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Studying the Properties of Nuclear Reaction (α,n) for Odd-even Nucleus ($21 \leq Z \leq 29$)

A Thesis

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بسم الله الرحمن الرحيم

يرفع الله الذين امنوا منكم والذين أوتوا العلم درجت والله بما تعملون خبير

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NOOR

With love to

My Mother

For her help and support

My Father

For his help and support

My brothers

"Ali, Amer, & Thamer"

MY SISTERS

"MAROWW & RABAB"

My Sweetie

"Rahaff"

Noor

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ABSTRACT

This work was concerned on study the properties of (alpha, neutron) reactions for nuclei that’s have odd atomic number in nuclear reactions [${}^{45}_{21}\mathrm{Sc}(\alpha,\mathrm{n}){}^{48}_{23}\mathrm{V}$، ${}^{51}_{23}\mathrm{V}(\alpha,\mathrm{n})$, ${}^{54}_{25}\mathrm{Mn}\ (\alpha,\mathrm{n}){}^{58}_{27}\mathrm{Co}$ ، ${}^{59}_{27}\mathrm{Co}(\alpha,\mathrm{n}){}^{62}_{29}\mathrm{Cu}$, ${}^{63}_{29}\mathrm{Cu}(\alpha,\mathrm{n}){}^{66}_{31}\mathrm{Ga}$] , by calculating the cross sections of (alpha, neutron) reactions. The nuclear reactions were published in the world libraries (EXFOR , ENDF , JEF , JEFF , GENDL) most recent to select the suitable energies in calculating reverse nuclear reactions for ground state. In the present work, the cross sections were calculated from semi-empirical formula which were obtained and listed in tables using computer programs(matlab 7.7R2008). These formulas represent the variation of the cross section with energy, which could be used to predict the values of uncalculated cross sections. The stopping power according to Zeigler formula was used in order to obtain the neutron yield for each nuclear reaction. Neutron yield is very important to determine the best way to produce specific isotopes. The evaluated cross sections for (α,n) are used to calculate the cross sections for inverse reactions (n,α) using empirical formula of the inverse cross sections .The values of neutron energy and inverse cross sections have been drown and listed in tables. Q_o-value, threshold energy, reduced mass and binding energy have been calculated and listed in tables for each reaction.

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Nomenclature

IAEA	**International Atomic Energy Agency.**
NNDC	**National Nuclear Data Center.**
EXFOR	**Exchange Format Library (The international experimental).**
ENDF	**Evaluated Nuclear Data File-B-Version6 (USA).**
JEF	**Joint Evaluated File-Version 2.2(European).**
JEFF	**Joint Evaluated Fission and Fusion File -Version 3.0 (European).**
CENDL	**Chinese Evaluated Nuclear Data Library-Version2.**

Chapter one

Introduction

1-1 Nuclear reaction :

Nuclear reaction are usually produced by bombarding a target nucleus with a nuclear projectile in most cases a nucleon (neutron or proton) or a heavy nucleus such as a deuteron or an α-particle [1]. The equation for Nuclear reaction may be shown in a form similar to chemical equation for which invariant mass must balance for each side of the equation , the final products can be different from the initial ones [2]. A typical nuclear reaction is written :

$$a + X \rightarrow Y + b \qquad \text{(1-1)}$$

Where (a) is the accelerated projectile coming from an accelerator or from a radioactive substance, (X) is the target (usually stationary in the laboratory),(b) is the a light particle that can be detected and measured while (Y) will be a heavy product that stops in the target and is not directly observed [3]. If the product nucleus (Y) is left in excited state after the emission of the light particle (b), it usually subsequently decays by radiating one or more gamma rays[4], alternatively if (Y) is unstable via beta will give electron or positron emission followed by gamma emission [4]. An alternative and compact way of indicating the same reaction is :

$$X(a,b)Y \qquad \text{(1-2)}$$

Which is convenient because it gives us a natural way to refer to a general class of reactions with common properties, for example (α,n) or (n, γ)reactions [3]. In general the nuclear reactions may be represented by a set of the following equations:

$$X + a \rightarrow \begin{bmatrix} X + a \\ X^* + a \\ Y + b \\ Y^* + b \end{bmatrix} \qquad \text{(1-3)}$$

In the first two reactions of the set (1-3) the outgoing particle is of the same kind as the incident particle ,and the process is called scattering[5].The first reaction represents elastic scattering and the second reaction represents inelastic scattering in which the target nucleus X is raised into an excited (X^*) . The other reactions of the set represent different possible nuclear transmutation in which the product nuclei may be found in their ground states or, more often ,in excited states. The excited product nucleus usually decays very quickly to the ground state with the emission of γ –rays[5]. In all nuclear reactions , the following entities must be conserved [6] :

1-The mass number A and the charge Z must balance on each side of the reaction arrow .

2-The total energy before the reaction must equal the total energy after the reaction. The total energy includes the particle kinetic energy plus the energy equivalent of the particle rest masses , $E=mc^2$ (where m represent the rest mass and c^2 represent the square of velocity of light in the vacuum) .

3-Linear momentum before and after the reaction must be equal.

4-Quantum rules govern the balancing of the angular momentum and parity of the nuclear levels .

1-2 Compound-nucleus reactions :

The compound nucleus hypothesis of Bohr is probably the most often used concept for the description of nuclear reactions [7].

According to Bohr, the nuclear reaction takes place in two distinct and independent stages [8]:

1- Formation of a compound nucleus C in an excited energy state .

2-The disintegration of the compound nucleus into the products of the reaction, the compound nucleus, which is a many body system of strongly interacting particles, is formed by the amalgamation of an incident particle(a) with a target nucleus (X)

$$X + a \rightarrow C^{*} \quad \text{...(1-4)}$$

The incident particle captured by a nucleus gives up its energy to few nucleons and, as the results of the interaction of these nucleons with all the others, the energy is quickly distributed among all the nucleons of the compound nucleus[8]. The new nucleus thus formed is in excited state. The mode of disintegration of compound nucleus ($C^{*} \rightarrow Y + b$) is independent on the mode of formation and depends only on its energy, angular momentum and parity[8]. If the different processes lead to the same compound nucleus the decomposition is identical .A compound nucleus, once formed, can decay in a number of different ways, each with its own-intrinsic probability[8]. The compound nucleus reactions have a definite intermediate state ,after the absorption of the incident particle but before the emission of the outgoing particle(or particles)[3].Symbolically then the reaction $a + X \rightarrow Y + b$ becomes:

$$a + X \rightarrow C^{*} \rightarrow Y + b \quad \text{.................................(1-5)}$$

Where:

C^* : Is the indicates of the compound nucleus .

The compound nucleus model work best for low incident energies (10-20 MeV), where the incident projectile has a small chance of escaping from the nucleus with its identity and most of its energy intact. It also works best for medium-weight and heavy nuclei, where the nuclear interior is large enough to absorb the incident energy[3] . The compound nucleus, has a life time which is long (10^{-14}- 10^{-18} sec) compared to the time for a nucleon to traverse a nucleus (10^{-20}-10^{-23} sec) [8].

1-3 Alpha particle or helium nucleus (${}^4_2$He):

An α-particle is a doubly magic nucleus consisting of two protons and two neutrons all in an S=1/2 shell having a zero total spin and even parity [3].Thus α-particles have an extra ordinary stability ,and therefore have instances as a single unit or particle, similar to protons and neutrons . The most well-known source of alpha particles is alpha decay of heavier atoms. Many heavy nuclei, especially those of the naturally occurring radioactive series decay through alpha emission[9], where most nuclides with A >190 (and many with 150<A<190) are unstable against alpha decay[1]. For the lighter nuclides, the half –life to α-decay are so long that this decay mode is practically unobservable.

The phenomenon of α-radioactively is intimately connected with exceptionally large binding energy of (28.3) MeV of the α-particle. A nucleus (Z,A) is unstable against α-emission if the mass of the nucleus (Z-2, A-4) plus the mass of α-particle is less than the mass of the nucleus (Z,A), i.e, a nucleus is unstable against α-decay if the sum of the binding energies of the last two protons and last two neutrons (which have the smallest binding energies) is less than the α-binding energy of 28.3 MeV [10].

The energy released in α-decay (Q_α) is given by the difference in mass between the parent nucleus and final products and appears as kinetic energy shared between the outgoing particles[11] .Thus we can write

$$Q_\alpha=(m_P - m_D - m_\alpha)\, c^2= T_D+T_\alpha \quad \text{.................................(1-6)}$$

Where :

m_P : Is the masses of parent .

m_D: Is the mass of daughter.

m_α: Is the mass of α-particle.

T_D: Is the kinetic energies of the daughter.

T_α : Is the kinetic energies of the α-particle.

Assuming the decaying nucleus at rest ,the daughter must recoil in the opposite direction to α-particle and with the same momentum .i.e [1].

$$m_D \vartheta_D = m_\alpha \vartheta_\alpha \quad \text{...(1-7)}$$

Where :

ϑ_D : is the velocity of daughter nucleus.

ϑ_α : is the velocity of alpha particle .

The ratio of their kinetic energies ,therefore, is

$$\frac{T_D}{T_\alpha} = \frac{1/2 m_D \vartheta^2{}_D}{1/2 m_\alpha \vartheta_\alpha^2} = \frac{(m_D \vartheta_D)^2}{(m_\alpha \vartheta_\alpha)^2}\frac{m_\alpha}{m_D} = \frac{m_\alpha}{m_D} \quad \text{.........................(1-8)}$$

From eqs. (1-6) and (1-8) ,we can determine T_α or T_D in terms of Q_α, m_D and m_α from the following equations:

$$Q_\alpha = T_\alpha\left[1 + \frac{T_D}{T_\alpha}\right] = T_\alpha\left[1 + \frac{m_\alpha}{m_D}\right] \quad \text{.............................. (1-9a)}$$

Or: $$Q_\alpha = T_D\left[1 + \frac{T_\alpha}{T_D}\right] = T_D\left[1 + \frac{m_D}{m_\alpha}\right] \quad \text{..............................(1-9b)}$$

1-4 Interaction charged particles with matter :

A charged particle passing through neutral atoms interacts mainly by means of the coulomb force with the electrons in the atoms[1]. Even though in each encounter the particle loses on the average not more than a few electron volts of kinetic energy, ionization and excitation of atoms give the greatest energy loss per unit path length of the particle[1]. The loss of kinetic energy in a nuclear encounter would be much larger, but such collisions are extremely rare compared to atomic encounters, roughly in proportion to the area of cross section of a nucleus compared to that of an atom, i.e. , $10^{24}\ \text{cm}^2/10^{16}\ \text{cm}^2 = 10^8$ Hence, they do not contribute appreciably to the overall energy loss [1]. For kinetic energies larger than about M_oc^2, where M_o is the rest mass of the particle, energy loss by emission of electromagnetic radiation becomes increasingly important. The radiation is called bremsstrahlung (decelerating radiation). It is caused by the same mechanism as the emission of continuous X-rays. The basic process can be understood classically. According to Maxwell's equations, any accelerated charge radiates electromagnetic radiation. If a charged particle passes close to a nucleus, its velocity vector will be rapidly changed (at least in direction if not in magnitude), so that the particle undergoes an acceleration and hence it radiates [1].

1-5 Neutrons:

Neutron is fundamental particle which is zero net charge and the first experimental observation of the neutron occurred in (1932) by James Chadwick [12]. Theory about neutron properties has led to astounding technological advances in science, industry, medicine, some nuclear power, neutron radiography, neutron activation analysis and neutron capture therapy [13]. Our study to neutron reveals the following properties:

1- Negative magnetic moment; is of -9.66237× 10^{-27} JT^{-1} [14].

2- Zero net charge; so that a moving neutron has great penetrating power in materials consisting of charged particles [13].

3-Size; a neutron radius on the order of 10^{-15} m [15].

4-Rest-mass; is 1.67493 × 10^{-27} kg .[13].

5-Stability; Neutrons confined to the atomic nucleus seem to be stable indefinitely. Free neutrons (outside the atom) are observed to decay into a proton, an electron, and antineutrino, or $^{1}_{0}n \rightarrow ^{1}_{1}p + e + \upsilon$, with a half-life of 885.7 seconds [16] .

6-Nuclear forces; scattering experiments have shown that neutrons respond to nuclear forces [15][17].

7-Spin; the angular momentum of a neutron-defined as the product of mass, velocity, and radius, or $L_S = M_n v_n R_n$, has been measured and reported to equal ħ/2 where h is Planck's constant (h= 6.623*10^{-34} j.sec)[18],[19].

8-Negative meson cloud; for a small fraction of time, the neutron separates into, a positively charged core (proton) surrounded by a circulating negative meson (cloud) [13][14].

1-6 Classification of neutrons:

In a nuclear reaction, neutrons can be classified according to their kinetic energies [20]:

1-Cold neutrons: **(**E_n = 0.0002) eV.

2-Thermal neutrons : (0.0002< E_n < 0.1) eV.

3-Epithermal neutrons: **(**E_n ~ 0.5**)** eV.

4-Resonance neutrons : (E_n = 1 - 100**)** eV.

5-Slow neutrons : (E_n = 100 – 1000) eV .

6-Intermediate neutrons : **(**E_n = 1 keV - 0.5 MeV**)** .

7-Fast neutrons: E_n = (0.5 – 10) MeV.

8-High energy neutrons : (E_n = 10 – 200) MeV.

9-Very high energy neutrons : (E_n > 200) MeV.

1-7 Nuclear reaction cross sections :

The probability of a neutron interacting with a nucleus for a particular reaction is dependent upon not only the kind of nucleus involved, but also the energy of the neutron. Accordingly, the absorption of a thermal neutron in most materials is much more probable than the absorption of a fast neutron. Also, the probability upon the type of reaction is involved. The probability of a particular reaction occurring between a neutron and a nucleus is called the microscopic cross section (σ) of the nucleus for a particular reaction. This cross section will vary with the energy of the neutron [21].

There are two types of cross sections:

1-The microscopic cross section.

2-The macroscopic cross section.

The microscopic cross section (σ) represents the effective target area that a single nucleus presents to a bombarding particle. The microscopic cross section can be defined as follows :

$$\sigma = R/I \quad \text{...(1-10)}$$

Where :

σ : Is the Microscopic cross-section (cm^2).

R: Is the number of reactions per unit time per nucleus .

I: Is the number of incident particles per unit time per unit area .

While, the macroscopic cross section $(\sum)$ represents the effective target area that is presented by all of the nuclei contained in1 cm^2 of the material. Since the microscopic and macroscopic cross sections expressed in terms of cm^2 or barns (1 barn = 10^{-24} cm^2). A neutron will interact with a certain volume of material depends not only on the microscopic cross section of the individual nuclei but also on the number of nuclei within that volume. Therefore, the macroscopic cross section is the probability of a given reaction occurring per unit travel of the neutron. $(\sum)$ is related to the microscopic cross section (σ) by the relationship shown below [21][22].

$$\sum = N\sigma \text{..(1-11)}$$

Where :

$\sum$: Is the Macroscopic section(cm^{-1})

N: Is the Atom density of material (atoms/cm^3).

A neutron interacts with an atom of the material and enters in two basic ways. It will either interact through a scattering interaction or through an absorption reaction. The probability of a neutron being absorbed by a particular atom is the microscopic cross section for absorption, σ_a. The probability of a neutron scattering off of a particular nucleus is the microscopic cross section for scattering, σ_s .The total microscopic cross section σ_T is given by [21][23]:

$$\sigma_T = \sigma_a + \sigma_s \quad \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots(1\text{-}12)$$

Both the absorption and the scattering microscopic cross sections can be further divided. For instance, the scattering cross section is the sum of the elastic scattering cross section(σ_{se}) and the inelastic scattering cross section (σ_{si})

$$\sigma_s = \sigma_{se} + \sigma_{si} \quad \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots(1\text{-}13)$$

While the microscopic absorption cross section σ_a includes all reactions except scattering. However, for most purposes it is sufficient to merely separate it into two categories, fission σ_f and capture σ_c [21].

$$\sigma_a = \sigma_c + \sigma_f \quad \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots(1\text{-}14)$$

It is convenient to explain in Fig. (1-1) the types of cross sections for different typical nuclear reactions [24].

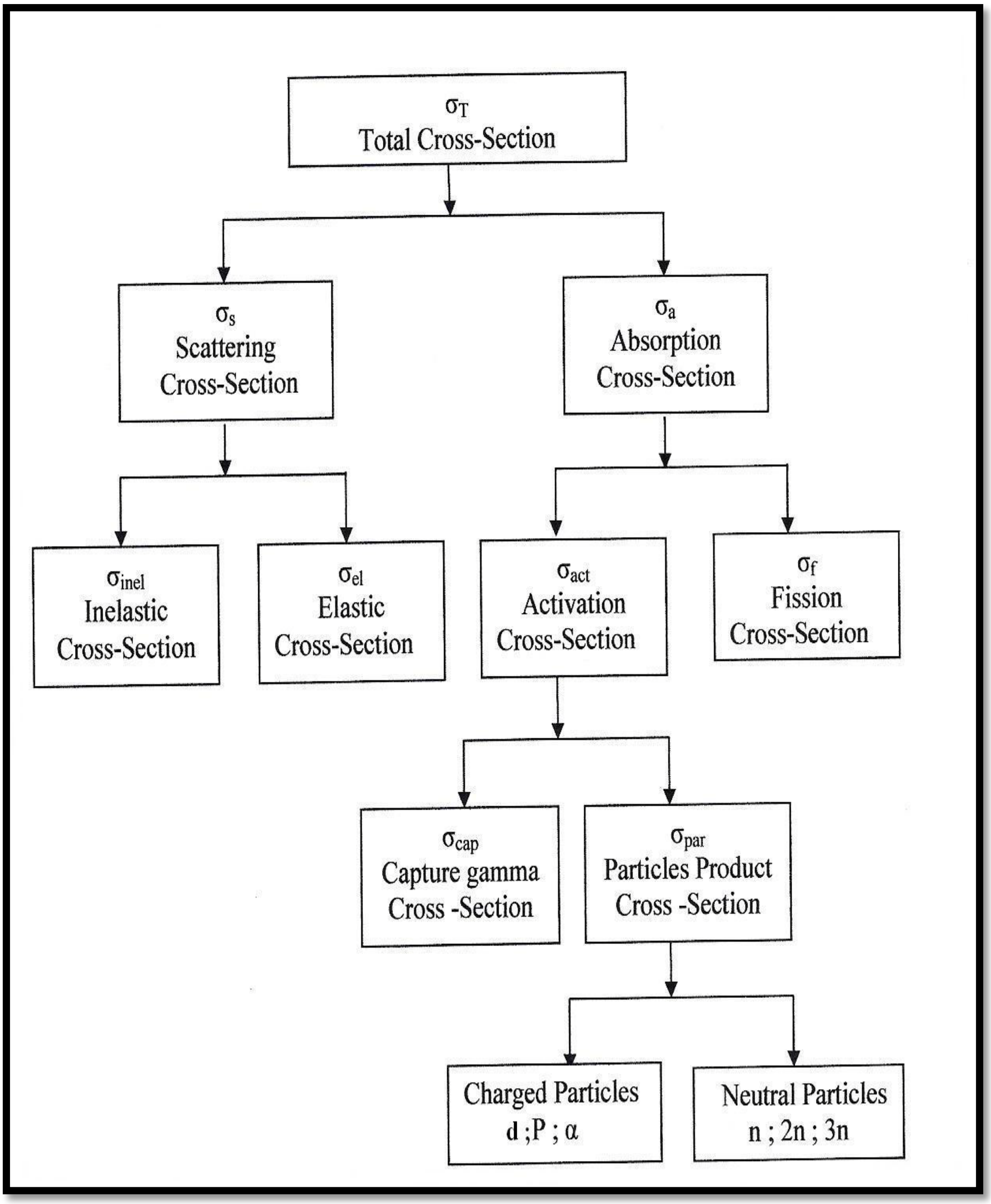


Fig. (1-1): The types of cross sections for different typical nuclear reactions [24].

1-8 Cross section of (α,n) reactions :

The problems of nuclear technology are many; one of them is the development of analytical methods for the control and protection from nuclear fuel radiation , another is the production of neutron and isotopic energy sources based on alpha emitting radio nuclides. This latter application requires the knowledge of the yield of neutrons resulting from the absorption of alpha particles by nuclei of elements [25]. The nuclear data on (α,n) reactions play an important role in the field of radiation shielding and criticality safety relating to storage, transport and handling of spent fuel [26].

1-9 Previous works :

The experimental and theoretical cross section of (α,n) reactions for intermediate element have been extensively studied the most important are :

(1-9-1) Cross section $^{45}_{21}\mathrm{Sc}(\alpha,n)^{48}_{23}\mathrm{V}$ reaction:

1-Chen K.L., Miller J.M. [27] (1964) .The cross section of this reaction was measured for energies (13.5 to 40.1) MeV .

2-Vlieks A.E., Morgan J.F.; and Blatt S.L. [28] (1974). The cross section of this reaction was measured for energies (6.38 to 10.93) MeV.

3-Hansper V.Y., Tingwell C.I.W.; and Tims S.G. [29] (1989). The cross section of this reaction was measured for energies (3.643 to 9.922) MeV.

4-LevkovskijV.N. [30] (1991) . The cross section of this reaction was measured for energies (6.9 to 45.8) MeV.

(1-9-2) Cross section of $^{51}_{23}\mathrm{V}(\alpha,n)^{54}_{25}\mathrm{Mn}$ reaction :

1-Vonach H., Haight R.C.; and Winkler G.[31] (1983). The cross section of this reaction was measured for energies(6.295 to 11.864) MeV.

2-RamaRao J., MohanRao A.V.; and Mukherjee S.[32] (1987). The cross section of this reaction was measured for energies (11.4 to 112) MeV.

3- Levkovskij V.N. [30] (1991). The cross section of this reaction was measured for energies (7.1 to 35)MeV.

4- Sonzogni A.A., Romo A.S.M.A.; and Mosca H.O. [33] (1993). The cross section of this reaction was measured for energies (6.01 to 84.02) MeV.

5- Singh. N.L., Agraval S.; and Ramarao J. [34] (1993). The cross section of this reaction was measured for energies (13.17 to 48) MeV.

6-Hansper V.Y., Morton A.J.; and Tims S.G.[35] (1993). The cross section of this reaction was measured for energies (5.62 to 9.412) MeV.

7-Singh N.L., Mukherjee S. ; and MohanRao A.V. [36] (1995). The cross section of this reaction was measured for energies (11.4 to 113) MeV.

8-BinduKumar.B., Mukherjee S.; and Singh N.L. [37] (1998). The cross section of this reaction was measured for energies (21.4 to 77.82) MeV.

7- XiufengP . , Fuqing H .; and Xianguan L . [38] (1999). The cross section of this reaction was measured for energies (7.7 to 26.4) MeV.

(1-9-3) Cross section $^{55}_{25}\mathbf{Mn}(\alpha, n)^{58}_{27}\mathbf{Co}$ reaction :

1-Tanaka S., Furukawa M.; and Mikumo T. [39] (1960). The cross section of this reaction was measured for energies (9.96 to 38.5) MeV .

2-Iwata S. J. [40] (1962) .The cross section of this reaction was measured for energies (9.98 to 38.5) MeV .

3-Rizvi I.A., Bhardwaj M.K., AfzalAnzari M.; and Chaubey A.K. [41] (1989). The cross section of this reaction was measured for energies (6.8 to 48.9) MeV .

4-Levkovskij V.N. [30] (1991). The cross section of this reaction was measured for energies (7.3 to 35.1)MeV .

5-Singh B.P., Bhardwaj H.D.; and Prasad R. [42](1991). The cross section of this reaction was measured for energies (9.37 to 59.96) MeV .

6-Tims S.G., Scott A.F.; and Morton A.J. [43] (1993). The cross section of this reaction was measured for energies (5.025 to 9.970)MeV.

7-Sudar S., Qaim S.M. [44] (1994) . The cross section of this reaction was measured for energies (7.06 to 25.06) MeV.

8-Sudar S.; and Qaim S.M. [45] 1996. The cross section of this reaction was measured for energies (7.06 to 25.06) MeV.

(1-9-4) Cross section $^{59}_{27}\mathbf{Co}(\alpha, \mathbf{n})^{62}_{29}\mathbf{Cu}$ reaction:

1-Stelson P.H.; and Mcgowan F.K. [46] (1964). The cross section of this reaction was measured for energies (5.8 to 11) MeV.

2-D`auria J.M, Fluss M.J.; and Kowalski L. [47] (1968). The cross section of this reaction was measured for energies (8-19.7) MeV.

3-Zhukova O.A., Kanashevich V.I.; and Laptev S.V. [48](1972). The cross section of this reaction was measured for energies(5.9 to 36.3)MeV.

4-Tims S.G., Tingwell C.I.W.; and Hansper V.Y. [49] (1988). The cross section of this reaction was measured for energies (5.571 to 8.977) MeV.

5-Skulski W. , Fornal B.; and Broda R. [50] (1992) . The cross section of this reaction was measured for energies (10.97 to 25.36) MeV.

6- Szelecsenyi F., Suzuki K.; and Kovacs Z. [51] (2002). The cross section of this reaction was measured for energies (17.6 to 57.8) MeV.

(1-9-5) Cross section $^{63}_{29}\mathbf{Cu}(\alpha, \mathbf{n})^{66}_{31}\mathbf{Ga}$ reaction :

1-Rizvi I.A, AfzalAnsari M.; and Gautam R.P. [52] (1987). The cross section of this reaction was measured for energies (16.8to 25.9) MeV.

2-Zweit J., Sharma H.; and Downey S.[53] (1987). The cross section of this reaction was measured for energies (7.982To 31.161) MeV.

3- Levkovskij V.N.[30] (1991). The cross section of this reaction was measured for energies (7.8to 46) MeV.

4-Singh N.L, Patel B.J.; and Somayajulu D.R.S. [54] (1994). The cross section of this reaction was measured for energies (11.6to 26.5) MeV.

5-Navin A., Tripathiand V.; and Blumenfeld Y. [55] (2004). The cross section of this reaction was measured for energies (16.6107 to 30.0256) MeV.

6-Bhardwai H.D., Gautam A.K.,; and Prasad R.[56] (1988). The cross section of this reaction was measured for energies(9 to 38.2) MeV.

1-10 The aim of the present work:

1- Study the nuclear properties of (alpha, neutron) reactions for the nuclear reactions under study to know which nuclear reaction has good properties above others to make it important in many nuclear applications.
2- Study of the different possible reactions for the alpha and neutron product of isotopes.
3- Obtain the semi empirical formula for ground state to calculate the cross sections in order to produce some element by inverse reaction technique. We have attempted to formulate parametric expressions for cross sections using fitting type of fitting and written computer program. The cross sections of the mentioned reactions were reproduced in fine steps of energy for the incident projectile on thick targets with elements have odd atomic number (Z = 21, 23, 25, 27 and 29) using the latest available data in the literature.
4- Calculating the Q_o-value, threshold energy, stopping power and neutron yield and the probability of occurrence of their reactions as well as the nuclear properties for the isotopes of mentioned reactions have been calculated . The most important for present work was covered the energy range which the other authors data didn’t cover it, that is indicated the present measurements necessarily involves the ground state .

Chapter Two

Theory

2-1 Nuclear reaction kinematics :

They are certain restriction in the conservation of energy and momentum. These restriction are called kinematic restriction and this mathematical method is known as kinematics [8]. Consider a nuclear reaction:

$$X + a \rightarrow Y + b \quad \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots(2\text{-}1)$$

Where :

X : Is the target nucleus.

a : Is the bombarding particle.

Y: Is the product nucleus

b : Is the product particle .

It will be assumed that target nucleus X is at rest so it has no kinetic energy(T_x=0) and no velocity (V_x=0) [8]. Since total energy is conserved in a nuclear reaction, therefore, we get:

$$M_Xc^2 +(T_a + M_ac^2) = (T_Y +M_YC^2) +(T_b + M_bc^2)\ldots\ldots\ldots\ldots\ldots\ldots (2\text{-}2)$$

Where :

T_a : Is the laboratory kinetic energy of the incident particle.

T_y : Is the laboratory kinetic energy of the product nucleus.

T_b : Is the laboratory kinetic energy of outgoing particle.

Mc^2: Is represent the rest masses of each particles[8].

2-2 Energy of nuclear reaction:

The nuclear reaction energy is called energy balance of reaction or more commonly (Q-value) of the reaction[8]. The Q- value of the reaction is defined as the difference between the final and initial kinetic energies or masses energies [3] :

$$Q = T_Y + T_b - T_a \quad \ldots\ldots\ldots (2\text{-}3)$$

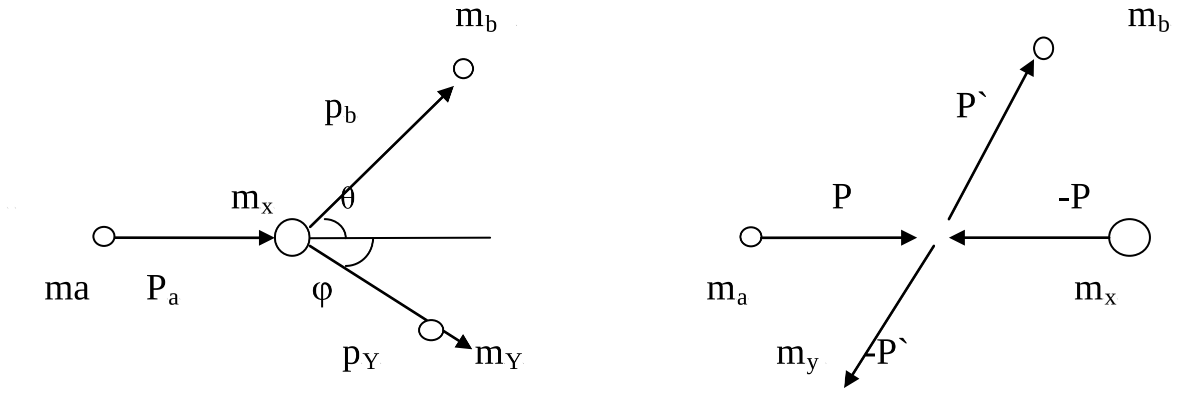
$$Q = [(M_x + M_a) - (M_Y + M_b)]c^2 \ldots\ldots\ldots (2\text{-}4)$$

If the reaction energy (Q- value) is positive (Q>0) the reaction is exo-ergic reaction, if reaction is negative, it is endo-ergic reaction [57]. A reaction cannot take place unless particles b and Y emerge with positive kinetic energies, that is,

$$T_b + T_Y \geq 0 \ldots\ldots\ldots (2\text{-}5)$$

Or $$Q + T_a \geq 0 \ldots\ldots\ldots (2\text{-}6)$$

Although this condition is necessary ,it is not sufficient [57]. In older to study nuclear reaction we need laboratory system and center of mass system as shown in Fig (2-1).



(a) Laboratory system. (b) C.M. system.

Fig. (2-1):The nuclear reaction observed in laboratory and center of mass coordinates[58]

From Fig. (2-1) we have $T_x = 0$, $p_x = 0$ because the target nucleus at rest .

in lab system $\upsilon_a = (2T_a/m_a)^{1/2}$ and $P_a = (2m_aT_a)^{1/2}$ [58].

where :

P_a : is the momentum of the projected particle .

υ_a : is the velocity of the projected particle.

In the C.M. system[58]:

$$P_{c.m.} = P_a + P_X \quad \text{……………………………………...…………..… (2-7)}$$

And

$$V_{c.m.} = P_a / (m_a + m_X) \quad \text{……………………………………..... (2-8)}$$

$$Q_0 = M_a c^2 + M_X c^2 \quad M_b c^2 \quad M_Y c^2 = T_b + T_Y \quad T_a \quad \text{…………….…… (2-9)}$$

Where :

Q_0 : Is the Q-value of the reaction with the product nucleusY(in the ground state).

On the other hand, many reactions leave Y in excited states, in that case[57]:

$$Q = M_a c^2 + M_X c^2 - M_b c^2 - M_Y c^2 = T_b + T_Y \quad T_a \quad \text{…..…...……. (2-10)}$$

Then for ; $Q > 0$

$$M_a c^2 + M_X c^2 > M_b c^2 + M_Y c^2 ; T_b + T_Y \quad T_a > 0 \quad \text{…………….… (2-11)}$$

And for ; $Q < 0$

$$M_a c^2 + M_X c^2 < M_b c^2 + M_Y c^2 ; T_b + T_Y \quad T_a < 0 \quad \text{…..…………… (2-12)}$$

So the $Q < 0$ process cannot occur spontaneously, which means that there is a threshold energy $T_{a(th)}$ or (E_{th}) given by [57]:

$$T_{a(th)} = E_{th} = \left| -Q \right| (1 + M_a / M_X) \quad \text{……………………..……………...…. (2-13)}$$

In general, the Q-value of reactions in terms of T_a, T_b, M_a, M_X, M_b, M_Y, and angle θ given by :

$$Q = T_b(1+\frac{M_b}{M_Y}) \quad T_a(1 \quad \frac{M_a}{M_Y}) \quad \frac{2}{M_Y}(M_a T_a M_b T_b)^{1/2}\cos\theta \ldots\ldots\ldots\ldots.. \text{(2-14)}$$

which is called the Q equation. For special case when we are observing the out coming b at 90^o to a collimated beam of projectile, the above relation reduces to :

$$Q = T_b(1+\frac{M_b}{M_Y}) \quad T_a(1 \quad \frac{M_a}{M_Y}) \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots.. \text{(2-15)}$$

2-3 Nuclear binding and separation energy:

The difference between the actual nuclear mass and the mass of all the individual nucleons is called the total binding energy $B_{tot}(A,Z)$.It represents the work necessary to dissociate the nucleus into separate nucleons or, conversely, the energy which would be released if the separated nucleons were assembled into a nucleus. [1] For convenience, the masses of atoms rather than the masses of nuclei are used in all calculations [1]. This causes no difficulty, except that the binding energy of the atomic electrons should also be considered For simplicity, one can write[1] :

$$B_{tot}(A,Z) = [(ZM_P + NM_n) - M(A,Z)]c^2 \ldots\ldots\ldots\ldots\ldots\ldots.. \text{(2-16)}$$

Where :

M(A,Z): Is the mass of a specific nucleus.

M_p: Is the mass of a proton.

M_n : Is the mass of a neutron.

A: Is the mass number of the nucleus.

Z: Is the number of protons in a nucleus.

N: Is the number of neutrons in a nucleus.

The binding energy of nuclei is always a positive number, since all nuclei require net energy to separate them into individual protons and neutrons [3]. Thus, the mass of an atom nucleus is always less than the sum of the individual masses of the constituent protons and neutrons when separated [3]

The average binding energy per nucleon is given by[1].

$$B_{ave}(A, Z)= \frac{B_{tot}(A,Z)}{A} \quad \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots (2\text{- }17)$$

The binding energy per nucleon (B_{tot} / A) is shown in Fig. (2-2)[59].

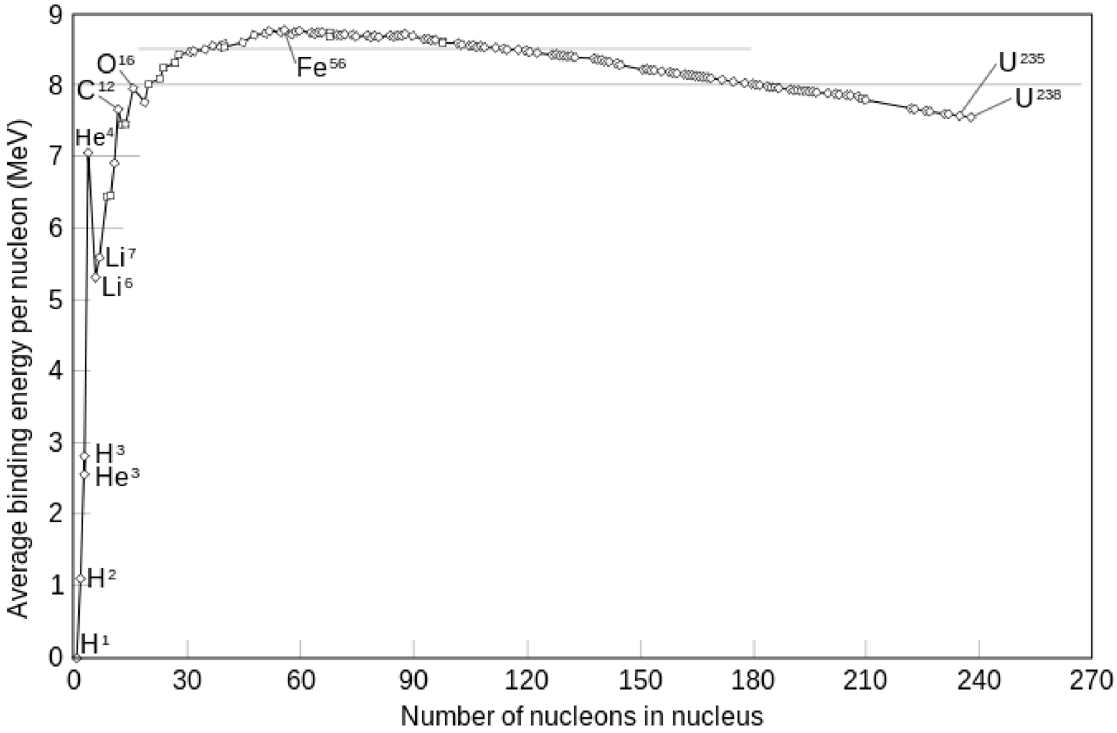


Fig. (2-2): Binding energy per nucleon of common isotopes [59].

Any process that results in nuclides being converted to other nuclides with more binding energy per nucleon will result in the conversion of mass into energy. The combination of low A nuclides to form higher A nuclides with a higher (B_{tot} / A) value is the basis for the fusion process for the release of nuclear energy [59]. The splitting of very high A nuclides to from intermediate A nuclides with a higher (B_{tot} / A) value is the basis of the fission process for the release of nuclear energy.

It is observed experimentally that the mass of the nucleus is smaller than the number of nucleons each counted with a mass of 1 a.m.u [59].

The difference between the actual mass of the nucleus measured in atomic mass units and the number of nucleons is called mass excess i.e [1]:

$$\text{Mass excess} = M - A = \text{Excess energy}/c^2 \quad \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots \text{(2-18)}$$

Where :

M : Is the actual mass of the nucleus in (a.m.u).

A : Is the mass number.

This mass excess is a practical value calculated from experimentally measured nucleon masses and stored in nuclear data bases. For middle-weight nuclides this value is negative in contrast to the mass change which is never negative for any nuclide [1] .

Packing fraction is defined as a way of expressing the variation of isotopic mass from whole mass number (atomic mass) [1] . Is given by:

$$\text{Packing Fraction} = \frac{M \quad A}{A} \quad \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots \text{(2-19)}$$

This fraction can have positive or can have negative sign. A positive packing fraction describes a tendency towards instability. A negative packing fraction means isotopic mass is less than actual mass number. This difference is due to the transformation of mass into energy in the formation of nucleus [1].

The reduced mass(**μ**) is calculated from the following equation [1]:

$$\mu = \frac{M_a M_X}{M_a + M_X} \quad \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots \text{(2-20)}$$

Where :

M_a : Is the atomic mass of the projectile

M_X: Is the atomic mass of the target nucleus

The energy required to separate a particle e.g., alpha particle separation energy (SE_α) is the amount of energy that is needed to remove alpha particle from a nucleus ${}^{A}_{Z}X_N$ [1], or equals the difference in binding energies between ${}^{A}_{Z}X_N$ and ${}^{A-4}_{Z-2}X_{N-2}$ [3]. SE_α is given by:

$$SE_\alpha = 931.5[M_X + M_\alpha - M_C] \quad \ldots\ldots\ldots\ldots (2\text{-}21)$$

Or $$SE_\alpha = B({}^{A}_{Z}X_N) - B({}^{A-4}_{Z-2}X_{N-2}) \quad \ldots\ldots\ldots\ldots (2\text{-}22)$$

Where :

M_X: Is the mass of specific nucleus after alpha particle separation.

M_C: Is the mass of specific nucleus before alpha particle separation.

And in similar way, we can define neutron separation energy (SE_n) as the energy needed to remove a neutron out of the nucleus ${}^{A}_{Z}X_N$ [1], or equals the difference in binding energies between ${}^{A}_{Z}X_N$ and ${}^{A-1}{}_{Z}X_{N-1}$ [3]. SE_n is given by:

$$SE_n = 931.5\ [M_Y + M_n - M_C] \quad \ldots\ldots\ldots\ldots (2\text{-}23)$$

Or $$SE_n = B({}^{A}_{Z}x) - B({}^{A-1}{}_{Z}X_{N-1}) \quad \ldots\ldots\ldots\ldots (2\text{-}24)$$

Where :

M_Y: Is the mass of specific nucleus after neutron separation.

M_C: Is the mass of specific nucleus before neutron separation.

2-4 Angular momentum, parity and energy level :

The nucleus can be considered as an isolated system and so has a well defined angular momentum . This is the vector sum of the intrinsic spins (S) and orbital angular momentum(L) of the individual nucleons and is a characteristic property of nuclear states as Fig. (2-3) [60]. The orbital angular momentum is an integer multiple of Planck's constant while the intrinsic spin of the nucleus is half integer. For even A nuclei have integer values for the total nuclear angular momentum quantum number I and odd A nuclei have half integer values. All nuclei with even Z and even N have zero total nuclear angular momentum , I = 0 [60].

Like atoms, the nucleus has discrete energy level whose location and properties are governed by the rules of quantum mechanics. The locations of the excited states differ for each nucleus. Each excited state is characterized by quantum numbers that describe its angular momentum and parity. The parity, π, of a nuclear energy level is a statement about what the nuclear structure of the state would look like if the spatial coordinates of all the nucleons were reversed [1].

Parity is a fundamental concept. It characterizes the symmetry properties of nuclei, elementary particles and all physical systems in general with respect to reflections [60],[61].

The substitution $r \rightarrow -r$ is called the parity operation and a potential(V) which has the property expressed as

$$V(-x, -y, -z) = V(x, y, z) \quad \text{(2-25)}$$

Is said to be conservative under the parity operation, or "conserve parity". It turns out that practically all physical potentials, including those generated by nuclear forces, possess this property[60].

For a potential obeying eq.(2-25), the wave function ψ is solution of Schrodinger equation

$$\left[\ \hbar^2/2m\ \partial^2/\partial^2\ \psi + V\psi = E\psi\right] \quad \text{(2-26)}$$

Must have one of the following property

$$\Psi(-r) = +\Psi(r) \quad \text{(2-27)}$$

Or $\Psi(-r) = -\Psi(r)$

The parity conservation for nuclear reaction in[60] :

$$\pi_X\ .\pi_a\ (-1)^{\ell a,\ X} = \pi_Y\ .\pi_b\ (-1)^{\ell b,Y} \quad \text{(2-28)}$$

where:

π : Is the parity of each nuclear state involved in the nuclear reaction.

This conservation law impose restrictions on the reaction probability. But even if the conservation law allow a nuclear reaction to proceed, sometimes the reaction rate may be so minute that its occurrence cannot be detected with available equipment [1] .

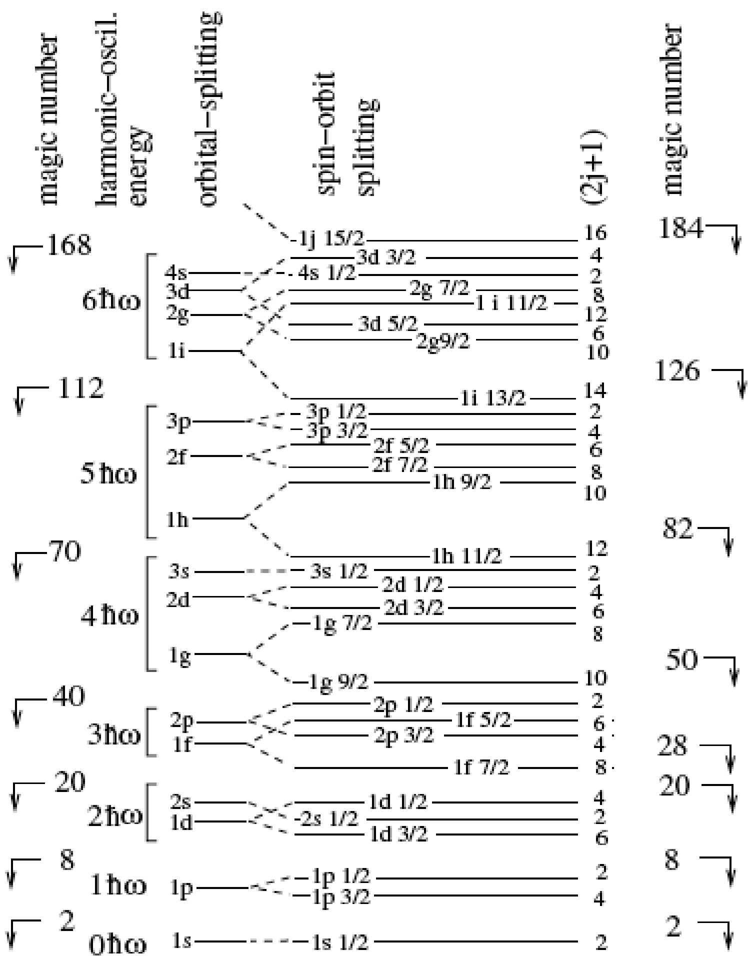


Fig.(2-3): Energy level in a rounded potential well including a strong spin-orbit splitting [60]

2-5 Cross section of compound nucleus:

The cross section of compound nucleus is given by [3]:

$$\sigma_{sc} = \frac{\pi}{k^2}(2\ell + 1)\frac{\Gamma^2}{(T \quad E_R)^2 + \Gamma^2/4} \quad \text{.................................(2-29)}$$

Where :

T : Is the kinetic energy of an incident particle.

E_R : Is a single isolated resonance energy.

Γ : Is the width of the state.

ℓ : Is the orbital angular momentum.

k : Is the wave number which is given by:

$$k = \frac{1}{\lambda\!\!\!^{-}} = \frac{p}{\hbar} = \frac{Mv}{\hbar} = \frac{\sqrt{2MT}}{\hbar} \quad \text{....................................... (2-30)}$$

$\lambda\!\!\!^{-}$: Is the de-Broglie wavelength divided by 2π of incident particle.

$\hbar$: Is the Plank constant divided by 2π.

p : Is the momentum of an incident particle.

M: Is the mass of an incident particle .

v : Is the velocity of an incident particle

This result can be generalized in two ways in the first, we can account for the effect of reacting particles with spin. If S_a and S_x are the spin of the incident and target particles, and if I is the total angular momentum of the resonance, which is given by[3] :

$$I_c = S_a + S_X + \ell_a \quad \text{.................................... (2-31)}$$

Where :

S_a : Is the spin of the incident particle.

S_X : Is the spin of the target.

ℓ_a : Is the orbital angular momentum of incident particle.

Then the factor $(2\ell+1)$ in eq. (2-29) should be replaced by the more general statistical factors(g) :

$$\sigma = \frac{\pi}{k^2} g \frac{\Gamma^2}{(T \quad E_R)^2 + \Gamma^2/4} \quad \text{………………………..………… (2-32)}$$

The statistical factor (g) is given by[3] :

$$g = \frac{2I_c + 1}{(2S_a + 1)(2S_X + 1)} \quad \text{…………………………………..... (2-33)}$$

Where :

I_c : Is the total angular momentum of compound nucleus .

The second change we must make is to allow for partial entrance and exit widths. If the resonance has many ways to decays, then the total width of the state is the sum of the partial widths [62],[63]:

$$\Gamma = \sum_i \Gamma_i \quad \text{…………………………………………..………….. (2-34)}$$

Where :

$$\Gamma = \frac{\hbar}{\tau} \quad \text{…………………...………………………...……………………...... (2-35)}$$

And τ : Is the mean life time of any decay state.

The Γ^2 in equation (2-32) is directly related to the formation of the resonance and to its probability to decay into a particular exit channel. That is, for the reaction a+X=b+Y, a different exit width must be used [64]:

$$\sigma = \frac{\pi}{k^2} g \frac{\Gamma_{aX}\Gamma_{bY}}{(T \quad E_R)^2 + \Gamma_{aX}\Gamma_{bY}/4} \quad \text{…………………..……………… (2-36)}$$

Where :

Γ_{aX} : Is the partial width for decay into a+X.

Γ_{bY} : Is the partial width for a different exit.

Eq.(2-36) is the Breit-Wigner formula for the shape of a single, isolated resonance.

At resonance $T = E_R$ and $\Gamma_{aX}\Gamma_{bY} = \Gamma^2$ since $\Gamma_{aX} = \Gamma_{bY} = \Gamma$, we call Γ_{aX} the partial width for decay into a+X and Γ_{bY} the partial width for any other channels energetically allowed, then eq. (2-36) becomes:

$$\sigma = \frac{4\pi}{k^2} g \quad \text{...} \quad (2\text{-}37)$$

The basic assumption of the compound nucleus model is that the compound nucleus has been formed in such a complicated set of interactions that it does not remember the initial stage of formation[64]. The cross sections for the reaction X(a,b)Y can be split into a formation cross section of the compound nucleus $[C]^*$ corresponding to the process:

$$a + X \rightarrow [C]^* \rightarrow Y + b \quad \text{..} \quad (2\text{-}38)$$

And the fractional probability that $[C]^*$ breaks up into particles b+Y. We can therefore write [1]:

$$\sigma(a,b) = \sigma_{a,c}(T_0)Pb(E) \quad \text{...} \quad (2\text{-}39)$$

Where :

T_0 : Is the bombarding energy in center of mass.

E : Is the corresponding excitation energy of the compound nucleus.

Pb(E) : Is the Fractional probability of $[C]^*$ to break up into Y+b.

2-6 Reciprocity theory:

If the cross sections of the reaction X(a,b)Y are measured as a function of T_α (T_α= kinetic energy of the incident alpha), the cross sections of the reverse reaction Y(b,a)X can be calculated as a function of T_n (T_n= kinetic energy of the incident neutron). This is called the reciprocity theory which states that [65]:

$$\frac{\sigma(\alpha,n)}{g(\alpha,n)\lambda_{\alpha}^{2}}=\frac{\sigma(n,\alpha)}{g(n,\alpha)\lambda_{n}^{2}} \quad \text{(2-40)}$$

Where :

$\sigma(\alpha,n)$: Represents the cross sections of X(α,n)Y reactions.

$\sigma(n,\alpha)$: Represents the cross sections of Y(n,α)X reactions.

g(α,n): Represents the statistical factors of X(α,n)Y reactions.

g(n,α): Represents the statistical factors of Y(n,α)X reactions.

λ_{α}: Is the de-Broglie wave length of alpha particle given by [5]:

$$\lambda=\frac{\hbar}{Mv} \quad \text{(2-41)}$$

From eq.(2-41) ,we have :

$$\lambda^{2}=\frac{\hbar^{2}}{2MT} \quad \text{(2-42)}$$

With the aid of eqs.(2-40 and 42), obtained the equation;

$$\sigma_{(n,\alpha)}=\frac{g_{(n,\alpha)}\,M_{\alpha}\,T_{\alpha}}{g_{(\alpha n)}\,M_{n}\,T_{n}}\,\sigma_{(\alpha n)} \quad \text{(2-43)}$$

It is clear from this equation that the cross sections of reverse reaction have available parameters such as; the statistical factor and neutron energy.

2-6-1 The statistical g-factors:

The statistical g-factors are givens by [65]:

$$g_{(\alpha n)}=\frac{2J_{c}+1}{(2I_{X}+1)(2I_{\alpha}+1)} \quad \text{(2-44)}$$

And

$$g_{(n,\alpha)}=\frac{2J_{c}+1}{(2I_{Y}+1)(2I_{n}+1)} \quad \text{(2-45)}$$

The conservation low of the momentum and parity implique that :

$$I_X + I_\alpha = J_c = I_Y + I_n$$ ……………………………...…………...(2-46)

And

$$\pi_X \cdot \pi_\alpha (-1)^{\ell\alpha} = \pi_c = \pi_Y \cdot \pi_n (-1)^{\ell n}$$ ……..………………………...(2-47)

Where :

J_c and π_c: Total angular momentum and parity of the compound nucleus C

I_X and π_X : Total angular momentum and parity of nucleus X.

I_Y and π_Y : Total angular momentum and parity of nucleus Y.

I_α and π_α : Total angular momentum and parity of alpha .

I_n and π_n : Total angular momentum and parity of neutron .

$$\pi_\alpha = \pi_n = +1$$ ………………………………..……........……(2-48)

$$I_\alpha = s_\alpha + \ell_\alpha$$ ………………………………..……......……(2-49)

Where :

I_α : The total angular momentum of alpha.

s_α : spin of alpha =0 .

ℓ_α : the orbital angular momentum of alpha.

And

$$I_n = s_n + \ell_n$$ ……………………………………...…………...(2-50)

Where :

I_n : Is the total angular momentum of the neutron.

s_n : Is spin of neutron = ½ .

ℓ_n : Is the orbital angular momentum of neutron.

From eq.(2-46) ,we have :

$$\left|J_c \quad I_X\right| \le I_\alpha \le J_c + I_X \quad \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots(2\text{-}51)$$

And

$$\left|J_c \quad I_Y\right| \le I_n \le J_c + I_Y \quad \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots(2\text{-}52)$$

2-6-2 The neutron energy :

The reactions X(α,n)Y and Y(n,α)X can be represented with the compound nucleus C as in the schematic diagram (Fig.(2-4)). It is clear that there are some important and useful relations between the kinetic energies of the neutron T_n and alpha particle T_α.

$$E \ = SE_\alpha + \frac{M_X}{M_X + M_\alpha} T_\alpha \ \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots(2\text{-}53a)$$

$$E \ = SE_n + \frac{M_Y}{M_Y + M_n} T_n \ \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots(2\text{-}53b)$$

Where :

SE_α: Is the separation energy for alpha which has been given in eq. (2-21).

SE_n : Is the separation energy for neutron which has been given in eq.(2-23).

By combining (2-53a) , (2-53b) , (2-21) , (2-23), and the equation of Q- value of the reaction X(α,n)Y which is given by[65] :

$$Q = 931.5\ [\ M_X + M_\alpha - M_Y - M_n\ ] \ \ldots\ldots\ldots\ldots\ldots\ldots\ldots(2\text{-}54)$$

We get that :

$$Q = \frac{M_Y}{M_Y + M_n} T_n \quad \frac{M_X}{M_X + M_\alpha} T_\alpha \ \ldots\ldots\ldots\ldots\ldots\ldots\ldots(2\text{-}55)$$

Or $$T_n = \frac{M_Y + M_n}{M_Y} \quad \frac{M_X}{M_X + M_\alpha} T_\alpha + Q$$ ……………………………..……..(2-56)

Then the threshold energy E_{th} is :

$$E_{th} = \left| Q \frac{M_X + M_\alpha}{M_X} \right|$$ ………………...…………………...……….(2-57a)

Or $$Q = \frac{M_X}{M_X + M_\alpha} E_{th}$$ ………………………………………………(2-57b)

Then:

$$T_n = \frac{M_Y + M_n}{M_Y} \times \frac{M_X}{M_X + M_\alpha} (T_\alpha \quad E_{th})$$ ………………….……………...…(2-58)

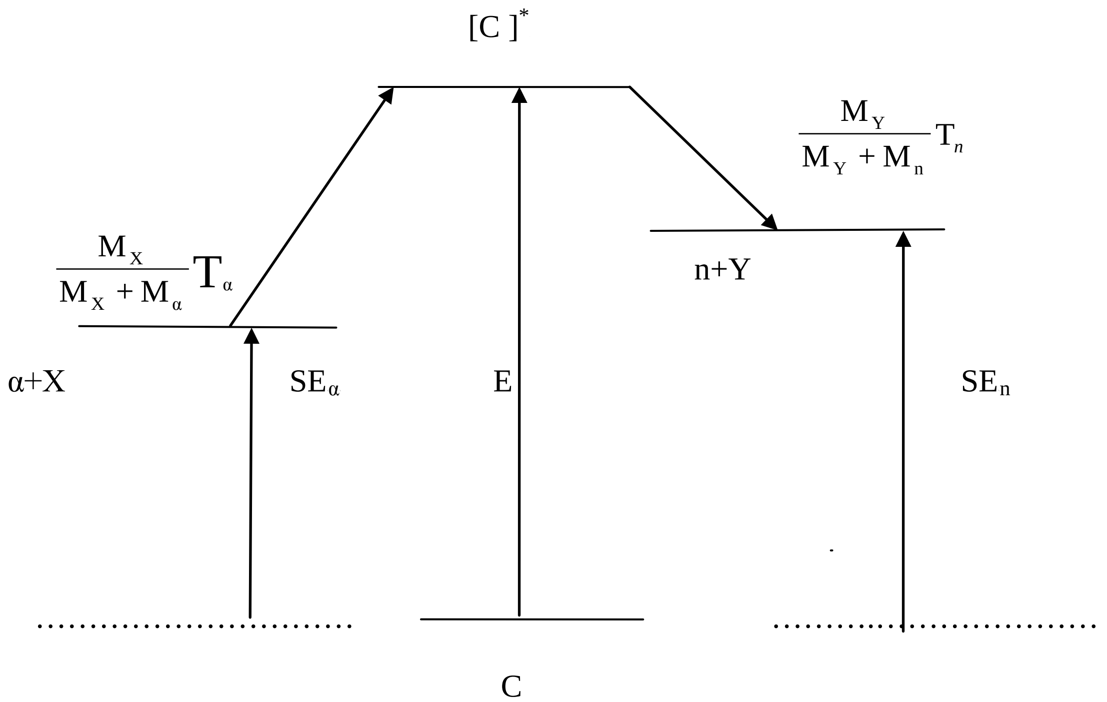


Fig.(2-4): A schematic diagram of the reactions X(α,n)Y proceed in through a compound nucleus [65].

2-7 α-Particle stopping power :

Stopping power is a measure of the effect of a substance on the kinetic energy of a charged particle passing through it, and it is often quoted relative to that of a standard substance, usually air or aluminum [66].

The stopping power of α-particle is mainly due to the ionization of the target electrons, excitation of the lowest levels, charge-exchange between the target and the projectile, and the nuclear stopping power, that is[66]:

$$S_{tot} = S_n + S_e \quad \text{……………………………………….……...…(2-59)}$$

Where :

S_{tot}: Is the total stopping power.

S_n : Is the nuclear stopping power.

S_e : Is the electric stopping power.

(2-7-1) Nuclear stopping power (S_n) :

A beam of charged particles bombarding the neutral atoms of a gas interacts with the atomic nuclei and atomic electrons of the gas. In this case of gas medium, the ratio of the energy lost in interaction with the atomic electrons, to the energy lost in the interaction with the atomic nuclei (except of hydrogen), is ≈ $2m_p / m_e \cong$

$4x10^3$ [67]. Thus the energy lost by interaction with the nuclei is negligible compared with that lost by interaction with the electrons.

For solid targets with a given thickness (= neutron energy width) there will be a more nuclear interactions and hence the electronic stopping cross sections is comparable with the nuclear cross section[67].

The nuclear stopping power (S_n) of the α-particle with different energy ranges have been presented by Ziegler [68] as follows:

$$S_n = 1.593\,\varepsilon^{1/2} \qquad (\varepsilon < 0.01 \text{ MeV}) \ldots\ldots (2\text{-}60)$$

$$S_n = 1.7(\varepsilon^{1/2})\left[\frac{\ln(\varepsilon+\exp 1)}{1+6.8\varepsilon+3.4\varepsilon^{3/2}}\right] \qquad (0.01 \le \varepsilon \le 10\text{MeV}) \ldots\ldots (2\text{-}61)$$

$$S_n = (\ln 0.47\,\varepsilon)/2\varepsilon \qquad (\varepsilon > 10 \text{ MeV}) \ldots\ldots (2\text{-}62)$$

Where :

ε : Is the reduced ion energy which is given by[68] :

$$\text{Reduced ion energy } (\varepsilon) = \frac{32.53 M_2 E}{Z_1 Z_2 (M_1 + M_2)(Z_1^{2/3} + Z_2^{2/3})^{1/2}} \ldots\ldots (2\text{-}63)$$

Where :

E : Is ion energy in keV.

M_1 : Is the mass of projectile in amu.

M_2 : Is the mass of target element in amu.

Z_1 : Is the atomic number of the projectile.

Z_2 : Is the atomic number of the target.

(2-7-2) Electronic stopping power (S_e):

A beam of particles hitting a target get slowed down by interactions with the electrons (straggling) until they are in thermal equilibrium with their surroundings. As a consequence, one gets a white neutron spectrum if the projectiles are completely stopped in the target, even if all nuclear reactions were two-body reactions[68]. The loss of kinetic energy in a nuclear encounter would be much larger, but such collisions are extremely rare compared to atomic encounters, roughly in proportion to the area of cross section of a nucleus compared to that of an atom [1], i.e.,

$$10^{-24}\ cm^2 / 10^{-16}\ cm^2 \cong 10^{-8}$$

In the scope of this work, the electronic stopping powers were calculated using the Ziegler formulae [68] expressions valid for the energy range (10-140) keV.

$$(\frac{1}{S_e}) = (\frac{1}{S_{Low}}) + (\frac{1}{S_{High}}) \quad \text{.......................................(2-64)}$$

$$S_{Low} = A_1 E^{A_2} \quad \text{.......................................(2-65)}$$

$$S_{High} = (\frac{A_3}{E/1000}) \ln[1 + (\frac{A_4}{E/1000}) + (\frac{A_5 E}{1000})] \quad \text{..........................(2-66)}$$

Where :

A_i : Are coefficients given by Ziegler [68].

2-8 Neutron yields :

For an accelerating beam traversing a target, the occurred nuclear reactions produce N light product particles per unit time. Referring to Fig. (2-5) the yield is given by[69]:

$$Y(x) = I_o \; N_d \; \sigma \; X \qquad \text{……………………………………..……..……(2-67)}$$

Where :

I_o : Is the number of incident particles per unit time per unit area

N_d X : Is the a real number density of target atom.

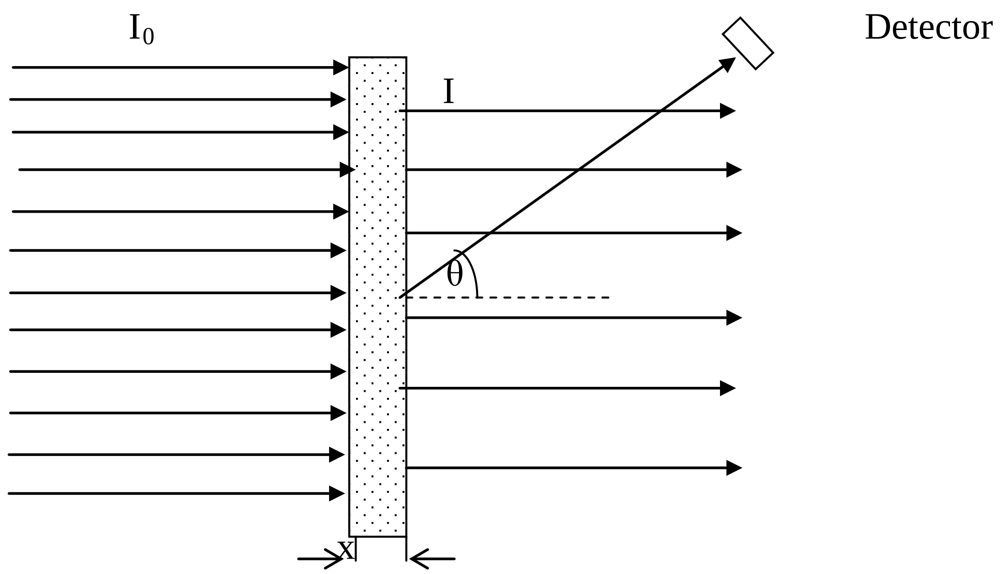


Fig.(2-5) : A schematic diagram illustrating the definition of total cross section in terms of the reduction of intensity[69].

Experimentally, the yield of neutrons detected per incident particle, Y_n , for an ideal, thin and uniform target and mono-energetic beam of energy E is given by[69]:

$$Y_n = (N_d \ x) \ \sigma(E_b) \ \eta(E_b) \quad \text{..................................(2-68)}$$

Where :

η : Is the neutron-detection efficiency.

E_b: Is bombarding energy .

For a target which is not infinitesimally thin, the beam loses energy as it passes through the target, and the yield is then given by [69]:

$$Y_n = \int_{E_t}^{E_b} \frac{\sigma(E`)\eta(E`)f \ dE`}{-\frac{dE}{dx}(E`)} \quad \text{..................................(2-69)}$$

$$E_t = E_b - \Delta E \quad \text{..................................(2-70)}$$

Where :

ΔE: Is the energy loss of the beam in the target.

f : Is the number of target atoms in each target molecule.

$\frac{dE}{dx}(E`)$: Is the stopping power per target molecule.

If the target is sufficiently thick, and there exists one atom per each molecule (i.e., f = 1) and taking $\eta(E`) = 1$, then the resulting yield is called the thick-target yield which is given by [70]:

$$Y(E_b) = \int_{E_{thr}}^{E_b} \frac{\sigma(E)dE}{-(dE/dx)} \quad \text{..................................(2-71)}$$

Where :

E_{thr} : Is the reaction threshold energy.

Thus, by measuring the yield at two closely spaced energies E_1 and E_2, one can determine the average value of the integrand over this energy interval as follows [70]:

$$\left[\frac{\sigma(E)}{-dE/dx}\right]_{E_b} = \frac{Y(E_2) \quad Y(E_1)}{E_2 - \quad E_1} \quad \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots(2\text{-}72)$$

If $\sigma(E)$ are available as a function of projectile energy E_b for natural elements, then the neutron yield can be calculated using eq.(2-72). If neutron yield is available as a function of projectile energy E_b, then eq. (2-72) can be used to calculate $\sigma(E)$ as a function of E_b. Thus, consequently the neutron yield can be calculated using eq. (2-72).

For natural elements and if only one stable isotope is available in nature, then [71]:

$$Y_o = Y(E) \quad \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots(2\text{-}73)$$

Where :

Y_o: Is the neutron yield per 10^6 bombarding particle for the natural element.

If $\sigma(E)$ is calculated for a certain isotope whose concentration (enrichment) is C %, then [71]:

$$Y_o = \frac{a}{c} Y(E) \quad \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots(2\text{-}74)$$

Where :

a : Is the abundance of the isotope in the natural element.

C: Is the concentration of the isotope in the natural element.

If there exists more than one isotope that can be involved in the nuclear reaction and the cross sections are calculated as a function of incident energy for each isotope, then [71]:

$$Y_o = \frac{a_1}{c_1} Y_1(E) + \frac{a_2}{c_2} Y_2(E) + ... \qquad \text{……………...…………...…(2-75)}$$

Chapter Three

Data reduction and analysis

3-1 The atomic mass of isotopes :

By using atomic mass of isotopes for elements mentioned in this study which have been taken from the latest nuclear wallet cards released by the National Nuclear Data Center (NNDC) [72] . We have calculated mass excess and packing fraction in keV for each element by using equations (2-18) and(2-19) respectively, also in table(3-1)the abundances are given for isotopes from reference International Atomic Energy Agency (IAEA) [73] . For the sake of completeness, the atomic masses are expressed in (a.m.u), while mass excess and packing fraction in (keV) as mentioned previously .

Table (3-1) : The properties of nuclides used in the present work .[72][73]

Chemical symbol	Atomic Mass (a m u) [72]	Mass Excess (keV)P.W	Packing fraction P.W	Abundance . % [73]
^{1}n	1.008664	8071.3	8071.3	----
^{1}p	1.007825	7288.9	7288.9	99.985
^{4}He	4.002603	2424.9	606.2	99.999
^{45}Sc	44.955910	- 41069.3	-912.6	100
^{48}V	47.952254	-44474.7	-926.5	----
^{49}V	48.948516	-47956.2	-978.6	-----
^{51}V	50.943963	-52197.5	-1023.4	99.750
^{54}Mn	53.940363	-55551.3	-1028.7	----
^{55}Mn	54.938049	-57706.4	-1049.2	100
^{58}Co	57.935757	-59841.7	- 1031.7	----
^{59}Co	58.933200	-62223.6	-10546.3	100
^{62}Cu	61.932587	-62795	-1012.8	-----
^{63}Cu	62.929601	-65576.2	-1040.8	69.17
^{66}Ga	65.931592	-63721	-965.4	-----
^{67}Ga	66.9282049	-66876.7	-998.1	----

3-2 Q_o-values, threshold energies, binding energy and reduced mass:

The Q_o-value, threshold energy for (α,n) reaction have been calculated for reactions maintained in table (3-2)using equation(2-4) and (2-13)respectively. Binding energy to target particles and reduce mass for reaction particles are also calculated in table (3-2) using equation (2-16)and (2-20) respectively.

Table (3-2): Q_o -values , threshold energies, binding energy and reduced mass for (α,n) reactions(in the ground state) .

Reaction	Q_o-Value (MeV)	Threshold Energy (MeV)	Binding Energy (p.w.)MeV	Reduced Mass (a.m.u)
${}^{45}_{21}Sc(\alpha,n){}^{48}_{23}V$	-2.2405	2.4399	387.850	3.6754
${}^{51}_{23}V(\alpha,n){}^{54}_{25}Mn$	-2.2924	2.4725	445.864	3.7110
${}^{55}_{25}Mn(\alpha,n){}^{58}_{27}Co$	-3.4921	3.7469	482.072	3.7308
${}^{59}_{27}Co(\alpha,n){}^{62}_{29}Cu$	-5.07480	5.4195	517.310	3.7480
${}^{63}_{29}Cu(\alpha,n){}^{66}_{31}Ga$	-7.4967	7.9735	551.383	3.7632

3-3 Separation energy of neutron in (α,n) reactions and separation energy of alpha particle in (n,α) reactions :

The separation energy of neutron (ESn) has been calculated for compound nucleus of (α,n) reactions as shown in table (3-3) by using equation (2-23), in addition to calculating of the separation energy of alpha particle (ES_α) to the compound nucleus in (n,α) reactions shown in it by using equation (2-21).

Table(3-3) : Separation energy of neutron in (α,n) reactions and separation energy of alpha particle in (n,α) reactions(present work) :

Reaction	Compound nucleus	ESn (MeV)	Inverse Reaction	Compound nucleus	ESα (MeV)
${}^{45}_{21}Sc(\alpha,n){}^{48}_{23}V$	${}^{49}_{23}V$	11.553	${}^{48}_{23}V(n,\alpha){}^{45}_{21}Sc$	${}^{49}_{23}V$	9.312
${}^{51}_{23}V(\alpha,n){}^{54}_{25}Mn$	${}^{55}_{25}Mn$	10.226	${}^{54}_{25}Mn(n,\alpha){}^{51}_{23}V$	${}^{55}_{25}Mn$	7.933
${}^{55}_{25}Mn(\alpha,n){}^{58}_{27}Co$	${}^{59}_{27}Co$	10.453	${}^{58}_{27}Co(n,\alpha){}^{55}_{25}Mn$	${}^{59}_{27}Co$	6.941
${}^{59}_{27}Co(\alpha,n){}^{62}_{29}Cu$	${}^{63}_{29}Cu$	10.853	${}^{62}_{29}Cu(n,\alpha){}^{59}_{27}Co$	${}^{63}_{29}Cu$	5.777
${}^{63}_{29}Cu(\alpha,n){}^{66}_{31}Ga$	${}^{67}_{31}Ga$	11.227	${}^{66}_{31}Ga(n,\alpha){}^{63}_{29}Cu$	${}^{67}_{31}Ga$	3.726

3-4 Spin and parity:

Parity is a fundamental concept. It characterizes the symmetry properties of nuclei, elementary particles and all physical systems in general with respect to reflections [61]. The spins of the proton and the neutron measured in experiment have been found to be equal to (1/2) just like the spin of the electron, where the spin of alpha particle is equal to zero. The nuclear spin is equal to the geometric sum of angular moment of the alpha particles and the neutrons constituting the nucleus [70]. In ground state, spin and parity of isotopes are used in the present work are given in table (3-4) [74] . Table (3-4) also include the half life for the product nuclei [74].

Table (3-4): The spin and parity of isotopes in the ground state and life time for product nuclei are used in the present work [74].

Target Nuclide	Spin and parity	Compound Nuclide	Spin and parity	Product Nuclide	Spin and parity	Half life ($t_{1/2}$)
$^{45}_{21}Sc$	$7/2^-$	$^{49}_{23}V$	$7/2^-$	$^{48}_{23}V$	4^+	16.0 d
$^{51}_{23}V$	$7/2^-$	$^{55}_{25}Mn$	$5/2^-$	$^{54}_{25}Mn$	3^+	312.3 d
$^{55}_{25}Mn$	$5/2^-$	$^{59}_{27}Co$	$7/2^-$	$^{58}_{27}Co$	2^+	70.86 d
$^{59}_{27}Co$	$7/2^-$	$^{63}_{29}Cu$	$3/2^-$	$^{62}_{29}Cu$	1^+	9.673min
$^{63}_{29}Cu$	$3/2^-$	$^{67}_{31}Ga$	$3/2^-$	$^{66}_{31}Ga$	0^+	9.49 h

3-5 Cross sections of (α,n) reactions:

The cross sections of(α,n) reactions for the isotop($^{45}_{21}SC$, $^{51}_{23}V$, $^{55}_{25}Mn$, $^{59}_{27}Co$, $^{63}_{29}Cu$) that have odd atomic numbers (Z=21, 23, 25, 27 and 29) available in the literature as mentioned in subsection (1-9), have been taken, re-plotted and listed in tables (3-5) to (3-9). These plots were analyzed using the Matlab computer program (version 7.7 R2008b) to obtain the cross sections for different energy intervals as follows:

1- The cross section of limited fine steps depends on reaction type which has been directly reproduced from the plots which shows the variation of cross section with alpha particle energy.

2- Plots have been analyzed to obtain the formula for each reactions from the cross sections values for each author.

3- The normalization for the statistical distribution of cross sections errors to the corresponding cross section values for each author has been done.

4- The interpolation for the nearest data for each energy interval as a function of cross sections by using computer program Matlab (version7.7 R2008b).

3-6 Stopping power :

The total stopping powers of elements with odd atomic numbers (Z= 21, 23, 25, 27, 29) have been calculated in the present work by using computer program (SRIM(2013 [75])). The results of this program are regarded as an experimental stopping power, and it is valid for energies needed in our calculations for incident alpha . By using the results in computer program (SRIM(2013) and equation(2-59)we have calculated the total stopping powers in unite (MeV/(mg/cm^2)) shown in table (3-5) to (3-9) . In Matlab computer program (version 7.7 R2008b) the present work of total stopping powers have been treated by spline , interpolated by fine steps and plotted as shown in Figs. (3-6) to (3-10).

3-7 The Neutron Yield :

The thick target neutron yields (TTY) from (α,n) reaction are very important quantity as well as the cross sections in analyzing problems of radiation shielding and criticality safety in spent fuel [25].

Therefore, the thick target neutron yield for intermediate elements $^{45}_{21}Sc$, $^{51}_{23}V$, $^{55}_{25}Mn$, $^{59}_{27}Co$, $^{63}_{29}Cu$) are calculated on the basis of the evaluated (α,n) reactions with the stopping power of alpha particle energy by using equation (2-72). The reproduce cross sections from these reactions have been used to obtain the neutron yield as shown in tables(3-5), (3-6), (3-7), (3-8) and (3-9).

The neutron yields of the following (α,n) reactions have been obtained by using the above equation, and by using computer program (Matlab version 7.7R2008) the results are plotted in Fig. (3-11) to (3-15) with energy of alpha particle in steps according to the nuclear reaction .

3-8 Analysis for (α, n) reactions:

(3-8-1) The cross sections, stopping power and neutron yield of $^{45}_{21}Sc(\alpha, n)^{48}_{23}V$ reaction:

The cross section as of $^{45}_{21}Sc(\alpha, n)^{48}_{23}V$ reaction have been plotted, spline interpolated and recalculated in fine steps(0.5MeV) for alpha energy from (7.0MeV) to (32MeV)[30], by using Matlab program, as shown in table (3-5). The reproduced cross sections are from author Levkovskij V.N. [30]. From the results in table (3-5) we get the equation of 10^{th} degree for plotted shown in Fig (3-1) as follows:

$$\sigma=-1.6*10^{-13}*E^{10}+4.1*10^{-11}*E^{9}-4.3*10^{-9}*E^{8}+2.6*10^{-7}*E^{7}-9*1^{6}*E^{6}+0.00019*E^{5}-0.0019*E^{4}+0.0026*E^{3}+0.15*E^{2}-1.3*E+3.7 \quad ....(3-1)$$

With percentage error (±0.1561).

The stopping powers of Scandium element for alpha particles are calculated in the same range of alpha energy and in the same interval of energy (0.5MeV) as shown in table (3-5).These data are plotted in Fig. (3-6) and we get equation of 9^{th} degree as follows:

$$-\frac{dE}{dX} = -3.2*10^{-14}*E^{9} + 8.8*10^{-12}*E^{8} - 1*10^{-9}*E^{7} +7.1*10^{-8}*E^{6} - 3.1*10^{-6}*E^{5} + 8.9*10^{-5}*E^{4} - 0.0017*E^{3} + 0.022*E^{2} - 0.19*E + 1.1 \quad ....(3-2)$$

Where :

$-\frac{dE}{dX}$: Is the stopping power .

By using equation (2-72) the cross sections and stopping power with the same interval (0.5MeV) of alpha particle we have calculated the neutron yield in unite (neutron/10^{6} alpha particle). The results are listed in table (3-5) and plotted in Fig.(3-11).

Table (3-5):The cross sections of $^{45}_{21}Sc(\alpha,n)^{48}_{23}V$ reaction as a function of alpha energy with threshold energy (2.4399) MeV .

Alpha- energy (MeV)	Cross Section (barn)	Total stopping power (MeV/(mg/cm^2))	Neutron Yield (neutron/10^6alpha particle)
7	0.3303	0.4275	0.3863
7.5	0.3317	0.4085	0.406
8	0.3331	0.3895	0.4277
8.5	0.3476	0.3757	0.4626
9	0.3815	0.3619	0.527
9.5	0.4154	0.3489	0.5953
10	0.4275	0.3359	0.6363
10.5	0.425	0.3253	0.6533
11	0.4225	0.3146	0.6715
11.5	0.4245	0.3054	0.6951
12	0.4277	0.2962	0.7221
12.5	0.4175	0.2881	0.7246
13	0.3985	0.2801	0.7113
13.5	0.3884	0.273	0.7114
14	0.3919	0.2659	0.737
14.5	0.3798	0.2595	0.7318
15	0.3443	0.2532	0.68
15.5	0.3226	0.2474	0.6518
16	0.3214	0.2417	0.6649
16.5	0.286	0.2366	0.6043
17	0.2277	0.2315	0.4916
17.5	0.1933	0.2269	0.4261
18	0.165	0.2222	0.3712
18.5	0.1589	0.2181	0.3642
19	0.1491	0.214	0.3484
19.5	0.1247	0.2099	0.2969
20	0.1053	0.2058	0.2557

To be continued

Table (3-5):

Alpha- energy (MeV)	**Cross Section (barn)**	**Total stopping power (MeV/(mg/cm^2))**	**Neutron Yield (neutron/10^{6}alpha particle)**
20.5	0.0934	0.2024	0.2306
21	0.0815	0.1991	0.2047
21.5	0.0701	0.1957	0.1792
22	0.0608	0.1923	0.1581
22.5	0.0515	0.1889	0.1362
23	0.0429	0.1861	0.1153
23.5	0.0375	0.1833	0.1024
24	0.0322	0.1804	0.0891
24.5	0.0294	0.1776	0.0826
25	0.0283	0.1748	0.0809
25.5	0.0272	0.1724	0.0789
26	0.0246	0.17	0.0724
26.5	0.0217	0.1677	0.0646
27	0.019	0.1653	0.0574
27.5	0.0173	0.1629	0.053
28	0.0156	0.1608	0.0485
28.5	0.0142	0.1588	0.0448
29	0.0128	0.1567	0.0409
29.5	0.0119	0.1546	0.0385
30	0.0117	0.1526	0.0383
30.5	0.0114	0.1508	0.0379
31	0.011	0.1491	0.0369
31.5	0.0105	0.1473	0.0356
32	0.0099	0.1455	0.0342

(3-8-2): The cross sections, stopping power and neutron yield of $^{51}_{23}\mathbf{V}(\boldsymbol{\alpha},\mathbf{n})^{54}_{25}\mathbf{Mn}$ reaction:

The cross sections of $^{51}_{23}\mathrm{V}(\alpha,\mathrm{n})^{54}_{25}\mathrm{Mn}$ reaction have been plotted, spline interpolated and recalculated in fine steps(2.5MeV) for alpha energy from (13.5) MeVto(111) MeV[36] using Matlab program, as shown in table(3-6). The reproduced cross sections are from authors Singh N.L., Mukherjee S. ; and MohanRao A.V. [36]. From the results in table (3-6) we get the equation of 10th degree for plotted shown in Fig.(3-2) as follows:

$$\sigma = -1.2*10^{-15}*E^{10} + 7.8*10^{-13}*E^{9} - 2.2*10^{-10}*E^{8} + 3.6*10^{-8}*E^{7} - 3.7*10^{-6}*E^{6}+0.00025*E^{5}-0.011*E^{4}+0.33*E^{3}-5.9*E^{2}+58*E-2.3*10^{+2} \quad ....(3\text{-}3)$$

With percentage error ($\pm$1.4167).

The stopping powers of Vanadium element for alpha particles are calculated in the same range of alpha energy and in the same interval of energy (2.5MeV) as shown in table (3-6). These data are plotted in Fig. (3-7) and we get equation of 9th degree as follows:

$$-\frac{dE}{dX}=-3.3*10^{-17}*E^{9}+2*10^{-14}*E^{8}-5*10^{-12}*E^{7}+7.4*10^{-10}*E^{6}-6.7*10^{-8}*E+4*10^{-6}*E^{4}-0.00016*E^{3}+0.0041*E^{2}-0.066*E+0.69 \quad ....(3\text{-}4)$$

Neutron yield in unite(neutron/10^{6}alpha particle) with the interval(2.5MeV) of alpha particle had been obtained as in previous nuclear reaction . The results are listed in table (3-6) and plotted in Fig.(3-12).

Table (3-6): The cross sections of $^{51}_{23}V(\alpha, n)^{54}_{25}Mn$ reaction as a function of alpha energy with threshold energy (2.4725)MeV.

Alpha -Energy (MeV)	Cross Section (barn)	Total stopping power (MeV/(mg/cm^2))	Neutron Yield* (neutron/10^{6}alpha particle)
13.5	4.75	0.2543	46.7056
16	5.2974	0.2257	58.6693
18.5	3.4061	0.204	41.7483
21	1.7911	0.1864	24.0194
23.5	0.908	0.1718	13.2135
26	0.4959	0.1596	7.7681
28.5	0.3926	0.1492	6.579
31	0.2893	0.1402	5.1602
33.5	0.186	0.1323	3.515
36	0.155	0.1254	3.0919
38.5	0.1241	0.1192	2.6031
41	0.1025	0.1138	2.2516
43.5	0.091	0.1089	2.0896
46	0.0796	0.1043	1.907
48.5	0.0689	0.1002	1.7175
51	0.0581	0.0964	1.5077
53.5	0.0505	0.093	1.3585
56	0.0458	0.0898	1.2747
58.5	0.041	0.0868	1.1805
61	0.0362	0.0841	1.0771
63.5	0.0314	0.0815	0.9638
66	0.0252	0.0791	0.795
68.5	0.0207	0.0769	0.6729
71	0.0196	0.0748	0.6553
73.5	0.0169	0.073	0.5792
76	0.0134	0.0711	0.47
78.5	0.013	0.0693	0.4705

To be continued :

Table (3-6):

Alpha- energy (MeV)	Cross Section (barn)	Total stopping power (MeV/(mg/cm^2))	Neutron Yield (neutron/10^{6}alphaparticle)
81	0.0127	0.0676	0.4711
83.5	0.0124	0.0661	0.4703
86	0.0112	0.0646	0.4327
88.5	0.0098	0.0631	0.3881
91	0.0085	0.0618	0.3451
93.5	0.0073	0.0605	0.3008
96	0.0069	0.0593	0.2901
98.5	0.0065	0.0581	0.279
101	0.0061	0.057	0.267
103.5	0.0057	0.0559	0.2546
106	0.0056	0.0549	0.2547
108.5	0.0055	0.0539	0.2549
111	0.0054	0.0529	0.257

(3-8-3) The cross sections, stopping power and neutron yield of $^{55}_{25}Mn(\alpha,n)^{58}_{27}Co$ reaction:

The cross sections of $^{55}_{25}Mn(\alpha,n)^{58}_{27}Co$ reaction have been plotted, spline interpolated and recalculated in fine steps (0.5MeV) for Alpha energy from (7.5) MeV to (34.5) MeV [30] using Matlab program, as shown in table (3-7) the reproduced cross sections are from author Levkovskij V.N. [30]. From the results in table (3-7) we get the equation of 9th degree for plotted shown in Fig. (3-3) as follows:

$\sigma = 4.2 *10^{11}*E^9 – 9*10^{-9}*x^8 +8.3*10^{-7}*E^7 - 4.4*10^{-5}*E^6 +0.0014*E^5 - 0.029*E^4 + 0.39*E^3 - 3.1*E^2 + 14*E - 27$……………………………..(3-5)

With percentage error(±0.1764) .

The stopping powers of Manganese element for alpha particles are calculated in the same range of alpha energy and in the same interval of energy (0.5MeV) as shown in table (3-7).These data are plotted in Fig. (3-8) and we get equation of 10^{th} degree as follows:

$$-\frac{dE}{dX}= 4.6*10^{-14}*E^{10} - 9.8*10^{-12}*E^{9} + 9.3*10^{-10}*E^{8} -5.1*10^{-8}*E^{7} +1.8*10^{-6}*E^{6} -4.3*10^{-5}*E^{5} +0.00069*E^{4} - 0.0078*E^{3} + 0.06*E^{2} - 0.31*E + 1.2 \quad ...(3\text{-}6)$$

The cross sections and stopping power with the same interval(0.5MeV) of alpha particle is used to calculate the neutron yield in unite (neutron/10^6 alpha particle). The results are listed in table (3-7) and plotted in Fig.(3-13).

Table (3-7):The cross sections of $^{55}_{25}Mn(\alpha,n)^{58}_{27}Co$ reaction as a function of alpha energy with threshold energy (3.7469)MeV .

Alpha-Energy (MeV)	Cross Section (barn)	Total stopping power (MeV/(mg/cm^2)	Neutron Yield neutron/10^{6}alpha particle)
7.5	0.1993	0.3671	0.2714
8	0.2249	0.3508	0.3206
8.5	0.2506	0.3386	0.3701
9	0.2764	0.3263	0.4236
9.5	0.3025	0.3148	0.4805
10	0.3286	0.3033	0.5417
10.5	0.3362	0.294	0.5719
11	0.3317	0.2847	0.5825
11.5	0.3402	0.2766	0.6149
12	0.4011	0.2686	0.7467
12.5	0.462	0.2615	0.8833
13	0.4411	0.2545	0.8667
13.5	0.4202	0.2482	0.8466
14	0.4492	0.2418	0.9287
14.5	0.4907	0.2363	1.0383
15	0.4874	0.2307	1.0563
15	0.473	0.2307	1.0563
15.5	0.4691	0.2257	1.0479
16	0.4641	0.2206	1.0631
16.5	0.4547	0.2161	1.0739
17	0.4412	0.2115	1.0747
17.5	0.4218	0.2074	1.0638
18	0.4	0.2032	1.0377
18.5	0.3767	0.1996	1.0022
19	0.3392	0.1959	0.9613
19.5	0.2982	0.1923	0.8821
20	0.2763	0.1886	0.7905

To be continued :

Table (3-7):

Alpha -Energy (MeV)	Cross Section (barn)	Total stopping power (MeV/(mg/cm^2)	Neutron Yield neutron/10^{6}alpha particle
20.5	0.2591	0.1856	0.7443
21	0.2419	0.1825	0.7097
21.5	0.2194	0.1795	0.6738
22	0.1934	0.1764	0.6217
22.5	0.1674	0.1734	0.5577
23	0.1503	0.1709	0.4898
23.5	0.1392	0.1684	0.4464
24	0.128	0.1658	0.4196
24.5	0.1115	0.1633	0.3919
25	0.1993	0.1608	0.3466
25.5	0.0949	0.1586	0.2992
26	0.081	0.1565	0.2588
26.5	0.071	0.1543	0.2301
27	0.061	0.1521	0.2005
27.5	0.0546	0.15	0.1821
28	0.0483	0.1481	0.1629
28.5	0.0439	0.1463	0.1501
29	0.0401	0.1445	0.1387
29.5	0.0367	0.1426	0.1286
30	0.0352	0.1408	0.1249
30.5	0.0336	0.1392	0.1208
31	0.0323	0.1376	0.1172
31.5	0.031	0.136	0.114
32	0.0298	0.1344	0.1109
32.5	0.0288	0.1328	0.1085
33	0.0278	0.1313	0.1059
33.5	0.0269	0.1299	0.1036
34	0.026	0.1285	0.1012
34.5	0.0228	0.1271	0.0898

(3-8-4) The cross sections, stopping power and neutron yield of $^{59}_{27}Co(\alpha,n)^{62}_{29}Cu$ reaction:

The cross sections of $^{59}_{27}Co(\alpha,n)^{62}_{29}Cu$ reaction have been plotted, spline interpolated and recalculated in fine steps(1.0MeV) for Alpha energy from (18) MeV to (57)MeV [51] using Matlab program, as shown in table (3-8). The reproduced cross sections are from authors Szelecsenyi F., Suzuki K. and Kovacs Z [51]. From the results in table (3-8), we get the equation of 9th degree for plotted shown in Fig.(3-4) as follows:

$$\sigma = 3*10^{-12}*E^9-1.1*10^{-9}*E^8+1.7*10^{-7}*E^7-1.5*10^{-5}*E^6+0.00086*E^5-0.032*E^4+0.79*E^3-12*E^2+1.1*10^{+2}*E-4*10^{+2} \quad ....(3\text{-}7)$$

With percentage error(±0.1919) .

The stopping powers of Cobalt element for alpha particles are calculated in the same range of alpha energy and in the same interval of energy (1.0MeV) as shown in table (3-8).These data are plotted in Fig. (3-9) and we get equation of 9th degree as follows:

$$-\frac{dE}{dX}= 9.7*10^{-15}*E^9-3.4*10^{-12}*E^8+5.1*10^{-10}*E^7-4.4*10^{-8}*E^6+2.4*10^{-6}*E^5-8.4*10^{-5}*E^4+0.0019*E^3-0.027*E^2+0.2*E-0.3 \quad .... (3\text{-}8)$$

The neutron yield in unite (neutron/10^6 alpha particle) have been calculated with the interval(1.0MeV) of alpha particle. The results are listed in table (3-8-4) and plotted in Fig.(3-14).

Table (3-8): The cross sections of $^{59}_{27}Co(\alpha, n)^{62}_{29}Cu$ reaction as a function of alpha energy with threshold energy (5.4195) MeV .

Alpha -Energy (MeV)	Cross Section (barn)	Total stopping power (MeV/(mg/cm^2)	Neutron Yield (Neutron/10^{6}alpha particle
18	0.6316	0.1974	3.1991
19	0.5622	0.1905	2.9518
20	0.4929	0.1835	2.6858
21	0.4187	0.1777	2.3565
22	0.325	0.1718	1.8917
23	0.2314	0.1665	1.39
24	0.1538	0.1616	0.9515
25	0.1402	0.1568	0.8943
26	0.1266	0.1527	0.8296
27	0.1131	0.1485	0.7612
28	0.0995	0.1447	0.6877
29	0.0859	0.1411	0.6089
30	0.0724	0.1376	0.526
31	0.0588	0.1345	0.4373
32	0.0564	0.1313	0.4295
33	0.054	0.1284	0.4206
34	0.0516	0.1257	0.4107
35	0.0435	0.123	0.3534
36	0.0422	0.1206	0.3503
37	0.0473	0.1182	0.4002
38	0.0305	0.1159	0.263
39	0.0198	0.1137	0.1745
40	0.0196	0.1115	0.1756
41	0.0193	0.1096	0.1761
42	0.019	0.1077	0.1766
43	0.0197	0.1059	0.1859
44	0.0204	0.104	0.1965

To be continued :

Table (3-8):

Alpha -Energy (MeV)	**Cross Section (barn)**	**Total stopping power (MeV/(mg/cm^2)**	**Neutron Yield (neutron/10^{6}alpha particle**
45	0.0212	0.1022	0.2075
46	0.022	0.1006	0.2182
47	0.0227	0.0991	0.2292
48	0.0235	0.0975	0.2406
49	0.0242	0.096	0.2523
50	0.0246	0.0945	0.2599
51	0.0245	0.0932	0.2626
52	0.0285	0.0919	0.3097
53	0.0302	0.0906	0.3331
54	0.0268	0.0893	0.3006

(3-8-5) The cross sections, stopping power and neutron yield of $^{63}_{29}\mathrm{Cu}(\alpha,n)^{66}_{31}\mathrm{Ga}$ reaction:

The cross sections of $^{63}_{29}\mathrm{Cu}(\alpha,n)^{66}_{31}\mathrm{Ga}$ reaction have been plotted, spline interpolated and recalculated in fine steps(0.5MeV) for Alpha energy from (17) MeV to (30) MeV [55] using Matlab program, as shown in table (3-9). The reproduced cross sections are from authors Navin A., Tripathi V., Blumenfeld Y.; and Nanal V.[55]. From the results in table (3-9), we get the equation of 5th degree for plotted shown in Fig (3-5) as follows:

$$\sigma = 1.4*10^{-5}*x^5 - 0.0018*x^4 + 0.09*x^3 - 2.2*x^2 + 27*x - 1.3*10^{+2} \quad \text{……...(3-9)}$$

With percentage error (±0.2149) .

The stopping powers of Copper element for alpha particles are calculated in the same range of alpha energy and in the same interval of energy (0.5MeV) as shown in table (3-9). These data are plotted in Fig. (3-10) and we get equation of 9th degree as follows:

$$-\frac{dE}{dX} = 3.4*10^{-11}*E^{9} - 7.7*10^{-9}*E^{8} + 7.7*10^{-7}*E^{7} - 4.4*10^{-5}*E^{6} + 0.0016*E^{5} - 0.038*E^{4} + 0.6*E^{3} - 6.1*E^{2} + 35*E - 90 \quad \text{.........................(3-10)}$$

The neutron yield in unite (neutron/10^6alpha particle) with the interval (0.5MeV) of alpha particle that can be obtained are listed in table(3-9) and plotted in Fig.(3-15).

Table (3-9):The cross sections of $^{63}_{29}Cu(\alpha, n)^{66}_{31}Ga$ reaction as a function of Alpha energy with threshold energy (7.9735) MeV .

Alpha -Energy (MeV)	Cross Section (barn)	Total stopping power (MeV/(mg/cm^2))	Neutron Yield (neutron/10^6alpha particle
17	0.5701	0.2005	1.4216
17.5	0.5792	0.1967	1.4726
18	0.5883	0.1928	1.5256
18.5	0.5704	0.1895	1.5052
19	0.5421	0.1861	1.4564
19.5	0.4988	0.1828	1.3646
20	0.4502	0.1794	1.2547
20.5	0.4082	0.1766	1.1559
21	0.3684	0.1738	1.06
21.5	0.3354	0.1709	0.981
22	0.3044	0.1681	0.9052
22.5	0.2733	0.1653	0.8268
23	0.2423	0.163	0.7435
23.5	0.2113	0.1606	0.6578
24	0.1803	0.1583	0.5695
24.5	0.1642	0.1559	0.5265
25	0.1512	0.1536	0.4921
25.5	0.1381	0.1516	0.4557
26	0.1251	0.1496	0.4182
26.5	0.1121	0.1476	0.3798
27	0.0991	0.1456	0.3403
27.5	0.086	0.1436	0.2996
28	0.073	0.1418	0.2574
28.5	0.06	0.1401	0.2141
29	0.047	0.1384	0.1697
29.5	0.0339	0.1366	0.1242
30	0.0209	0.1349	0.0776

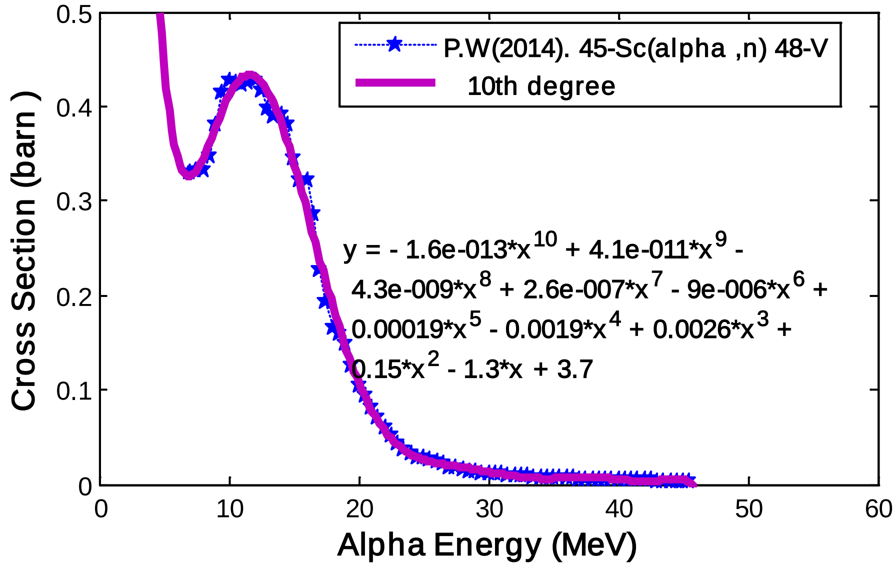


Fig. (3-1): The cross sections of $^{45}_{21}\mathrm{Sc}(\alpha,n)^{48}_{23}\mathrm{V}$ reaction by fitting and interpolation.

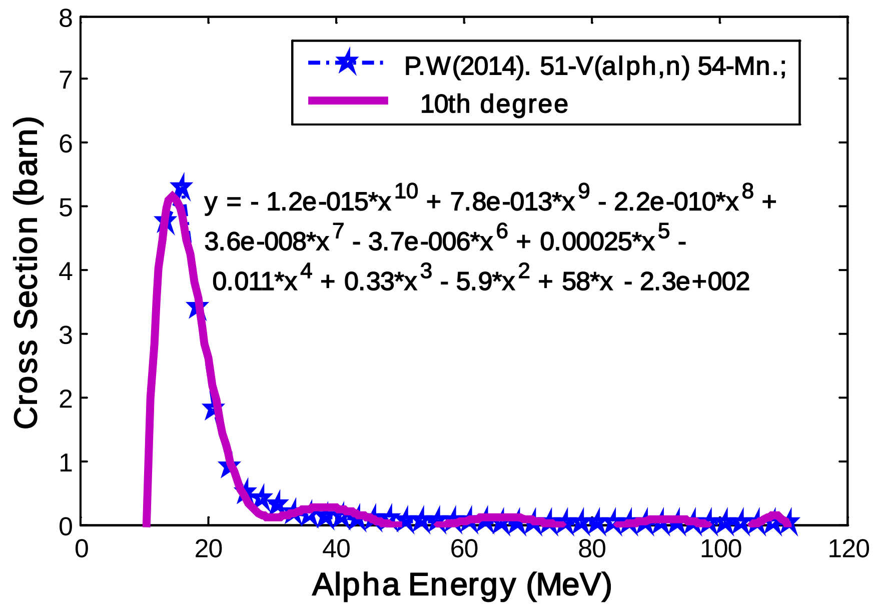


Fig. (3-2): The cross sections of $^{51}_{23}\mathrm{V}(\alpha,n)^{54}_{25}\mathrm{Mn}$ reaction by fitting and interpolation.

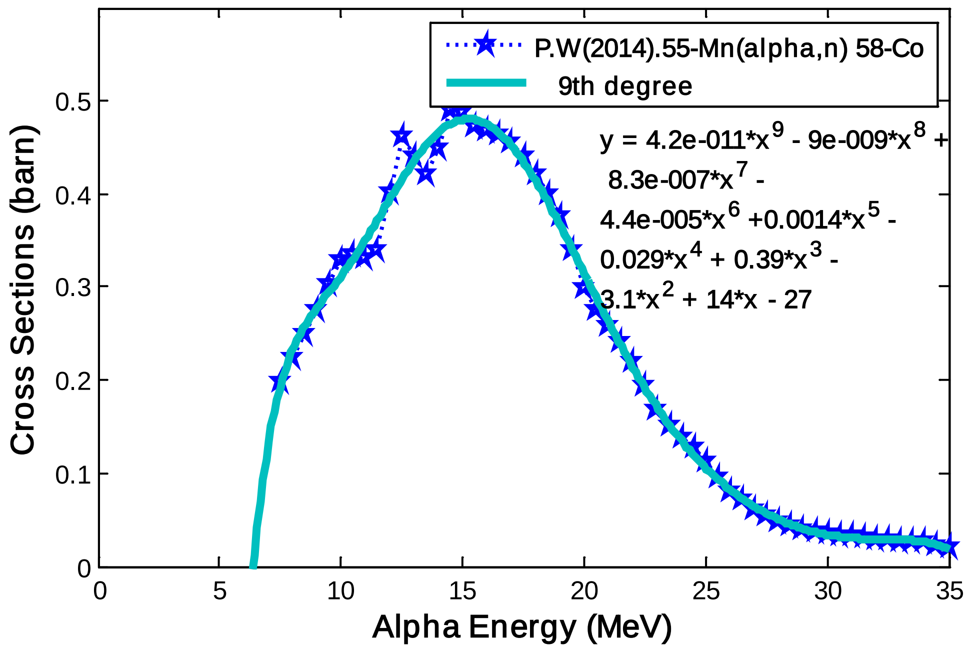


Fig. (3-3): The cross sections of $^{55}_{25}\mathrm{Mn}(\alpha,\mathrm{n})^{58}_{27}\mathrm{Co}$ reaction by fitting and interpolation.

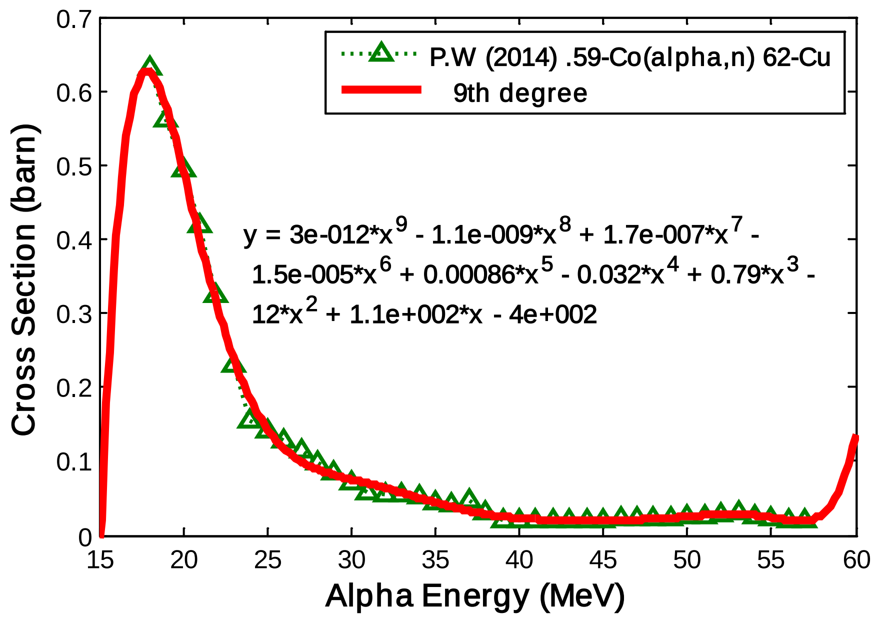


Fig. (3-4): The cross sections of $^{59}_{27}\mathrm{Co}(\alpha,\mathrm{n})^{62}_{29}\mathrm{Cu}$ reaction by fitting and interpolation.

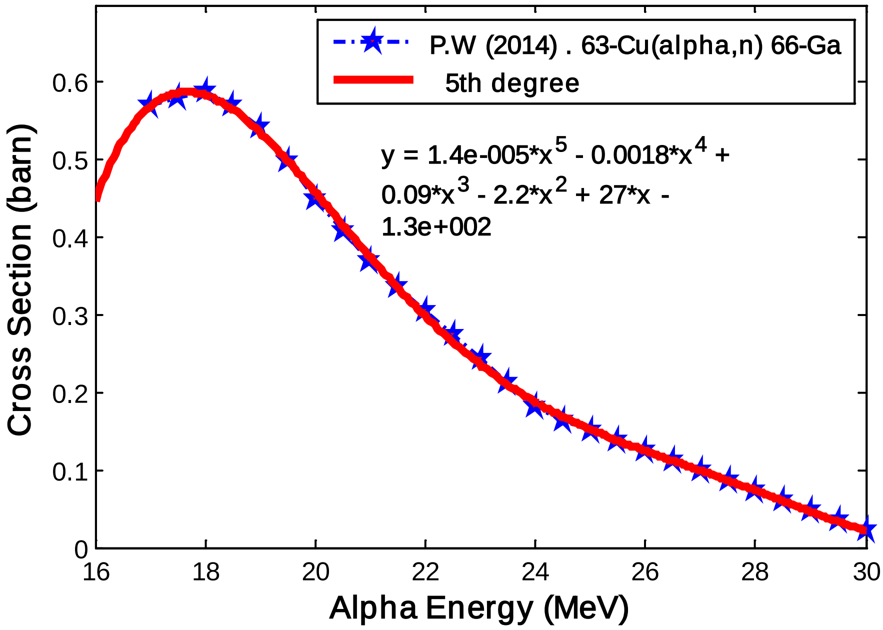


Fig. (3-5): The cross sections of $^{63}_{29}Cu(\alpha, n)^{66}_{31}Ga$ reaction by fitting and interpolation.

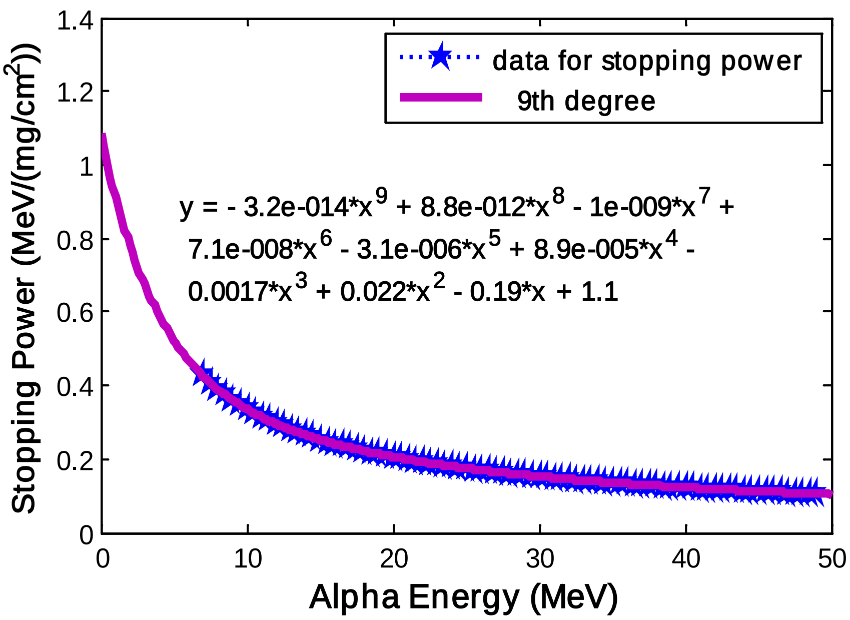


Fig. (3-6): The stopping power for $^{45}_{21}Sc(\alpha, n)^{48}_{23}V$ reaction(present work).

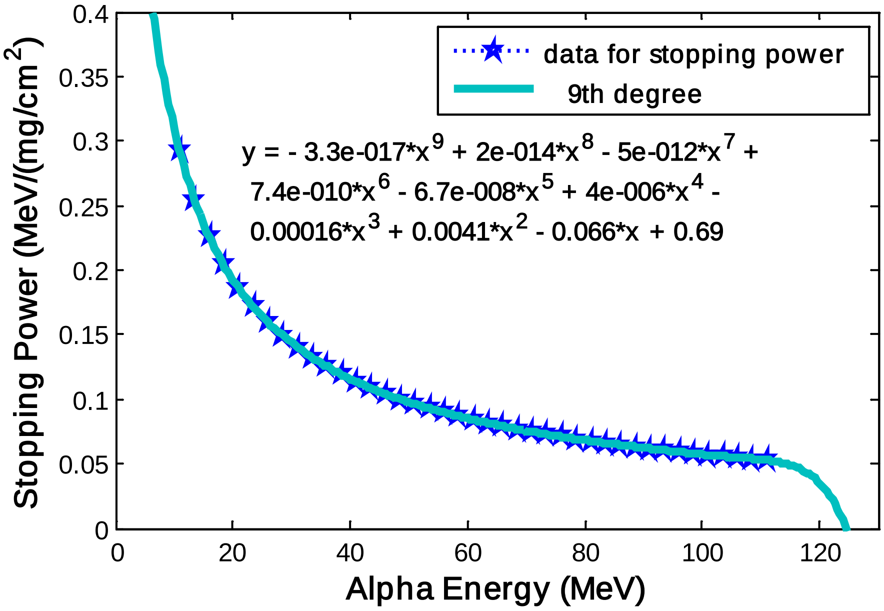


Fig.(3-7): The stopping power for $^{51}_{23}V(\alpha,n)^{54}_{25}Mn$ reaction(present work)

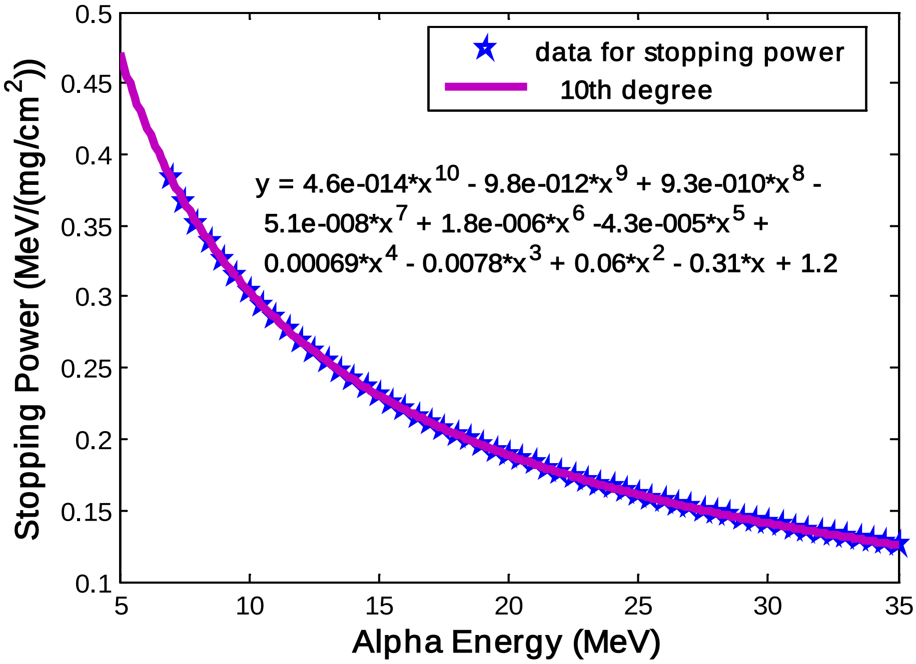


Fig.(3-8): The stopping power for $^{55}_{25}Mn(\alpha,n)^{58}_{27}Co$ reaction (present work).

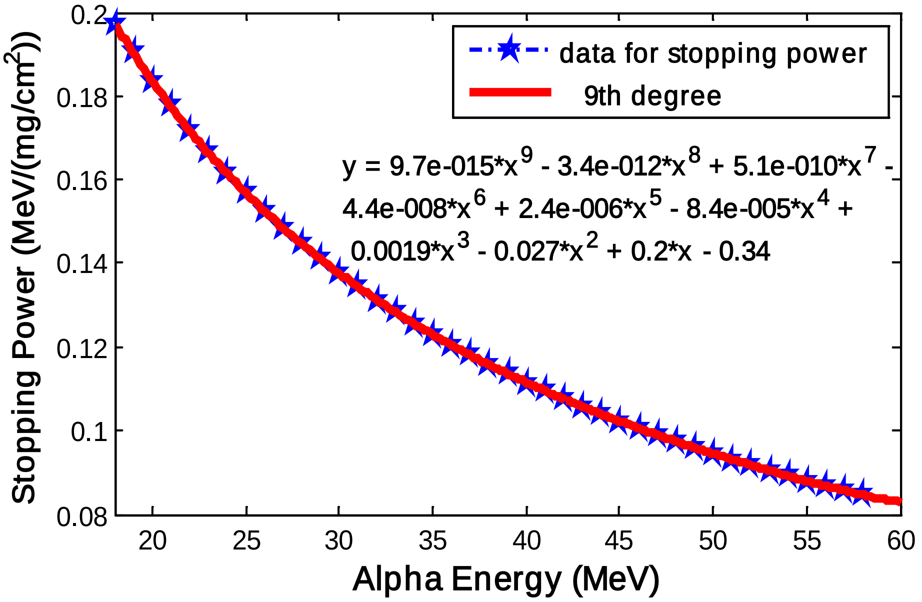


Fig. (3-9): The stopping power for $^{59}_{27}Co(\alpha, n)^{62}_{29}Cu$ reaction (present work).

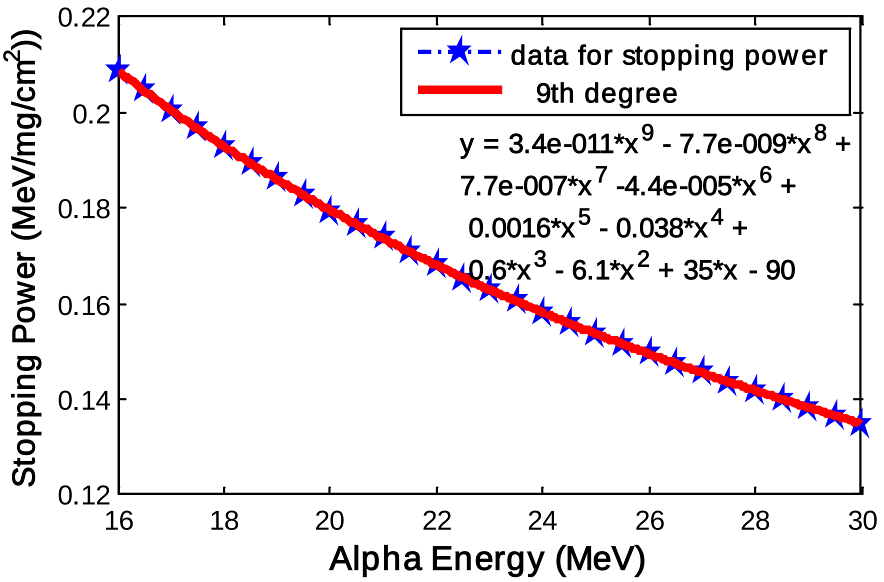


Fig.(3-10): The stopping power for $^{63}_{29}Cu(\alpha, n)^{66}_{31}Ga$ reaction (present work).

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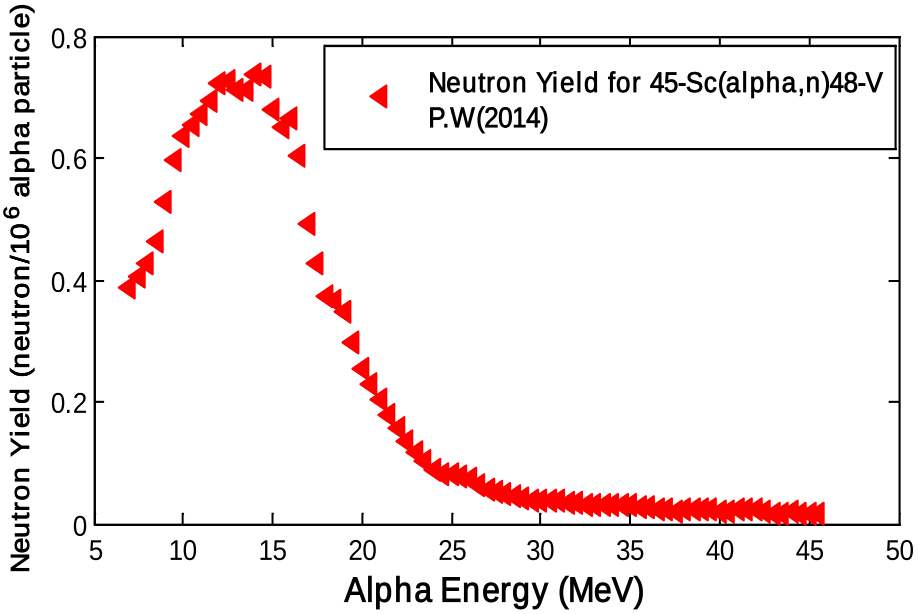

Fig. (3-11) :The neutron yield for $^{45}_{21}\mathrm{Sc}(\alpha,\mathrm{n})^{48}_{23}\mathrm{V}$ reaction (present work).

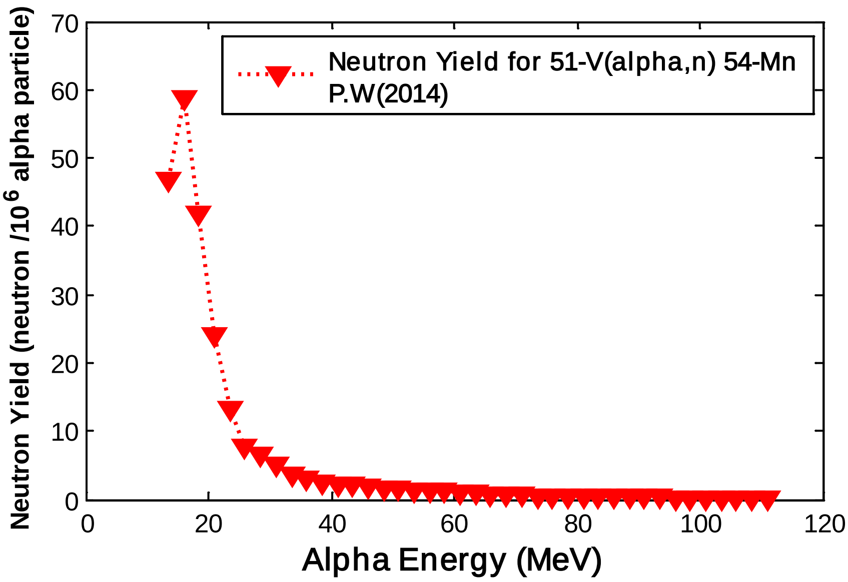

Fig. (3-12): The neutron yield for $^{51}_{23}\mathrm{V}(\alpha,\mathrm{n})^{54}_{25}\mathrm{Mn}$ reaction(present work).

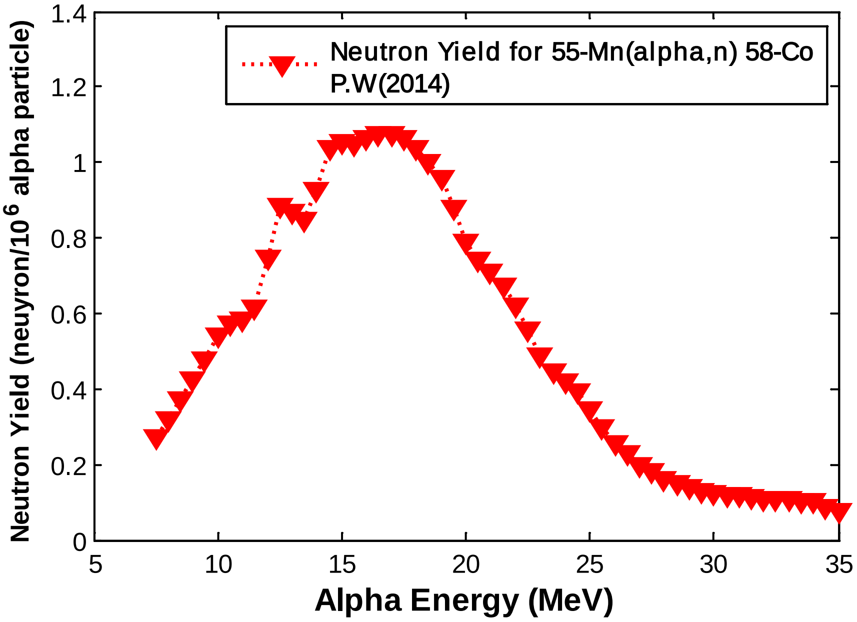

Fig.(3-13): The neutron yield for $^{55}_{25}Mn(\alpha,n)^{58}_{27}Co$ reaction(present work).

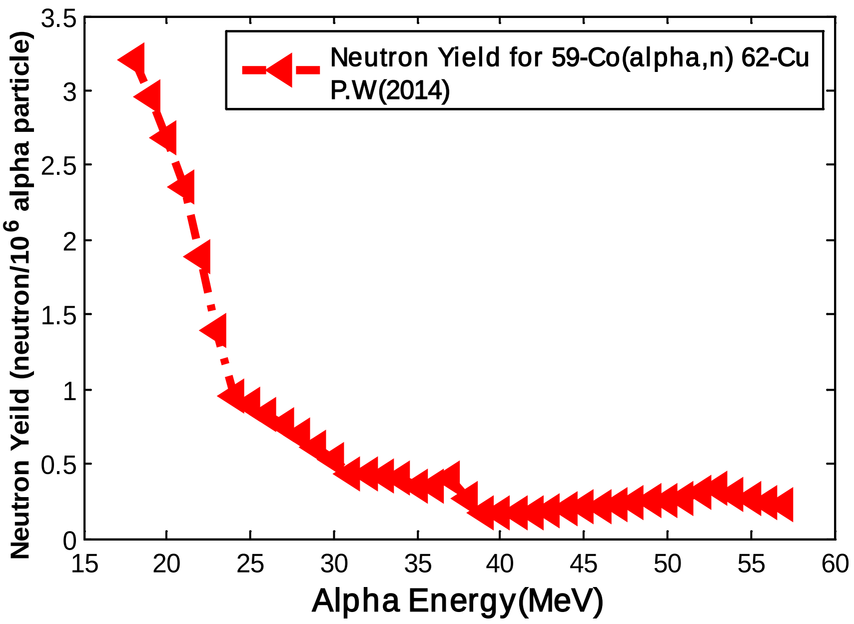

Fig. (3-14): The neutron yield for $^{59}_{27}Co(\alpha,n)^{62}_{29}Cu$ reaction(present work).

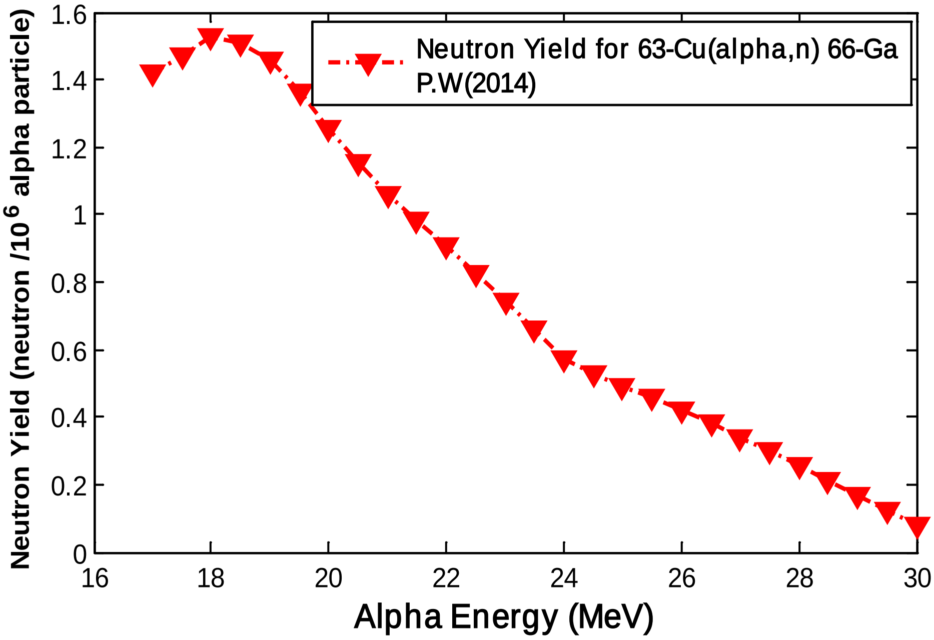

Fig.(3-15) : The neutron yield for $^{63}_{29}Cu(\alpha, n)^{66}_{31}Ga$ reaction (present work).

3-9 The reciprocal cross sections of (α,n) reactions:

The evaluated cross sections of (n,α) reactions for target intermediate isotopes ($^{48}_{23}V$, $^{54}_{25}Mn$, $^{58}_{27}Co$, $^{62}_{29}Cu$, $^{66}_{31}Ga$)are calculated using reciprocity theory.The cross sections as a function of neutron energy are listed in tables (3-10) to (3-14) and plotted in Figs. (3-16)to(3-20) .

Then we applied the reciprocity theory of reaction to get the semi empirical formula for the reactions in equation (2-43) :

$$\sigma_{(n,\alpha)} = \frac{g_{n,\alpha} M_\alpha T_\alpha}{g_{\alpha,n} M_n T_n} \sigma_{(\alpha,n)}$$

Depending on parity and spin of isotopes in the ground state which is given in table (3-4)[74] of calculation the g-statistical factor for every reaction by using equations (2-44) and(2-45). From table (3-1) and (3-2), we get atomic mass, Q_o-value and threshold energy to calculate the kinetic energy of neutron by using equation (2-58) .

(3-9-1) The cross sections of $^{48}_{23}V(n,\alpha)^{45}_{21}Sc$ reaction :

We calculated the cross sections for $^{48}_{23}V(n,\alpha)^{45}_{21}Sc$ reaction of neutron energy(4.2727) MeV to (40.3472) MeV by using the reciprocity theory (equation (2-43)) as follows:

$$\sigma_{n,\alpha} = 0.44 \frac{M_n T_n}{M_\alpha T_\alpha} \sigma_{\alpha,n} \quad \text{……………………………………..…...…..(3-11)}$$

From eqs.(2-44) and (2-45) we get that, $g_{\alpha,n}$=1 and $g_{n,\alpha}$=8/18.The evaluations of cross sections are listed in table (3-10) and plotted in Fig.(3-16) also we get semi empirical formula of 10th degree by using computer program (Matlab version 7.7 R2008)).

Table (3-10) : The cross sections of $^{48}_{23}V(n,\alpha)^{45}_{21}Sc$ reaction as a function of neutron energy.

Neutron Energy (MeV)	Cross Section (barn)	Neutron Energy (MeV	Cross Section (barn)
4.2727	1.6523	22.5442	0.1084
4.7412	1.6595	23.0127	0.0949
5.2097	1.6666	23.4812	0.0865
5.6782	1.7388	23.9497	0.078
6.1467	1.9085	24.4182	0.0711
6.6152	2.0783	24.8867	0.0642
7.0837	2.1386	25.3552	0.0596
7.5522	2.1261	25.8237	0.0584
8.0207	2.1136	26.2922	0.0573
8.4892	2.1239	26.7607	0.055
8.9577	2.1398	27.2292	0.0525
9.4262	2.0888	27.6977	0.0498
9.8947	1.9933	28.1662	0.0466
10.3632	1.943	28.6347	0.0437
10.8317	1.9605	29.1032	0.0421
11.3002	1.9	29.5717	0.0405
11.7687	1.7224	30.0402	0.0405
12.2372	1.6136	30.5087	0.0401
12.7057	1.6081	30.9772	0.037
13.1742	1.4308	31.4457	0.0345
13.6427	1.1389	31.9142	0.032
14.1112	0.9672	32.3827	0.0293
14.5797	0.8254	32.8512	0.0265
15.0482	0.7949	33.3197	0.0285
15.5167	0.746	33.7882	0.0297
15.9852	0.6237	34.2567	0.0282
16.4537	0.5265	34.7252	0.0269
16.9222	0.4671	35.1937	0.0264
17.3907	0.4077	35.6622	0.0261
17.8592	0.3509	36.1307	0.0263
18.3277	0.3042	36.5992	0.0263
18.7962	0.2575	37.0677	0.0257
19.2647	0.2147	37.5362	0.0235
19.7332	0.1878	38.0047	0.0202

To be continued :

Table (3-10) :

Neutron Energy (MeV)	Cross Section (barn)	Neutron Energy (MeV	Cross Section (barn)
20.2017	0.1609	38.4732	0.0201
20.6702	0.1469	38.9417	0.0209
21.1387	0.1415	39.4102	0.0203
21.6072	0.1361	39.8787	0.0195
22.0757	0.1232	40.3472	0.0179

(3-9-2) The cross sections of $^{54}_{25}\mathbf{Mn}(\mathbf{n},\boldsymbol{\alpha})^{51}_{23}\mathbf{V}$ reaction :

We calculate the cross sections for $^{54}_{25}\mathrm{Mn}(\mathrm{n},\alpha)^{51}_{23}\mathrm{V}$ reaction of neutron energy (10.0585) MeV to (102.5585) MeV by using the reciprocity theory (equation(2-43)) as follows:

$$\sigma_{n,\alpha} = 1.4\frac{M_n E_n}{M_\alpha E_\alpha}\sigma_{\alpha,n} \qquad \text{(3-12)}$$

From eqs.(2-44) and (2-45) we get $g_{\alpha,n}$=3/20 and $g_{n,\alpha}$=3/14. The evaluations of cross sections are listed in table (3-11) and plotted in Fig. (3-17) also we get semi empirical formula of 10^{th} degree by using computer program (Matlab version 7.7 R2008)).

Table (3-11): The cross sections of $^{54}_{25}Mn(n,\alpha)^{51}_{23}V$ reaction as a function of neutron energy.

Neutron -Energy (MeV)	Cross- Sections (barn)	Neutron -Energy (MeV)	Cross- Sections (barn)
10.421	28.5552	57.671	0.189
12.7835	31.8459	60.0335	0.1513
15.146	20.4761	62.396	0.1244
17.5085	10.7675	64.7585	0.1179
19.871	5.4586	67.121	0.1016
22.2335	2.981	69.4835	0.0804
24.596	2.36	71.846	0.0784
26.9585	1.7391	74.2085	0.0766
29.321	1.1182	76.571	0.0748
31.6835	0.9321	78.9335	0.0672
34.046	0.746	81.296	0.0589
36.4085	0.6161	83.6585	0.0512
38.771	0.5472	86.021	0.0438
41.1335	0.4784	88.3835	0.0414
43.496	0.4139	90.746	0.039
45.8585	0.3495	93.1085	0.0366
48.221	0.3037	95.471	0.0342
50.5835	0.2751	97.8335	0.0336
52.946	0.2465	100.196	0.033
55.3085	0.2177	102.5585	0.0327

(3-9-3) The cross sections of $^{58}_{27}Co(n,\alpha)^{55}_{25}Mn$ reaction:

We calculate the cross sections for $^{58}_{27}Co(n,\alpha)^{55}_{25}Mn$ reaction of neutron energy(3.5094)MeV to (28.88894) MeV by using the reciprocity theory (equation(2-43)) as follows:

$$\sigma_{n,\alpha} = 1.5\,\frac{M_n E_n}{M_\alpha E_\alpha}\,\sigma_{\alpha,n} \quad \ldots\ldots\ldots\ldots(3\text{-}13)$$

From eqs. (2-44) and (2-45) we get $g_{\alpha,n}$=4/15 and $g_{n,\alpha}$=2/5. The evaluations of cross sections are listed in table (3-12) and plotted in Fig. (3-18) also we get semi empirical formula of 9th degree by using computer program (Matlab version 7.7

R2008)). This empirical formula that was getting is fitting remained nuclear reactions results under present consideration .

Table (3-12): The cross sections of $^{58}_{27}Co(n,\alpha)^{55}_{25}Mn$ reaction as a function of neutron energy.

Neutron -Energy (MeV)	Cross-Sections (barn)	Neutron -Energy (MeV)	Cross- Sections (barn)
3.5094	1.4833	16.6694	1.8005
3.9794	1.6744	17.1394	1.6332
4.4494	1.8655	17.6094	1.4397
4.9194	2.0577	18.0794	1.2461
5.3894	2.2518	18.5494	1.1189
5.8594	2.4459	19.0194	1.0359
6.3294	2.503	19.4894	0.9528
6.7994	2.4689	19.9594	0.8297
7.2694	2.5323	20.4294	0.7066
7.7394	2.9857	20.8994	0.603
8.2094	3.4391	21.3694	0.5285
8.6794	3.2835	21.8394	0.4541
9.1494	3.1278	22.3094	0.4067
9.6194	3.3438	22.7794	0.3593
10.0894	3.6528	23.2494	0.327
10.5594	3.6285	23.7194	0.2983
11.0294	3.521	24.1894	0.2731
11.4994	3.4921	24.6594	0.2617
11.9694	3.4548	25.1294	0.2502
12.4394	3.3845	25.5994	0.2401
12.9094	3.2845	26.0694	0.2308
13.3794	3.1397	26.5394	0.2218
13.8494	2.9776	27.0094	0.2144
14.3194	2.8039	27.4794	0.2071
14.7894	2.525	27.9494	0.2003
15.2594	2.2198	28.4194	0.1935
15.7294	2.0564	28.8894	0.1699

(3-9-4) The cross sections of $^{62}_{29}\mathrm{Cu}(n,\alpha)^{59}_{27}\mathrm{Co}$ reaction :

We calculate the cross sections for $^{62}_{29}\mathrm{Cu}(n,\alpha)^{59}_{27}\mathrm{Co}$ reaction of neutron energy(11.9515)MeV to(49.0015)MeV by using the reciprocity theory (equation(2-43)) as follows:

$$\sigma_{n,\alpha} = 3.33\,\frac{M_n E_n}{M_\alpha E_\alpha}\,\sigma_{\alpha,n} \quad \text{...(3-14)}$$

From eqs.(2-44) and (2-45) we get $g_{\alpha,n}$=1/10 and $g_{n,\alpha}$=1/3. The evaluations of cross sections are listed in table (3-13) and plotted in Fig. (3-19).

Table (3-13) : The cross sections of $^{62}_{29}\mathrm{Cu}(n,\alpha)^{59}_{27}\mathrm{Co}$ reaction as a function of neutron energy.

Neutron - Energy (MeV)	Cross- Sections (barn)	Neutron-Energy (MeV)	Cross- Sections (barn)
11.9515	9.9888	30.9515	0.482
12.9015	8.892	31.9015	0.3138
13.8515	7.7953	32.8515	0.3095
14.8015	6.6217	33.8015	0.3052
15.7515	5.1408	34.7515	0.3009
16.7015	3.6599	35.7015	0.3113
17.6515	2.4323	36.6515	0.3232
18.6015	2.2177	37.6015	0.3352
19.5515	2.003	38.5515	0.3472
20.5015	1.7884	39.5015	0.3592
21.4515	1.5738	40.4515	0.3711
22.4015	1.3592	41.4015	0.3831
23.3515	1.1446	42.3515	0.3884
24.3015	0.93	43.3015	0.3869
25.2515	0.8921	44.2515	0.45
26.2015	0.8543	45.2015	0.4771
27.1515	0.8164	46.1515	0.4244
28.1015	0.6873	47.1015	0.3717
29.0515	0.6679	48.0515	0.3355
30.0015	0.7478	49.0015	0.2994

(3-9-5) The cross sections of $^{66}_{31}\mathrm{Ga}(\mathrm{n},\alpha)^{63}_{29}\mathrm{Cu}$ reaction :

We calculate the mathematical equation for $^{66}_{31}\mathrm{Ga}(\mathrm{n},\alpha)^{63}_{29}\mathrm{Cu}$ reaction of neutron energy (8.5714)MeV to(20.9214)MeV by using the reverse reaction technique(equation (2-43)) as follows:

$$\sigma_{n,\alpha} = 5\frac{M_n E_n}{M_\alpha E_\alpha}\sigma_{\alpha,n} \quad \text{..(3-15)}$$

From eqs. (2-44) and (2-45) we get $g_{\alpha,n}$=1/5 and $g_{n,\alpha}$=1. The evaluations of cross sections are listed in table (3-14) and plotted in Fig. (3-20) .

Table (3-14): The cross sections of $^{66}_{31}\mathrm{Ga}(\mathrm{n},\alpha)^{63}_{29}\mathrm{Cu}$ reaction as a function of neutron energy.

Neutron - Energy (MeV)	Cross- Sections (barn)	Neutron-Energy (MeV)	Cross- Sections (barn)
8.5714	17.739	15.2214	5.6091
9.0464	18.0221	15.6964	5.1087
9.5214	18.3053	16.1714	4.7035
9.9964	17.7465	16.6464	4.2982
10.4714	16.8671	17.1214	3.893
10.9464	15.5195	17.5964	3.4877
11.4214	14.0073	18.0714	3.0825
11.8964	12.7014	18.5464	2.6772
12.3714	11.4615	19.0214	2.2719
12.8464	10.4347	19.4964	1.8667
13.3214	9.4695	19.9714	1.4614
13.7964	8.5044	20.4464	1.0562
14.2714	7.5393	20.9214	0.6509

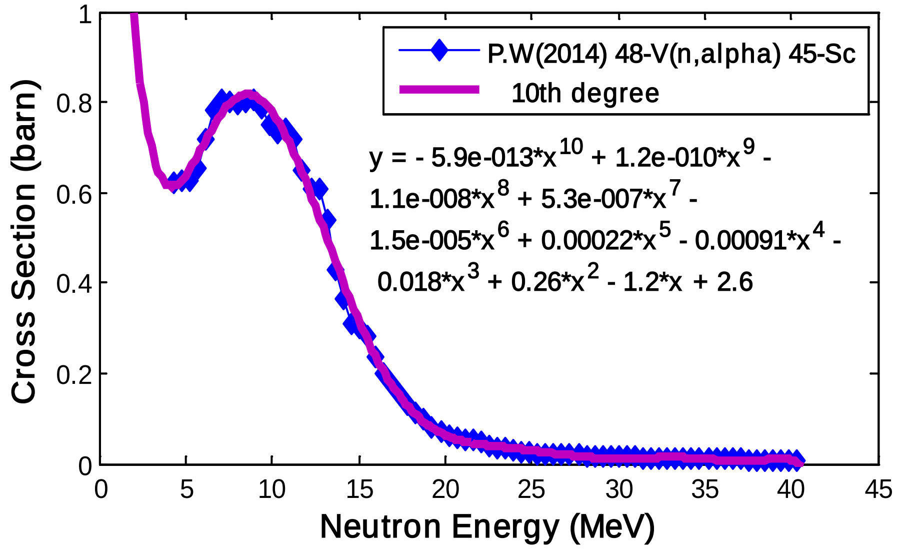

Fig. (3-16): The cross sections of $^{48}_{23}V(n,\alpha)^{45}_{21}Sc$ reaction

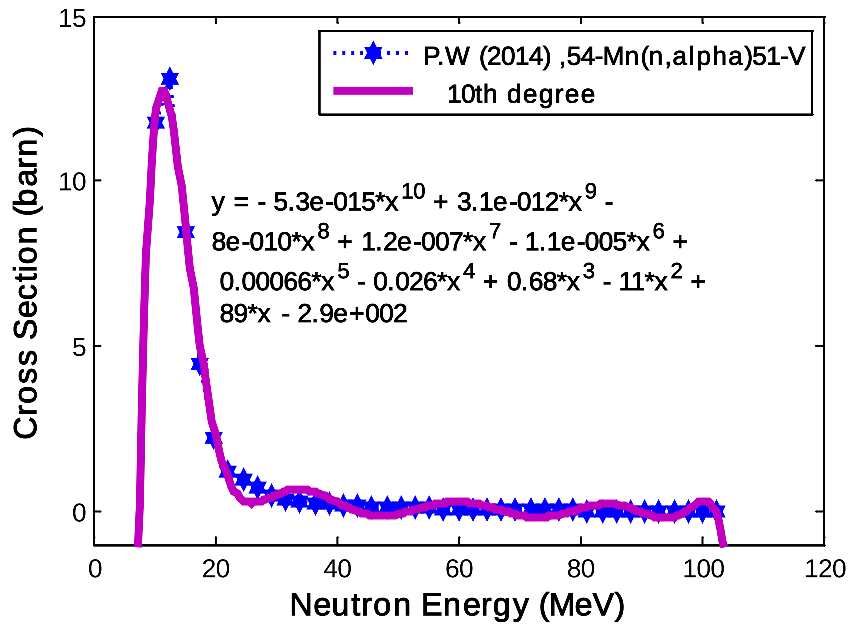

Fig. (3-17): The cross sections of $^{54}_{25}Mn(n,\alpha)^{51}_{23}V$ reaction.

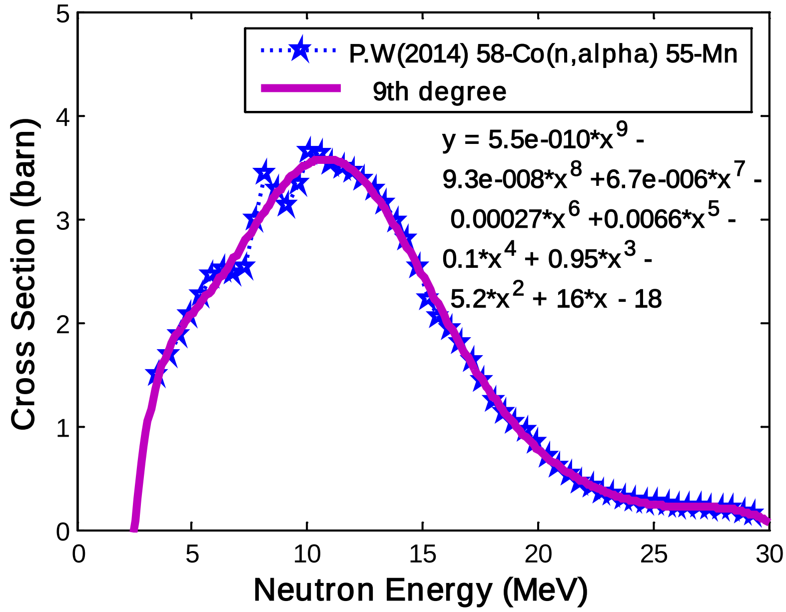

Fig. (3-18): The cross sections of $^{58}_{27}Co(n,\alpha)^{55}_{25}Mn$ reaction.

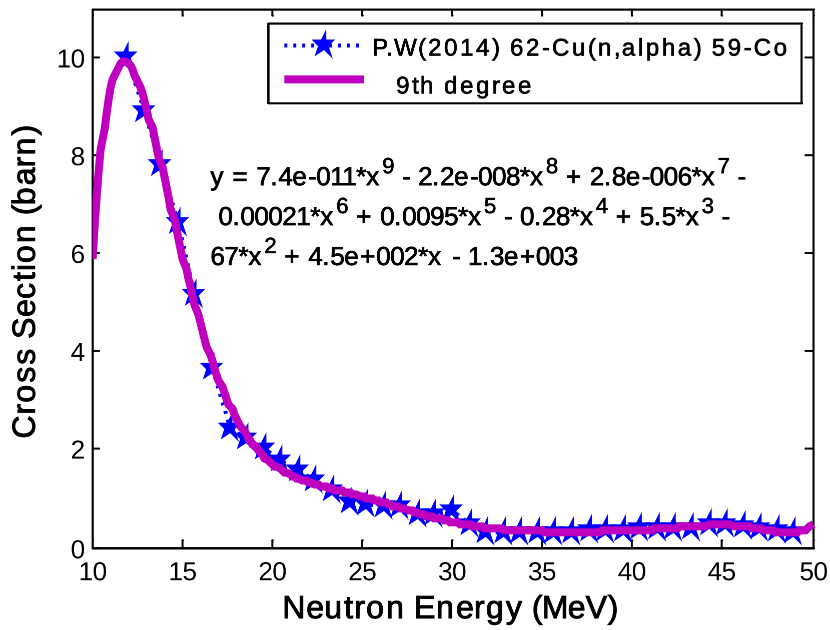

Fig. (3-19): The cross sections of $^{62}_{29}Cu(n,\alpha)^{59}_{27}Co$ reaction.

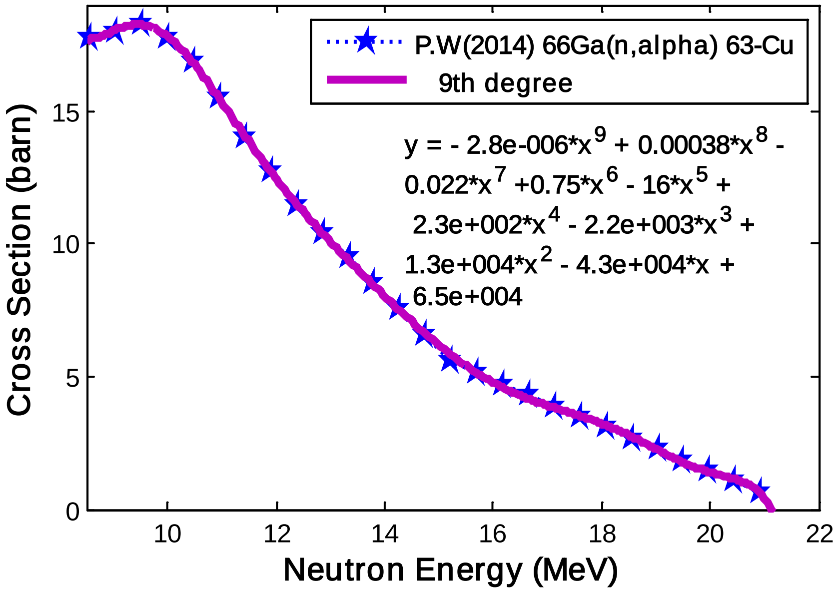

Fig. (3-20): The cross sections of $^{66}_{31}\mathrm{Ga}(\mathrm{n},\alpha)^{63}_{29}\mathrm{Cu}$ reaction.

Chapter Four

Discussion and conclusions

4-1 Basic properties for the nuclear reaction :

In present study our observations depend on some basic properties for nuclear reaction which requires for several purposes in comparison with the stability of nucleus with another nucleus such as :

1- Mass excess and packing fraction has negative value for each intermediate element as mentioned in table (3-1) from ^{45}Sc to ^{67}Ga , also element abundance was listed in the same table .

2- The Q_o-value and threshold energy for (α,n) reaction have been calculated as shown in table (3-2) . The (α,n) reactions are endoergic reactions, they have negative value with the range -2.2405MeV for ^{45}Sc to -7.5004MeV for ^{63}Cu. The value of binding energy for any nuclide is easily calculated, from the difference in mass of nucleus and the sum of the masses of the number of free neutrons and protons that make up the nucleus, for the imbalance of neutrons and protons in the nucleus.

3- The separation energy of neutron and alpha particle were maximum for ^{45}Sc(α,n)^{48}V .

4-2 The properties of nuclear cross section reactions of (α,n):

4-2-1: The $^{45}_{21}\mathrm{Sc}(\alpha,\mathrm{n})^{48}_{23}\mathrm{V}$ reaction:

From calculating the cross sections, stopping power and neutron yield of this reaction which has odd-even target nucleus $^{45}_{21}\mathrm{Sc}_{24}$ as mentioned in chapter three in table(3-5) and Fig. (3-1), we observe that the high probability to produce $^{48}_{23}$V by bombard $^{45}_{21}$Sc with alpha energy(12MeV) is (0.4277 barn), where the cross sections as a function of alpha energy are increased in range

(7-12MeV) and above (12MeV) are decreased. The short half-life of the isotopes produced by neutron capture makes vanadium a suitable material for the inner structure of a fusion reactor[76]. In Fig. (3-11) the maximum neutron yield in(14Mev)for alpha energy is (0.7221 number of neutron /10^6 alpha particle), this nuclear reaction has the minimum values of cross sections and the neutron yield form all other reactions.

The evaluations of inverse cross sections are listed in table (3-10) and plotted in Fig.(3-16), we observed that the inverse cross sections are increased from (4.27 MeV) to(7.08MeV) but above this energy are decreasing smoothly. We deduced that the high probability to produce $^{45}_{21}Sc$ is by bombard $^{48}_{23}V$ with fast neutron.

4-2-2 The $^{51}_{23}V(\alpha,n)^{54}_{25}Mn$ Reaction:

From the results of this reaction, we observe this reaction has odd-even target nucleus$^{51}_{23}V_{28}$ with magic number of neutrons and we observe that the high probability to produce$^{54}_{25}Mn$ by bombard $^{51}_{23}V$ with alpha energy(16 MeV) is (5.2974barn). The cross sections as a function of alpha energy are increased with range (13.5-16) MeV and above (16MeV) are decreasing smoothly as shown in table (3-6) and Fig.(3-2). In general, isotope $^{54}_{25}Mn$ is very important because it is used in industrial field [77] . In Fig.(3-12) the maximum neutron yield in(16Mev) for alpha energy is (58.6693 number of neutron /10^6 alpha particle), this reaction has a maximum value of cross sections with comparison with other nuclear reactions under present work, and it has the maximum values of neutron yield. For calculating the cross sections of inverse reactions by applying the reciprocity theory, we observed the inverse cross sections has maximum at (12.78MeV) but above this energy are decreasing smoothly as shown in table (3-11)and Fig.(3-17) . We deduced that the high probability to produce$^{51}_{23}V$ by bombard $^{54}_{25}Mn$ with fast neutron.

(4-2-3) The $^{55}_{25}\mathrm{Mn}(\alpha,n)^{58}_{27}\mathrm{Co}$ Reaction:

In this reaction which has odd-even nuclear target $^{55}_{25}\mathrm{Mn}_{30}$, the results from table (3-7) and Fig.(3-3) showed that the high probability to produce $^{58}_{27}\mathrm{Co}$ by bombard $^{55}_{25}\mathrm{Mn}$ with alpha energy(14.5MeV)is(0.4907barn).The cross sections as a function of alpha energy are increased with range (7.5-14.5) MeV and above (14.5MeV) are decreasing. In general isotope $^{58}_{27}\mathrm{Co}$ is very important because it is used in industrial field [78]. In Fig.(3-13) the maximum neutron yield alpha energy (17Mev) is (1.0747number of neutron /10^6 alpha particle)

The evaluations of inverse cross sections are listed in table (3-12) and plotted in Figure (3-18), we noticed the inverse cross sections are increased from (3.5MeV) to (10.08 MeV) but above this energy are decreased and this decrease is smoothly. We deduced the high probability to produce $^{55}_{25}\mathrm{Mn}$ bombard $^{58}_{27}\mathrm{Co}$ with fast neutron.

(4-3-4) The $^{59}_{27}\mathrm{Co}(\alpha,n)^{62}_{29}\mathrm{Cu}$ reaction:

For this reaction which have odd-even nuclear target $^{59}_{27}\mathrm{Co}_{32}$, we observe that the high probability to produce $^{62}_{29}\mathrm{Cu}$ by bombard $^{59}_{27}\mathrm{Co}$with alpha energy (18MeV) is (0.6316barn). The cross sections as a function of alpha energy has maximum in (18 MeV) and above (18MeV) are decrease smoothly as shown in table (3-8) and Fig.(3-4). In general isotope $^{62}_{29}\mathrm{Cu}$ is important because it is used in nuclear medicine for diagnostic purposes[79]. In Fig.(3-14) the maximum neutron yield with alpha energy (18Mev) is (3.1991 number of neutron /10^6 alpha particle) with maximum values of cross sections. The cross sections to inverse nuclear reaction $^{59}_{27}\mathrm{Co}(\alpha,n)^{62}_{29}\mathrm{Cu}$ are calculated as we have done previously in studies to nuclear reaction properties to $^{55}_{25}\mathrm{Mn}(\alpha,n)^{58}_{27}\mathrm{Co}$ and $^{51}_{23}\mathrm{V}(\alpha,n)^{54}_{25}\mathrm{Mn}$ reactions.

The evaluations of the inverse cross sections are listed in table (3-13) and plotted in Fig.(3-19), we observed that the cross sections were maximum at (11.9515 MeV) but above it the cross sections decreased smoothly. We deduced the high probability to produce $^{59}_{27}Co$ bombard $^{62}_{29}Cu$ with fast neutron.

(4-2-5) The $^{63}_{29}\mathbf{Cu}(\alpha,\mathbf{n})^{66}_{31}\mathbf{Ga}$ reaction:

For this reaction which have odd-even target nuclear ($^{63}_{29}Cu_{34}$), the results from table (3-9) and Fig.(3-5) as mentioned in chapter three, we observe that the high probability to produce $^{66}_{31}Ga$ by bombard $^{63}_{29}Cu$ with alpha energy (18MeV)is(0.5883barn). The cross sections as a function of alpha energy are increased in range (17-18) MeV and above (18MeV) are decreasing. In general isotope $^{66}_{31}Ga$ is very important because it is used in the medical field for treatment of pancreatic tumors and diseases of the blood and bone marrow[80].

In Fig.(3-15) the maximum neutron yield with alpha energy (18Mev) is (1.5256 number of neutron /10^6 alpha particle) with maximum values of cross sections as shown in Fig.(3-15).

For this reaction the calculation of the cross sections to inverse nuclear reaction by applying the reciprocity theory done in the same method in previous nuclear reactions studies and we observed that the cross sections were increased from (8.571MeV) to (9.5214MeV) but above it the cross sections are decreased smoothly as shown in table (3-14) and Fig.(3-20). We deduced that the high probability to produce $^{63}_{29}Cu_{34}$bombard $^{66}_{31}Ga_{35}$with fast neutron.

4-3 Conclusions and suggestions for future works:

4-3-1 Conclusions:

We can concluding the following points:

1- The cross sections of ${}^{45}_{21}Sc(\alpha,n){}^{48}_{23}V$ reaction (odd-even target nuclei) was the less cross sections than for others reactions with maximum separation energy of neutron and alpha particle .

2- The cross sections of ${}^{51}_{23}V(\alpha,n){}^{54}_{25}Mn$ reaction which has odd-even nuclei with magic number of neutron was the highest than other reactions .

3- The cross sections of ${}^{54}_{25}Mn(n,\alpha){}^{51}_{23}V$ reaction was the highest than other reactions, which has a number of neutron nearing the magic number.

4- Neutron yield in ${}^{51}_{23}V(\alpha,n){}^{54}_{25}Mn$ nuclear reaction is greater than other reactions, and the behavior of neutron yield with energy in most nuclear reaction in this work is smooth and it is constant for rhomb range.

5- The production of some isotopes is depending on bombarded energy for alpha particle , where these isotopes are very important in many applications.

4-3-2 Suggestions and future work:

1- Study the nuclear properties of (α,n) and (n,α) reactions for excited state.
2- Study the nuclear properties of (α,n) and (n,α) reactions for nucleuses that have even atomic number and compare them with these in present work.
3- Study the nuclear properties of (α,p) and (p,α) by using inverse reactions technique .
4- Use the computer codes that available in the Nuclear Data Centers (high cost codes) to study the most important properties like cross sections theoretically and compare them with the previous available experimental values, then estimate the neutron yields for (n,n`) , (p,n) and (γ,n) reactions for the other reactions.

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الخلاصة

الدراسة الحالية تركزت على دراسة الخواص النووية للتفاعل النووي (ألفا، نيوترون) لنويات الهدف ذات الأعداد الذرية الفردية وللتفاعلات ($^{45}_{21}Sc(\alpha,n)^{48}_{23}V$ ، $^{51}_{23}V(\alpha,n)^{54}_{25}Mn$ ، $^{55}_{25}Mn(\alpha,n)^{58}_{27}Co$ ، $^{59}_{27}Co(\alpha,n)^{62}_{29}C$ ، $^{63}_{29}Cu(\alpha,n)^{66}_{31}Ga$)من خلال حساب المقاطع العرضية لتفاعلات (ألفا ، نيوترون) للتفاعلات المذكورة أعلاه والمنشورة في الأدبيات العالمية (EXFOR , ENDF , JEF , JEFF , GENDL) لانتقاء الطاقات الملائمة في حساب التفاعل للمستوى الأرضي باستعمال على برنامج الحاسوب (Matlab-7.6) وبخطوات طاقية معينة . تم رسم وجدولت النتائج المستحصلة من تطبيق المعادلات شبه التجريبية لتمثيل جميع التفاعلات التي تربط بين تغير المقطع العرضي مع مدى الطاقة المعين . بالإضافة إلى حساب وجدولت بعض الخواص النووية للنظائر الموجود ة في هذه التفاعلات كما وتم حسا ب وجدولت كل من طاقة التفاعل وطاقة العتبة لكل تفاعل ومقارنتها مع النتائج الموجودة في مركز الدراسات النووية (NNDC) وهي متوافقة معها بشكل جيد جدا .

وكذلك تم حساب قدرة الإيقاف باستعمال برنامج SRIMو تم حساب الحاصل النيوتروني وفقا لصيغة زكلر لكل تفاعل بالاستعانة بقدرة الإيقاف .

وقد استعملت قيم المقاطع العرضية لتفاعلات (ألفا ، نيوترون) في حساب المقاطع العرضية لتفاعلات العكسية (نيوترون ،ألفا) وللمستوى الأرضي وذلك باشتقاق المعادلة شبه التجريبية لقيم المقاطع العرضية العكسية لكل من التفاعلات الآتية $^{48}_{23}V(n,\alpha)^{45}_{21}Sc$ ، $^{54}_{25}Mn(n,\alpha)^{51}_{23}V$ ، $^{58}_{27}Co(n,\alpha)^{55}_{25}Mn$ ، $^{62}_{29}Cu(n,\alpha)^{59}_{27}Co$ ، $^{66}_{31}Ga(n,\alpha)^{63}_{29}Cu$ وإيجاد الثوابت لكل تفاعل . تم رسم وجدولت النتائج المستحصله وإيجاد معادلة ملائمة للرسم التي يمكن من خلالها الحصول على مقاطع عرضية بطريقة مباشرة وسريعة وبسيطة وموثوقة .

جمهورية العراق
وزارة التعليم العالي والبحث العلمي
جامعة بغداد – كلية التربية للعلوم الصرفة ابن الهيثم

دراسة خصائص التفاعل النووي (n،α) للنوى الفردية-الزوجية
$(21 \leq Z \leq 29)$

رسالة
مقدمة إلى كلية التربية للعلوم الصرفة / ابن الهيثم- جامعة بغداد
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من قبل

نور عادل محمد

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