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A Comparison Between the Theoretical Cross Section Based on the Partial Level Density Formulae Calculated by the Exciton Model with the Experimental Data for $^{197}_{79}Au$ nucleus

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Abstract:

In this paper, the theoretical cross section in pre-equilibrium nuclear reaction has been studied for the reaction $^{197}_{79}Au\ (n,p)^{198}_{78}Hg$ at energy 22.4 MeV. Ericson's formula of partial level density PLD and their corrections (William's correction and spin correction) have been substituted in the theoretical cross section and compared with the experimental data for $^{197}_{79}Au$ nucleus. It has been found that the theoretical cross section with one-component PLD from Ericson's formula when $n = 5$ doesn't agree with the experimental value and when $n = 7$. There is little agreement only at the high value of energy range with the experimental cross section. The theoretical cross section that depends on the one-component William's formula and on-component corrected to spin PLD formula doesn't agree with the experimental cross section. But in case of theoretical cross section based on two-component Ericson's and William's PLD formulae it has been found that there is acceptable agreement when the exciton number is taken $n = 5$.

Key words: Cross section, Exciton model, Pre-equilibrium cross section.

Introduction:

The cross section is an important quantity in studying the nuclear reaction, where it helps to calculate the probability of nuclear reaction, therefore, it became the main concern since the beginning of nuclear reaction studies. Many models have been supposed in order to describe the cross sections theoretically, as an example the compound nucleus model for describing the emission from the nucleus in statistical equilibrium (compound nucleus) (1). Also, when the pre-equilibrium emission was suggested many models were supposed for cross section calculations one of them is the exciton model.

Many studies were made for the cross section of pre-equilibrium emission. For example, in 2007 Sharma et.al. (2) studied the pre-equilibrium emission mechanism of ∝-induced reactions the excitation functions for $^{93}_{41}Nb(\alpha,n)^{96m}Tc, ^{93}_{41}Nb(\alpha,2n)^{95m}Tc,$ $^{93}_{41}Nb(\alpha,2n)^{95}Tc, and\ ^{93}_{41}Nb(\alpha,3n)^{94}Tc$ have been measured in the energy range threshold to ≅ 10 MeV using the activation technique. The measured excitation functions have also been compared with theoretical predictions based on the semi-classical code, which considers compound nucleus as well as pre-equilibrium emission.

Tatar and Tel 2010 (3) studied proton emission spectra produced by (p,xp) reactions for some nuclear reactors and particle accelerator material $^{56}_{26}Fe$ and $^{60}_{28}Ni$ target nuclei have been investigated by a proton beam up to 50 MeV. In these calculations the pre-equilibrium effects have been investigated, the results are compared with the experimental data from literature.

Noori et al. 2016 (4) studied the excitation functions for the reaction between deuteron and light nuclei. The following reactions $^{6}_{3}Li(d,n)$ $^{7}_{4}Be, ^{12}_{6}C(d,n)^{13}_{7}N, ^{16}_{8}O(d,n)^{17}_{9}F$ have been investigated using the code TALYS and the results were compared to the experimental results.

Korkmaz et. al. (5) studied the induced reactions of neutron with cobalt isotopes. They obtained the nuclear cross section data for the reactions $^{59}_{27}Co(n,2n)^{58}_{27}Co, ^{59}_{27}Co(n,3n)^{57}_{27}Co, ^{59}_{27}Co(n,4n)$ $^{56}_{27}Co, ^{59}_{27}Co(n,np)^{58}_{26}Fe,\ ^{59}_{27}Co(n,t)^{57}_{26}Fe, ^{59}_{27}Co(n,^{3}_{2}He)^{57}_{25}Mn$ and $^{59}_{27}Co(n,2n\propto)^{54}_{25}Mn$.They used the codes TALYS 1.8 and AL ICE/ASH to obtain the theoretical data and compared them with the experimental data.

They also investigated the action of different nuclear level density models on the cross section.

In this paper the theoretical cross section has been calculated for the reaction $^{197}_{79}Au\,(n,p)^{198}_{78}Hg$ at energy 22.4 MeV using different PLD formulae and the results are compared with the experimental data in order to test the most suitable formula.

Theory

The emission cross section in pre-equilibrium nuclear reactions is given by (1)(6)

$$I_\beta(\varepsilon,t)d\varepsilon = \frac{d\boldsymbol{\sigma}}{d\varepsilon} = \sum_n P(n,t)W_\beta(n,\varepsilon)d\varepsilon \ldots.1$$

The quantity P(n, t) represents the occupation probability of the exciton state n with excitation energy E for time t. $W_\beta(n,\varepsilon)$ is the emission probability of a particle β with emission energy ε from n excitation state in a nucleus of excitation energy E, it is given by

$$W_\beta = \frac{2s_\beta+1}{\pi^2\hbar^3}\mu_\beta\varepsilon\frac{\omega(n-1,U)}{\omega(n,E)}\boldsymbol{\sigma}_\beta(\varepsilon) \ldots..2$$

Where $S_\beta$the spin of the emitted particle is $\beta, \mu_\beta$is the reduced mass, $\boldsymbol{\sigma}_\beta(\varepsilon)$ is the total cross section of the inverse of the excitation channel for more details see (7), $\omega(n,E)$ is the level density of the excited nucleus with excitation energy E and $\omega(n-1,U)$, where U is the energy of the residual nucleus.

The partial level density PLD in pre-equilibrium reactions (it represents the level density of excitation of some nucleons in nuclei) is used from exciton model that was suggested by J.J. Griffin in 1966 (1).

Then the PLD formula for the case of the one-component (i. e the protons and the neutrons are considered as indistinguishable particles) is (1) (8)

$$\omega(n,E) = \frac{g^n E^{n-1}}{p!\,h!\,(n-1)!} \ldots..3$$

Where n is the exciton number $n = p + h, p$ is the particle number, h is the hole number and E is the excitation energy. G is the single particle level density in equidistant spacing model (the model considered the spaces between the levels are equal) and it is given by

$$g = \frac{A}{d} \ldots\ldots\ldots\ldots\ldots\ldots\ldots4$$

Where A is the mass number and d represents the spacing between the energy level d=13 MeV^{-1} .

Eq.3 is called one-component Ericson's formula and it represents the crude formula of level density, but if the protons and the neutrons are taken as distinguishable particles two-component formula must be used

$$\omega_2(\mathrm{n,E}) = \frac{(g_\pi)^{n\pi}\,(g_\upsilon)^{n\upsilon}E^{n-1}}{p_\pi!h_\pi!p_\upsilon!h_\upsilon!(n-1)!} \ldots\ldots\ldots5$$

Where p_π, h_π are particles and holes numbers of protons, p_ν, h_ν are particles and holes numbers of neutrons, g_π, g_ν are single particles state density of protons and neutrons respectively.

Pauli's correction

This correction was made by adding the factor A_{ph} which represents the effect of Pauli's principle(1)(8)

$$A_{ph} = \frac{p(p+1)+h(h+1)}{2g} \ldots\ldots6$$

The Ericson's formula then

$$\omega(n,E) = \frac{g^n(E-A_{ph})^{n-1}}{p!\,h!\,(n-1)!} \ldots\ldots7$$

In case of two components the factor becomes

$$A_{p_\pi,h_\pi,p_\nu h_\nu} = \frac{p_\pi(p_\pi+1)+h_\pi(h_\pi+1)}{2g_\pi} + \frac{p_\nu(p_\nu+1)+h_\nu(h_\nu+1)}{2g_\nu} \ldots\ldots.8$$

and the PLD formula becomes

$$\omega_2(n,E) = \frac{g_\pi^{n_\pi}g_\nu^{n_\nu}\left(E-A_{p_\pi,h_\pi,p_\nu h_\nu}\right)^{n-1}}{p_\pi!h_\pi!p_\nu!h_\nu!(n-1)!} \ldots\ldots\ldots\ldots.9$$

Spin correction

In this correction the PLD is multiplied by the angular momentum factor R_J (1)

$$R_J = \frac{2J+1}{2\sqrt{2}\pi\boldsymbol{\sigma}_n^3}\exp\left[\frac{(J+\frac{1}{2})^2}{2\boldsymbol{\sigma}_n^2}\right] \ldots..10$$

The parameter J represents the total angular momentum of the target nucleus and σ_n is the spin cut off parameter. Then the PLD formula becomes

$$\omega(n,E) = \frac{g^n E^{n-1}}{p!\,h!\,(n-1)!}R_J \ldots\ldots11$$

In the results a comparison will be made between the different theoretical cross section formulae based on the different PLD formulae (Ericson's formula and its corrections) with the experimental data to test how each one of them is useful in PLD calculations.

Results and Discussion:

In this section the theoretical cross section given by eq. 1 has been compared with the experimental data for $^{197}_{79}Au$ nucleus. All partial level density (PLD) formulae are substitute in eq.1 and the effect of each formula of PLD is studied by making a comparison with the experimental data taken from reference (9) for $^{197}_{79}Au$ nucleus. The equations were programed by Matlab 2015.

Figure 1 shows a comparison between theoretical cross section when PLD from one

component Ericson's formula was used with the experimental data and the exciton number is taken $n = 5$. One can notice that the theoretical cross section magnitude is bigger than the experimental one and the difference between them decreases with increasing the energy.

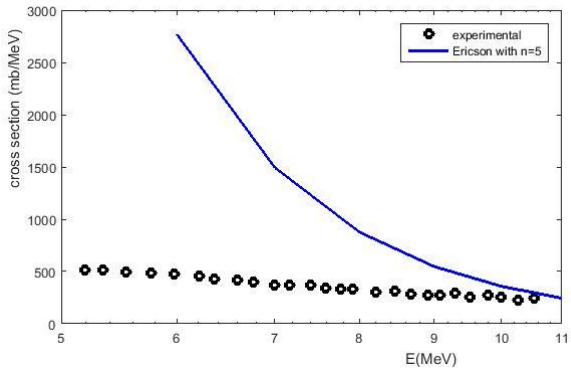


Figure 1. a comparison between the cross section based on one component PLD Ericson's formula when $n = 5$ with the experimental data for the reaction $^{197}_{79}Au(n,p)^{198}_{78}Hg$ at energy 22.4 MeV.

Figure 2 also demonstrates the theoretical cross section with PLD from Ericson with the experimental data but n was taken equal to 7. One can find that the theoretical cross section is closer to the experimental data from the case when $n = 5$ and applies on the experimental data with increasing the energy.

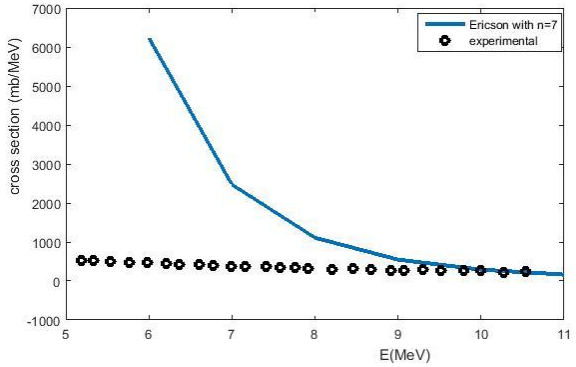


Figure 2. a comparison between the cross section based on one component PLD Ericson's formula when $n = 7$ with the experimental data for the reaction $^{197}_{79}Au(n,p)^{198}_{78}Hg$ at energy 22.4 MeV.

The convergence and the agreement of the curve with the experimental data when $n = 7$ can be interpreted as the exciton number $n = 7$ may be the most probable exciton number for emission, therefore it agrees with the experimental curve.

Figure 3 gives a comparison of the theoretical cross section with PLD from two-component Ericson's formula when $n = 5$ and the experimental data. Good agreement is maintained between them.

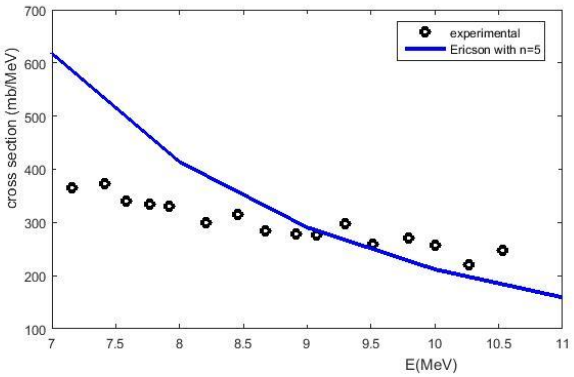


Figure 3. a comparison between the cross section based on two component PLD Ericson's formula when $n = 5$ with the experimental data for the reaction $^{197}_{79}Au(n,p)^{198}_{78}Hg$ at energy 22.4 MeV.

Figure 4 gives a comparison of the theoretical cross section with PLD from two-component Ericson's formula when $n = 7$ and the experimental data. The theoretical cross section is bigger than the experimental data. And there is little agreement at the end of the curve.

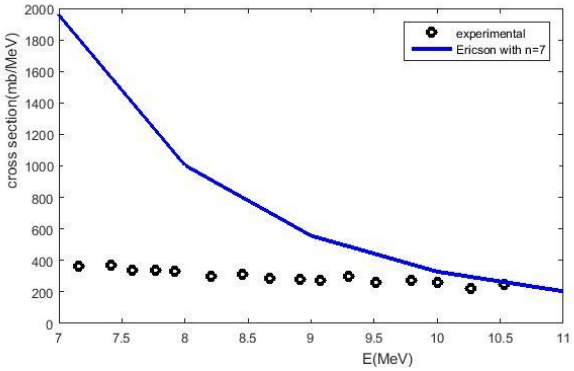


Figure 4. a comparison between the cross section based on two component PLD Ericson's formula when $n = 7$ with the experimental data for the reaction $^{197}_{79}Au(n,p)^{198}_{78}Hg$ at energy 22.4 MeV.

Figure 5 shows a comparison between the experimental cross section with the theoretical cross section based on the one-component William's formula of PLD. One can notice the theoretical cross section by using one-component William's formula of PLD in which $n = 5$ or $n = 7$ is less than the experimental data. This can be justified by the effect of Pauli correction factor A_{ph} which decreases the excitation energy value and this leads to decrease the theoretical cross section.

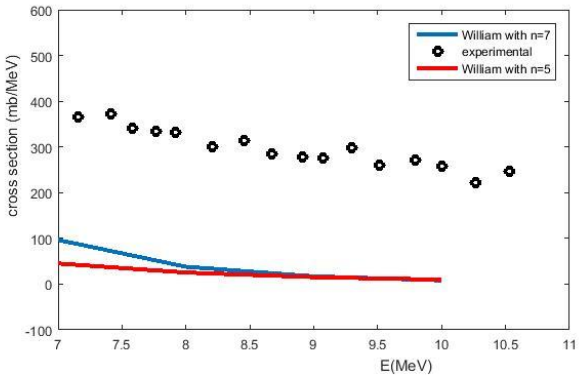


Figure 5. a comparison between the cross section based on one component PLD William's formula when $n = 5$and $n = 7$ with the experimental data for the reaction $^{197}_{79}Au(n,p)^{198}_{78}Hg$ at energy 22.4 MeV.

In Fig.6. a comparison between theoretical cross section which depends on two-component William's formula of PLD with the experimental data is made, where the exciton number is taken $n = 5$. There is good agreement between the theoretical and the experimental results.

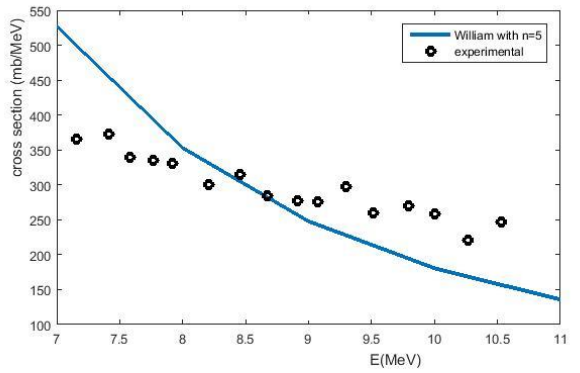


Figure 6. a comparison between the cross section based on two component PLD William's formula when $n = 5$ with the experimental data for the reaction $^{197}_{79}Au(n,p)^{198}_{78}Hg$ at energy 22.4 MeV.

Figure 7 shows a comparison between theoretical cross section based on William's formula with $n = 7$ and the experimental cross section, one can notice that the theoretical cross section is so bigger than the experimental data.

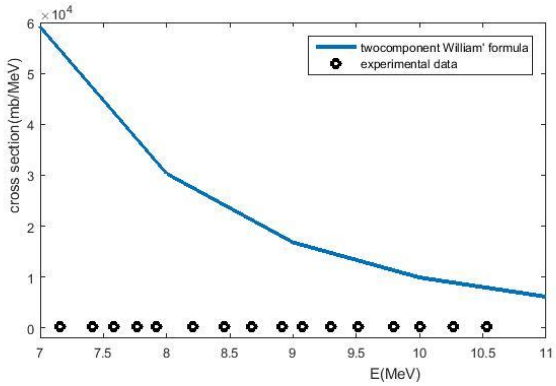


Figure 7. a comparison between the cross section based on one component PLD William's formula when $n = 7$ with the experimental data for the reaction $^{197}_{79}Au(n,p)^{198}_{78}Hg$ at energy 22.4 MeV.

Figure 8 shows a comparison between the theoretical cross section with spin correction PLD formula and the experimental data where it is noticed that the theoretical cross section for the two cases $n = 5$ and $n = 7$is more than the experimental cross section. The increasing in theoretical cross section comes from the multiplication by the factor RJ which represents the spin correction factor.

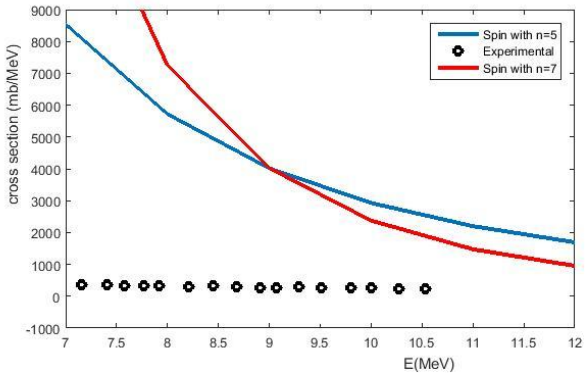


Figure 8. a comparison between the cross section based on one component PLD Ericson's formula corrected for spin when $n = 5$ and $n = 7$ with the experimental data for the reaction $^{197}_{79}Au(n,p)^{198}_{78}Hg$ at energy 22.4 MeV.

Conclusion:

In case of the theoretical cross section based on one-component of PLD Ericson's formula with exciton number $n = 7$. It can be stated that it agrees with the experimental data only at the end of the energy range and it is better from the same formula when $n = 5$. In case of the cross section based on the two-component Ericson's and William's PLD formulae when $n = 5$, this gives the best agreement with the experimental data. The theoretical cross section that depends on the one-component PLD formulae that are corrected for William correction and spin correction does not

agree with the Experimental cross section. Therefore, one can say the theoretical cross section based on two-component formula of PLD is the best to describe the cross section.

Authors' declaration:

- Conflicts of Interest: None.
- We hereby confirm that all the Figures and Tables in the manuscript are mine ours. Besides, the Figures and images, which are not mine ours, have been given the permission for re-publication attached with the manuscript.
- Ethical Clearance: The project was approved by the local ethical committee in University of Baghdad.

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مقارنة المقطع العرضي النظري المعتمد على صيغة كثافة الحالة الجزئية بمركبة واحدة مع القيم التجريبية لنواة الذهب $^{197}_{79}Au$

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الخلاصة:

في هذا البحث، تمت دراسة المقطع العرضي النظري لتفاعلات قبل التوازن للتفاعل $^{197}_{79}Au\ (n,p)^{198}_{78}Hg$ بطاقة 22.4 MeV. حيث تم تعويض صيغة اركسون للمركبة الواحدة لكثافة الحالات الجزئية PLD وتصحيحاتها (تصحيح وليم، وتصحيح البرم) بالمقطع العرضي النظري وقورنت النتائج مع النتائج العملية لنواة الذهب $^{197}_{79}Au$. حيث وجد ان المقطع العرضي النظري مع صيغة اركسون لمركبة واحدة لا يتفق مع للمقطع العرضي العملي عندما $n = 5$ وعندما$n = 7$ هناك اتفاق بسيط عند القيم الكبيرة للطاقة. المقطع العرضي النظري المعتمد على صيغة كثافة الحالات الجزئية PLD المصححة بتصحيح وليم لحالة المركبة الواحدة و صيغة المركبة الواحدة المصححة للزخم الزاوي لا يتطابقان مع القيم العملية. ولكن في حالة المقطع العرضي النظري المعتمد على صيغتي اركسون و وليم ذواتا المركبتين وجد ان هناك تطابق جيد لصيغتي اركسون و وليم عندما n=5.

الكلمات المفتاحية: المقطع العرضي، نموذج الاكسايتون ، تفاعلات قبل التوازن.