Reciprocity method in \((p,\alpha)\) and \((\alpha,p)\) cross sections reactions for Zn \((A=64, 68, 70)\) target element

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ABSTRACT
Reciprocity method has been applied and Empirical formulae have been obtained for calculating cross sections for \((p,\alpha)\) and \((\alpha,p)\) reactions on Zn\((A=64, 68, 70)\) thick targets medium elements in the energy range from threshold up to \(36.67\) MeV proton energy and to 200 MeV alpha energy. The reciprocity method has been applied with good estimation of the cross sections for the reactions that have experimental cross sections.

INTRODUCTION
The incident and product nuclear particles to be considered in the present work are protons and alpha that can cause nuclear reactions. Protons are one of the basic components of the nuclei of atoms (alpha being the other). They have about the same mass as alpha, but they have a positive charge of one unit. As a result, they interact strongly with the electrons in normal matter, and they have shorter ranges than alpha of similar energy[1]. They can penetrate through material easily. As was the case of gamma rays, this makes them both useful and dangerous. Alpha can induce nuclear reactions readily, and they are products of many reactions[2].

The \((p,\alpha)\) reactions induced by bombardment of medium elements have been intensively studied with high energy resolution up to energies accessible with conventional electrostatic accelerators. In addition to the intrinsic value of \((p,\alpha)\) cross section in the investigation of nuclear spectroscopy and reaction mechanisms, such data are essential for the polarization of \((p,\alpha)\) reactions as alpha sources[3,4].

For \((\alpha,p)\) reactions; as a beam of alpha travels through bulk matter, the intensity will decrease as alpha are removed from the beam by nuclear reactions. For fast alpha, many reactions such as \((\alpha,p), (\alpha,\alpha),\) are possible[2]. Absorption reactions include those where the alpha becomes part of the nucleus, and another type of particle is emitted. The absorption reactions most important to nuclear well logging are \((\alpha,p)\) reaction; where alpha absorption is followed by the emission of a gamma ray or proton, respectively[4]. The interaction of alpha with
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matter is not only of experimental or theoretical interest but has important practical applications, particularly in the operation of reactors [1].

There are many detailed theories of nuclear reaction. In Bohr Theory (1936) [5], it was assumed that a nuclear projectile incident on a nucleus would interact strongly with all the nucleons in the nucleus and quickly share its energy with them to form a nucleus in a highly excited state. The compound nucleus so created would decay in a manner independent of its mode of formation, and depends only on the properties of the compound nucleus itself, such as its energy and angular momentum. In Fernbach et al. theory (1949) [6]; it was proposed that an incident nucleon would interact with the nucleus and that the probability of absorption into the compound nucleus would be relatively small. These different aspects of a nuclear reaction can be unified into a single theory (Weisskopf), (1957) [7]; Feshbach,(1958) [8]. According to Weisskopf, any nuclear reaction proceeds through a series of stages. When the incident particle reaches the edge of the nuclear potential, the first interaction will be a partial reflection of the wave function, called shape elastic scattering. We recall that any potential discontinuity has a finite reflection coefficient for an incident wave which is independent of the direction of the travel of the wave. The part of the wave function which enters the nucleus undergoes absorption. Feshbach proposes that the first step in the absorption process consists of a two-body collision. If the struck nucleon leaves, a direct reaction occurs. Presumably this process becomes more probable at higher energies because, then, at least one nucleon would have a good chance of receiving enough energy to leave the nucleus. If the struck nucleon does not leave the nucleus, more complicated interactions can set in. The cross sections of (p,α) and (α,p) reactions published by different authors [9,12] for Zn (A=64, 68, 70) target elements were plotted, interpolated and recalculated. Adopted values have been calculated, the cross sections were reproduced in fine steps of incident proton energy in 0.01 MeV intervals with corresponding errors.

Theoretical Basics

If the cross sections of the reaction X(a,b)Y are measured as a function of $E_p$ ($E_p=$ kinetic energy of incident proton), the cross sections of the inverse reaction Y(b,a)X can be calculated as a function of $E_a$ ($E_a=$ kinetic energy of incident alpha). This is called the Reciprocities method which states that [13]:

$$\frac{\sigma(a,b)}{g(a,b)\lambda_a^2} = \frac{\sigma(b,a)}{g(b,a)\lambda_b^2} \quad \cdots (1)$$

Where $\sigma(a,b)$ and $\sigma(b,a)$ represent cross sections of X(a,b)Y and Y(b,a)X reactions respectively, g(a,b) and g(b,a) represent a statistical
factors of X(a,b)Y and Y(b,a)X reactions respectively, \( \lambda_a \) is the de-Broglie wave length divided by \( 2\pi \) for incident particle \( a \) and \( \lambda_b \) is that for product particle \( b \), which is regarded as incident particle in the reverse reaction.

a. Cross Section of Compound Nucleus

The cross section of compound nucleus is given by [2]:

\[
\sigma = \frac{\pi}{k^2} g \frac{\Gamma^2}{(E - E_R)^2 + \Gamma^2/4} \quad \cdots (2)
\]

Where the wave number \( k = 1/\lambda = p/h = mv/h = 2mE/h \) \( \cdots (3) \)

\( \lambda \) is the de-Broglie wave length divided by \( 2\pi \) of incident particle.

\( h \) is the Plank constant divided by \( 2\pi \).

\( p \) is the momentum of incident particle.

\( E \) is the kinetic energy of incident particle.

\( E_R \) is single isolated resonance energy.

The statistical \( g \)-factors is given by [2]:

\[
g = \frac{2I_c + 1}{(2S_a + 1)(2S_X + 1)} \quad \cdots (4)
\]

The total angular momentum of the resonance (compound nucleus) is given by:

\[
I_c = S_a + S_X + \ell_a \quad \cdots (5)
\]

Where \( S_a \) is the spin of the incident particle.

\( S_X \) is the spin of the target.

\( \ell_a \) is the orbital angular momentum of incident particle.

The total width of the state is the sum of the partial widths [14,15]:

\[
\Gamma = \sum_i \Gamma_i \quad \cdots (6)
\]

or \( \Gamma = h/\tau \) \( \cdots (7) \)

Where \( \tau \) is the lifetime of any decay state.

At resonance \( E = E_R \) equation (2) becomes:

\[
\sigma = \frac{4\pi}{k^2} g \quad \cdots (8)
\]

Therefore, equation (8) becomes

\[
\sigma(p,\alpha) = \frac{4\pi}{k_p^2} g(p,\alpha) \quad \cdots (9)
\]

and \( \sigma(\alpha, p) = \frac{4\pi}{k_\alpha^2} g(\alpha, p) \quad \cdots (10) \)

Which gives the compound nucleus cross section for \((p,\alpha)\) and \((\alpha,p)\) respectively.

Hence, using the definition of \( k \), equation (9) and (10) states that:
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\[
\frac{k_p^2 \sigma(p, \alpha)}{g(p, \alpha)} = \frac{k_\alpha^2 \sigma(\alpha, p)}{g(\alpha, p)} \quad \ldots (11)
\]

Since
\[
k_p = \frac{m_p v_p}{\hbar} = \frac{2m_p E_p}{\hbar} \quad \ldots (12)
\]
And
\[
k_\alpha = \frac{m_\alpha v_\alpha}{\hbar} = \frac{2m_\alpha E_\alpha}{\hbar} \quad \ldots (13)
\]

Substituted equation (12) and (13) in equation (11) we get:
\[
\frac{m_p^2 v_p^2 \sigma(p, \alpha)}{g(p, \alpha)} = \frac{m_\alpha^2 v_\alpha^2 \sigma(\alpha, p)}{g(\alpha, p)} \quad \ldots (14)
\]

In terms of \(E_p\) and \(E_\alpha\), equation (14) becomes:
\[
\frac{2m_p E_p \sigma(p, \alpha)}{g(p, \alpha)} = \frac{2m_\alpha E_\alpha \sigma(\alpha, p)}{g(\alpha, p)} \quad \ldots (15)
\]

Thus, equation (15) can be rewritten as follows:
\[
\sigma(p, \alpha) = \frac{g(p, \alpha)m_\alpha E_\alpha}{g(\alpha, p)m_p E_p} \sigma(\alpha, p) \quad \ldots (16)
\]

Where \(m_p\) and \(m_\alpha\) are the proton and alpha masses with their kinetic energies \(E_p\) and \(E_\alpha\) respectively.

It is clear from this equation that the cross sections of reverse reaction are related by variable parameters which can be calculated if the nuclear characteristics of the reactions are known.

b. Derivation the Proton and Alpha Energy

The reactions \(X(p, \alpha)Y\) and \(Y(\alpha, p)X\) can be represented with the compound nucleus (C.N.) at energy \(E\). It is clear that there are some important and useful relations between the kinetic energies of proton and alpha. The separation energies of proton (S.E.\(p\)) and neutron (S.E.\(\alpha\)) can be calculated using the following relations [13,16]:

\[
E = S.E_p + \frac{M_X}{M_X + M_p} E_p \quad \ldots (17)
\]

\[
E = S.E_\alpha + \frac{M_Y}{M_Y + M_\alpha} E_\alpha \quad \ldots (18)
\]

With
\[
S.E_p = [M_X + M_p - M_{C.N.}] \times 931.5 \quad \ldots (19)
\]

\[
S.E_\alpha = [M_Y + M_\alpha - M_{C.N.}] \times 931.5 \quad \ldots (20)
\]

Equating equation (17) and (18) and combining them with subtraction of equation (19) and (20) we get:

\[
S.E_p + \frac{M_X}{M_X + M_p} E_p = S.E_\alpha + \frac{M_Y}{M_Y + M_\alpha} E_\alpha \quad \ldots (21)
\]

\[
S.E_p - S.E_\alpha = [M_X + M_p - M_\alpha - M_{C.N.}] \times 931.5 \quad \ldots (22)
\]

It is clear that the Q-value of the reaction \(X(p, \alpha)Y\) is given by:
\[ Q(p, \alpha) = [M_X + M_p - M_Y - M_\alpha] \times 931.5 \]  \quad \text{... (23)}

or \[ Q(p, \alpha) = S.E_p - S.E_\alpha \]  \quad \text{... (24)}

\[ Q(p, \alpha) = \frac{M_Y}{M_Y + M_\alpha} E_\alpha - \frac{M_X}{M_X + M_p} E_p \]  \quad \text{... (25)}

Therefore,
\[ E_n = \frac{M_Y + M_\alpha}{M_Y} \left( Q(p, \alpha) + \frac{M_X}{M_X + M_p} E_p \right) \]  \quad \text{... (26)}

Since \[ Q(p, \alpha) = -\frac{M_X}{M_X + M_p} E_{thr}(p, \alpha) \]  \quad \text{... (27)}

Then
\[ E_n = \frac{M_Y + M_\alpha}{M_Y} \left[ \frac{M_X}{M_X + M_p} E_p - \frac{M_X}{M_X + M_p} E_{thr}(p, \alpha) \right] \]  \quad \text{... (28)}

\[ E_n = \frac{M_Y + M_\alpha}{M_Y} \cdot \frac{M_X}{M_X + M_p} \left[ E_p - E_{thr}(p, \alpha) \right] \]  \quad \text{... (29)}

For the reverse reaction \[ p + X \leftrightarrow \alpha + Y \] the Q-value of the reaction \[ Y(\alpha, p)X \] is given by:
\[ Q(\alpha, p) = [M_Y + M_\alpha - M_X - M_p] \times 931.5 \]  \quad \text{... (30)}

or \[ Q(\alpha, p) = S.E_\alpha - S.E_p \]  \quad \text{... (31)}

\[ Q(\alpha, p) = \frac{M_X}{M_X + M_p} E_p - \frac{M_Y}{M_Y + M_\alpha} E_n \]  \quad \text{... (32)}

Therefore,
\[ E_p = \frac{M_X + M_p}{M_X} \left[ Q(\alpha, p) + \frac{M_Y}{M_Y + M_\alpha} E_n \right] \]  \quad \text{... (33)}

Since \[ Q(\alpha, p) = -\frac{M_Y}{M_Y + M_\alpha} E_{thr}(\alpha, p) \]  \quad \text{... (34)}

Then
\[ E_p = \frac{M_X + M_p}{M_X} \left[ \frac{M_Y}{M_Y + M_\alpha} E_\alpha - \frac{M_Y}{M_Y + M_\alpha} E_{thr}(\alpha, p) \right] \]  \quad \text{... (35)}

\[ E_p = \frac{M_X + M_p}{M_X} \frac{M_Y}{M_Y + M_\alpha} \left[ E_\alpha - E_{thr}(\alpha, p) \right] \]  \quad \text{... (36)}

Data Reduction and Analysis

a. Method Used to Obtain the Adopted Cross Sections

1. The sets of experimental cross sections data were collected for different authors and with different energy intervals. The cross sections with their corresponding errors for each value are re-arranged according to the energy interval 0.01 MeV for available different energy range for each author.
2. The normalization for the statistical distribution of cross sections errors to the corresponding cross section values for each author has been done.

3. The interpolation for the nearest data for each energy interval as a function of cross sections and their corresponding errors has been done.

4. The interpolated values were calculated to obtain the adopted cross section which is based on the weighted average calculation according to the following expressions [17].

\[
\sigma_{w.a.} = \frac{\sum_{i=1}^{n} \frac{\sigma_i}{(\Delta\sigma_i)^2}}{\sum_{i=1}^{n} \frac{1}{(\Delta\sigma_i)^2}}
\] … (37)

Where the standard deviation error is:

\[
S.D. = \sqrt{\frac{\sum_{i=1}^{n} \frac{1}{(\Delta\sigma_i)^2}}}{\sum_{i=1}^{n} \frac{1}{(\Delta\sigma_i)^2}}
\] … (38)

Where \(\sigma_i\) : is the cross section value.

\(\Delta\sigma_i\) : is the corresponding error for each cross section value.

b. Adopt.m program

The adopt.m program, which is written in the present work using Matlab program version 7.0, to calculated the adopted cross section by programming equation (37).

c. Reverse.m program

The reverse.m program, which is written in the present work using Matlab version 7.0, to calculate \(E_\alpha\) and \(E_p\) by programming equation (29) and (36) respectively. Also this program is used to calculated \(\sigma(p,\alpha)\) and \(\sigma(\alpha,p)\) by programming equation (16).

4. Results and Discussion

The experimental results in the international Atomic Energy Agency (IAEA) libraries (EXFOR, ENDF-B-VI, and ENDF-B-VII) leave little doubt that the hypothesis of compound nucleus formation gives an excellent account of many diverse types of nuclear reactions. Table (1) present the available data collected for Zn \((A=64, 68, 70)\) target elements, from (IAEA), concerning the measurements of \((p,\alpha)\) and \((\alpha,p)\) reactions and their products. The features of nuclear reactions induced by particles (protons or alpha) starting from threshold energy has been proceeded.

The compound nuclear processes arise because the former are two-stage processes in which the momentum is conveyed in first instance to the compound nucleus. The compound nucleus mechanism still accounts for a large part of the observable yield for many reactions. For \((p,\alpha)\) and \((\alpha,p)\) reactions in Zn isotopes of mass number \((A=64,68,70)\), the
interaction cross sections are usually considerable less for the compound nucleus process. This is the reason for our interest in the present work for the considered reactions to be studied.

Table-1: International libraries used for available measuring data collection for \((p,\alpha)\) and \((\alpha,p)\) reactions for Zn (A=64, 68, 70) target elements.

<table>
<thead>
<tr>
<th>Target Element</th>
<th>Library</th>
<th>Product</th>
</tr>
</thead>
<tbody>
<tr>
<td>(^{64}<em>{30})Zn(</em>{34})</td>
<td>EXFOR, ENDF-B-VI, ENDF-B-VII</td>
<td>(^{67}<em>{31})Ga(</em>{42})</td>
</tr>
<tr>
<td>(^{68}<em>{30})Zn(</em>{38})</td>
<td>EXFOR, ENDF-B-VI, ENDF-B-VII</td>
<td>(^{65}<em>{29})Cu(</em>{38}), (^{71}<em>{31})Ga(</em>{40})</td>
</tr>
<tr>
<td>(^{70}<em>{30})Zn(</em>{40})</td>
<td>EXFOR, ENDF-B-VI, ENDF-B-VII</td>
<td>(^{67}<em>{31})Ga(</em>{42})</td>
</tr>
</tbody>
</table>

a. Adopted Cross Sections of \((p,\alpha)\) and \((\alpha,p)\) Reactions
The \((\alpha,p)\) cross sections data for the target elements \(^{64}_{30}\)Zn\(_{34}\), \(^{68}_{30}\)Zn\(_{38}\) and \(^{70}_{30}\)Zn\(_{40}\), are not available in the EXFOR library concerning the measurement of \((\alpha,p)\) reactions. The \((p,\alpha)\) cross sections data for the target elements \(^{64}_{30}\)Zn\(_{34}\), \(^{68}_{30}\)Zn\(_{38}\) and \(^{70}_{30}\)Zn\(_{40}\) are available in the EXFOR library concerning the measurement of \((p,\alpha)\) reactions, have been taken and plotted as shown in figures (1,2 and 3). These plots were analyzed using the Matlab-7.0 for selected energies given by different authors. In order to calculate the cross sections of \((p,\alpha)\) reactions for the maintained target elements, we adopt the cross sections for EXFOR library using the adopt.m program. It is important to note that the energy range of the reaction, taken from different authors, must be identical. For this reason, the determination of the energy range have been done in the present work by interpolated and recalculated the energy in steps of interval of 0.01 MeV starting from the threshold energy, ending with energy given for the incident alpha particle, in addition to the statistical treatments for cross section errors distribution have been made in order to obtain the adopted cross sections of a given reaction, which is based on the statistical variation treatment as a weighted average calculation according to equation (37).

b. Adopted Cross Sections of \((p,\alpha)\) Reactions and the Reciprocity method
The available data in the literature, taken from EXFOR library, concerning the measurement of the \((p,\alpha)\) reaction cross sections for the target elements mentioned above were evaluated in the present work in order to calculate the adopted cross sections using adopt.m program, and then recalculated by using the reciprocity theory, using revers.m
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program to get the reverse reaction cross sections. The results for each \((p,\alpha)\) reaction are discussed as follows:

1. \(^{64}\text{Zn}\)\(_{34}(p,\alpha)^{61}\text{Cu}\)\(_{32}\) Reaction

The sets of measured data for the cross sections of \(^{64}\text{Zn}\)\(_{34}(p,\alpha)^{61}\text{Cu}\)\(_{32}\) reaction reported by Cohen et al.\((1954)\) \([9]\), and Levkovskij \((1991)\) \([10]\), have been plotted, interpolated and recalculated in steps of 0.01 MeV starting from threshold energy 7.1 MeV up to 29.5 MeV. The measured data and the calculated adopted cross sections results are drawn as a function of incident proton energy as shown in figures \((1\text{ and } 4)\). One peaks appear \((\text{one states)}\); their calculated results are shown in table-2.

The results of the adopted cross sections of this reaction have been recalculated by using the reciprocity method, especially the reverse.m program to obtain the reverse reaction \(^{61}\text{Cu}\)\(_{32}(\alpha,p)^{64}\text{Zn}\)\(_{34}\) cross sections at threshold energy 7.449 MeV in steps of 0.01 MeV up to 30.95 MeV and then plotted to compared with the \(^{64}\text{Zn}\)\(_{34}(p,\alpha)^{61}\text{Cu}\)\(_{32}\) reaction cross sections as shown in figure \((4)\); the results are in a good agreement. The two reactions have the same behavior, but there is a difference in the range of cross section, which is caused by the difference in threshold energy and the spin for target \(^{64}\text{Zn}\)\(_{34}\) and the product \(^{61}\text{Cu}\)\(_{32}\).

2. \(^{68}\text{Zn}\)\(_{38}(p,\alpha)^{65}\text{Cu}\)\(_{36}\) Reaction

The cross sections data published by Esat et. al.\((1981)\) \([11]\). for this reaction have been plotted, interpolated, and recalculated in steps of 0.01 MeV from threshold energy 3.36 up to 5 MeV of the incident proton energy in order to obtain the adopted cross sections of this reaction. The measured data and the calculated adopted cross sections results are drawn as a function of incident proton energy as shown in figures \((2\text{ and } 5)\). Seven peaks appear \((\text{seven states)}\); their calculated results are shown in table-2.

The results of the adopted cross sections calculation for this reaction have been recalculated by using the reciprocity method to obtain the reverse reaction \(^{65}\text{Cu}\)\(_{36}(\alpha,p)^{68}\text{Zn}\)\(_{38}\) cross sections at threshold 3.515 MeV in steps of 0.01 MeV up to 5.23 MeV, and then are plotted to compared with the reaction \(^{68}\text{Zn}\)\(_{38}(p,\alpha)^{65}\text{Cu}\)\(_{36}\) cross sections; figure \((5)\) shows the results that the two reactions have the same behavior, but there is a difference in the range of cross section and energy, which is caused by the difference in threshold energy and the spin of target \(^{68}\text{Zn}\)\(_{38}\) and the product \(^{65}\text{Cu}\)\(_{36}\).
The reproduced of the comparison of both reactions are shown in figure (5).

3. \(^{70}_{30}Zn_{40}(p,\alpha)^{67}_{29}Cu_{38}\) Reaction

The cross sections data published by Levkovskij (1991) [10], and Kastleiner et al. (1999) [12]. For this reaction have been plotted, interpolated, and recalculated in steps of 0.01 MeV from threshold energy 7.70 up to 36.67 MeV of the incident proton energy in order to obtain the adopted cross sections of this reaction. The measured data and the calculated adopted cross sections results are drawn as a function of incident proton energy as shown in figures (3 and 6).

One peak appear (one state); their calculated results are shown in table-2.

The results of the adopted cross sections calculation for this reaction have been recalculated by using the reciprocity method to obtain the reverse reaction \(^{65}_{29}Cu_{36}(\alpha,p)^{68}_{30}Zn_{38}\) cross sections at threshold 10.8 MeV in steps of 0.01 MeV up to 39.43 MeV, and then are plotted to be compared with the reaction \(^{67}_{29}Cu_{38}(\alpha,p)^{70}_{30}Zn_{40}\) cross sections; figure (6) shows the results that the two reactions have the same behavior, but there is a difference in the range of cross section and energy, which is caused by the difference in threshold energy and the spin of target \(^{70}_{30}Zn_{40}\) and the product \(^{67}_{29}Cu_{38}\).

The reproduced of the comparison of both reactions are shown in figure (6).

<table>
<thead>
<tr>
<th>Reaction</th>
<th>State Number</th>
<th>maximum cross section (mb) at energy (MeV)</th>
<th>Half maximum cross section (mb)</th>
<th>FWHM (\Gamma) (MeV)</th>
<th>Life time (\tau=\hbar/\gamma) x10^{-22}(s)</th>
<th>Decay probability ((1/\tau)) x10^{22}(s^{-1})</th>
</tr>
</thead>
<tbody>
<tr>
<td>(^{64}<em>{30}Zn(p,\alpha)^{61}</em>{29}Cu)</td>
<td>1st</td>
<td>84.973(15.3)</td>
<td>42.487</td>
<td>9.19</td>
<td>0.7162</td>
<td>1.3962</td>
</tr>
<tr>
<td></td>
<td>1st</td>
<td>0.872(3.88)</td>
<td>0.436</td>
<td>...</td>
<td>...</td>
<td>...</td>
</tr>
<tr>
<td></td>
<td>2nd</td>
<td>0.966(4)</td>
<td>0.483</td>
<td>0.07</td>
<td>94.031</td>
<td>0.0106</td>
</tr>
<tr>
<td></td>
<td>3rd</td>
<td>1.076(4.06)</td>
<td>0.538</td>
<td>0.07</td>
<td>94.031</td>
<td>0.0106</td>
</tr>
<tr>
<td>(^{68}<em>{30}Zn(p,\alpha)^{61}</em>{29}Cu)</td>
<td>4th</td>
<td>1.32(4.1)</td>
<td>0.660</td>
<td>0.09</td>
<td>73.135</td>
<td>0.0136</td>
</tr>
<tr>
<td></td>
<td>5th</td>
<td>0.953(4.72)</td>
<td>0.477</td>
<td>...</td>
<td>...</td>
<td>...</td>
</tr>
<tr>
<td></td>
<td>6th</td>
<td>0.989(4.8)</td>
<td>0.495</td>
<td>...</td>
<td>...</td>
<td>...</td>
</tr>
<tr>
<td></td>
<td>7th</td>
<td>1.11(4.92)</td>
<td>0.555</td>
<td>...</td>
<td>...</td>
<td>...</td>
</tr>
<tr>
<td>(^{70}<em>{30}Zn(p,\alpha)^{61}</em>{29}Cu)</td>
<td>1st</td>
<td>14.813(14.8)</td>
<td>7.407</td>
<td>9.87</td>
<td>0.6669</td>
<td>1.4994</td>
</tr>
</tbody>
</table>

In analyzing the \((p,\alpha)\) reactions we note the following:

A- The discrete nuclear states that are populated in ordinary decays have discrete separations, widths, and lifetimes. Thus if we were to calculate the cross sections at a given incident proton or alpha energy of a nuclear state, it is very unlikely that the overlap of the energy...
distributions of two different states could cause confusion as to the stationary state resulting from the decay.
When the widths of unstable states are small compared with their separation, the states are distinct and observable. And if the states are overlap and strongly mixed, these states do not have distinctly observable wave functions, as shown in figure (3).
Because of the instability of the compound nucleus results in an uncertainty in the energy of these states. The energy uncertainty is given by the width of the resonance and lifetime of the state as calculated in the present work for each state. Therefore, the resonance will have the character of the energy distribution of any decaying state of width r, lifetime τ, and a maximum total cross section.

B- The \((p,\alpha)\) reactions and their reverse \((\alpha,p)\) reactions show resonances, corresponds to the same excited level of the compound nucleus formation. It is clear to see that each resonance in the \((\alpha,p)\) reaction is higher by the same amount (close to threshold energy) than the corresponding resonance in the \((p,\alpha)\) reaction, as shown in figure (3); but it is not appreciable in figure (4).

Figure -1: The adopted cross section of the \(^{64}_{30}Zn_{34}(p,\alpha)^{61}_{29}Cu_{32}\) reaction (present work) compared with EXFOR Library.
Data 3:Present Work(PW)
Figure -2: The adopted cross section of the $^{68}\text{Zn}_{38}(p,\alpha)^{65}\text{Cu}_{36}$ reaction

Figure -3: The adopted cross section of the $^{70}\text{Zn}_{40}(p,\alpha)^{67}\text{Cu}_{38}$ reaction (present work) compared with EXFOR Library.

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Figure -4: The adopted cross section of $^{64}_{30}Zn_{34}(p,α)^{61}_{29}Cu_{32}$ reaction as a function of proton energy with threshold of 7.10 Mev compared with the cross section of $^{61}_{29}Cu_{32}(α,p)^{64}_{30}Zn_{34}$ reaction as a function of alpha energy with threshold of 7.449 Mev using reciprocity method.

Figure -5: The adopted cross section of $^{68}_{30}Zn_{38}(p,α)^{65}_{29}Cu_{36}$ reaction as a function of proton energy with threshold of 3.36 Mev compared with the cross section of $^{65}_{29}Cu_{36}(α,p)^{68}_{30}Zn_{38}$ reaction as a function of alpha energy with threshold of 3.515 Mev using reciprocity method.
Evaluated Cross Sections of \((p,\alpha)\) and \((\alpha, p)\) Reactions

The evaluated ENDF library cross sections data of the following \((p,\alpha)\) reactions have been plotted, as a function of incident proton energy. Using reciprocity theory by using reverse.m program in order to obtain the cross sections of reverse \((\alpha, p)\) reactions and then plotted, as a function of incident alpha energy. The results plotted in figures (7,8 and 9) show that both reactions have the same behavior but the difference is in the cross section range, energy range, threshold energy and the spin of the target and the product.

**a. \(^{64}_{30}Zn_{34}(p,\alpha)^{61}_{29}Cu_{32}\) Reaction**

Figure (7) shows the evaluated ENDF-B-VI,VII library cross section of \(^{64}_{30}Zn_{34}(p,\alpha)^{61}_{29}Cu_{32}\) reaction with threshold energy 1.00E-11 MeV of incident proton up to 200 MeV. Figure (7) also shows the calculated reverse reaction \(^{61}_{29}Cu_{32}(\alpha, p)^{64}_{30}Zn_{34}\) cross sections with threshold energy 1.0491 MeV of incident alpha up to 209.83 MeV.

**b. \(^{68}_{30}Zn_{38}(p,\alpha)^{65}_{29}Cu_{36}\) Reaction**

Figure (8) shows the evaluated ENDF-B-VI,VII library cross section of \(^{68}_{30}Zn_{38}(p,\alpha)^{65}_{29}Cu_{36}\) reaction with threshold energy 1.00E-11 MeV of incident proton up to 200 MeV. Figure (8) shows the calculated reverse
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reaction $^{65}\text{Cu}_{36}(\alpha,p)^{68}\text{Zn}_{38}$ cross sections with threshold energy 1.0461 MeV of incident alpha up to 209.33 MeV.

c. $^{70}\text{Zn}_{40}(p,\alpha)^{67}\text{Cu}_{38}$ Reaction

Figure (9) shows the evaluated ENDF-B-VI,VII library cross section of $^{70}\text{Zn}_{40}(p,\alpha)^{67}\text{Cu}_{38}$ reaction with threshold energy 1.00E-11 MeV of incident proton up to 200 MeV. Figure (9) shows the calculated reverse reaction $^{67}\text{Cu}_{38}(\alpha,p)^{70}\text{Zn}_{40}$ cross sections with threshold energy 1.0447 MeV of incident alpha up to 208.95 MeV.

2. Evaluated Cross Sections of (α,p) Reactions and the Reciprocity method

The evaluated international libraries cross sections data of (α,p) reactions have been plotted in the present work as a function of incident alpha energy for Ni (A=58,60,61) target elements as shown in figures (10,11 and 12) respectively, using Matlab-7.0 program. The reciprocity theory has applied for each (α,p) reaction and separately for individual international libraries, by using reverse.m program. The details are as the following:

a. $^{64}\text{Zn}_{34}(\alpha,p)^{67}\text{Ga}_{36}$ Reaction

For $^{64}\text{Zn}_{34}(\alpha,p)^{67}\text{Ga}_{36}$ reaction, the evaluated cross sections data were available in ENDF-B-VI,VI, and ENDF-B-VI,VI libraries. These data have been plotted at threshold energy 4.2376 MeV, and recalculated by using the reciprocity method to obtain the reverse reaction $^{67}\text{Ga}_{36}(p,\alpha)^{64}\text{Zn}_{34}$ cross sections at threshold energy 0.1699 MeV, and then plotted as a function of incident proton energy, to compare with the $^{64}\text{Zn}_{34}(\alpha,p)^{67}\text{Ga}_{36}$ reaction. The results of this study show that both reactions have the same behavior. The reproduced cross sections for this reaction and the results of reverse reactions shown in figure (10).

b. $^{68}\text{Zn}_{38}(\alpha,p)^{71}\text{Ga}_{40}$ Reaction

The evaluated cross sections data of $^{68}\text{Zn}_{38}(\alpha,p)^{71}\text{Ga}_{40}$ reaction measured and declared by ENDF-B-VI,VI, and ENDF-B-VI,VII libraries. These data have been plotted at threshold energy 5.0098 MeV, and recalculated by using the reciprocity method to obtain the reverse reaction $^{71}\text{Ga}_{40}(p,\alpha)^{68}\text{Zn}_{38}$ cross section at threshold energy 0.3967 MeV, and then plotted as a function of incident proton energy, to compared with the $^{68}\text{Zn}_{38}(\alpha,p)^{71}\text{Ga}_{40}$ reaction. The results of this study show that both reactions have the same behavior. The reproduced cross sections from each library are shown in figure (11).

c. $^{70}\text{Zn}_{40}(\alpha,p)^{73}\text{Ga}_{42}$ Reaction

The evaluated cross sections data of $^{70}\text{Zn}_{40}(\alpha,p)^{73}\text{Ga}_{42}$ reaction measured and declared by ENDF-B-VI,VI, and ENDF-B-VI,VII libraries. These
data have been plotted at threshold energy 5.00008 MeV, and recalculate by using the reciprocity method to obtain the reverse reaction $^{73}_{31}Ga_{42}(p,\alpha)^{70}_{30}Zn_{40}$ cross sections at threshold energy 0.2013 MeV, and then plotted the cross section as a function of incident proton energy, to compared with the $^{70}_{30}Zn_{40}(\alpha, p)^{73}_{31}Ga_{42}$ reaction. The results of this study show that both reactions have the same behavior. The reproduced cross sections from each library are shown in figure (12).

Figure (7): The cross section of $^{64}_{30}Zn_{34}(p,\alpha)^{61}_{29}Cu_{32}$ reaction with threshold of 0.00 Mev compared with the cross section of $^{61}_{29}Cu_{32}(\alpha, p)^{64}_{30}Zn_{34}$ reaction with threshold 1.0491 Mev as calculated by the present work using reciprocity method for $^{64}_{30}Zn_{34}(p,\alpha)^{61}_{29}Cu_{32}$ as given by ENDF-B-VI,ENDF-B-VII library.

Figure (8): The cross section of $^{68}_{30}Zn_{38}(p,\alpha)^{65}_{29}Cu_{36}$ reaction with threshold of 0.00 Mev compared with the cross section of $^{65}_{29}Cu_{36}(\alpha, p)^{68}_{30}Zn_{38}$ reaction with threshold 1.0461 Mev as calculated by the present work using reciprocity method for $^{68}_{30}Zn_{38}(p,\alpha)^{65}_{29}Cu_{36}$ as given by ENDF-B-VI,ENDF-B-VII library.
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Figure -9: The cross section of $^{70}_{30}Zn(p,α)^{67}_{29}Cu$ reaction with threshold of 0.00 Mev compared with the cross section of $^{67}_{29}Cu(α,p)^{70}_{30}Zn$ reaction with threshold 1.0447 Mev as calculated by the present work using reciprocity method for $^{70}_{30}Zn(p,α)^{67}_{29}Cu$ as given by ENDF-B-VI,ENDF-B-VII library.

Figure -10: The cross section of $^{64}_{30}Zn(α,p)^{67}_{29}Ga$ reaction with threshold of 4.2376 Mev Compared with the cross section of $^{67}_{29}Ga(α,p)^{64}_{30}Zn$ reaction with threshold 0.1699 Mev as calculated by the present work using reciprocity method for $^{64}_{30}Zn(α,p)^{67}_{29}Ga$ as given by ENDF-B-VI,ENDF-B-VII library.

Figure -11: The cross section of $^{68}_{30}Zn(α,p)^{71}_{31}Ga$ reaction with threshold of 5.0098 Mev Compared with the cross section of $^{71}_{31}Ga(α,p)^{68}_{30}Zn$ reaction with threshold 0.3967 Mev as calculated by the present work using reciprocity method for $^{68}_{30}Zn(α,p)^{71}_{31}Ga$ as given by ENDF-B-VI,ENDF-B-VII library.
Conclusions
Because the widths of nuclear states are either small compared with their separation or overlapped. We therefore, conclude that it is reasonable to speak of discrete quasibound stationary states because their separation is far greater than their width, and we also conclude that such nuclear states do not contribute to the density of final states because there is only one nuclear state that can be reached in a given decay process.

The alpha production by proton incident reactions, \((p,\alpha)\) reactions, with medium nuclei have large cross sections for alpha production and they could have influence on safety design and operation of these facilities. Hence, accelerators using protons are used in such fields as physics, biology, proton therapy and medicines.

The reciprocity method is a good theory for the calculation of reverse reactions to estimate the cross sections for the reactions that have no atomic mass for their products or to calculate the cross sections of the reactions that have no experimental data.

It is able to estimate a mathematical empirical formulae for \((p,\alpha)\) and \((\alpha,p)\) reactions. Which could be used to predict the values of uncalculated cross sections.

REFERENCES


