emitted immediately after the interaction as in the direct reaction case nor after long time by statistical decay of the compound nucleus. The projectile may share its energy among a small number of nucleons which may further interact with other nucleons and during this cascade of nucleon –nucleon interaction through which the projectile energy is progressively shared among the target nucleons a particle may be emitted long before the attainment of statistical equilibrium. These processes are referred to as pre-equilibrium reaction.Their time scale is between the direct (fast) and the compound nucleus formation(slow) reactions.

Compound nuclear reaction

In this reaction, the projectile is captured by the target nucleus and its energy is shared among the nucleons of the compound nucleus until its energy reaches a state of statistical equilibrium. After a time much longer than the transient time a nucleon or a group of

nucleons near the surface may, by statistical fluctuation, receive enough energy to escape just as a molecule may evaporates from a heated drop of liquid .This energy is near the smallest possible energy and for charged particle it is the height of coulomb potential, at the nuclear surface, known as the coulomb barrier. The compound nucleus may decay in one or more different ways depending up on the excitation energy. Thus decay takes place independently to the formation of CN(Hilaire, 2000).

$$a + X \rightarrow C' \rightarrow b + Y' \qquad (2.2)$$

Some of the compound nucleus reactions include:

Capture reaction

It is a reaction type in which emission of particles does not take place and the compound system emits gamma-radiation to be stable or the residual nucleus may give delayed emission of radiation.

Photodisintegration

When γ-radiations fall on a nucleus a neutron may be emitted. Interaction of γ-ray with deuteron may yield a neutron and a proton. Thus the target nucleus is disintegrated into small fragments by gamma radiation, which is known as photodisintegration.

Heavy Ion Reaction

Heavy ions, beginning from alpha to 238U can react to give heavy and /or super heavy new elements. When a nucleus captures a neutron it often tries to correct for its neutron excess by beta decay ,turning a neutron into a proton and thus creating an atom with atomic number

greater than the initial value by one (Z+1). This suggests a way to create new elements of increased atomic number and to create even massive elements(Hendee, 2014).

2.2.2 Resonance in excited state of compound nucleus

Information about excited states of nuclei can be gained from a nuclear reaction as well as from a radioactive decay .The presence of excited state can be detected by the pulse peak in the cross-section vs energy curve of a particular reaction. Such a peak is called resonance. A compound nucleus more likely to be formed when the excitation energy provided exactly matches with one of the energy levels than if the excitation energy has some other values. The instability of compound nucleus results in an uncertainty in the energy of these states. Hence the possible energy values follow a probability distribution. The energy uncertainty is given by the *width*of the resonance as related in Heisenberg's uncertainty principle(MUKHIN, 1970):

$$\tau = h/(2\pi)\,\Gamma \qquad (2.3)$$

Where τ is the lifetime, Γ is width and h isplanck's constant.

2.2.3 Coulomb Barrier Potential

Every nucleon surrounded by an electrostatic potential (V) that opposes the entry and escape of the positively charged particles (proton, alpha, deuteron, etc.).Neutrons which are neutral particles are not faced coulomb barrier and accordingly are more readily absorbed and emitted by nuclei than the charged particles.An atomic nucleus is a rigidly bound system of nucleons localized in a region of radius(Al Saleh, Al Mugren, & Azzam, 2007)

$$R = 1.4 * 10^{-13} A^{1/3} cm \qquad (2.4)$$

The electrostatic potential V is given by

$$V = \frac{Zze^2}{r} \qquad (2.5)$$

where Z is the nuclear charge, z is the atomic number of the particle and r the distance between them.When a proton approaches a nucleus, it faced with a potential hill and,

1) Classically it would have to posses at least as much the energy as the height of the barrier in order to enter the nucleus,

2) Quantum mechanically, proton can get in with energy less than this (less probability which is different from zero).

when r=R, Equation (2.4) became

$$V = B_c = \frac{Zze^2}{R} \qquad (2.6)$$

where B_c is the height of coulomb barrier which represents effective threshold energy for nuclear reaction initiated by the charged particle.The coulomb barrier also impedes the emission of a charged particle from the CN.

2.2.4 Reaction Threshold

The minimum energy for a nuclear reaction to occur is what we called threshold energy.By considering the reaction;

$$a + X \rightarrow b + Y \qquad (2.7)$$

We can use the law of conservation of energy and momentum to prove that the minimum kinetic energy of particle "x" to initiate the endoergic process is

$$T_{min} = T_{th} = \frac{|Q|(M_X + m_a)}{M_X} \qquad (2.8)$$

This equation is valid if the energies are much less than rest mass energies of the involved particles. The general relationship when the rest mass energy of the particles is

taken into account, we must use the relativistic equations for energy and momentum. The results for the threshold kinetic energy necessary for initiating an endoergic process is given as(G. N. Kim, Khandaker, Kim, Lee, & Kim, 2011)

$$T_{min} = T_{th} = \frac{|Q|(M_X + m_a + M_Y + m_b)}{2M_X} \tag{2.9}$$

This equation may be written in a more general form

$$T_{min} = T_{th} = \frac{|Q|(restenergyofallparticles)}{(restenergyoftargetparticles)} \tag{2.10}$$

2.2.5 Nuclear Cross-section

The knowledge of nuclear reaction cross-sections is very important both from practical point of view and for theoretical understanding of nuclear interactions. The interaction of a nucleus with light particles such as alpha, proton, neutron etc. is of foremost importance as it changes the configuration of the nucleus and is useful in transformations of the nucleus into various other nuclides(Iida, Kohama, & Oyamatsu, 2007). When a beam of nucleons impinges upon a nucleus, the ratio of the reaction rate (in units of s^{-1}) to the incident flux (in units of $cm^{-2}s^{-1}$) is defined as the "cross-section" (σ) (in units of cm2 or barn with 1 barn = 10^{-24} cm^2).

$$\sigma = \frac{numberofeventsofagiventypepernucleus}{numberofincidentparticlesperunittime} \tag{2.11}$$

The cross-section is thus a measure of the strength of a reaction. The cross-section of a target material for any given reaction thus represents the probability of a particular interaction and is a property of a nucleus and incident energy. The reaction cross-section is a function of not only the target nucleus, but also of the type and energy of the bombarding particle.

Nuclear cross-section is associated with each particular type of nuclear reaction. Thus, a scattering cross-section (σs) is implied when referring to a nuclear scattering process, an absorption cross-section (σa) when referring to an absorption process or a fission cross-section (σf) when dealing with a nuclear fission reaction and so on. Such also implies with the probability to find the outgoing particle at certain angle or certain energy i.e. the angular or energy differential cross-section, while the reaction cross-section represents the probability of finding it over all energies and all angles. The various possibilities are then represented by the total cross-sectionσt which is equal to the sum of all partial cross-sections involved.

Suppose that N number of each event is produced by incident particleof flux I. The probability of nuclear interaction, P is given by (Sahan, Sahan, & Tel, 2018)

$$P = \frac{N}{I} \tag{2.12}$$

This can also be expressed by the ratio of effective area as seen by the projectile to the totalarea of the target;

$$P = \frac{\sigma n A dx}{A} \tag{2.13}$$

Equating the expressions for P yields

$$\sigma = \frac{N}{Indx} \tag{2.14}$$

where n is the nuclear density,

$$n = \frac{\rho Na}{A} \tag{2.15}$$

Na-Avogadro's number of nuclei,A -atomic weight and ρ-is the density of the target.

Thus the cross-section can be measured experimentally by the attenuation of the incidentbeam.

2.2.7 Excitation Function

Excitation function is the term used in nuclear physics to describe a graphical plot of the yield of a radionuclide as a function of the bombarding projectile energy or the calculated excitation energy of the compound nucleus.Excitation function can also be described as the graphical representation of nuclear cross-section against incident energy.

In order to describe a nuclear reaction by the completed study of the exit channel, an excitation function allows determining the optimum energy to be used to maximize the yield.

2.2.8 Nuclear Reaction Models

Nuclear reactions are described by several models which are linked together to calculate reaction cross-sections. In this process, the basic model is the Optical model which gives way for separating total cross-section into various components. Therefore, a particle induced nuclear reaction processes are classified according to the time scale of interaction as direct reaction (DR) which occurs in a time scale of 10^{-22} s' and compound nuclear reaction (CN) that occur on a slower time scale of 10^{-16}s or more. Between these two is the pre-equilibrium reaction (PER). All these processes contribute to calculating particle induced cross-sections.

Optical model

It is called optical model because it resembles the case light incident on an opaque glass sphere; this means the reaction is independent of the internal structure of the nucleus and behaves like the scattering of light from a crystal ball (Ulmer & Matsinos, 2012). It is also known as the cloud crystal ball model.

Pre-equilibriummodels

Many semi classical and quantum mechanical models have been developed to treat the pre-

equilibrium phase of reactions leading to formation of compound nucleus. The work of Griffin in 1966 was the first model capable of reproducing the shapes of the continuous spectra; he has shown that if justification is overlooked and assumption of binary collision is retained even at lower energies, the newly observed experimental features can be qualitatively explained. He proposed the so-called statistical model of intermediate structure.

Another complex but powerful model called the Fermi gas equilibration model was developed by Harp, Miller and Berne in 1968 is widely known as HMB model(Ahmad & Koki, 2017). In 1971 Gadioli et al developed and perfected the original Griffin model into what came to be known as Exciton model(Hibstie et al., 2018). Exciton and hybrid models are only special cases of a more general master equation approach, originally proposed by Pauli in 1928(Heraltov, 2014).

Mountzouranis et al in 1976 proposed a generalized exciton model which had an additional capability of predicting angular distribution. Later in 1980, Ackerman improved and refined this model but also proposed a random-walk model of equilibrium decay which can describe multinuclear emission in pre-equilibrium phase(Tarik & Saadoon, 2016).

Machner in 1979 further extended the generalized exciton model and developed the exciton coalescence model to account for complex particle emission in pre-equilibrium phase and as well predict angular distribution. In 1987 Ernst et al proposed the index model, by projecting in the hybrid model and a unified model incorporating multiple chance pre-equilibrium probability for nucleons (Ahmad, Yola, & Koki, 2017).

Statisticalmultistep reaction

The concept of statistical multistep processes has over the years, become more and more important for the understanding of nuclear reaction mechanism, especially above 20 MeV(Yamoah & Asamoah, 2013). These models enable the description of scattering process that takes place in two ways; namely direct and compound (pre-equilibrium, and equilibrium) nucleus formation processes and these are, respectively, called shape elastic and compound elastic scattering(Hilaire, 2000). The direct process is too short (10^{-22}-10^{-23} s) while the compound nucleus process takes much longer time (10^{-16}-10^{-17} s).If many strongly overlapping resonances contribute and the cross-section is average over sufficiently large energy intervals to include very many resonances, the two processes (shape & compound) are incoherent so their cross-sections are calculated independently and added to fit the experimental data.Shape elastic scattering takes place at all energies whereas compound elastic scattering is important at low energies(Ahmad et al., 2017).

This model is formulated in detail for predicting emission spectra for neutrons, protons, alphas and photons. It includes equilibrium, pre-equilibrium, direct as well as MPE processes in a consistent way. The calculation of Multiple Particle Emission (MPE) is generalized. Up to three decays of the compound nucleus are considered. Calculations are performed with one physical parameter set for several nuclei, several energies, and several reaction types.Statistical multistep models are very successful in describing nuclear reactions at energies up to about 100 MeV.

The application of a statistical multistep model to heavy nuclei requires the consideration of fission as a competing process to particle and “gamma-ray” emissions. Therefore, statistical multistep models should be extended to the fission channel.

In the Statistical Multistep Model, the total emission spectrum of the process (a, xb) is divided into three main parts(Ahmad & Koki, 2017).

$$\frac{d\sigma_{a,xb(E_a)}}{dE_b} = \frac{d\sigma_{a,b}^{SMD}(E_a)}{dE_b} + \frac{d\sigma_{a,b}^{SMc}(E_a)}{dE_b} + \frac{d\sigma_{a,xb}^{MPE}(E_a)}{dE_b} \quad (2.16)$$

Where $\sigma_{a,xb}$ is the probability for (a,xb) process, $\sigma_{a,b}^{SMD}$ is the probability for direct reactionfor production of b from a and E_b is the excitation energy for the formation of b.

The first term on the right-hand side of the Equation (2.16) represents the statistical multistep direct (SMD) cross section part. This process is a sum over s-step direct processes from single multistep to five-step contributions which is given by

$$\frac{d\,\sigma_{a,b}^{SMD}(E_a)}{dE_b} = \sum_{s=1} \frac{d\,\sigma_{a,b}^{S}(E_a)}{dE_b} \quad (2.17)$$

The second term represents the statistical multistep compound (SMC) emission which is based on a master equation.The SMC Cross-section has the form

$$\frac{d\,\sigma_{a,b}^{SMC}(E_a)}{dE_b} = \sigma_a^{SMC}(E_a) \sum_{N=N_0}^{N1} \frac{\tau_N(E)}{\hbar} \sum_{(\Delta N)} \Gamma_{N,b}^{(\Delta N)}(E, E_b) \uparrow \quad (2.18)$$

where τ_N (E) satisfies the time-integrated master equation.$\tau_N$is the lifetime of the exciton state N, $\Gamma_{N,b}^{(\Delta N)}$ is the width of N state. The first summation from Equation 2.18 runs from N_0up to a reliable maximum N, which includes the so called equilibrium state. The initial exciton numbers are N_0= 2,3 or 6for photon, nucleon or alpha – induced reactions respectively. Equation (2.18) includes in a consistent manner, both the precompound and pure compound emissions. Both terms together (SMD + SMC) of Equation (2.16) represents the first chance emission process (Kalka, 1992).

The last term of the Equation (2.16) represents multiple particle emission (MPE) which includes the second chance, third chance emissions etc. These terms are summarized below

$$\frac{d\sigma_{a,xb}^{MPE}(E_a)}{dE_b} = \Sigma\frac{d\sigma_{a,cb(E_a)}}{dE_b} + \Sigma\frac{d\sigma_{a,cdb(E_a)}}{dE_b} \quad (2.19)$$

2.2.9 Shell Structure Effects

The shell structure effects are considered in statistical multistep compound (SMC) processes. It has also been implemented in the EXIFON code as the only adjustable factor to understand the mechanism of the compound nucleus and pre-equilibrium models over the neutron energy for reaction threshold to 20 MeV. Under such a situation, the single - particle state density g is multiplied by the factors(Kalka, 1992)

$$\left(1 + \frac{\delta W}{E_X}[1 - \exp(-\gamma E_X)]\right) \quad (2.20)$$

With γ = 0.05MeV and δW as the shell correction energy (Yamoah & Asamoah, 2013).The quantity E_x = E or U denotes the excitation energy of the composite or residual systems respectively.

The single – particle state density of bound particles g (at Fermi energy E_F) is then defined by

$$g = 4\rho(E_F) \quad (2.21)$$

2.3 APPLICATIONS OF NUCLEAR DATA

Nuclear data in general and cross-section data are of great importance with respect to applications in a wide variety of fields from the earth crust to the upper atmosphere. The starting point of any reliable computational modeling of nuclear system is the accurate

knowledge of reliable nuclear information often referred to as nuclear data. The specific areas of applications of particle induced cross-section data include but not limited to:

i. Radioisotope production - radioisotopes are used often in medicine for diagnosis, therapy and research. Radiotracers are also used in tomographic investigations (PET, SPECT, etc)

ii. Design, commissioning and optimal utilization of fission reactors.

iii. Design of fuel cycle in fusion (thermonuclear) reactor.

iv. Generation IV reactors design which is designed to give 100-300 times more energy than conventional reactors and ability to consume existing waste to produce electricity.

v. Energy Amplifiers /Accelerator Driven Systems.

vi. Dosimetry – this concerns calculations of the amount of radioactivity required for the specific diagnostic andtherapeutic applications and is very important in nuclear medicine.

CHAPTER THREE
(MATERIALS AND METHOD)

3.1 MATERIALS

1. Personal Computer

2. EXIFON Code Software

3. Microsoft Excel

4. International Atomic Energy Agency (IAEA) Nuclear Data Section

3.1.1 Computer Code EXIFON

EXIFON code is based on an analytical model for the description of excitation function of particle induced reactions within a statistical multistep direct and multistep compound reactions (SMD/SMC) model. The computer code is very important for several technical applications if the experimental data are not available or unable to measure the reaction cross-sections due to the experimental difficulties. This code is capable of calculating equilibrium and pre-equilibrium emission cross-section, and valid for excitation energy of the compound nucleus up to 100 MeV.

EXIFON code provides continuous and smooth description of nuclear reactions over a wide energy and mass range which is based on an analytical model for statistical multistep direct and multistep compound reactions (SMD/SMC model). It predicts emission spectra, angular distribution and activation cross-section for neutrons, protons, alpha particles and photons. Multiple particle emissions are considered for up to three decays of the compound system. EXIFON is a fast, easy to handle code which predicts cross-sections from one global parameter set. The only adjustable quantity is the pairing shift. The INPEXI code creates

input files for EXIFON 2.0 from mass and shell – correction tables. The MAKE6 code transforms EXIFON output into an ENDF-6 format file (Ebiwonjumi, 2014).

3.1.2 General Features of EXIFON Code

Computer: PC/AT, Programming language: FORTRAN 77, Characters: ASCII (IBM International Graphic), Memory size: 300kbyte, Number of subroutines: 13, Records; about 1600, running time: about 20 seconds per incident energy.

3.1.3. Standard Parameters Set

The following global parameters are used

Strength of surface – delta interaction:	$F_0 = 27.5$MeV
Radius Parameter:	$r_0 = 1.21 + 4.0A^{-2/3} - 15A^{-4/3}$
Fermi energy:	$E_f = 33$MeV
Potential energy:	$V_0 = 52 - 0.3E_\alpha$MeV
Pairing shift:	$\Delta = 12.8A^{-1/2}$ MeV
Phonon (Breit-Weigner) width:	$\Delta w = 14$MeV
Optical Model Potential OM:	Wilmore-Hodgson (for neutrons)
	Perey et al (for protons)
	Huizenga et al (for alpha)

In the calculations, the following parameters can be changed; Strength of surface-delta interaction F_0, Radius parameter r_0, Fermi energy E_f, Phonon width Δw and global OM parameter for protons. Calculations can be performed with (dW=0) shell corrections.

3.2 PROCEDURE

Input:

i. Target nucleus (A, Z)

ii. Incident particle type a

iii. Incident energy Ea

iv. Only for excitation functions (number and binding energies of incident)

v. Standard and modifier description

Output:

i. Emission spectra for all (a, xb) channels

ii. Activation cross-sections (a, p), (a, α), (a, 2n) etc

3.2.1 Input Data and Output Data files

For each target nucleus, input data files are necessary. They contain all binding energies B_C and shell correction energies dW, as well as phonon parameters. They can be created with code INPEXI.EXE. One input data file contains all the information for neutron, proton and alpha induced reactions.Output data files are equally necessary for each target nucleus. The emission spectra of neutrons, protons and alpha particles are stored in the file AXN.DAT, AXP.DAT, AXA.DAT and AXG.DAT respectively. A short documentation is written to OUTEXI after each run.

3.2.2 Nuclear Model Calculations

Theoretical calculations of nuclear cross-sections were performed using nuclear model code EXIFON, the program was run and the input and output directories were defined; this is followed by target nucleus specification. The incident particle and target nucleus were selected and excitation function in the general options section for this calculation was chosen.

The number of incident energy was specified followed by the first incident energy, and then the incident energy step is equally specified. Subsequently, the cross-section corresponding to each particular energy step was generated.

The output data (OUTEXI) for the calculation is then stored in the output directory, also DAT file name are stored in the set output directory.The computer program Python was used to generate a code that can convert the results which comes in complex notepad format into a simple format for easy processing.

3.2.3 Data Analysis Procedure

The data of this work has been arranged in proper orders and organized by using tabulation method. These organized data was analyzed and described graphically with the help of spreadsheet (Microsoft Excel). Results generated from this analysis were then compared with the experimental (EXFOR data library) and recommended evaluated nuclear data libraries around the globe (ENDF), from the International Atomic Energy Agency (IAEA), was used to validate the calculated data.

CHAPTER FOUR
(RESULTS AND DISCUSSIONS)

4 RESULTS

The nuclear reaction cross-sections generated from EXIFON code based on the proton, neutron and alpha nuclear interaction with Iodine nucleusare given in Table (1–18) along with the available experimental EXFOR and evaluated ENDF data. EXIFONwt represent excitation function with shell correction, while EXIFONwot represent excitation function without shell correction. All cross-sections are expressed in millibarns (mb) and energies in mega electro volt (MeV) throughout this project. Thus four sets of results were generated as EXIFONwith EXFORand ENDF data comparison, EXIFON with EXFOR data comparison, EXIFON with ENDF data comparison and Exifon only (with no comparative EXFOR or ENDF data).

Table 4.1Cross-sections Obtained in I-127 (n,2n) I-126 reaction (Exifon with and without shell structure) and comparative EXFOR and ENDF data

ENERGY	EXIFONwot	EXFOR	ENDF	EXIFONwt
9	0	0	243.182	0
10	17.5	894	808.233	17.4
11	250.2	1407	808.233	242.7
12	709	1508	1326.36	689.6
13	1111.9	1594	1425.82	1089.7
14	1365.1	1632	1481.72	1346.3
15	1495.9	1707	1543.83	1481.5
16	1559.4	1665	1563.29	1549.1
17	1583	1624	1548.52	1575.4
18	1585.7	-	1443.09	1580
19	1577.8	-	-	1573.1
20	1564.2	-	-	1560.2

Table 4.2Cross-sections Obtained in I-127(n,np)Te-126 reaction (Exifon with and without shell structure) and comparative EXFOR and ENDF data

ENERGY	EXIFONwot	EXFOR	ENDF	EXIFONwt
7	0	0	0	0
8	0	0	9.7E-17	0
9	0	1.5E-05	6E-13	0
10	0	0.00017	1.5E-09	0
11	0	0.00056	7.8E-06	0
12	0	0.00237	0.00271	0
13	0	0.00793	0.01291	0
14	0	0.02044	0.03188	0
15	0	0.04314	0.06114	0
16	0	0.07895	0.10221	0
17	0.1	0.12917	0.15594	0.1
18	0.2	0.19455	0.22165	0.2
19	0.3	0.27376	0.29606	0.4
20	0.5	0.36572	0.37815	0.6

Table 4.3Cross-sections obtained inI-127(n,na)Sb-123 reaction (Exifon with and without shell structure) and comparative EXFOR and ENDF data

Energy	EXIFONwot	EXFOR	ENDF	EXIFONwt
10	0	0	1.03E-05	0
11	0	0	0.000142	0
12	0	0	0.000861	0
13	0	0	0.003282	0
14	0	0.02	0.010643	0
15	0	0.026	0.025434	0
16	0	0.03	0.060571	0
17	0	0.055	0.112109	0
18	0	0.08	0.196949	0
19	0	-	0.304941	0
20	0.1	-	0.427486	0.1

Table 4.4Cross-sections obtainedinI-127(p,3n)Xe-125 reaction (Exifon with and without shell structure) and comparative EXFOR and ENDF data

Energy	EXIFONwot	EXFOR	ENDF	EXIFONwt
17	0	0	0	0
18	0	2.8	0	0
19	58.8	2.8	0.03333	61.6
20	314.7	23.5	22.5454	327.5

Table4.1-4.4 show the EXIFON code cross- sections (EXIFON with and without shell structure) generated in I-127(n, 2n) I-126, I-127(n,np)Te-126 , I-127(n,na)Sb-123 and I-127(p,3n)Xe-125 reactionsrespectively, from 1MeV to respective energies the cross-sections are zero. The obtained data compared with EXFOR and ENDF data.

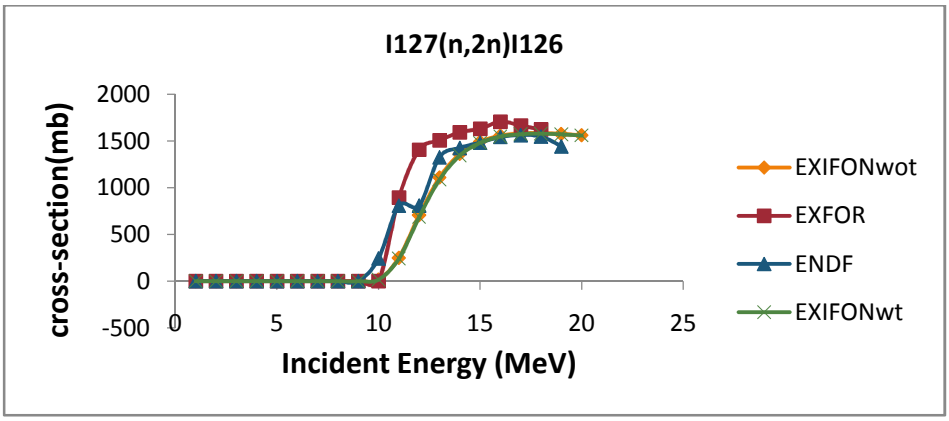

Fig 4.1 **Excitation function I-127 (n, 2n) I-126 reaction** (Barrell & Silbergeld, 2007)

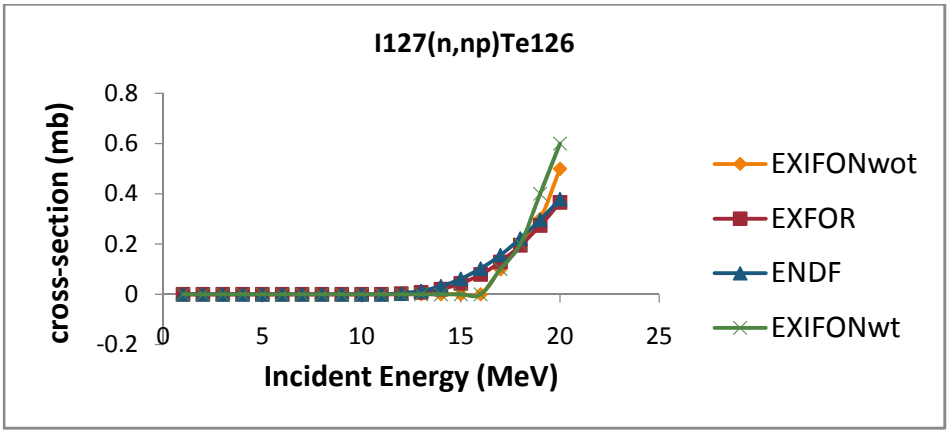

Fig 4.2**Excitation function I-127 (n,np) Te-126 reaction**

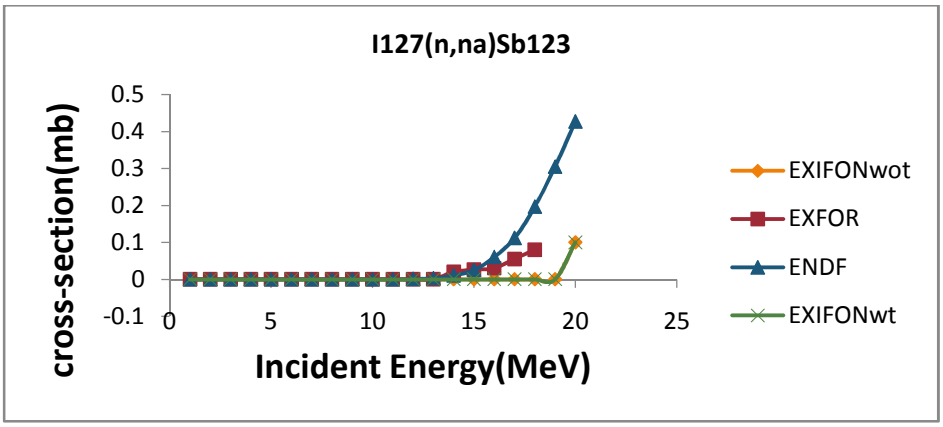

Fig.4. 3 Excitation function for I-126 (n, na) Sb-123 reaction (Ebiwonjumi, 2014)

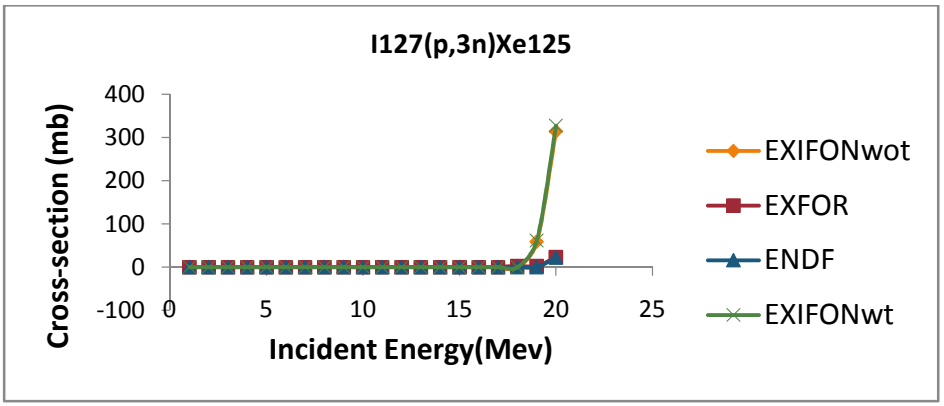

Fig 4.4**Excitation function I-127 (p,3n) Xe-125 reaction**

From the results above there is little difference between excitation functions with shell and the ones without shell structure, implying that shell structure has little effect on the excitation functions.

Figure 4.1 shows I-127 (n,2n) I-126 reaction which is a spallation reaction where neutron particle passes through I-127 nucleus and eject with less energy together with another neutron from I-127 and produce I-126. I-126 radioisotope is useful for the production of medically important radioiodine such as I- 123 and I-124. EXIFON data shows threshold energy of 11.5 MeV. Both experimental data (EXFOR) and evaluated data (ENDF) appear to show very good agreement with calculated data.

Tellurium 126 serves as useful target for reactions that produce other important radionuclides.Figure 4.2 shows a many body reaction I-127 (n,np) Te-126 for the production of Tellurium 126. From the graph both experimental data EXFOR and evaluated data (ENDF) show a good agreement with the calculated data.

Antimony 123 is important in nuclear medicine for its use as biological and biomedical labeling radionuclide.Figure 4.3 shows reaction I-127(n, na) Sb-123, a many body reaction

for the production of Antimony123. Threshold energy was 19 MeV and nuclear cross-section appears to rise commensurately with increasing incident energy.

Xenon 125 is useful for serving as target nucleus in production of medical radionuclides such as I-123.Figure 4.4 shows threshold energy for the I-127 (p, 3n) Xe-125 spallation reaction as 18MeV for the production of Xenon 125. There is agreement in the upward trend of the excitation function.

Table 4.5 cross-sections obtained in I-127(p,n)X e-127 reaction (EXIFON with and without shell structure) and comparison with EXFOR data. Incident energies (1-4MeV) yielded zero cross-section .

Energy	EXIFONwt	EXIFONwot	EXFOR
4	0	0	0
5	18.3	18.2	0
6	67.3	67.1	0
7	138.7	138.6	0
8	232.2	232	0
9	347	346.8	3.94289
10	482.5	482.3	118.432
11	618.5	618.3	344.276
12	728.3	728.1	559.084
13	817.3	817.1	717.673
14	889.8	889.5	828.544
15	948.9	948.6	905.955
16	997.1	996.7	962.569
17	1036.1	1035.8	1001.89
18	1067.6	1067.1	1032.95
19	1092.5	1092	1055.01
20	1111.9	1111.3	1054.94

Figure 4.5 shows the reaction data forEXIFON with and without shell structure, and EXFOR data only in the reaction, I-127(p.n) Xe-127.

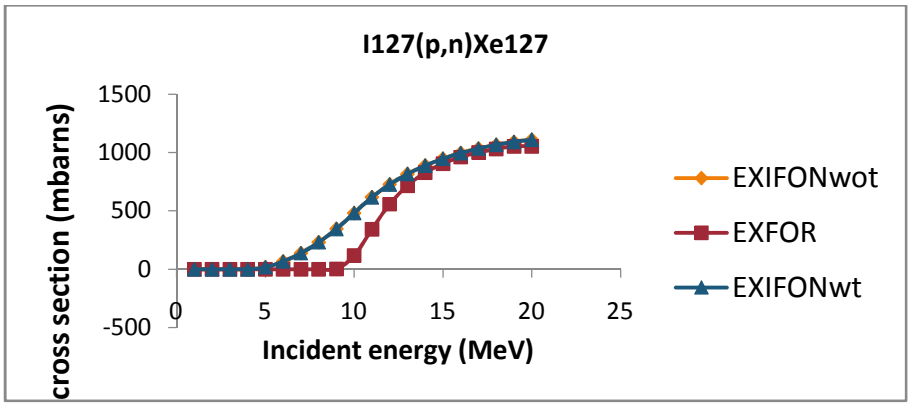

Fig 4.5 Excitation for I-127 (p, n) Xe-127(West , Nuckoll & Hudson, 1993)

Figure 4.5 is a knockout reaction in which proton particle displaces neutron in nucleus of I-127 to produce Xenon 127.Xenon 127 is an important isotope for study of blood flow through brain as well as flow of air through lungs. Figure 5 shows that both calculated (EXIFON) datasets and experimental data (EXFOR) appear to exhibit a good agreement. EXIFON threshold is 5MeV while EXFOR threshold is 9MeV, however, common is the proportionate trend of rise in cross-section while incident energy increases. Xe-127 has a half life of 75 seconds and decays through gamma emission.

Table 4.6 cross- sections Obtained in I^{127} (n,p)Te-127 reaction (EXIFON with and without shell structure) and comparison with ENDF data.

ENERGY	EXIFONwot	ENDF	EXIFONwt
1	0	5.2E-17	0
2	0	2.1E-13	0
3	0	9.1E-10	0
4	0	3.4E-06	0
5	0	1.1E-02	0
6	0	8.9E-02	0
7	0.1	1.9E-01	0.1
8	0.2	4.4E-01	0.2
9	0.5	1.0E+00	0.5
10	1	2.4E+00	1.1
11	1.8	4.7E+00	1.9
12	2.9	7.8E+00	3.1
13	4.5	1.1E+01	4.7
14	6.5	1.4E+01	6.8
15	9	1.7E+01	9.3
16	11.9	2.0E+01	12.3
17	15.3	2.2E+01	15.8
18	19	2.3E+01	19.6
19	23.1	2.3E+01	23.7
20	27.4	2.3E+01	28.2

Table 4.7 cross-section obtained for I-127(p,2n)Xe-126 reaction

Energy	Exifon wot	ENDF	Exifon wt
8	0	0	0
9	0	3.94289	0
10	92.7	118.432	86.4
11	335.1	344.276	324.8
12	556.9	559.084	548.6
13	715.2	717.673	709.8
14	823.5	828.544	820.3
15	899.6	905.955	897.7
16	955.3	962.569	954.2
17	997.3	1001.89	996.6
18	1029.5	1032.95	1029
19	1054.2	1055.01	1053.9
20	1073	1054.94	1072.8

Table 4.8 cross-sections obtained in I-127(p,p)I-127 reaction

Energy	EXIFONwo	ENDF	EXIFONwt
1	0	0	0
2	0	4.37E-12	0
3	0	1.91E-07	0
4	0	0.000102	0
5	0	0.005264	0
6	0	0.073945	0
7	6.8	0.480073	6.8
8	11.8	1.95315	11.8
9	18.6	5.79315	18.6
10	28.1	12.8301	28.1
11	39.7	22.28	39.7
12	52	32.9092	52.1
13	65.2	44.0936	65.2
14	79.1	54.09	79.2
15	93.8	66.9608	93.9
16	109.2	76.966	109.4
17	125.3	90.2161	125.5
18	142	101.189	142.3
19	159.3	110.798	159.6
20	177.1	118.37	177.4

Table 4.9 Cross-section obtained forI-127(p,g) Xe-128 Reaction

Energy	EXIFONwt	EXIFONwot	ENDF
1	0	0	3.11E-11
2	0	0	6.49E-06
3	0	0	7.62E-04
4	0	0	1.63E-02
5	0.6	0.7	9.78E-02
6	1.1	1.2	2.61E-01
7	1.3	1.4	4.27E-01
8	1.4	1.6	5.67E-01
9	1.5	1.7	6.90E-01
10	1.7	1.9	8.18E-01
11	1.9	2	9.50E-01
12	1.9	2.1	1.07E+00
13	2	2.1	1.17E+00
14	2	2.2	1.23E+00
15	2.1	2.2	1.26E+00
16	2.1	2.2	1.24E+00
17	2.2	2.3	1.15E+00
18	2.2	2.3	1.03E+00
19	2.3	2.3	9.20E-01
20	2.3	2.4	8.26E-01

Table 4.10 Cross-section obtained for I-127(n,3n) I-125 Reaction

Energy	ENDF	EXIFONwt	EXIFONwot
6	0	0	0
7	6.9E-14	0	0
8	1E-09	0	0
9	2.1E-07	0	0
10	3.2E-06	0	0
11	2.5E-05	0	0
12	0.00016	0	0
13	0.00083	0	0
14	0.00313	0	0
15	0.00954	0	0
16	0.02528	0	0
17	0.07379	0	0
18	0.16988	0.1	0.1
19	0.33516	0.2	0.2
20	0.40601	0.3	0.3

Table 4.11 cross-sections obtainedin I-127(p,np) I-126 reaction

ENERGY	EXIFONwo	ENDF	EXIFONwt
9	0	0	0
10	0	5.67E-07	0
11	0	3.27E-05	0
12	0	3.89E-04	0
13	0	3.68E-03	0
14	0.1	2.73E-02	0.1
15	0.2	1.12E-01	0.2
16	0.4	3.00E-01	0.4
17	0.8	6.26E-01	0.7
18	1.2	1.14E+00	1.2
19	1.8	1.86E+00	1.7
20	2.5	2.88E+00	2.4

Table 4.12 Cross-section obtained for I-127(p,a)Te-124 Reaction

Energy	EXIFONwot	ENDF	EXIFONwt
1	0	2.03E-16	0
2	0	1.43E-09	0
3	0	2.16E-07	0
4	0	1.44E-05	0
5	0	2.82E-04	0
6	0	2.13E-03	0
7	0	8.70E-03	0
8	0	2.39E-02	0
9	0.1	5.38E-02	0.1
10	0.3	1.15E-01	0.3
11	0.6	2.41E-01	0.6
12	1.1	4.82E-01	1.1
13	1.8	8.85E-01	1.8
14	2.6	1.49E+00	2.6
15	3.6	2.41E+00	3.6
16	4.6	4.12E+00	4.7
17	5.8	9.91E+00	5.9
18	7	1.29E+01	7.2
19	8.3	1.52E+01	8.5
20	9.7	-	9.9

Table 4.13 Cross-sections obtained from I-127(p,na)Te-123 Reaction

Energy	ENDF	EXIFONwt	EXIFONwot
6	0	0	0
7	6.9E-14	0	0
8	1E-09	0	0
9	2.1E-07	0	0
10	3.2E-06	0	0
11	2.5E-05	0	0
12	0.00016	0	0
13	0.00083	0	0
14	0.00313	0	0
15	0.00954	0	0
16	0.02528	0	0
17	0.07379	0	0
18	0.16988	0.1	0.1
19	0.33516	0.2	0.2
20	0.40601	0.3	0.3

Tables 4.6 – 4.13 show the generated EXIFON code cross-sections (EXIFON with and without shell structure) in (n,p) Te-127, (p,2n) Xe—126, (p,p) I-127, (p,g) Xe—128, (n,3n) I-125, (p,a) Te-124 and (p,na) Te-123 and comparative ENDF data.

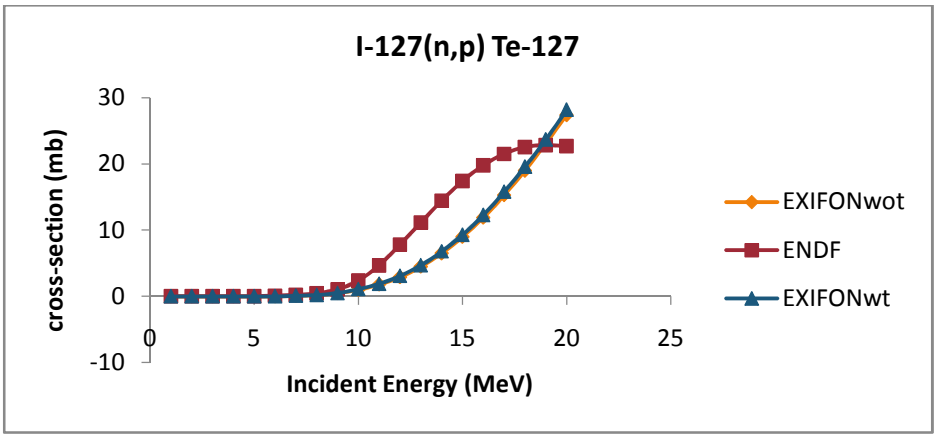

Fig 4.6 Excitation function I-127 (n, p) Te-127 reaction(Bass, 2013)

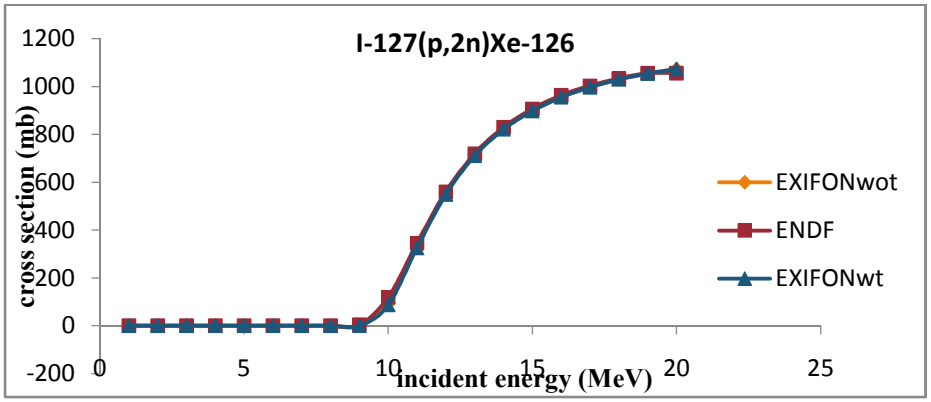

Fig 4.7 Excitation function I-127 (p, 2n) Xe-126 reaction(Koning , 2011)

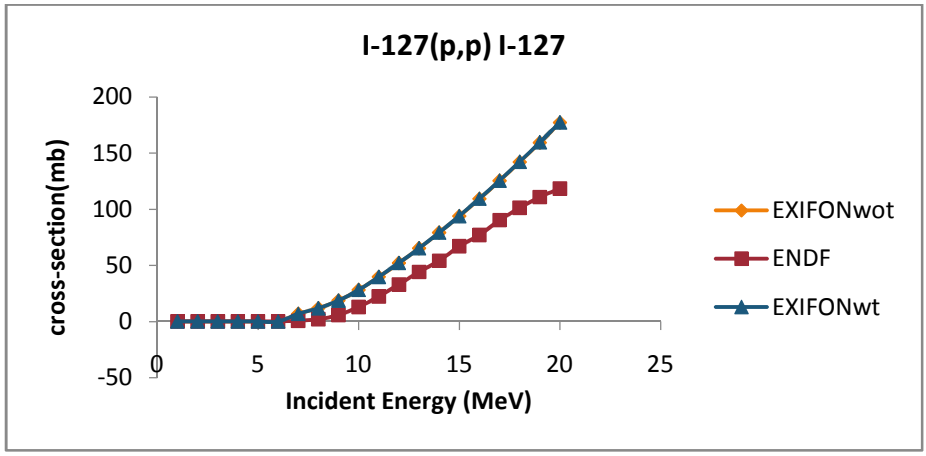

Fig4.8 Excitation function I-127 (p, p) I-127 reaction(West , Nuckoll & Hudson, 1993)

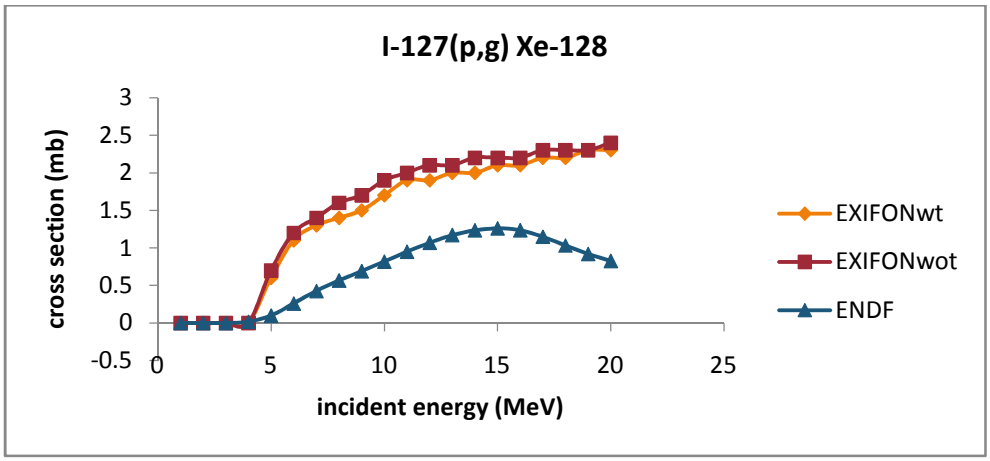

Fig4.9Excitation function I-127 (p,g)Xe-128 reaction(Vladuca et al., 2004)

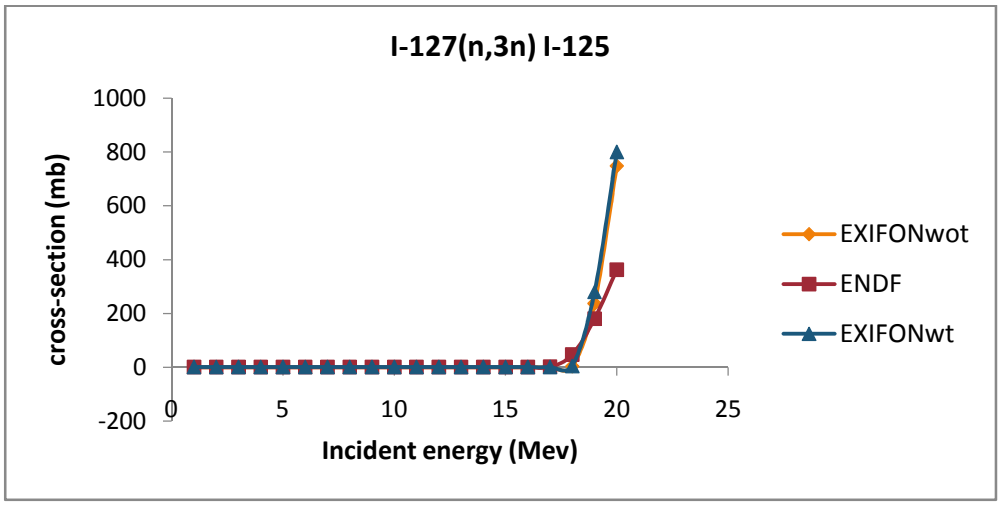

Fig.4.10 Excitation function I-127 (n, 3n) I-125 reaction

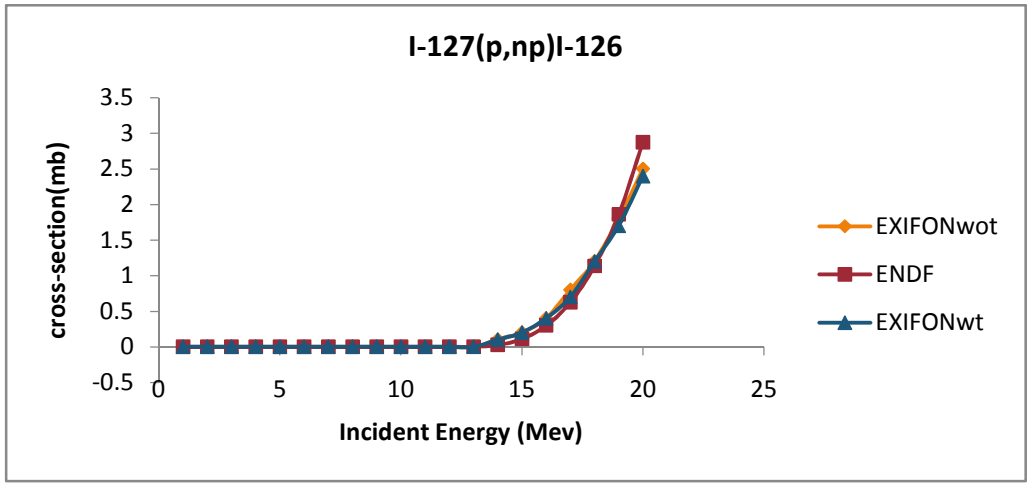

Fig 4.11 Excitation function I-127 (p, np) I-126 reaction

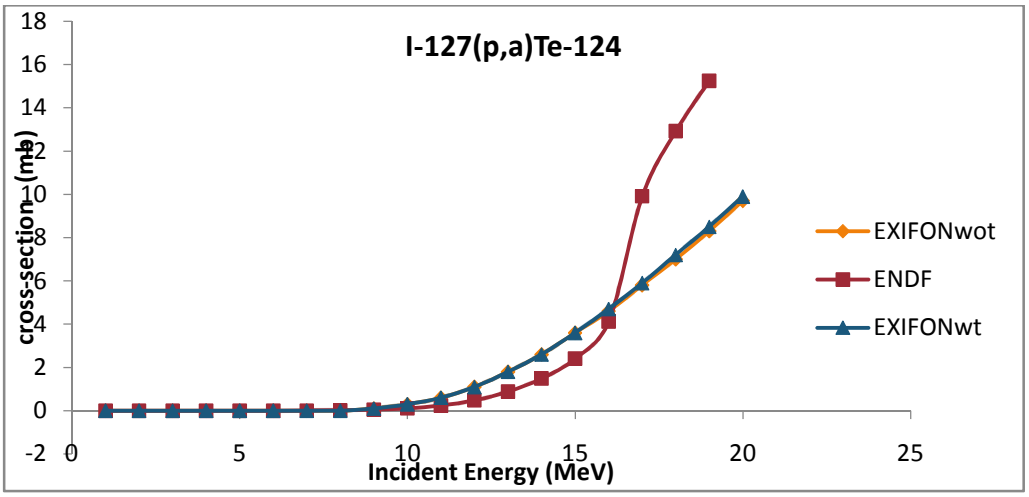

Fig4.12 Excitation function I-127 (p, a) Te-124 reaction

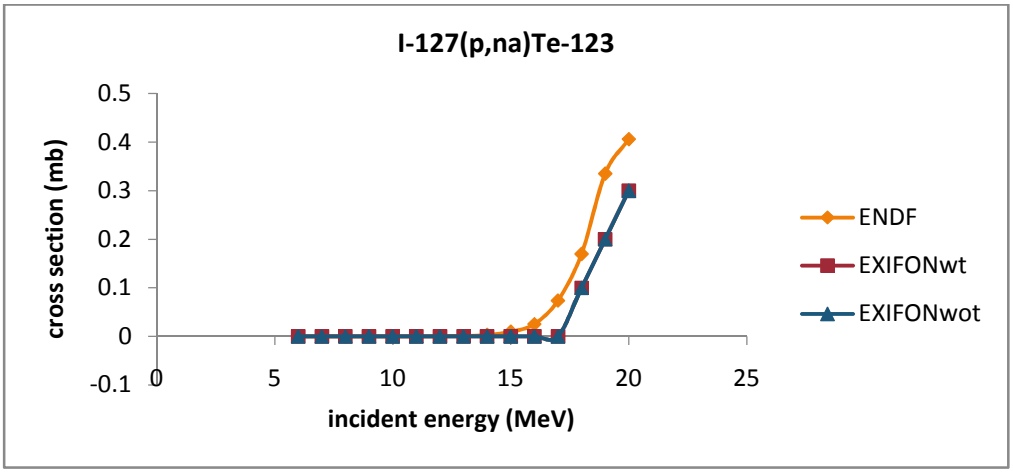

Fig 4.13 Excitation function I-127 (p, na) Te-123 reaction

I-127(n,p)Te 127 reaction shown in Figure4.6 is a direct reaction in which neutron replaces proton particle from I-127 nucleus for the production of Te-127.The graph shows agreement of calculated and ENDF data, but, at 19MeV incident energy there appears to be an intersection of the two datasets from where ENDF data file drops while calculated dataset continues to rise.Tellurium 127 is useful for serving as precursor in production of other radioisotopes; it has a half life of 113 days and decays through emitting gamma radiation.

I-127(p, 2n) Xe-126 depicted in Figure 4.7 is a break up reaction in which proton particle break up I-127 nucleus leading to the production of Xenon 126.Xenon 126 is useful for the production of radioactive Barium 128, which is important in diagnosis of gastric ailments. Calculated datasets (EXIFON) and ENDF data file in this graph shows a perfect match, an indication total agreement of the two datasets. Both datasets exhibit threshold energy of 10MeV and peak cross-section at incident energy of 20MeV and 19MeV respectively.

The picture exhibited in Figure 4.8 shows an elastic scattering reaction I-127(p,p)I-127 between target nucleus of I27 and incident proton particle leading to ejection of proton. This graph shows the two datasets exhibit similar trend of rising cross-section as incident energy increases.

In Figure 4.9, the reaction I-127(p,g)Xe-128 produces radioisotope Xe-128. Xenon-128 is useful in serving as target nucleus for other nuclear reactions.

There is general agreement between calculated datasets (EXIFON) and ENDF data file. It is further observed that there was much deviation between the two data sets. The calculated data sets cross-section was higher than the ENDF data file. This type of reaction is a radiative capture in which I-127 nucleus capture the incident proton particle and absorbs it to produce a compound Xenon 128.

The graph in Figure 4.10 shows a spallation reaction I-127(n, 3n)I-125 in which neutron particle ejects three neutron particles from the nucleus of I-127 to produce I-125, an important radioisotope with half life of 56 days and decays by k-capture and gamma emission.I-125 is useful in treatment of prostate cancer, and for production of other

medically important radioisotopes of Iodine. The graph shows a good agreement between calculated data (EXIFON) and ENDF data file cross-sections.

Figure 4.11 shows the excitation function for the production of I-126 which can be produced through I-127(p,np) I-126 reaction.I-126 can be a useful target nucleus for production of I-123, I-124 and I-125. The graph shows a very good agreement between calculated datasets (EXIFON) and evaluated ENDF data file. 14MeV is the common threshold energy for the two datasets and the reaction is essentially a many body reaction.

The graph in Figure 4.12 shows the excitation function for the production Tellurium 124 in the reaction I-127(p,a) Te 124.Tellurium - 124 is important for the production of I-123 and I-124 which is a PET isotope. Both calculated datasets and ENDF data file indicate increase cross-section as incident energy increases. The reaction appears to be a break up where proton particles break up I-127 nucleus to produce Te-124 and alpha particle.

In Figure 4.13, the graph shows I-127(p,na) reaction for the production of Tellurium 123 isotope.Tellurium 123 is important for production radioactive I-123 and biological and biomedical labelling. Calculated data (Exifon) and ENDF data file agree only in the proportionate increase in cross-section with corresponding increase in incident energy. Te-123 isotope has a half life of 121 days and decays by gamma emission.

Table 4.16EXIFON cross-sectiondata for different reaction channels.

ENERGY	(p,an) Te^{123}	(p,ag) Te^{124}	(p,pn) I^{126}	(p,ng) Xe^{127}	(p,2ng) Xe^{126}	(a,pn) Xe^{129}	(a,p) Xe^{130}	(a,pg) Xe^{130}	(a,2n) Cs^{129}	(a,2ng) Cs^{129}	(a,n) Cs^{130}	(a,ng) Cs^{130}	(a,g) Cs^{131}
5	0	0	0	18.2	0	0	0	0	0	0	0	0	0
6	0	0	0	67.1	0	0	0	0	0	0	0	0	0
7	0	0	0	138.6	0	0	0	0	0	0	0	0	0
8	0	0	0	232	0	0	0	0	0	0	0	0	0
9	0	0.1	0	346.8	0	0	0	0	0	0	0	0	0
10	0	0.3	0	389.6	92.7	0	0	0	0	0	0	0	0
11	0	0.6	0	283.2	335.1	0	0	0	0	0	0	0	0
12	0	1.1	0	171.2	556.9	0	0	0	0	0	0	0	0
13	0	1.8	3.1	101.9	715.2	0	0	0	0	0	42.7	42.7	0.3
14	0	2.6	11.8	65.9	823.5	0	0.1	0	0	0	107.3	107.3	0.5
15	0	3.5	25.2	48.8	899.6	0	0.2	0	0	0	191.4	191.3	0.7
16	0.3	4.4	37.7	41	955.3	0	0.4	1.3	1.3	1	294.6	293.2	0.9
17	0.7	5.1	49	37.7	997.3	0	0.9	90.2	90.2	80.7	416.7	326.3	1.1
18	1.3	5.7	59.7	36.4	1029.5	0	1.7	275.5	275.5	264.3	552.5	276.6	1.2
19	2.1	6.2	70.6	36	995.4	0	2.8	495.7	495.7	486.7	675.9	179.7	1.4
20	3	6.7	81.8	35.7	758.3	0.1	4.2	675.7	675.7	670.1	785.9	109.4	1.4

Table 4.16 shows the cross-sections obtained for various reaction channels with I^{127} target using EXIFON code for different energies (no comparative EXFOR or ENDF data).

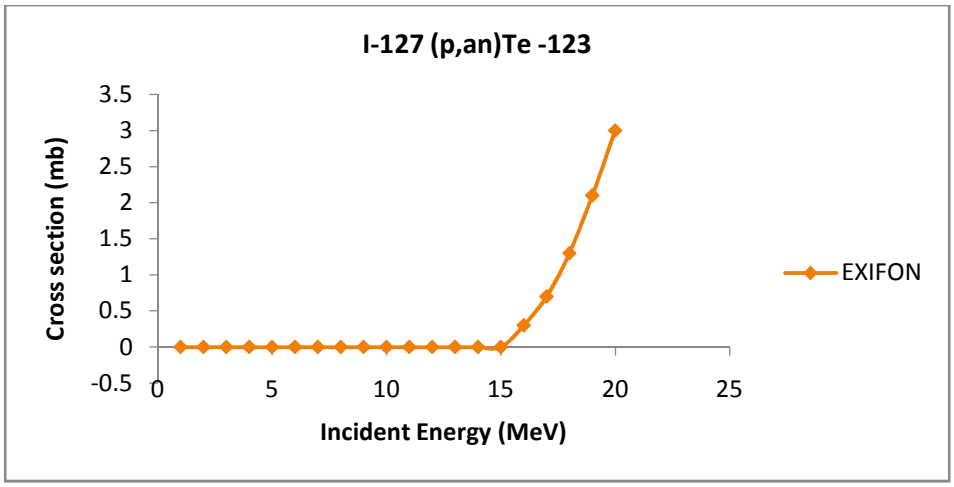

Figure 4.14 Excitation function I-127 (p,an) Te123 reaction

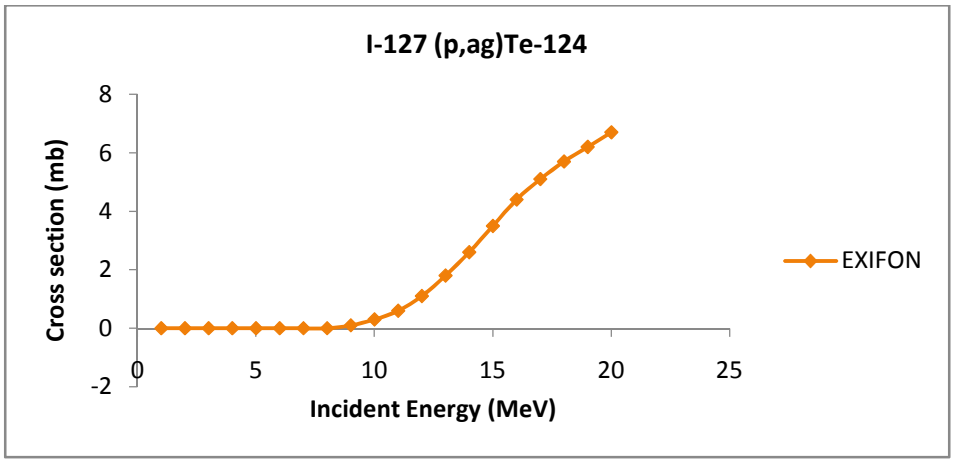

Figure 4.15 Excitation function I-127 (p,ag) Te-124 reaction

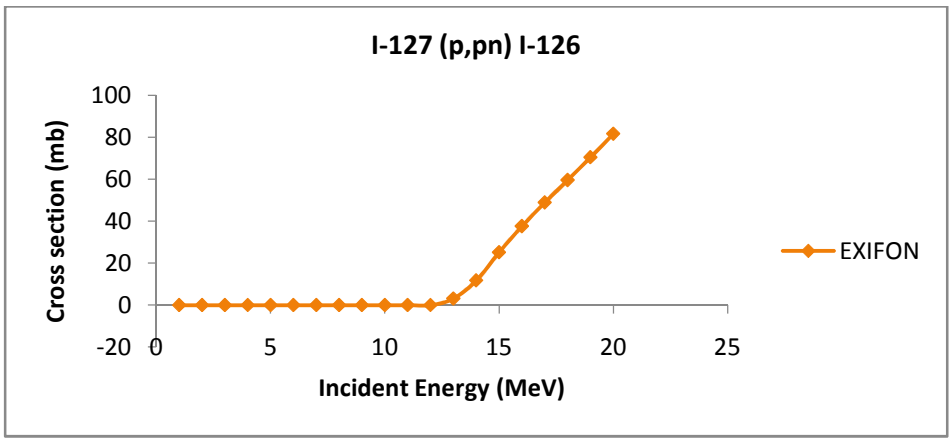

Figure 4.16 Excitation function I-127 (p,pn) I-126 reaction

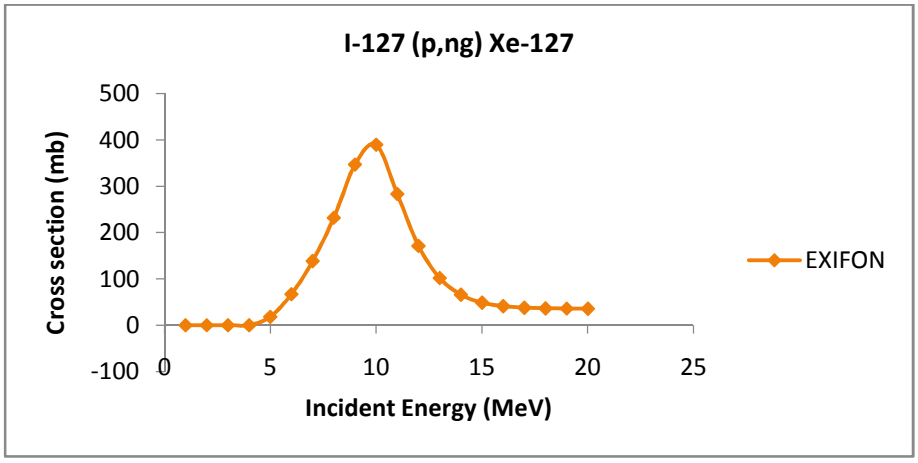

Figure 4.17 Excitation function for I-127 (p,ng)XeI-127 reaction

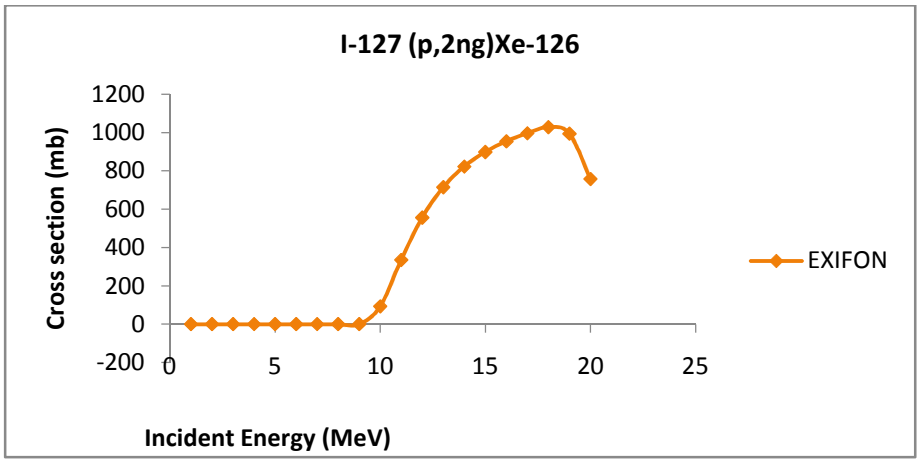

Figure 4.18 Excitation function I-127 (p,2ng) Xe-126 reaction

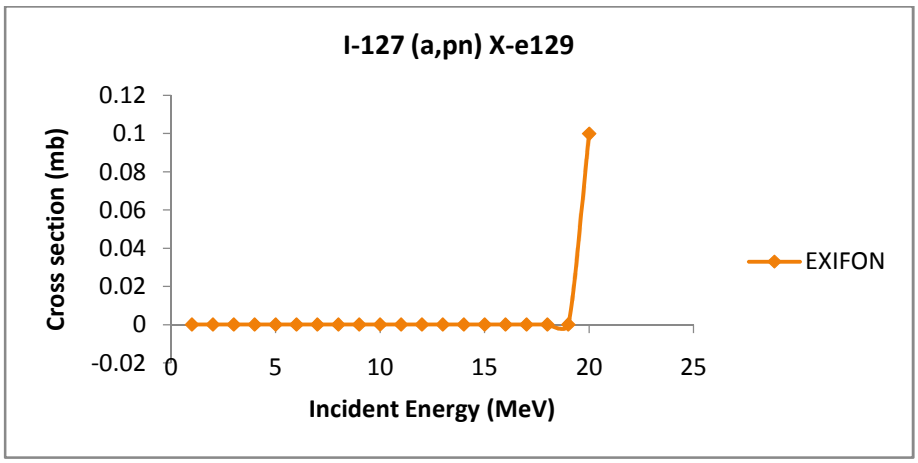

Figure 4.19 Excitation function I-127 (a,pn) Xe-129 reaction

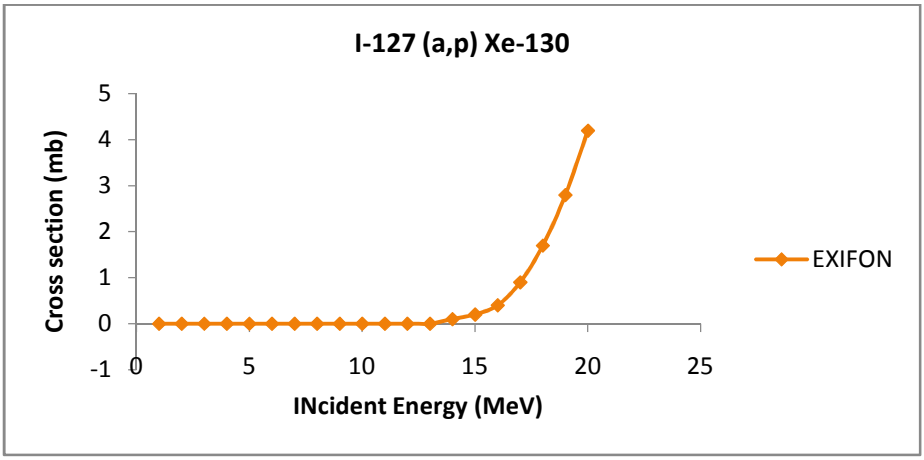

Figure 4.20 Excitation function I-127 (a,p) Xe130 reaction

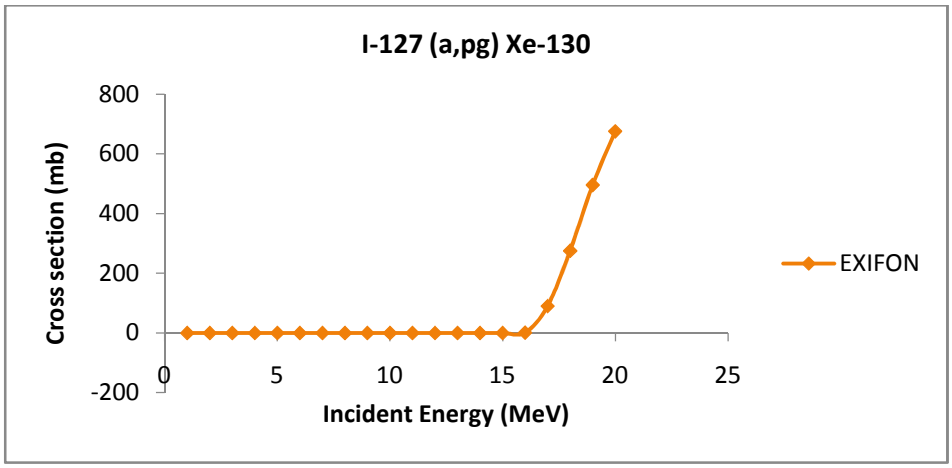

Figure 4.21 Excitation function I-127 (a,pg)Xe-130 reaction

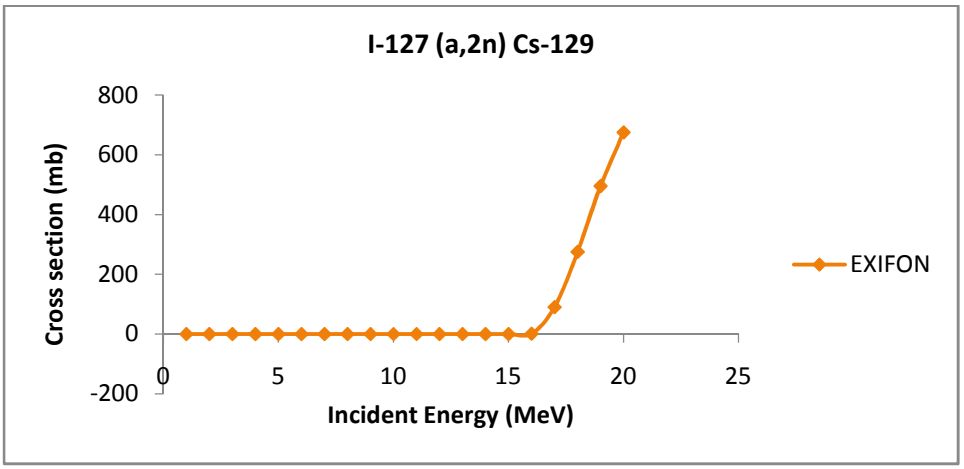

Figure 4.22 Excitation function I-127 (a,2n) Cs-129 reaction

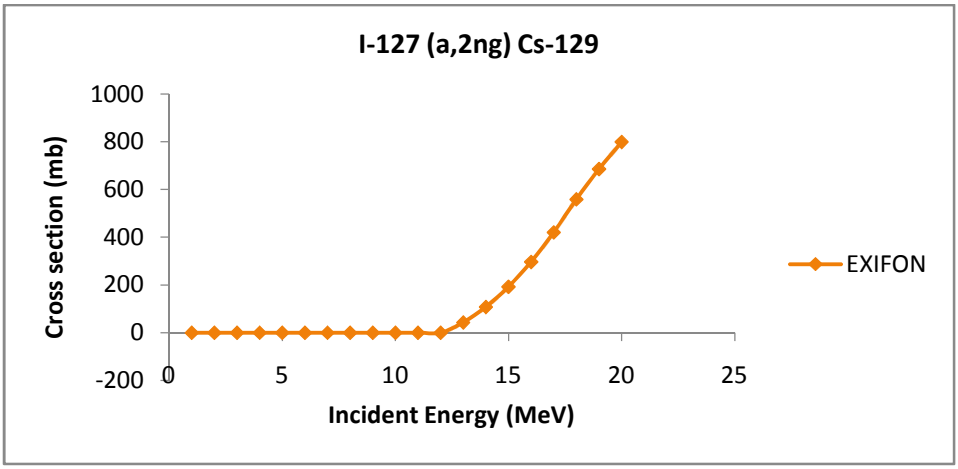

Figure 4.23 Excitation function I-127 (a,2ng) Cs129 reaction

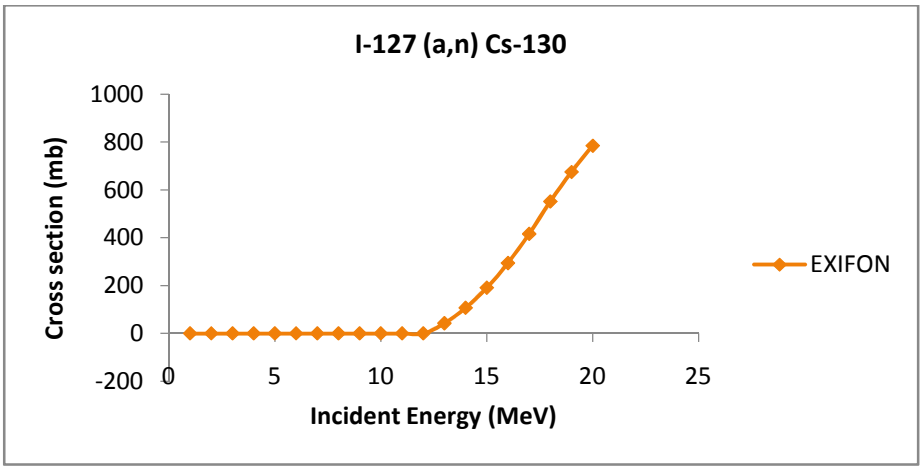

Figure 4.24 Excitation function I-127 (a,n) Cs-130reaction

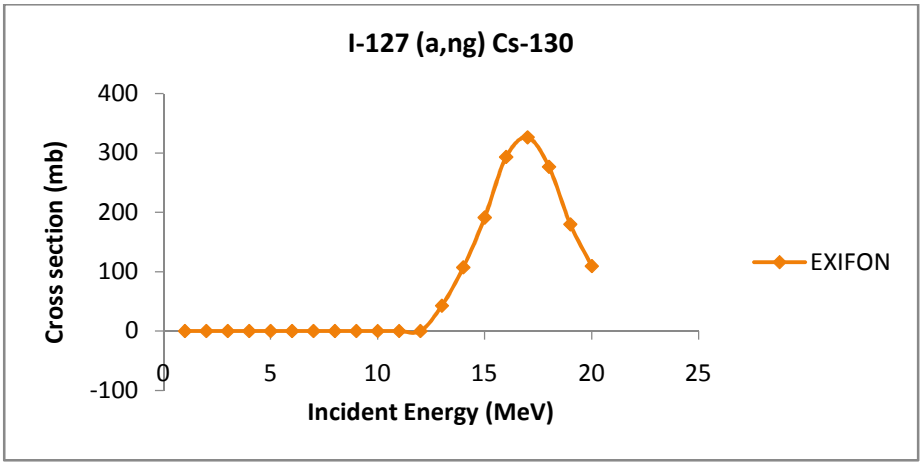

Figure 4.25 Excitation function I-127 (a,ng) Cs-130 reaction

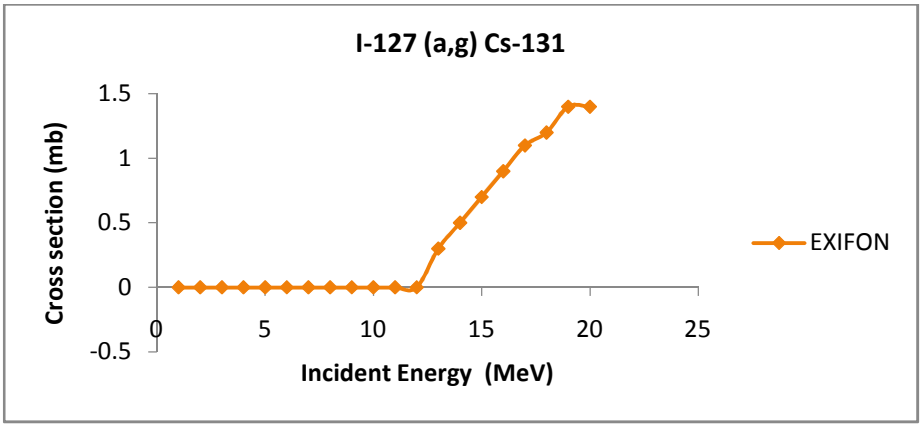

Figure4.26 Excitation function I-127 (a,g)Cs-131 reaction

Figure 4.14 shows the reaction I-127(p, an) Te-123 for the excitation function for the production of radioisotope Tellurium 123 with the half life of 121 days. It decays with gamma emission. The reaction is a many body reaction where proton hits with higher kinetic energy and emits alpha and neutron particles. The graph shows threshold energy for the reaction to be 16MeV.

Figure 4.15 shows reaction I-127(p, ag) Te-124 for the production of Tellurium -124. The threshold energy for the production of Tellurium 124 at excited state is 9MeV.Figure 4.16 is a graph that features a many body reaction where proton particle passes through I-127 nucleus and eject neutron particle to produce I-126. Threshold energy for this reaction is 13MeV with cross-section of 3.1mbarns. The cross-section is also proportional to incident energy from the calculated data.

Xenon 127 is useful for ventilation perfusion and VQ scan (medical imaging procedures).Figure 4.17 shows the excitation function of the interaction between proton and I-127 nucleus for the production of Xenon 127, with half life of 34 days. It emits only gamma rays while decaying. Threshold energy for the reaction is 5MeV, reaching peak cross-section of 389.6mbarns at 10MeV, which plunges thereafter with increasing incident energy to 35.7barns at peak range of the incident energy (20MeV).

Figure 4.18 is the excitation function for the production of Xenon 126 radioisotope. The threshold for this reaction is 10MeV with corresponding cross-section of 92.7mbarns. The cross-section increases as incident energy increases up to 18MeV which is its peak at 1029.5millibarns. From this point, the cross-section decreases with increasing energy within the calculated range.Figure 4.19 is a break up reaction where alpha particle breaks up

nucleus of I-127 to produce stable Xenon 129 and emit proton and neutron particles.Xenon 129 is used for magnetic resonance imaging of gas flow in lungs. The reaction commences at 20MeV.

Figure 4.20 is a knock out reaction in which alpha displaces proton particle from the nucleus of I-127 and produce Xenon 130.Xenon 130 is useful as target nucleus for other reactions. At threshold of 14MeV the reaction proceeds.Figure 4.21 shows a compound nuclear reaction I-127 (a,pg)Xe- 130 for production of Xenon 130 with threshold of 16MeV.

The I-127(a, 2n) Cs-129 in Figure 4.22 is a break up reaction for the production of caesium- 129 which has a half life of 31 hours. It decays through k-capture and gamma emission. 16MeV is the threshold energy for this reaction.Cs 129 could be a useful target in other nuclear reactions.The graph in Figure 4.23 shows a compound reaction I-127(a, 2ng) Cs-129 for the production of caesium- 129. Threshold energy of 13MeV initiates the reaction.

Figure 4.24 indicates the reaction I-127(a, n) Cs130 for the production of caesium- 130. This is a break up reaction; caesium 130 has a half life 30 minutes and decays by e+ and gamma emission while reaction threshold stands at 13MeV and cross-section rise from threshold proportionately.The situation in Figure 25 shows a compound reaction I-127 (a, ng) Cs-130 which produces caesium-130 at excited state. Cs-130 has half life of 30 minutes and decays from gamma and positron emission. 13MeV is threshold incident energy while the peak excitation function is at 326.3mbarns with 17MeV energy. Hence it lowers down as incident energy rises.

Figure 4.26 show excitation function for the reaction I-127(a, g)Cs-131.Cs-131 is important

for Brachytherapy, a form of topical tumor treatmentThreshold for this reaction is 13MeV which exhibits the radiative capture of alpha particle by I-127 to produce caesium -131 at excited state. This radioisotope has half life of 10.2days and decays through k-capture and positron emission.

The following reactions are the nuclear reactions for the calculated (EXIFON) datasets with zero cross- section.This infers that the probability for these reactions to take place within the stipulated energy range of this research (1-20MeV) is zero.Thus, these reactions can only take place at incident energies greater than 20MeV. The nuclear reactions are as follows: I-127(n,2p)Sb-126 half life 9 hours, I-127(n,2np)Te-125 half life 58days decays by gamma emission, I-127(p,2p)Te-126 (Stable), I-127(p,2np)I-125 half life 56days decays by k-capture and gamma emission, I-127(a,na)I-126 half life 13 days decays through e-, e+ and gamma emission, I-127(a,an)I-126 half life 13 days decays through e-, e+ and gamma emission, I-127(a,2p)I-129 half life 1.7E7years decays by e- and gamma emissionI-127(a,2np)Xe-128, I-127(a,np)Xe-129 and I-127(a,3n)Cs128 half life 3.1 minutes decays through e+ emission.

Table 4.17Threshold Energy and Maximum Cross Section for Particle Induced Reactions on I-127

REACTION	PRODUCT	THRESHOLD ENERGY (MeV)	MAXIMUM CROSS SECTION (mb)
I127(a,a) I127	Iodine127	20	10.7
I127(a,na) I126	Iodine126	17	2.7
I127(a,an)I126	Iodine126	-	-
I127(a,p) Xe130	Xenon130	18	0.3
I127(a,np) Xe129	Xenon129	16	3
I127(a,2p) I129	Iodine129	-	-
I127(a,2np) Xe128	Xenon128	9	9.7
I127(a,n) Cs130	caesium130	13	785.9
I127(a,2n) Cs129*	caesium129	17	0.4
I127(a,pn) Xe129	Xenon129	15	7.5
I127(a,3n) Cs128	Caesium 128	-	-
I127(a,g)Cs131	Caesium 131	7	19.9
I127(a,ng) Cs130	Caesium 130	13	326.3
I127(a,pg) Xe130	Xenon130	18	747.7
I127(a,2ng) Cs129	Caesium 129	16	670.1
I127(n,nà) Sb123	Antimony 123	20	-
I127(n,àg) Sb124*	Antimony 124	10	1564
I127(n,àn) Sb123	Antimony 123	10	760.4
I127(n,p) Te127	Tellurium 127	14	2.5
I127(n,np) Te126	Tellurium 126	13	81.8
I127(n,2p) Sb125	Antimony 125	-	-
I127(n,2np) Te125	Tellurium 125	-	-
I127(n,2n) I126	Iodine126	10	1585.7
I127(n,pn) Te126	Tellurium 126	7	177.1
I127(n,3n) I125	Iodine125	18	799.8
I127(n,g) I128	Iodine128	1	3.2
I127(n,pg) Te127	Tellurium 127	19	314.7
I127(n,2ng) I126	Iodine126	10	107.3
I127(P,à) Te124	Tellurium 124	10	758
I127(P,nà) Te123	Tellurium 123	5	1111.4
I127(P,àg) Te124	Tellurium 124	5	389
I127(P,àn) Te123	Tellurium 123	5	1.9
I127(p,np) I126	Iodine126	14	2.45
I127(p,2p) Te126	Tellurium 126	-	-
I127(p,2np) I125	Iodine 125	14	4.2
I127(p,n) Xe127	Xenon 127	16	675.7
I127(p,2n) Xe126	Xenon 126	10	1073
I127(p,pn) I126	Iodine126	13	765.9
I127(p,3n) Xe125	Xenon 125	16	670.1
I127(p,g) Xe128	Xenon 128	16	670.1
I127(p,ng) Xe127	Xenon 127	5	389.6
I127(p,2ng) Xe126	Xenon 126	10	1029.5

Table 4.17 shows the threshold energy and maximum cross-section for all reactions within this research work, except those produce I-127 as residue. The reactions with no data have not attained their threshold energy.

Table 4.18 Nuclear Data for Reactions with Energy for Maximum Cross Section

Reaction	Product	Threshold Energy (MeV)	Maximum cross section(mb)	Energy for max cross section(MeV)
I-127(p,ng) Xe-127	Xenon -127	5	389.6	10
I-127(p,2ng) Xe-126	Xenon -126	10	1029.5	18
I-127(a,ng) Cs-130	Caesium -130	13	326.3	17

Table 4.18 shows the only reaction channels that attain energy for maximum cross-section; all other reactions have only threshold energy but have not attained their pulse peak in the excitation function due to limitation of incident energy to 20 MeV.

CHAPTER FIVE
(SUMMARY AND CONCLUSION)

5.1SUMMARY

In this research work, the excitation functions for the formation of $^{123,124,125}Sb$; $^{123,124,125,126,127}Te$; $^{125,126,128,129}I$; $^{125,126,127,128,129}Xe$ and $^{128,129,130,131}Cs$ in the interactions of the nucleus of ^{127}I with protons, neutrons, and alpha particles were investigated using EXIFON code. Hence, this work has accomplished finding the Threshold energy for the production of all the above mentioned radionuclides, minimum and maximum cross-sections for the reactions.The results generated in this work were compared with experimental data (EXFOR) and evaluated data (ENDF).

Table 5.1 Nuclear Data Summary for (Exifon with and without shell structure) and comparative EXFOR and ENDF data.

REACTION	PRODUCT	THRESHOLD ENERGY (MeV)				MAXIMUM CROSS SECTION (mb)			
		EXIFONwt	EXIFONwot	EXFOR	ENDF	EXIFONwt	EXIFONwot	EXFOR	ENDF
I-127(n,2n)	I-126	10	10	10	9	1580	1585.7	1707	1563.29
I-127(n,np)	Te-126	17	17	9	8	0.6	0.5	0.37	0.38
I-127(n,na)	Sb-123	20	20	14	10	-	-	0.08	0.43
I-127(p,3n)	Xe-125	19	19	18	19	327.5	314.7	23.5	22.55

The above table shows the threshold energy, minimum cross-section and maximum cross-section for EXIFON, EXFOR and ENDF data sets for (n,2n), (n,np), (n,na) and (p,3n) reactions on I-127.

Table 5.2 Nuclear Data Summary for figures 6-13.

Reaction	Product	Threshold Energy (MeV)			Maximum cross section (MeV)		
		Exifon wt	Exifon wot	ENDF	Exifon wt	Exifon wo	ENDF
I-127(n,p)	T e-127	7	7	1	28.2	27.4	23
I-127(p,2n)	Xe-126	10	10	9	1072.88	1073	1055
I-127(p,p)	I-127	7	7	2	177.4	177.1	118.4
I-127(p,g)	Xe-128	5	5	1	2.4	2.3	11.7
I-127(n,3n)	I-125	18	18	17	747.7	799.8	362
I-127(p,np)	I-126	14	14	10	2.5	2.4	2.88
I-127(p,a)	Te-124	9	9	1	9.8	9.7	9.9
I-127(p,na)	Te-123	18	18	7	0.3	0.3	0.41

The above table shows the threshold energy, minimum cross – section and maximum cross – section for EXIFON and ENDF data sets,` for (n,p) (p,2n), (p,p), (p,g), (n,3n), (p,np),(p.a) and (p,na) reactions on I-127

Table 5.3 Summary of calculated reaction data for EXIFON ONLY particle induced reactions on I-127 target.

Reaction	**Product**	**Threshold Energy(MeV)**	**Maximum cross section(mb)**
I-127(P,àn) Te-123	Tellurium -123	5	1.9
I-127(P,àg) Te-124	Tellurium -124	5	389
I-127(p,pn) I-126	Iodine -126	13	765.9
I-127(p,ng) Xe-127	Xenon -127	13	109.4
I-127(p,2ng) Xe-126	Xenon -126	15	8.5
I-127(a,pn) Xe-129	Xenon -129	15	7.5
I-127(a,p) Xe-130	Xenon -130	18	0.3
I-127(a,pg) Xe-130	Xenon -130	18	747.7
I-127(a,2n) Cs-129	caesium -129	17	0.4
I-127(a,n) Cs-130	caesium -130	13	785.9
I-127(a,ng) Cs-130	Caesium -130	7	109.4
I-127(a,g)Cs-131	Caesium -131	7	19.9

The above table shows the threshold energy, minimum cross- section and maximum cross-section for EXIFON data sets only, for (p,ng), (p,2ng) and (a.ng) have 10MeV, 18MeV and 17MeV as energy for maximum cross-section respectively.

The study also obtained zero cross-section for reaction channels I-127 (n,2p)Sb-126, (n,2np)Te-125, (p,2p)Te-126, (p,2np)I-125, (a,an)I-126, (a,na)I-126, (a,2p)I-129, (a,2np)Xe-128, (a,np)Xe-129 and (a,3n)Cs128 across the energy range 1 – 20MeV. This infers that reaction on these channels could only take place at energies higher than 20 MeV.

5.2 CONCLUSION

This research work investigated the nuclear data for the production of medically important radioisotopes using particle induced reactions on stable I-127 using computer code EXIFON. In this work, incident particles that include protons, neutrons and alpha particles were used within the energy range of 0 – 20 MeV for particle induced reactions to produce a number of medically useful radioisotopes.

The essence of the research work is to generate the essential nuclear data necessary for optimizing radioisotope production route, efficiency and purity; these include nuclear cross section, excitation function, threshold energy, maximum cross section and energy for maximum cross section.

Four sets of results were generated with regard to comparison with experimental (EXFOR) and evaluated (ENDF) nuclear data files of the I.A.E.A. The first set of results have comparable EXFOR and ENDF and include I-127 (n,2n)I-126, (n,np)Te-126, (n,na)Sb-123 and (p,3n)Xe—125 reactions. The second is the only reaction that has both EXFOR and ENDF data comparison, the I-127 (p,n)Xe—127. The third set has comparison with ENDF data sets and comprise of I-127 (n,p)Te-127, (p,2n)Xe-126, (p,g)Xe-128, (n,3n)I-125, (p,np)I-126, (p,a)Te-124and (p,na)Te-123 reactions.

The fourth set are reactions that have EXIFON only, having neither EXFOR nor ENDF comparison and include the reactions I-127 (p,an)Te-123, (p,ag)Te-124, (ppn)I-126, (p,ng)Xe—127, (p2ng)Xe-126, (a,pn)Xe-129, (a,p)Xe-130, (a,pg)Xe-130, (a,2n)Cs-129, (a,ng)Cs-130 and (a,g)Cs-131. This nuclear data will be a useful addition to the I.A.E.A data libraries.

The research also found those with zero cross section within the 1 – 20MeV incident energy range indicating no probability of reaction taking place within this range; they include I-127 (n,2p)Sb-126, (n,2np)Te-125, (p,2p)Te-126, (p,2np)I-125, (a,an)I-126, (a,na)I-126, (a,2p)I-129, (a,2np)Xe-128, (a,np)Xe-129 and (a,3n)Cs128reactions.. Hence, the future research will be to obtain nuclear cross section, excitation function, threshold energy, maximum cross section and corresponding energy for these reactions by increasing the energy of the incident particles.

5.3 RECOMMENDATIONS

1. There is need for additional work for the experimental data to serve as comparison basis between measured data and theoretical code.
2. For reactions where zero cross-section were generated across the incident energy range of this work, it is recommended that additional work be conducted with higher incident energies to obtain the threshold energy for each reaction.
3. Institutions of learning should conduct further studies on more artificially producedradioisotopes and their applications on social life; one important area in this direction is malaria control where sterile methods can be used to limit mosquito reproduction.

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APPENDIX (A) - (Papers published from the Dissertation)

APPENDIX (A) papers published and presented from this dissertation include:

(I) - THEORETICAL CALCULATION OF EXCITATION FUNCTION OF (p,n), (p,np) AND (p,2n) REACTIONS ON STABLE I-127 FROM 1 TO 20MeV, published in the 50th edition of the Journal of Nigerian Association of Mathematical Physics, page 253 – 258.

(II) - THEORETICAL CALCULATION OF EXCITATION FUNCTION FOR Cs 130 AND Cs 131 PRODUCTION USING (a,n), (a,ng), (a,g) REACTIONS ON I ^{127} FROM 1 - 20 MeV. A paper presented at 42nd Annual Conference of the Nigerian Institute of Physics heldat Federal University of Technology, Owerri, Imo State. On 18th – 22ndNovember 2019.

Other Appendix materials include,

APPENDIX (B) – EXIFON Code Output

APPENDIX A (I)

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Theoretical Calculation of Excitation Function of (p, n), (p, na), (p, np) and (p, 2n) Reactions on Stable 127I from (1 to 20MeV)

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Abstract

Radioisotopes are becoming increasingly important in nuclear medicine in recent times. This is affirmingly connected with their use in nuclear diagnostic procedures especially the commonly employed positron emission tomography (PET) and single photon emission computed tomography (SPECT) as well in the therapy of a number of ailments such as cancer. This research aim to provide current cross-section production processes in the theoretical and experimental results of proton induced reaction of iodine isotope on projectile energy range of 1–20 MeV in order to improve the reliability of nuclear stimulation. The excitation functions for the production of $^{126,127}Xe$, ^{123}Te and ^{126}I from (p,2n), (p,n), (p,na) and (p, np) reactions on ^{127}I nucleus respectively, were investigated using EXIFON code. The calculated data were compared with experimental data (EXFOR database) and evaluated nuclear data files (ENDF) and a good agreement was obtained. The calculations were aimed to obtain a threshold for each reaction and the maximum cross-section so that to facilitate production of these radionuclides to prevent a medical crisis in the event of a shortage.

Keywords: *Cross section, ENDF, Excitation functions, EXFOR, EXIFON*

1. Introduction

Particles induced reaction cross-section database for both charged and neutral particle provides a fair chance to develop a theoretical tool to predict competing reaction cross-section.

Nuclear theory, using quantum mechanics, is used to predict the probability that a specific nuclear process will occur under certain conditions [1]. The quantitative measure of this prediction is the cross section of the process. This cross section may be measured in the laboratory using experimental techniques that have been strongly developed in the last decades, investigating nuclear reactions involving radioactive nuclei and playing a crucial role in many areas of basic and applied nuclear sciences.

Production of radioisotopes for medical applications is one of the most important directions of nuclear physics. It plays an important role in terms of beneficial applications in both diagnosis and therapy[2]. Treatment of thyroid disorder with radioiodine is one of the examples of therapy using radioisotopes. The diagnosis entails the introduction of a short-lived radionuclide, attached to a suitable pharmaceutical into the patient. followed by measurement of accumulation and movement of activity from outside [3]. using external detectors to capture and form images from the radiation emitted by the radiopharmaceutical, this process is called emission

tomography and involves single photon emission computed tomography (SPECT) and positron emission tomography (PET).

Nuclear diagnostics are now routinely employed throughout the developed world and in many developing countries to detect anomalies in the heart, brain, kidneys, lungs, liver, breast and glands[4]. Also benefitting directly from the routine use of radionuclides are bone and joint disorders along with spinal disorders. The primary principle in all diagnostic studies is that the radiation dose to the patient is kept as low as possible to avoid damage to underlying tissues[5].

However, with the expanding of radioisotopes in medical diagnosis and treatment, there is vulnerability to some sort of supply crisis. if anything hitches the availability of radioisotopes[6]. This was experienced due to shortages of some important radionuclides such as Technetium-99 [3]. This was apparently caused by Reactor stoppages, due to aging infrastructure. Leading to a shortage of Molybdenum-99 from which Technetium is produced. Many medical procedures were canceled leading to delays in diagnoses and use of inferior procedures[7]. These problems have the potential of halting the use of radionuclide in diagnoses and therapy, if alternative routes of production are not utilized to produce the radionuclide.

Looking at the current increase in population, and the teeming morbidity of various types across populations, a medical isotope crisis is sure to cause untold hardship and fatalities if the supply of radionuclides becomes compromised[8]. This forms the basis behind exploring the various alternative routes of radionuclide production. including inducement with particles (such as neutrons, proton), use of cyclotrons and accelerators and low enrichment to mention a few. Isotopes produced from 127I through (p,n), (p,na), (p, np) and (p,2n) reactions are also useful in diagnostics and therapy and hence play an important role in medical applications and research[2].

127I (p,n) produces Xenon 127 which is used in ventilation-perfusion, and for the study of cerebral blood flow measurements. 127I (p,na) yield Tellurium 123, a good precursor for the production of 123I, one of the most important isotopes of Iodine used chiefly for PET and SPECT. 127I (p, np) reaction produces 126I, a precursor for the production of 123,124,125I which are all imaging radioisotopes[9]. and 127I (p,2n) gives Xenon 126 which is used for the production of Ba128, an important nuclide for the study of gastric diseases as well as in tracing gas migration in geological studies.

For the purpose of optimization of the production route of medical radionuclides provide higher yield, and purity. There is a need for evaluating and maintaining nuclear data. which is to contain data on nuclear reaction cross section, excitation function, reaction energetic, angular distribution, etc [10]. Hence the collation, compilation and review the nuclear data. The International Atomic Energy Agency (IAEA) has been conducting this task for about five decades and which is made accessible online via the IAEA nuclear data services website. for the purpose of research, innovation[11], dissemination and development and further, through such data, the evaluation of reaction cross section and other calculations are validated through comparison.

The need for this research emanates from the fact that with an increasing world population and a commensurate rise in medical cases. requiring the use of radioisotopes for imaging or therapy. any shortage of

radionuclides may make procedures vulnerable to delay or halt[7]. This scenario may bring rancor, acrimony or even fatalities in hospitals. Hence there is a need for finding other alternative routes of production of radionuclide to take care of any eventual shortages[7].

The main objectives of this research are to obtain the minimum and maximum cross section for the reactions and their corresponding incident energies as well as to obtain the excitation functions also to relate the radioisotope products to their uses in nuclear medicine.

2. Theoretical Background

Nuclear reactions are described by several models which are linked together to calculate nuclear cross sections. The statistical (or compound nucleus) model of nuclear reactions belongs to the group of reaction models that are in slow order along with the pre-equilibrium model [12]. In the statistical model, this has over the years been receiving attention for a description of reactions. In the low and intermediate region up to 20MeV it is assumed that a compound nucleus is formed with excitation energy high enough so that the interactions of the incident particle with a target nucleus may excite many states. Further, the incident energy is shared between the individual components of the nucleus which fully equilibrate before decay takes place. This implies that CN formation does not correlate with the decay process and hence the existence of independent expressions to describe the ingredients of the process as summed up in equation 1.

The same residual interaction is used for computing both the formation and decay of the compound nucleus within SMC as well as SMD processes. Thus there is no reference to the optical model (OM) reaction cross section. The OM cross section for charged particles was used to simulate coulomb effects in the threshold region only [13].

The calculation of Multiple Particle Emission (MPE) is generalized. Up to three decays of the compound nucleus are considered. The model is formulated in detail for predicting emission spectra for neutrons, protons, alphas and photons including equilibrium, pre-equilibrium, direct as well as MPE processes in a consistent manner. Calculations are performed with one physical parameter set for several energies and several reaction types.

2.1 Statistical Multistep Model

Statistical multistep models are very successful in describing nuclear reactions at energies up to about 100 MeV. These models enable the description of direct, pre-equilibrium and equilibrium processes in a constant way for a wide number range and various reaction channels e.g. neutrons, protons, alpha particles, gamma rays.

The application of Statistical Multistep Model to heavy nuclei requires the consideration of fission as a competing process to particle and gamma-ray emissions. Therefore, Statistical Multistep Models should be extended to the fission channel.

In the Statistical Multistep Model, the total emission spectrum of the process (a, xb) is divided into three main parts [13].

$$\frac{d\,\sigma_{a,xb(E_a)}}{dE_b} = \frac{d\,\sigma_{a,b}^{SMD}(E_a)}{dE_b} + \frac{d\,\sigma_{a,b}^{SMc}(E_a)}{dE_b} + \frac{d\,\sigma_{a,xb}^{MPE}(E_a)}{dE_b} \quad \ldots\ldots (1)$$

The first term on the right-hand side of the equation (2) represents the statistical multistep direct (SMD) part which contains from single multistep to five-step contributions. Besides particle-hole excitations also collective photon excitations are considered. The second term represents the statistical multistep compound (SMC) emission which is based on a master equation. Both terms together (SMD+SMC) represent the first chance emission process (Kalka, 1992). The last term of the equation (2) represent multiple particle emission (MPE) reaction which includes the second chance, third chance emissions, etc. These terms are summarized below:

$$\frac{d\,\sigma_{a,xb}^{MPE}(E_a)}{dE_b} = \Sigma\frac{d\,\sigma_{a,cb(E_a)}}{dE_b} + \Sigma\frac{d\,\sigma_{a,cdb(E_a)}}{dE_b} + \ldots\ldots \quad (2)$$

To keep the model tractable, a simple two-body interaction is assumed [12]

$$I(r_1, r_2) = -4\pi \frac{F_0}{A} [\chi_{nl}(R)]^{-4}\, \delta(r_1 - r_2)\, \delta\,(r_{1-R)} \ldots\ldots\ldots\ldots \quad (3)$$

With F_0 = 27.5 MeV taken from nuclear structure consideration. The factor $[\chi_{nl}(R)]^{-4}$ contains the wave function at the nuclear radius $R = r_0 A^{1/3}$

3. METHODOLOGY

The computer code EXIFON has been used for the calculation of nuclear reactions cross-section induced from projectile energy range of 1–20 MeV. Commercially available radioisotope sources are: (1). nuclear reactor sources, (2). accelerator sources and (3). Cyclotrons sources.

The calculated results were compared with the experimental values taken from the EXFOR database as well as Evaluated data ENDF from IAEA nuclear data section (NDS).

EXFOR is the exchange format for the transition of experimental reaction data between national and international nuclear data centers for the benefit of nuclear users in all countries. It is the library and format for the collection, storage, exchange and retrieval of experimental nuclear reaction data

3.1 Computer code EXIFON

Various computer codes were developed based on different models, which are enable to study nuclear structure and reaction mechanisms. The computer code EXIFON is very important for several technical applications if the experimental data are not available or unable to measure the reaction cross-sections due to the experimental

difficulties. This code is capable of calculating equilibrium and pre-equilibrium emission cross-section, and valid for excitation energy of the compound nucleus up to 100 MeV.

EXIFON code was used to perform theoretical calculations of cross sections, the command prompt program was run with explicit definition of input and output directories followed by specification of target nucleus and incident particle. Excitation function in the general options section was chosen for this calculation.

Incident energy number was then specified as well as first incident energy and step, the corresponding cross-section in relation to each particular energy step was to obtain ed. In the output directory already set, output data (OUTEXT) for the calculation was then stored and so also was the.DAT filename stored in the output directory. Results obtained were analyzed in a spreadsheet into tabular form from which graphical charts of the results were obtained.

3.2 Data analysis procedure

The data of this work has been arranged in proper orders and organized by using tabulation method. These organized data, described graphically with the help of spreadsheet, analyzed and interpreted accordingly by comparing with the experimental data.

4. Results and Discussion

The computed reaction cross-sections based on the proton energy using different approaches for isotope are given in figure (1–4) along with the available experimental and evaluated data.

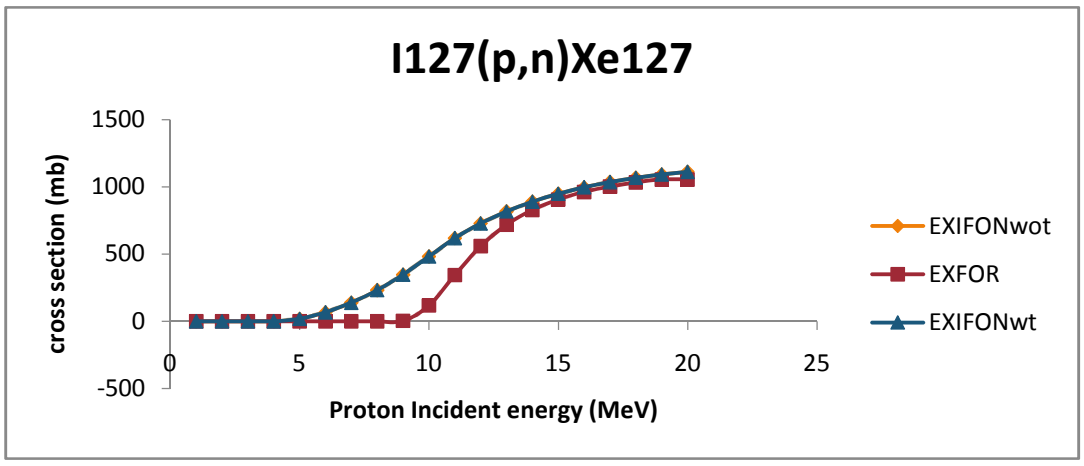

Figure 1. Excitation function for ^{127}I(p,n)Xe127 reaction

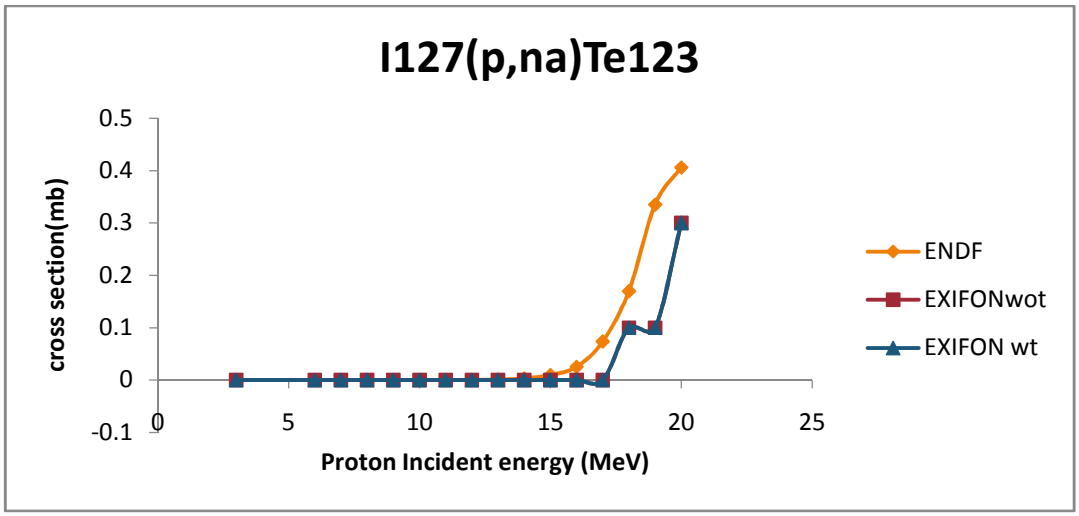

Fig 2 ***Excitation function for ^{127}I(p,na)Te123 reaction***

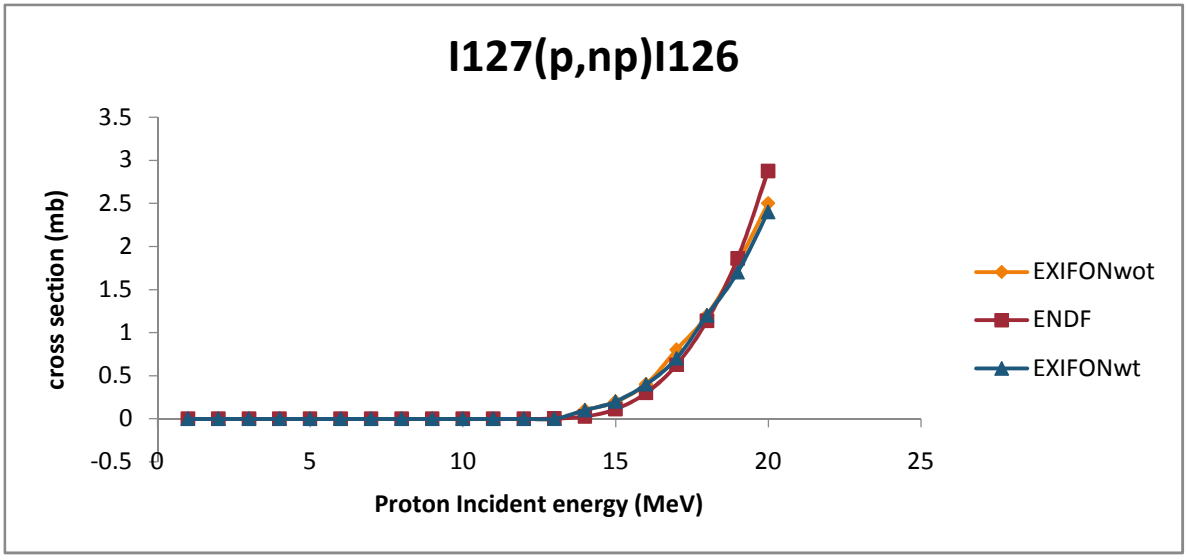

Fig 3 ***Excitation function for ^{127}I(p,np)I126 reaction***

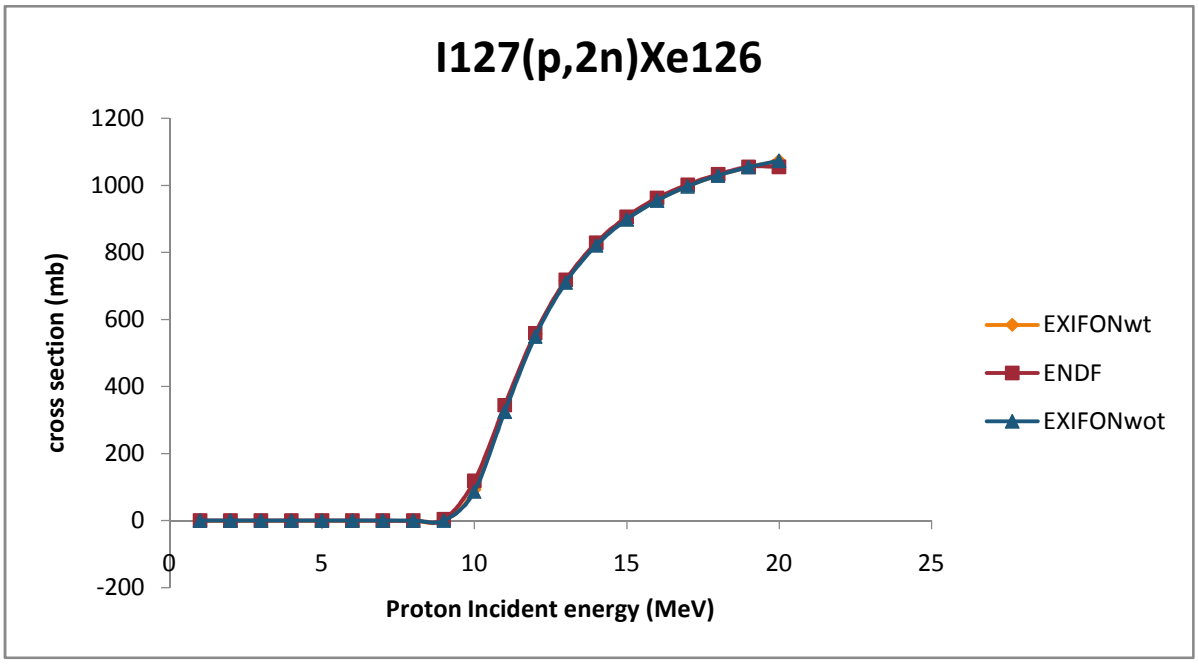

Fig 4 ***Excitation function for ^{127}I(p,2n)Xe126 reaction***

From the results above there is little or no difference between excitation functions with shell and the ones without shell structure, implying that shell structure has little or no effect on the excitation functions.

Xenon-127 is useful for lung ventilation imaging, cerebral brain measurement, and biological tracer studies.

Figure 1 is a knockout reaction in which proton particle displaces neutron in the nucleus of I-127 to produce Xenon 127. Figure 1 shows that both calculated (EXIFON) datasets and experimental data (EXFOR) appear to exhibit a good agreement. EXIFON threshold is 5MeV while EXFOR threshold is 9MeV, however, common is the proportionate trend of rising in cross section while incident energy increases. Xe-127 has a half-life of 75 seconds and decays through gamma emission.

Te123 is useful in the production of I123 which is an important radionuclide of Iodine used extensively in nuclear medical applications.

Figure 2 graph shows I-127(p,na) reaction for the production of Tellurium 123 isotope. Calculated data (EXIFON) and ENDF data file agree only in the proportionate increase in cross-section with a corresponding increase in incident energy. The Te123 isotope has a half-life of 121 days and decays by gamma emission.

I126 is a good isotope that can be used to produce important medical radionuclides like I123,124 and 125 which are good for diagnostics as well as therapy.

Figure 3 shows the production of I126 through I127(p, np) I126 reaction. The graph shows a very good agreement between calculated datasets (EXIFON) and evaluated ENDF data file. 14MeV is the common threshold energy for the two datasets and the reaction is essentially a many-body reaction.

Xe126 is useful for production of barium radioisotope Ba128 used in the study of gastric diseases as well in tracing of gas migration in geological studies.

In Figure 4, I127(p,2n)Xe126 is a break-up reaction in which proton particle break up I127 nucleus leading to the production of Xenon 126. Calculated datasets (EXIFON) and ENDF data file in this graph show a perfect match, an indication total agreement of the two datasets. Both datasets exhibit threshold energy of 10MeV and peak cross section at an incident energy of 20MeV and 19MeV respectively.

Table 1 ***calculated reaction data for the proton-induced reactions (without shell structure) in energy range 0 – 20MeV***

Reaction	**Product**	**Threshold energy (MeV)**	**Minimum cross section(mb)**	**Maximum cross section(mb)**
^{127}I(p,n)	**Xenon 127**	**5**	**18.2**	**1111.3**
^{127}I(p,na)	**Tellurium 123**	**18**	**0.1**	**0.3**
^{127}I(p,np)	**Iodine 126**	**14**	**0.1**	**2.4**
^{127}I(p,2n)	**Xenon 126**	**10**	**92.7**	**1073.0**

Table 2 ***calculated reaction data for the proton-induced reactions (with shell structure) in the energy range 0 – 20MeV***

Reaction	**Product**	**Threshold energy (MeV)**	**Minimum cross section(mb)**	**Maximum cross section(mb)**

^{127}I(p,n)	**Xenon 127**	**5**	**18.3**	**1111.9**
^{127}I(p,na)	**Tellurium 123**	**18**	**0.1**	**0.3**
^{127}I(p,np)	**Iodine 126**	**14**	**0.1**	**2.5**
^{127}I(p,2n)	**Xenon 126**	**10**	**86.4**	**1072.8**

5. Conclusion

The excitation function of the four proton induced nuclear reaction channels of 127I (p,n) 127Xe, 127I (p,na) 123 Te, 127I (p, np) 126I, 127I (p,2n) 126 Xe on iodine isotope were discussed. The reaction cross-section and excitation functions for the taken reaction channels have been studied in the energy range of (1–20MeV).

The experimental data and Evaluated Nuclear Data (ENDF File) were compared with those calculated values using the computer code EXIFON, it can be concluded that, having agreed with experimental and evaluated nuclear data and with little or no effects of the shell structure, the obtained data will be very useful for production of Xenon 127, Xenon126, Tellurium 123 and Iodine 126 with efficiency and purity. These radionuclides can directly be applied in nuclear medicine procedures, or indirectly be used to produce other radioisotopes for diagnostic and therapeutic purposes. Providing alternative routes for the production of radioisotope using nuclear reactions will certainly avoid shortages and its subsequent implications.

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APPENDIX A (II)

Theoretical Calculation of Excitation Function for Cs-130 and Cs-131 Production using (a,n), (a,ng) and (a,g) Reactions on Stable ^{127}I from (1 to 20MeV)

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ABSTRACT

Use of radionuclides in diagnoses and therapies of many diseases is becoming a routine part of national and even local healthcare systems around the globe in recent times. Commonly employed nuclear diagnostic procedures such as Positron Emission Tomography (PET) and Single Photon Emission Computed Tomography and many other specialist imaging procedures are now becoming choice means for detecting cancer of many organs and other anomalies just as radiotherapy is being utilized to treat cancers like that of the thyroid with I 131. This research investigates the excitation function calculation for the production of Caesium 130 and 131 via the (a,n), (a,ng) and (a,g) reactions on stable I 127 within energy range of 1-20 MeV using EXIFON Code. Cs-130 and 131 are important radionuclides for radiotherapies of several vital organs as Cs-130 serve as intracavity implant while 131 provides soft X-rays for Brachytherapy. The calculations aim to establish threshold energy, maximum cross sections and Excitation functions for the reactions in an effort to facilitate their production and to prevent medical crisis that could result in case of shortage of these radionuclides.

Keywords: EXIFON, Radionuclide, PET, SPECT

INTRODUCTION – Nuclear reaction parameters such as nuclear cross section and excitation function among others provide fundamental information that facilitate the prediction of the possibility and production as well as purity of nuclear reaction products, or radionuclides and hence play a crucial role in the course of nuclear energy and development of fusion and fission reactors. As a consequence of this principle, nuclear reaction data describes the interactions of various projectiles such as protons, neutrons or alpha particles with target nuclei. These data are becoming increasingly important for various reasons such as optimizing radionuclide production as per reaction channels, analysis of impurities and radionuclide purification as well as ascription of the most suitable method for radionuclide production with high efficiency(Iwamoto, 2007)

In nuclear theory, quantum mechanics is used to predict the probability that a specific nuclear reaction will occur under certain conditions (Hibstie, Mathuthu, & Derso, 2018). This quantitative prediction is the nuclear cross section which can be measured in the laboratory with the use of experimental techniques veritably developed to investigate nuclear reactions involving radioactive nuclei and playing a crucial role in many areas of basic and applied nuclear sciences over the past few decades.

Radioisotope production for use in nuclear medicine has already become one of the most important contributions of nuclear physics because radionuclides play a central role in life saving applications especially nuclear diagnostics and therapeutics. An example of radionuclide therapy is treatment of thyroid disease with radioiodine while nuclear diagnostics involves application of short half life nuclide attached to suitable radiopharmaceutical followed by measurement of nuclear emission as a result of accumulation and movement of activity from outside the body (Qaim, 2012) with the use of external detectors to capture and form images from the emission of radiation by the radiopharmaceutical; this process is called emission tomography which includes PET and SPECT.

Nuclear diagnostics are now routinely applied throughout the developed world and in many developing nations to detect disorders of the human body's vital organs such as the heart, liver, brain, kidney and glands (Ahmad & Koki, 2017). Bone and joint disorders as well as anomalies of the spinal cord are also detected with the same principles. However, as the

medical cases requiring nuclear diagnosis and therapy such as cancers of different organs as well as glandular anomalies are on steady rise, there appears vulnerability to failure of nuclear medical services in the event of radioisotope shortage. Thus if anything hitches the availability if radioisotope, a lot nuclear medical services may halt leading to use of inferior procedures bereft of the needed precision and may cause fatalities. This has happened in the United States during the shortage of Molybdenum which is used in producing Technetium. The shortage was due to stoppages' of nuclear reactors that are needed in the production of the radionuclides (Ruth, 2014). Hence with the teeming morbidity of the Nigerian population a crisis may unfold if steps are not taken to ensure radioisotope availability, this is the basis behind exploring the various routes of radionuclide production including particle inducement reactions with protons, neutrons, alpha particles and photons, use of cyclotrons, particle accelerators as well as low enrichment.

Radioisotopes produced from (a,n), (a,ng) and (a,g) reactions with ^{127}I have been found to play important medical roles. ^{127}I a,n) and ^{127}I a,ng) produces Caesium 130. This radionuclide has a half life of 30 minutes and is used as a localizing agent (Volkert & Huffman, 1999) . ^{127}I (a,g) reaction yields Cs 131 which has a half life of 10.2 days and is a gamma emitter. Cs- 131 is used in intracavity implantation for radiotherapy and also produces soft X-rays, which makes it very suitable for Brachytherapy (Volkert, 2003).

Production routes of medical radionuclides need to be optimized in order to produce higher yields and to achieve high purity (Ahmad & Koki, 2017) and for this to be accomplished, nuclear data which encompasses reaction cross section, excitation function, reaction energetic and angular distribution etc need to be evaluated (Chadwick, 1995). This underlines the theoretical and experimental calculations of excitation functions and other various but important nuclear parameters which the International Atomic Energy Agency (IAEA) has been undertaking for the past five decades for the purpose of research, innovation and nuclear information dissemination. Moreover, it's through such nuclear data evaluations that such parameters (cross section, excitation function etc) are validated through comparison with experimentally generated data.

Hence, the fundamental objectives of this research are obtaining minimum and maximum reaction cross sections for (a,n), (a,ng) and (a,g) reactions on stable ^{127}I and resultant

evaluation of excitation functionsfor the reactions. This is to facilitate the production of Cs 130 and Cs 131using other routes apart from the use of nuclear reactors such as cyclotrons. This will go a long way towards preventing medical crisis due to nuclear radionuclide shortage.

A nation can only achieve development with comprehensive, effective and efficient healthcare system because only healthy citizens are asset to a nation and productivity in all spheres of human Endeavour is only possible with adequate healthcare. Hence, with the indispensable role radioisotopes play in nuclear medical services, in detecting the teeming cases and anomalies that look to stretch our healthcare systems to the limits, production of medical radioisotopes will surely contribute immensely to national development.

THEORETICAL BACKGROUND

Description of nuclear reactions are usually achieved with the use of several nuclear models which are linked together to calculate nuclear cross sections. One of the most important models however, I the Statistical (or Compound nuclear)model which belongs to the group of reaction models in the slow order along with the pre-equilibrium model (Hilaire, 2000). This model has been receiving attention over the years for description of reactions in the low and intermediate region up to 20 MeV. The models provides that a compound nucleus is formed with high enough excitation energy so that the incident particle – target nucleus interaction may excite many states (Ahmad, Yola, & Koki, 2017). In addition, it assumes the incident energy is shared among individual components of the nucleus which equilibrate fully before nuclear decay takes place.

This implies no correlation of compound nucleus formation with the decay process and hence the existence of independent expressions to describe the ingredients of the process as summed up in equation (I). These processes include Statistical Multistep Direct (SMD) and Multistep Compound (SMC).

Same residual interaction was utilized in computing both the formation and decay within SMD and SMC. Thus reference is not tenable to the optical model (OM) reaction cross section. OM cross section for charged particles was used for simulation of Coulomb effects in the threshold region (Ahmad & Koki, 2017).

Multiple particle emission (MPE) calculation is generalized and up to three decays of the compound nucleus are considered. The statistical model is formulated in detail for predicting emission spectra for neutrons, protons, alpha particles and photons with inclusion of equilibrium, pre-equilibrium, direct and MPE processes with high degree of consistency. One physical l parameter set for several energies and reaction types was employed in performing calculations.

Statistical multistep models are very successful in describing nuclear reactions at energies up to about 100 MeV (Kalka, 1992). These models enable the description of direct, pre-equilibrium and equilibrium processes in a constant way for a wide number range and various reaction channels e.g. neutrons, protons, alpha particles, and gamma rays. The application of Statistical Multistep Model to heavy nuclei requires the consideration of fission as a competing process to particle and gamma-ray emissions. Therefore, Statistical Multistep Models should be extended to the fission channel.

STATISTICAL MULTISTEP MODEL

In the Statistical Multistep Model, the total emission spectrum of the process (a, xb) is divided into three main parts (Ahmad & Koki, 2017).

$$\frac{d\,\sigma_{a,xb(E_a)}}{dE_b} = \frac{d\,\sigma_{a,b}^{SMD}(E_a)}{dE_b} + \frac{d\,\sigma_{a,b}^{SMc}(E_a)}{dE_b} + \frac{d\,\sigma_{a,xb}^{MPE}(E_a)}{dE_b} \qquad (2)$$

The first term on the right-hand side of the equation (2) represents the statistical multistep direct (SMD) part which contains from single step to five-step contributions. Besides particle-hole excitations also collective photon excitations are considered. The second term represents the statistical multistep compound (SMC) emission which is based on a master equation. Both terms together (SMD+SMC) represent the first chance emission process (Pandey, Agrawal, & Kumar, 2011). The last term of the equation (2) represent multiple particle emission (MPE) reaction which includes the second chance, third chance emissions, etc. These terms are summarized below:

$$\frac{d\,\sigma_{a,xb}^{MPE}(E_a)}{dE_b} = \sum\frac{d\,\sigma_{a,cb(E_a)}}{dE_b} + \sum\frac{d\,\sigma_{a,cdb(E_a)}}{dE_b} + \ldots\ldots$$

(3)

METHODOLOGY

Theoretical calculations of nuclear cross-sections were performed using nuclear model code EXIFON, the program was run and the input and output directories were defined; this is followed by target nucleus specification. The incident particle and target nucleus were selected and excitation function of in the general options was chosen. The number of incident energy was specified followed by the first incident energy, and then the incident energy step is equally specified. Subsequently, the cross-section corresponding to each particular energy step was generated.

The output data (OUTEXI) for the calculation is then stored in the output directory, also DAT file name are stored in the set output directory. The computer program Python was used to generate a code that can convert the results which comes in complex notepad format into a simple format for easy processing.

COMPUTER CODE EXIFON

Various computer codes were developed based on different models, which are enabled to study nuclear structure and reaction mechanisms. The computer code EXIFON is very important for several technical applications if the experimental data are not available or unable to measure the reaction cross-sections due to the experimental difficulties. This code is capable of calculating equilibrium and pre-equilibrium emission cross-section, and valid for excitation energy of the compound nucleus up to 100 MeV.

EXIFON code was used to perform theoretical calculations of cross sections, the command prompt program was run with explicit definition of input and output directories followed by

specification of target nucleus and incident particle. Excitation function in the general options section was chosen for this calculation.

Incident energy number was then specified as well as first incident energy and step, the corresponding cross-section in relation to each particular energy step was to be obtained. In the output directory already set, output data (OUTEXT) for the calculation was then stored and so also was the.DAT filename stored in the output directory. Results obtained were analyzed in a spreadsheet into tabular form from which graphical charts of the results were obtained.

DATA ANALYSIS PROCEDURE

The data of this work has been arranged in proper orders and organized by using tabulation method. These organized data, described graphically with the help of spreadsheet, analyzed and interpreted accordingly by comparing with the experimental data.

RESULTS AND DISCUSSION

The computed reaction cross-sections based on the alpha particle energy using different approaches for isotope are given in figure (1–3) below. There is no experimental (EXFOR) and neither evaluated (ENDF) data on alpha particle reactions with ^{127}I within energy range of 1 – 20 MeV in the IAEA data section. However, for energies higher than 20 MeV, Smith et al. reported the discovery of ^{130}Cs in their 1952 paper *The disintegration of Cs^{130}*". The 23-MeV _-particle beam of the Indiana University cyclotron bombarded an iodine target and ^{130}Cs was formed in the reaction ^{127}I (a,n). Activities curves were measured following chemical separation. The period of the resulting activity was measured repeatedly and was found to be 30.1 min. This half-life agrees with the currently accepted value of 29.21 minutes (May & Thoennessen, n.d.)

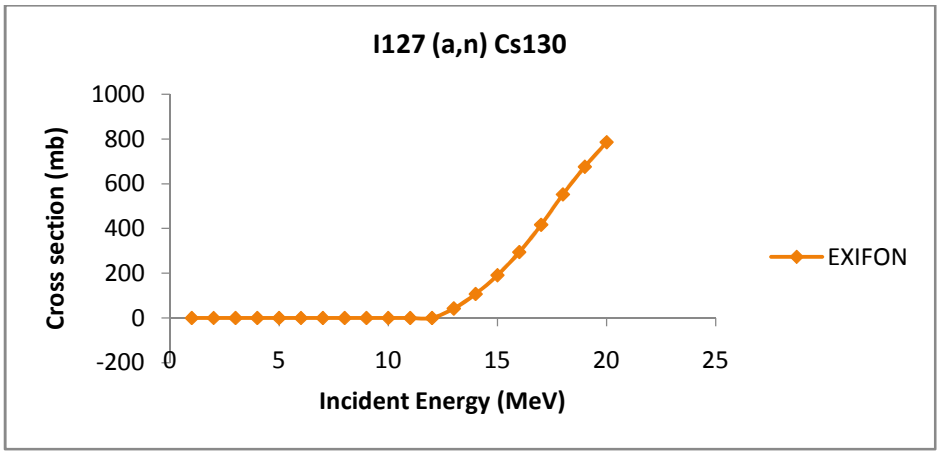

Figure 1. Excitation function of I-127 (a,n) Cs-130reaction

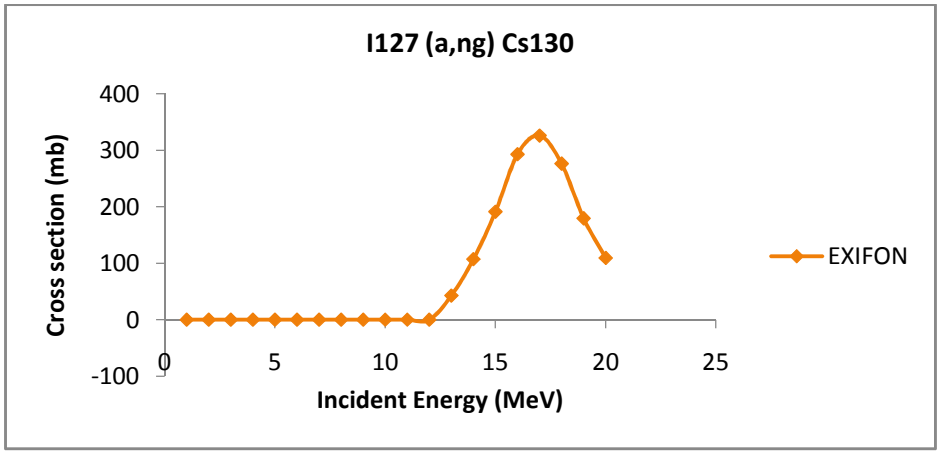

Figure 2. Excitation function of I-127 (a,ng) Cs-130reaction

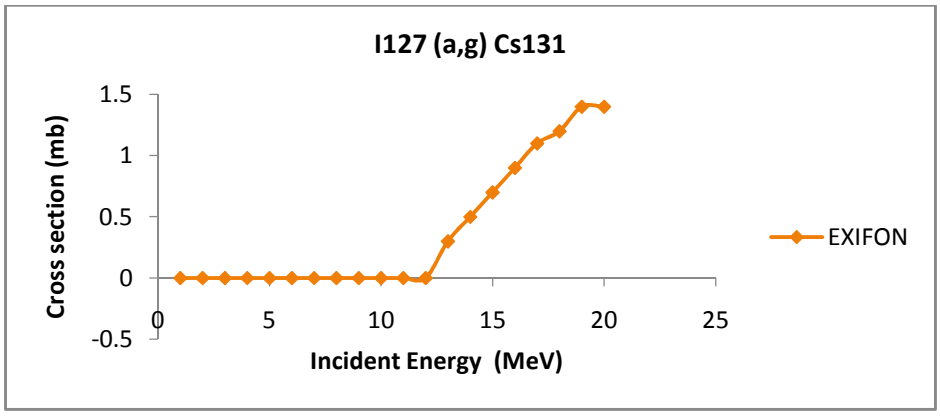

Figure 3 Excitation function of I-127 (a,g) Cs-131 reaction

Figure 1 indicates the reaction I-127(a, n) Cs 130 for the production of caesium- 130. This is a break up reaction; caesium 130 has a half life 30 minutes and decays by e+ and gamma emission while reaction threshold stands at 13MeV and cross-section rise from threshold proportionately.

The situation in Figure 2 shows a compound reaction I-127 (a, ng) Cs-130 which produces caesium-130 at excited state. Cs-130 has half life of 30 minutes and decays from gamma and positron emission. 13MeV is threshold incident energy while the peak excitation function is at 326.3mbarns with 17MeV energy. Hence it lowers down as incident energy rises.

Figure 3 show excitation function for the reaction I-127(a, g)Cs-131. Cs-131 is important for Brachytherapy, a form of topical tumor treatment Threshold for this reaction is 13MeV which exhibits the radiative capture of alpha particle by I-127 to produce caesium -131 at excited state. This radioisotope has half life of 10.2days and decays through k-capture and positron emission.

Table 1 Calculated Reaction Data for alpha induced Reaction on ^{127}I (1 -20 MeV)

Reaction	Product	Threshold Energy (MeV)	Maximum Cross Section (mb)
^{127}I (a,n) Cs 130	Caesium 130	13	785.9
^{127}I (a,ng) Cs 130	Caesium130	7	109.4
^{127}I (a,g) Cs 131	Caesium 131	7	19.9

CONCLUSION

In conclusion, it can be confidently stated that radioisotope production to produce important radionuclides that are a crucial part of modern medical diagnosis and therapy has the potential of contributing to national development through ensuring the health of citizens. A

successful nation is a healthy one, where healthcare is comprehensive, effective and efficient. With radioisotope production through cost-effective and less hazardous routes, the positive impacts of nuclear medicine would be felt in every corner of the nation to achieve a stance where an early and exact diagnosis of ailments could prevent tragic results.

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