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The Systematics Study of (n, p) Reaction Cross-Sections at 14.7 MeV Neutron Energy

Sadeem Abdulrahman Alsuhaibani, Khalda T. Osman

Department of Physics, College of Science, Qassim University, Buraydah, Saudi Arabia
Email: khaldateosman@gmail.com

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Abstract

Based on the statistical model and taking into account the Q-value dependence and odd-even effects, we proposed a new empirical formula to reproduce the cross sections of the (n, p) reactions at 14.7 MeV neutron energy and at the target mass number $14 \le A \le 198$ for even A and $29 \le A \le 205$ for odd A. All calculated results from the proposed empirical formula were compared to the experimental data as well as the available semi-empirical formula obtained by other authors. A high level of agreement has been found between the collected experimental data and the most of semiempirical formulae obtained by others.

Keywords

(n, p) Cross Section, Neutron Energy, Empirical Formula, Statistical Model, Odd Even Effect

1. Introduction

The data for gas formation via neutron induced reactions are critical in the field of fusion reactor technology, particularly in calculating nuclear transmutation rates, nuclear heating, and radiation damage due to gas formation. Unmeasured data can be estimated using model theory calculations and systematic predictions. However, because the 14.7 MeV neutron induced cross sections for different nuclei vary rather smoothly with their N and Z values, several semi-empirical relations to systematize the (n, p) reactions have been proposed [1]. In recent years, many experimental techniques for obtaining and detecting neutrons of various energies, as well as measuring the cross sections of various neutron-induced reactions, have been developed [2] [3]. In the present work a systematics is proposed to calculate the (n, p) reaction cross-sections based on the statistical model, with consideration of the Q-value dependence and odd-even effects. An empirical formula for odd-A and even-A nuclei is presented for the (n, p) reaction cross-sections at 14.7 MeV neutrons and the target mass range 14 ≤ A ≤ 198 for even A and 29 ≤ A ≤ 205 for odd A. The present formula is compared with recently proposed systematics based on the statistical model and the asymmetry parameter dependence.

2. Theoretical Framework

The aim of this work is to develop a semi empirical formula, which depends on the mass and charge numbers in order to calculate the (n, p) reaction for 14.7 MeV neutrons. The statistical evaporation model shows that the (n, p) cross section depends on the reaction energy Q, the nuclear temperature T and the Coulomb barrier V_p. The use of the effective reaction energy Q shows the important dependence of the (n, p) cross section on the $(2Z-1)/A$ term describing the Coulomb barrier and also a dependence on an additional $(N-Z+1)/A$ term that describes surface asymmetry effect. Thus, an analytical expression was derived and the parameters of the formula were determined with least-squared analysis of the existing cross section values for different nuclei. [4]

The evaluation of excitation functions with new theoretical calculations is at the forefront in reaction physics today. Thereby, semi-classical and quantum mechanics models, have been widely used for analysis of the new data of nuclear reactions [5] [6] [7].

In the present work the calculations of cross sections of (n, p) reactions at 14.7 MeV neutron energy based on the statistical model and taking into account the Q-value dependence and odd-even effects are discussed.

2.1. Empirical Formula

On the basis of statistical model, the (n, p) reaction cross-sections can be expressed as [8] [9] [10]:

$$\sigma_{n,p} = \sigma_R \left(\frac{\Gamma_p}{\Gamma_n}\right) \tag{1}$$

where σ_R is the reaction or formation cross-section for 14 MeV neutrons.

Γ_p is the decay width for a proton and Γ_n is the decay width for a neutron.

The decay width for a proton can be written by means of principle of detailed balance as follows:

$$\Gamma_p = \frac{\left(2s_p+1\right)M_p}{\pi^2 h^2 \rho_a E_a} \int_{V_p}^{E_a-B_p-\delta_p} \varepsilon_p \sigma_c\left(\varepsilon_p\right)\rho_{(E_b)} \mathrm{d}\varepsilon_p \tag{2}$$

where s_p and M_p are the spin statistical factor and mass of proton, respectively; B_p and δ_p are the separation energy of proton and odd even character of nucleus respectively; E_a and E_b are the excitation energies of compound and residual nuclei respectively; V_p is the coulomb barrier of proton and ε_p and σ_c are the emitted proton energy and cross section of reverse process respectively.

When the energy of the incident neutron is not too high, the inverse cross section remains approximately constant and can be taken as follows:
for neutrons:

$$\sigma_c(\varepsilon_n) = \pi R^2 \tag{3}$$

for protons:

$$\sigma_c(\varepsilon_p) = \begin{cases} \pi R^2 \left(1 - \frac{V_p}{\varepsilon_p}\right) & \text{for } \varepsilon_p > V_p \\ 0 & \text{for } \varepsilon_p < V_p \end{cases} \tag{4}$$

where $1 - \frac{V_p}{\varepsilon_p}$ is the probability for the barrier penetration for a proton in the classical limit, ε_n is the emitted neutron energy and R is the nuclear radius.

The level density can be approximately expressed as the function of the entropy of the nuclear system [6]:

$$\frac{\rho_b(E_b)}{\rho_a(E_a)} \approx \exp\left[S_b(E_b) - S_a(E_a)\right] \tag{5}$$

With the entropy of the system given by

$$\frac{\mathrm{d}s}{\mathrm{d}E} = \frac{1}{T} \tag{6}$$

Where is the nuclear temperature. Thus

$$S_b(E_b) - S_a(E_a) \approx (E_b - E_a)/T = -(\varepsilon_p + B_p + \delta_p)/T \tag{7}$$

By substituting the Relations (4)-(7) into Equation (2) the following expression can be obtained:

$$\Gamma_p = \frac{(2p+1)M_p R^2}{\pi h^2} \int_{v_p}^{E_a - B_p - \delta_p} \varepsilon_p \left(1 - V_p/\varepsilon_p\right) \exp\left(-(\varepsilon_p + B_p + \delta_p)/T\right) \mathrm{d}\varepsilon_p \tag{8}$$

Integration of Equation (8) gives for the decay width of a proton:

$$\Gamma_p \approx \frac{2S_p + 1}{\pi h^2} M_n R^2 T^2 \left(1 - V_p/\varepsilon_p\right) \exp\left[-(B_p + \delta_n + V_p)/T\right] \tag{9}$$

And similarly for the width of a neutron:

$$\Gamma_n \approx \frac{2S_n + 1}{\pi h^2} M_n R^2 T^2 \exp\left[-(\delta_n + B_n)/T\right] \tag{10}$$

where S_n and M_n are the spin statistical factor and mass of the neutron, respectively; B_n and δ_n are the separation energy of the neutron and the odd-even character of the nucleus, respectively.

Thus the (n, p) reaction cross-section will be:

$$\sigma_{n,p} = \sigma_R \left(\frac{2S_p + 1}{2S_n + 1}\right) \frac{M_p}{M_n} \left(1 - V_p/\varepsilon_p\right) \exp\left(\frac{Q_{n,p} - V_p}{T}\right). \tag{11}$$

$$\sigma_{n,p} = \sigma_R \left(\frac{2S_p + 1}{2S_n + 1}\right) \frac{M_p}{M_n} \left(1 - V_p/\varepsilon_p\right) \exp\left(\frac{a_c(2Z-1)}{TA^{1/3}} - 4a_a\left(\frac{A - 2Z + 1}{AT}\right) - \frac{V_p}{T}\right). \tag{12}$$

where $T = \left(\frac{E_n}{a}\right)^{1/2}$, with $a = \frac{A}{15}$ MeV^{-1} is the level density and E_n is the incident neutron energy; $\sigma_R = \pi r_o^2 \left(1 + A^{1/3}\right)^2$ mb is the reaction cross-section and r_o = 1.4 fm.

2.2. Fitting Procedure

For the fitting of Equation (11) it can be written as:

$$\ln \frac{\sigma_{n,p}}{\frac{M_p}{M_n}\sigma_R} = a_0 + a_1 \frac{2Z-1}{TA^{1/3}} - a_2 \frac{A-2Z+1}{TA} - \frac{a_3}{T} \tag{13}$$

where $a_0 = \ln c_3 \left(\frac{1-V_p}{\varepsilon_p}\right)$, $a_1 = a_c$ which is Coulomb constant, $a_2 = 4a_a$ which is the symmetry, $a_3 = V_p$ which is Coulomb barrier and $c_3 = \frac{2S_p+1}{2S_n+1}$.

The Legendre method of least squares and Cramer's rule can be applied to Equation (13) to obtain the values of a_0, a_1, a_2 and a_3.

The equation can be written in the following form:

$$X + aY + bZ + cF - K = 0 \tag{14}$$

where in case of Equation (12)

$X = a_0 = \ln c_3\left(1 - V_p/\varepsilon_p\right)$, $Y = a_1 = a_c$, $Z = a_2 = 4a_a$, $F = a_3 = V_p$, $K = \ln\left(\sigma_{n,p}/\left(\sigma_R M_p/M_n\right)\right)$, $a = (2Z-1)/TA^{1/3}$, $b = (A-2Z+1)/TA$; and $c = 1/T$.

We choose X, Y, Z and F such that the sum of the squares of the error is least *i.e.* the quantity $\sum_{s=1}^{n}\left(X + aY + bZ + cF - K\right)^2$ is a minimum. The input data used in the present analysis of (n, p) reaction cross sections at 14.7 MeV are given for even and odd A nuclides respectively, All the data were taken from [3].

3. Results and Discussion

The Best Fit Parameters

In this study, an even- and odd-target mass number semiempirical formula for computing the (n, p) reaction cross section at 14.7 MeV is established. The input parameters are the level density parameter, observed (n, p) cross sections at 14.7 neutron energy, and atomic number and mass number. For even and odd A nuclides, the values for the coefficients and their uncertainties derived from least square fit to the (n, p) reaction cross section with the obtained empirical formula are provided in **Table 1** and **Table 2**, respectively.

In **Figure 1** and **Figure 2** the effect of $(2Z-1)/TA^{1/3}$ on the cross-section $\ln\left(\frac{\sigma_{n,p}}{\left(M_p/M_n\right)\sigma_R}\right)$ for even and odd-A nuclides are shown and we noticed that the cross-section decreases with this parameter for even and odd A nuclides.

We also note that the decreasing of cross-sections with the parameter

Table 1. Present equation for even-A nuclides.

Parameters	$a_0 = \ln c_3\left(\frac{1-V_p}{\varepsilon_p}\right)$	$a_1 = a_c$ (MeV)	$a_2 = 4a_a$ (MeV)	$a_3 = V_p$ (MeV)	No. of data points
	0.697 ± 0.442	0.302 ± 0.036	65.544 ± 2.358	0.494 ± 1.342	88
Equation	$\sigma_{n,p} = \exp\left(0.697 + 0.302\frac{2Z-1}{TA^{\frac{1}{3}}} - 65.544\frac{A-2Z+1}{TA} - 0.494\frac{1}{T}\right)\frac{M_p}{M_n}\sigma_R$				

Table 2. Present equation for odd-A nuclides.

Parameters	$a_0 = \ln c_3\left(\frac{1-V_p}{\varepsilon_p}\right)$	$a_1 = a_c$ (MeV)	$a_2 = 4a_a$ (MeV)	$a_3 = V_p$ (MeV)	No. of data points
	2.153 ± 0.968	0.001 ± 0.064	11.316 ± 5.320	5.079 ± 2.898	53
Equation	$\sigma_{n,p} = \exp\left(2.153 + 0.001\frac{2Z-1}{TA^{\frac{1}{3}}} - 11.316\frac{A-2Z+1}{TA} - 5.079\frac{1}{T}\right)\frac{M_p}{M_n}\sigma_R$				

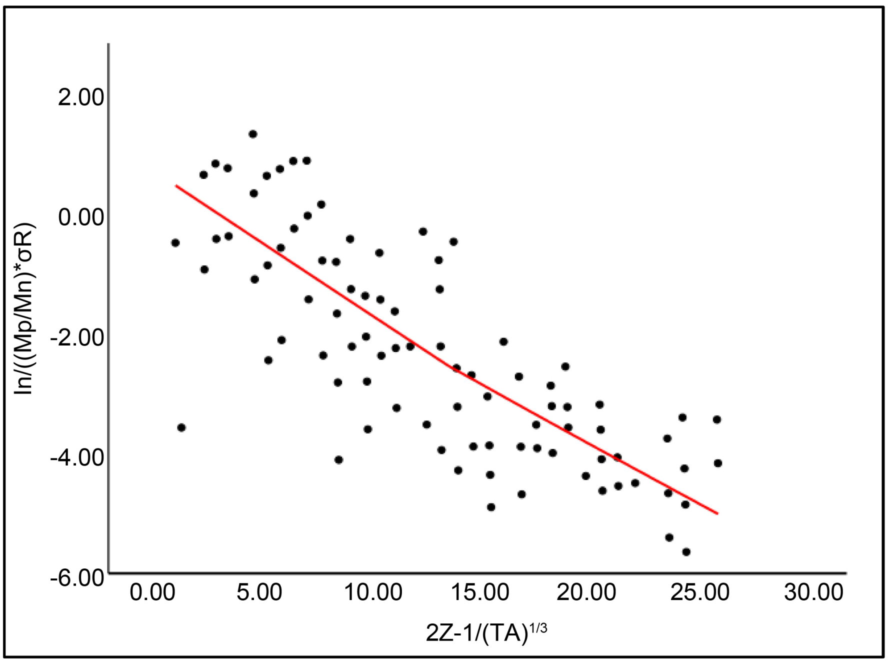

Figure 1. Study the effect of $(2Z-1)/TA^{1/3}$ on $\ln\left(\frac{\sigma_{n,p}}{(M_p/M_n)\sigma_R}\right)$ for even-A nuclides.

$(A-2Z+1)/TA$ for even and odd A nuclides as shown in Figure 3 and Figure 4. As illustrated in Figure 5 and Figure 6, the cross-section also decreases with temperature $1/T$. An illustration of the relationship between (n, p) cross sections for different elemental isotopes and mass number A for both even and odd A is shown in Figure 7 and Figure 8, the plot shows a decrease in (n, p) cross sections as isotope mass number increases.

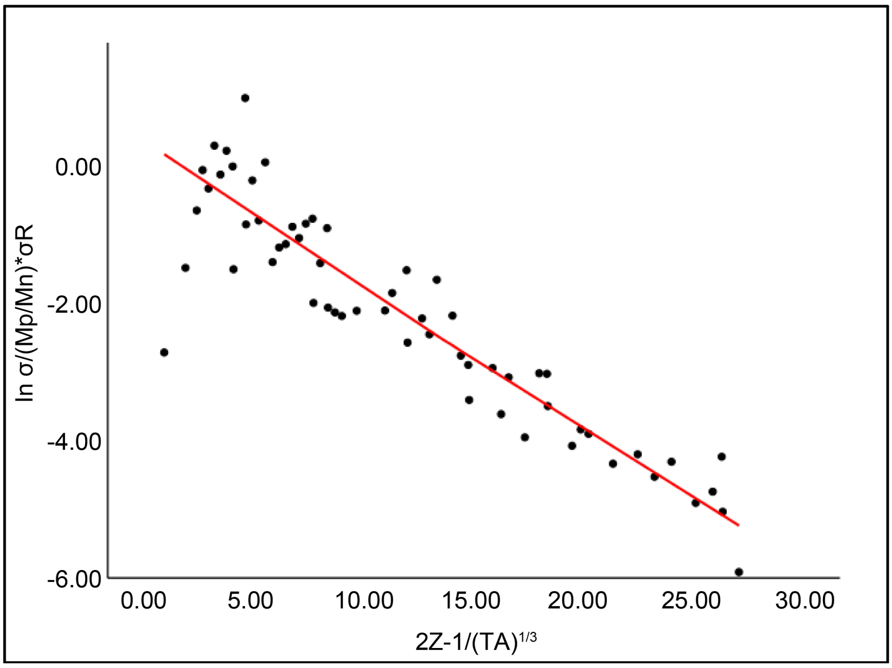

Figure 2. Study the effect of $(2Z-1)/TA^{1/3}$ on $\ln\left(\frac{\sigma_{n,p}}{(M_p/M_n)\sigma_R}\right)$ for odd-A nuclides.

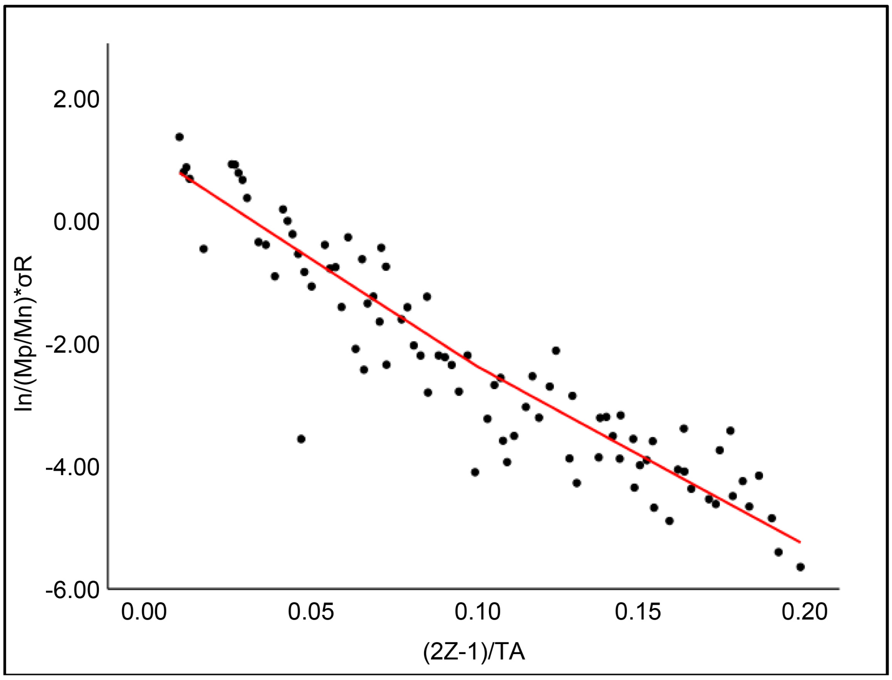

Figure 3. Study the effect of $(2Z-1)/TA$ on $\ln\left(\frac{\sigma_{n,p}}{(M_p/M_n)\sigma_R}\right)$ for even-A nuclides.

The odd-even effect correction as indicated in **Figure 9** and **Figure 10** and given by the following formula provides a satisfactory fit for the cross-section values obtained using the current formula.

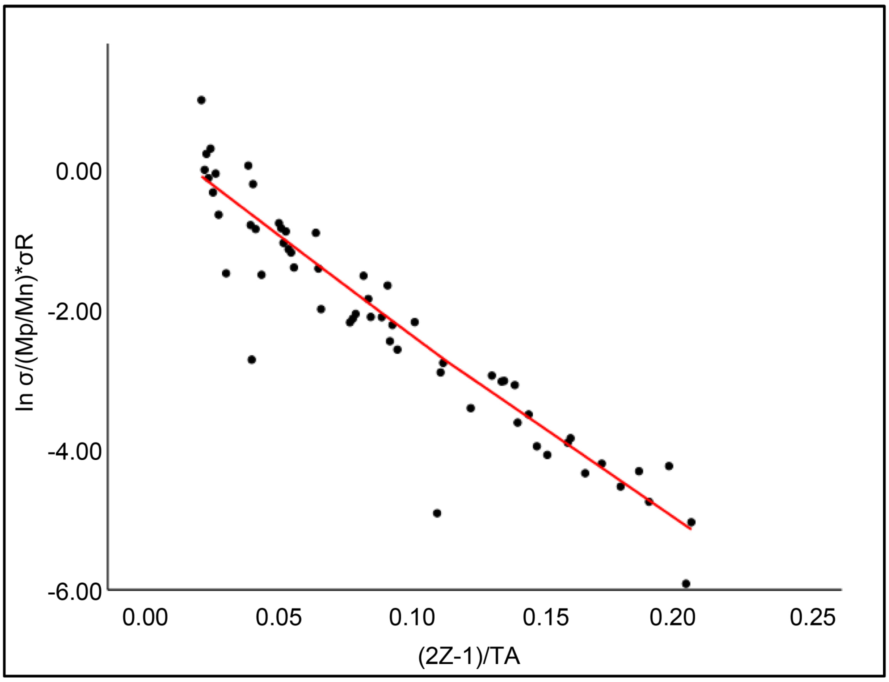

Figure 4. Study the effect of $(2Z-1)/TA$ on $\ln\left(\frac{\sigma_{n,p}}{(M_p/M_n)\sigma_R}\right)$ for odd-A nuclides.

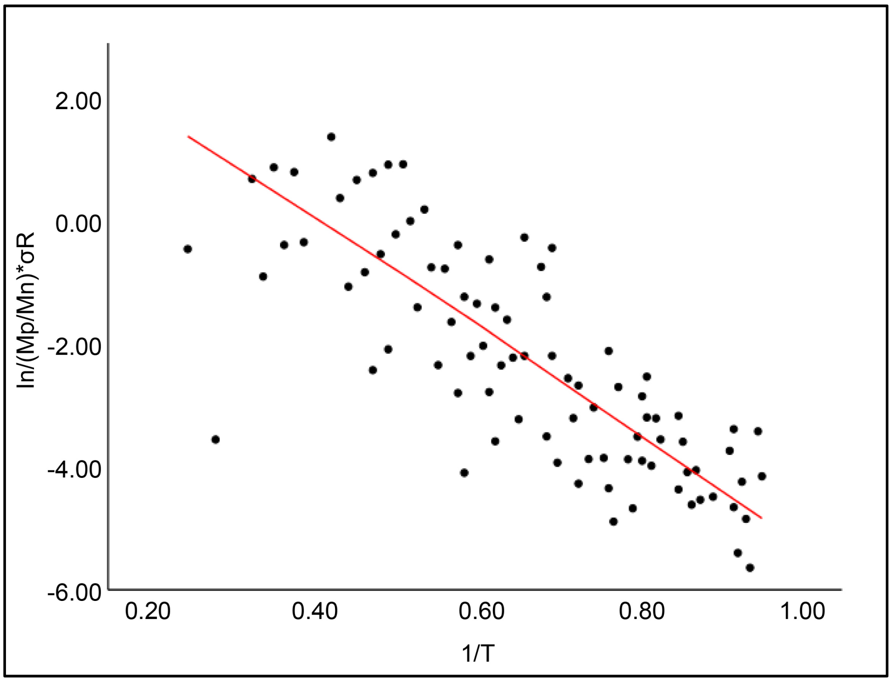

Figure 5. Study the effect of $1/T$ on $\ln\left(\frac{\sigma_{n,p}}{(M_p/M_n)\sigma_R}\right)$ for even-A nuclides.

$$\sigma_{n,p} = \left(1 + A^{\frac{1}{3}}\right)^2 \alpha \exp\left[\beta \frac{N - Z + \delta}{A}\right] \quad (14)$$

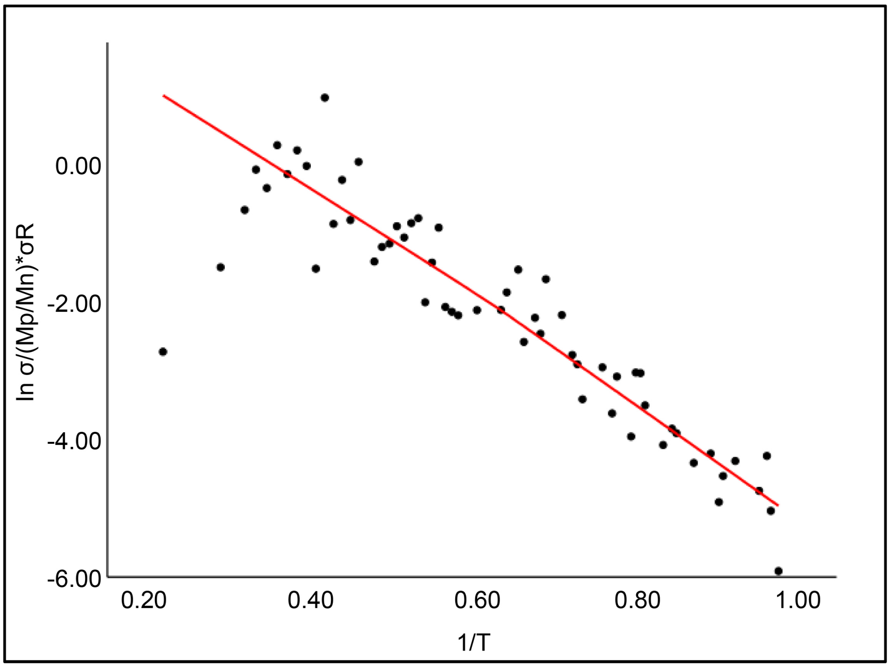

Figure 6. Study the effect of $1/T$ on $\ln\left(\frac{\sigma_{n,p}}{(M_p/M_n)\sigma_R}\right)$ for odd-A nuclides.

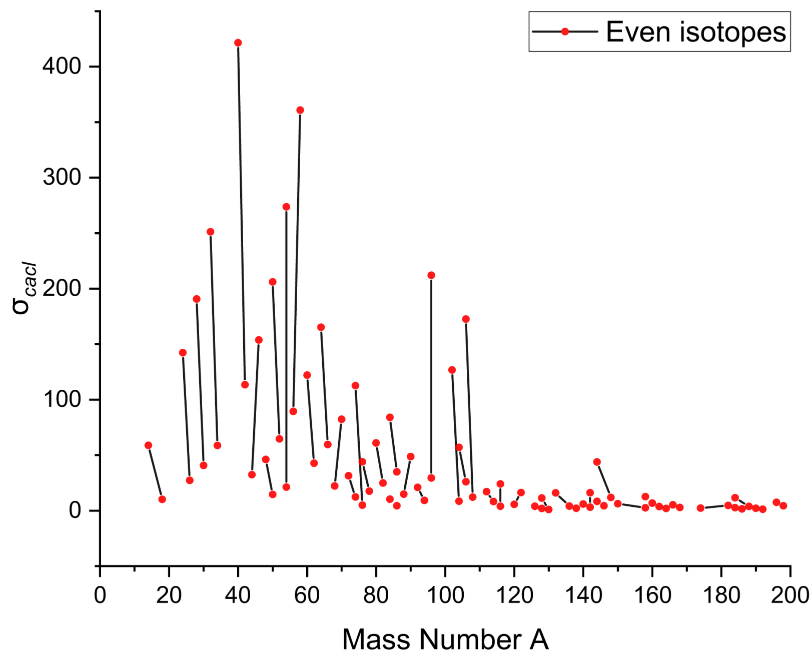

Figure 7. Study the effect of the mass number A on the cross-section for the even isotopes.

where α and β are fitting parameters and δ is odd-even character. They have the following values:

For even-A nuclides: $\alpha = 4.54 \pm 0.1169$, $\beta = -35.95 \pm 0.784$, $\delta = 1$.

and for odd-A nuclides: $\alpha = 3.06 \pm 0.1492$, $\beta = -28.029 \pm 0.784$, $\delta = 0$.

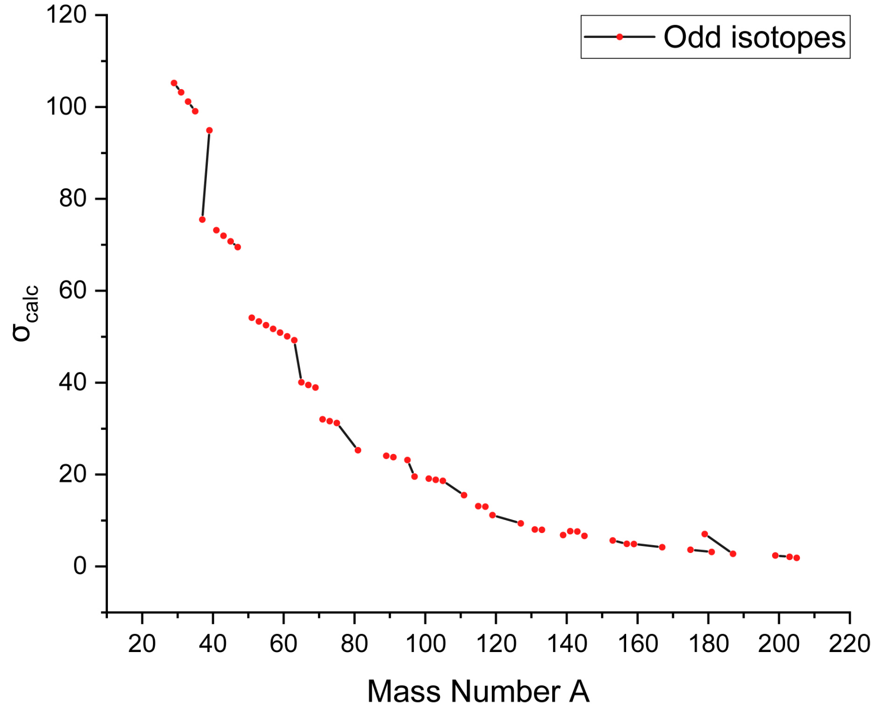

Figure 8. Study the effect of the mass number A on the cross-section for the odd isotopes.

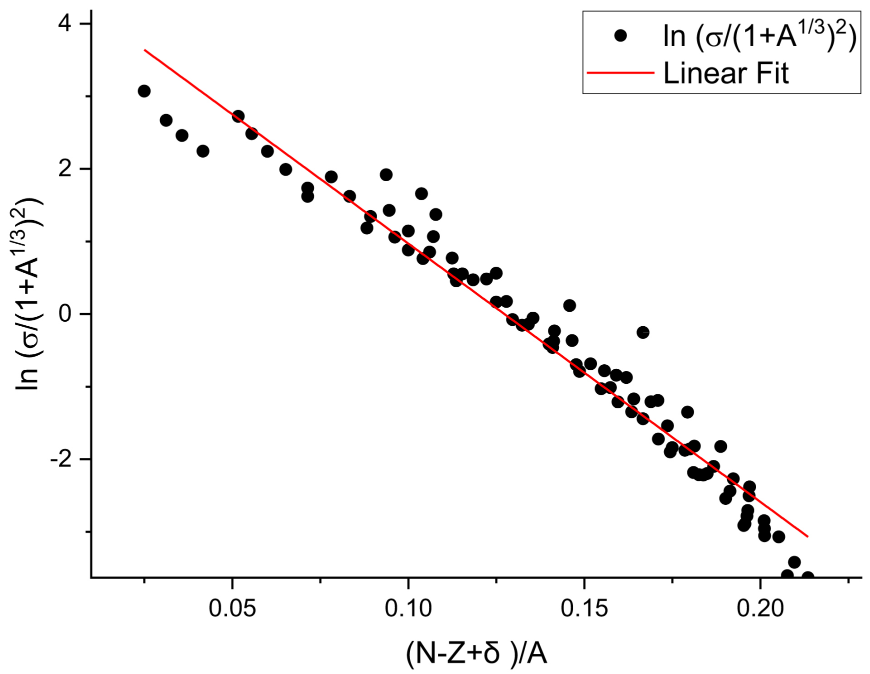

Figure 9. Study the effect of $\ln\frac{\sigma}{\left(1+A^{1/3}\right)^2}$ on the parameter $\left(\frac{N-Z+\delta}{A}\right)$ for the even-A nuclides.

4. Comparison with Others Systematics

As listed in Table 3, we have compared the present equation with the equations

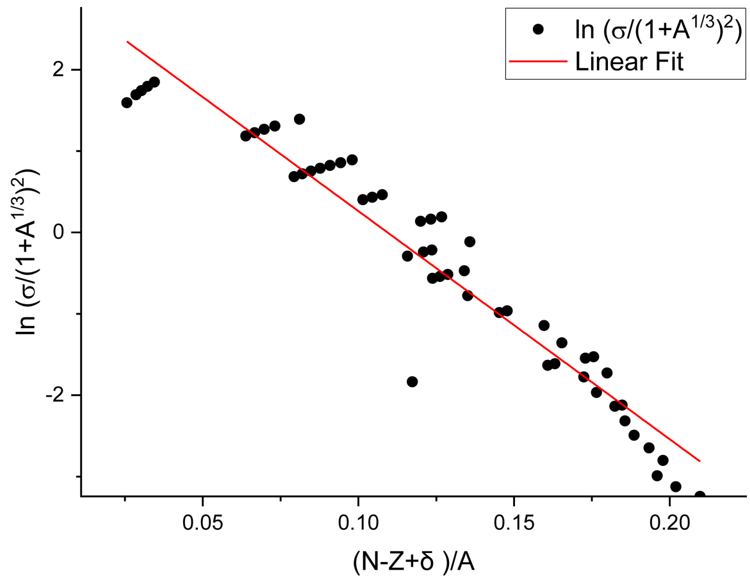

Figure 10. Study the effect of $\ln\frac{\sigma}{\left(1+A^{1/3}\right)^2}$ on the parameter $\left(\frac{N-Z+\delta}{A}\right)$ for the odd-A nuclides.

Table 3. Comparison of (n, p) systematics at 14.7 MeV [3].

Author	Formula, σ (mb)	Mass region
Levkovskii	$\sigma=\begin{cases}55.3\left(A^{\frac{1}{3}}+1\right)^2\exp\left(-38.4\frac{N-z+1}{A+1}\right)\\49.4\left(A^{\frac{1}{3}}+1\right)^2\exp\left(-35.1\frac{N-Z}{A}\right)\end{cases}$	$19\le A\le 40$ $40\le A\le 188$
Eder *et al.*	$\sigma=\exp\left(1.31+0.806A^{\frac{1}{2}}-10.3\frac{N-Z}{A^{\frac{2}{3}}}\right)$	$19\le A\le 188$
Bychkov *et al.*	$\sigma=\exp\left(A^{\frac{1}{3}}+1\right)^2\exp\left\{\sqrt{\frac{A}{140}}\left(-53.3\frac{N-Z+1}{A}+0.622\frac{Z-1}{A^{\frac{1}{3}}}-3.20\right)\right\}$	$40\le A\le 188$
Forrest	$\sigma=11.23\exp\left(A^{\frac{1}{3}}+1\right)^2\exp\left(-32.73\frac{N-Z}{A}-46.57\left(\frac{N-Z}{A}\right)^2+0.218A^{1/2}\right)$	$40\le A\le 188$
Kumabe and Fukuda	$\sigma=\begin{cases}27.9A\exp\left(-39.1\frac{N-z}{A}\right)\\0.58A^2\exp\left(-42.3\frac{N-Z}{A}\right)\\0.94A^2\exp\left(-47.8\frac{N-Z}{A}\right)\end{cases}$	$40\le A\le 62$ $63\le A\le 89$ $90\le A\le 188$
Ait-Tahar	$\sigma=140.2\left(A^{1/3}+1\right)^2\exp\left(-39.1\frac{N-Z+1}{A}\right)$	$40\le A\le 188$

Continued

Kasugai *et al.*	$\sigma = 1830(N-Z+1)\exp\left(-50.7\frac{N-Z+1}{A}\right)$	$19 \le A \le 188$
Korovin *et al.*	$\sigma = \pi r_o^2\left(A^{1/3}+1\right)^2 \times \left\{A^{1.1128}\left(\left(\frac{N-Z+1}{A}\right)^2 - 0.73212\left(\frac{N-Z+1}{A}\right)+0.11707\right)^3 + 0.4936\exp\left(-194.69\left(\frac{N-Z+1}{A}\right)^2 - 5.3778\left(\frac{N-Z+1}{A}\right)\right)\right\}$	$11 \le A \le 209$
Dóczi *et al.*	$\sigma = 23.659\left(A^{1/3}+1\right)^2\exp\left(-23.041\left(\frac{N-Z}{A}\right)+\left(\frac{N-Z}{A}\right)^2\right)$	$11 \le A \le 209$
Present (Even)	$\sigma = \exp\left(0.697+0.302\frac{2Z-1}{TA^{\frac{1}{3}}}-65.544\frac{A-2Z+1}{TA}-0.494\frac{1}{T}\right)\frac{M_p}{M_n}\sigma_R$	$14 \le A \le 198$
Present (Odd)	$\sigma_{n,p} = \exp\left(2.153+0.001\frac{2Z-1}{TA^{\frac{1}{3}}}-11.316\frac{A-2Z+1}{TA}-5.079\frac{1}{T}\right)\frac{M_p}{M_n}\sigma_R$	$29 \le A \le 205$

of other authors. To compare their results with the measured and computed data for (n, p) reaction cross-sections at 14.7 MeV neutron energy for both even-*A* and odd-*A* nuclides, reported in **Table 4** and **Table 5** respectively, we chose the authors Eder *et al.*, Kasugai *et al.*, Korovin *et al.*, and Dóczi *et al.* We observed that although the four systematics had a reasonable level of agreement, the present finding was the closest to the experimental value.

As can be seen from **Figure 11** for the even-*A* nuclides, we have plotted the effect of mass number *A* on the ratio $\left(\frac{\sigma_{exp}}{\sigma_{calc}}\right)$. We note that both authors Eder *et al.* and Kasukai *et al.* obtained results that are closer to the experimental results at high *A*, and in the present result, we obtained results that are closer to the experimental results at low *A*. On the contrary, we note that the results of the author Dóczi *et al.* as being closer to the experimental results in a low *A*, and the present results are closer to the experimental results at a high Abut in general, we see a good agreement between the present results with the results obtained by others. For the even-*A* nuclides, the discrepancy between the author's results (Korovin *et al.*) and the present results (**Figure 12**) can be clearly seen and the latter results are much closer to the experimental findings.

In **Table 4**, the comparison between the authors' results and the present result for even-*A* nuclides are given and shown in **Figure 11** for the even-*A* nuclides. In **Figure 11** the plot of mass number *A* versus the ratio $\left(\frac{\sigma_{exp}}{\sigma_{calc}}\right)$ are shown and we observed that both authors Eder *et al.* and Kasukai *et al.* obtained results closer to the experimental results in region of the middle *A*. And also, we can see that the results of the author Dóczi *et al.* are closer to the experimental results in

Table 4. Measured and calculated data for reaction cross-sections at 14.7 MeV (for even-*A* nuclides).

	Reaction	(n, p) Cross-Section (mb) at 14.7 MeV										
		Experimental	Eder *et al.*	Ratio	Kasugai *et al.*	Ratio	Korovin *et al.*	Ratio	Dóczi *et al.*	Ratio	Present	Ratio
1	$^{14}N(n,p)^{14}C$	45.2 ± 6	-	-	-	-	9.39	4.81	275.13	0.16	58.74	0.77
2	$^{18}O(n,p)^{18}N$	2.3 ± 0.5	-	-	-	-	0.11	21.03	18.04	0.13	10.16	0.23
3	$^{24}Mg(n,p)^{24}Na$	183.6 ± 9	192.21	0.96	221.31	0.83	28.36	6.47	357.00	0.51	142.27	1.29
4	$^{26}Mg(n,p)^{26}Na$	39 ± 11	21.60	1.81	15.81	2.47	2.31	16.87	55.08	0.71	27.26	1.43
5	$^{28}Si(n,p)^{28}Al$	238.7 ± 30	263.74	0.91	299.27	0.80	35.11	6.80	385.50	0.62	190.72	1.25
6	$^{30}Si(n,p)^{30}Al$	70.04 ± 20	36.27	1.93	34.49	2.03	5.04	13.90	77.54	0.90	40.73	1.72
7	$^{32}S(n,p)^{32}P$	237 ± 25	354.05	0.67	375.29	0.63	41.42	5.72	412.35	0.57	251.22	0.94
8	$^{34}S(n,p)^{34}P$	78 ± 8	57.22	1.36	62.62	1.25	8.75	8.91	101.25	0.77	58.68	1.33
9	$^{40}Ca(n,p)^{40}K$	470.01 ± 50	606.43	0.78	515.21	0.91	53.14	8.84	462.20	1.02	421.60	1.11
10	$^{42}Ca(n,p)^{42}K$	178.25 ± 12	125.03	1.43	146.83	1.21	18.13	9.83	150.17	1.19	113.37	1.57
11	$^{44}Ca(n,p)^{44}K$	43.27 ± 6	28.52	1.52	28.79	1.50	3.71	11.68	49.42	0.88	32.37	1.34
12	$^{46}Ti(n,p)^{46}Sc$	251 ± 13	176.26	1.42	201.17	1.25	23.37	10.74	174.71	1.44	153.76	1.63
13	$^{48}Ti(n,p)^{48}Sc$	57.2 ± 2.7	43.59	1.31	46.54	1.23	5.97	9.58	63.47	0.90	46.13	1.24
14	$^{50}Ti(n,p)^{50}Sc$	11.9 ± 6	11.66	1.02	10.59	1.12	1.21	9.86	23.46	0.51	14.52	0.82
15	$^{50}Cr(n,p)^{50}V$	294 ± 30	242.61	1.21	262.09	1.12	28.79	10.21	199.05	1.48	206.10	1.43
16	$^{52}Cr(n,p)^{52}V$	80 ± 4	64.38	1.24	69.86	1.15	8.79	9.10	78.57	1.02	64.62	1.24
17	$^{54}Cr(n,p)^{54}V$	17.4 ± 1	18.30	0.95	17.92	0.97	2.14	8.14	31.44	0.55	21.14	0.82
18	$^{54}Fe(n,p)^{54}Mn$	350 ± 15	327.33	1.07	328.33	1.07	34.31	10.20	223.08	1.57	273.73	1.28
19	$^{56}Fe(n,p)^{56}Mn$	115 ± 6	92.46	1.24	98.96	1.16	12.10	9.50	94.48	1.22	89.29	1.29
20	$^{58}Ni(n,p)^{58}Co$	366 ± 19	434.19	0.84	398.72	0.92	39.88	9.18	246.75	1.48	360.86	1.01
21	$^{60}Ni(n,p)^{60}Co$	148 ± 8	129.68	1.14	133.82	1.11	15.82	9.35	111.03	1.33	122.02	1.21
22	$^{62}Ni(n,p)^{62}Co$	37 ± 4	40.91	0.90	41.84	0.88	5.13	7.21	50.41	0.73	42.72	0.87
23	$^{64}Ni(n,p)^{64}Co$	185 ± 10	178.22	1.04	174.26	1.06	19.89	9.30	128.07	1.44	165.20	1.12
24	$^{66}Zn(n,p)^{66}Cu$	73.3 ± 8	58.79	1.25	59.19	1.24	7.23	10.14	61.19	1.20	59.58	1.23
25	$^{68}Zn(n,p)^{68}Cu$	15.2 ± 2.5	20.30	0.75	20.07	0.76	2.37	6.40	29.53	0.51	22.13	0.69
26	$^{70}Ge(n,p)^{70}Ga$	74 ± 8	82.68	0.90	80.48	0.92	9.70	7.63	72.70	1.02	82.26	0.90
27	$^{72}Ge(n,p)^{72}Ga$	31.6 ± 1.4	29.61	1.07	29.13	1.08	3.51	9.01	36.64	0.86	31.33	1.01
28	$^{74}Ge(n,p)^{74}Ga$	10.1 ± 0.5	11.02	0.92	10.73	0.94	1.22	8.25	18.65	0.54	12.24	0.83
29	$^{76}Ge(n,p)^{76}Ga$	2.8 ± 0.4	4.25	0.66	4.07	0.69	0.43	6.54	9.61	0.29	4.90	0.57
30	$^{74}Se(n,p)^{74}As$	112 ± 7	114.13	0.98	105.85	1.06	12.53	8.94	84.84	1.32	112.62	0.99
31	$^{76}Se(n,p)^{76}As$	49 ± 3	42.27	1.16	40.66	1.20	4.93	9.94	44.44	1.10	43.90	1.12
32	$^{78}Se(n,p)^{78}As$	19 ± 1.1	16.22	1.17	15.80	1.20	1.86	10.23	23.48	0.81	17.52	1.08
33	$^{80}Kr(n,p)^{80}Br$	45 ± 6	59.20	0.76	54.90	0.82	6.65	6.77	52.88	0.85	60.97	0.74
34	$^{82}Kr(n,p)^{82}Br$	23 ± 5	23.37	0.98	22.39	1.03	2.69	8.56	28.89	0.80	24.83	0.93

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35	^{84}Kr(n,p)^{84}Br	11 ± 2	9.52	1.16	9.31	1.18	1.07	10.24	15.91	0.69	10.33	1.07
36	^{86}Kr(n,p)^{86}Br	5 ± 1.5	3.99	1.25	3.96	1.26	0.43	11.64	8.85	0.57	4.38	1.14
37	^{84}Sr(n,p)^{84}Rb	95 ± 8	81.53	1.17	72.04	1.32	8.67	10.96	61.90	1.53	84.04	1.13
38	^{86}Sr(n,p)^{86}Rb	44 ± 4	33.05	1.33	30.73	1.43	3.73	11.80	34.85	1.26	34.87	1.26
39	^{88}Sr(n,p)^{88}Rb	17.4 ± 2	13.79	1.26	13.29	1.31	1.58	11.02	19.76	0.88	14.76	1.18
40	^{90}Zr(n,p)^{90}Y	37 ± 5	45.96	0.81	40.99	0.90	5.00	7.40	41.34	0.89	48.60	0.76
41	^{92}Zr(n,p)^{92}Y	20.23 ± 2.5	19.61	1.03	18.41	1.10	2.23	9.06	24.07	0.84	20.91	0.97
42	^{94}Zr(n,p)^{94}Y	7.5 ± 1.1	8.58	0.87	8.41	0.89	0.99	7.55	14.12	0.53	9.15	0.82
43	^{96}Mo(n,p)^{96}Nb	21.3 ± 1.1	27.44	0.78	24.81	0.86	3.05	6.99	28.83	0.74	29.40	0.72
44	^{96}Ru(n,p)^{96}Tc	146 ± 8	195.78	0.75	142.05	1.03	16.43	8.89	91.98	1.59	212.09	0.69
45	^{104}Ru(n,p)^{104}Tc	6 ± 0.7	7.99	0.75	7.83	0.77	0.95	6.30	12.88	0.47	8.46	0.71
46	^{102}Pd(n,p)^{102}Rh	93.6 ± 15	113.53	0.82	84.97	1.10	10.26	9.13	63.72	1.47	126.65	0.74
47	^{104}Pd(n,p)^{104}Rh	58 ± 15	51.45	1.13	42.08	1.38	5.23	11.09	39.66	1.46	56.98	1.02
48	^{106}Pd(n,p)^{106}Rh	22.5 ± 6	23.81	0.94	21.02	1.07	2.64	8.53	24.80	0.91	26.01	0.87
49	^{108}Pd(n,p)^{108}Rh	4 ± 1	11.24	0.36	10.64	0.38	1.33	3.01	15.60	0.26	12.04	0.33
50	^{106}Cd(n,p)^{106}Ag	130 ± 24	149.84	0.87	104.44	1.24	12.49	10.41	72.05	1.80	172.49	0.75
51	^{112}Cd(n,p)^{112}Ag	16.1 ± 3	15.60	1.03	14.15	1.14	1.80	8.96	18.63	0.86	17.04	0.94
52	^{114}Cd(n,p)^{114}Ag	8.5 ± 1.3	7.61	1.12	7.44	1.14	0.93	9.11	11.99	0.71	8.09	1.05
53	^{116}Cd(n,p)^{116}Ag	2.96 ± 0.3	3.78	0.78	3.97	0.75	0.48	6.18	7.75	0.38	3.89	0.76
54	^{116}Sn(n,p)^{116}In	14.6 ± 2	21.37	0.68	18.45	0.79	2.38	6.15	21.96	0.66	23.96	0.61
55	^{120}Sn(n,p)^{120}In	4.5 ± 0.5	5.32	0.85	5.39	0.84	0.68	6.64	9.43	0.48	5.58	0.81
56	^{122}Te(n,p)^{122}Sb	10.5 ± 1.5	14.52	0.72	12.94	0.81	1.69	6.20	16.99	0.62	16.25	0.65
57	^{126}Te(n,p)^{126}Sb	4.7 ± 0.2	3.82	1.23	4.03	1.17	0.50	9.33	7.59	0.62	3.95	1.19
58	^{128}Te(n,p)^{128}Sb	2.9 ± 0.1	2.01	1.45	2.29	1.27	0.27	10.92	5.11	0.57	1.98	1.47
59	^{130}Te(n,p)^{130}Sb	1.7 ± 0.1	1.07	1.59	1.32	1.29	0.13	12.69	3.45	0.49	1.00	1.70
60	^{128}Xe(n,p)^{128}I	27 ± 4	10.16	2.66	9.38	2.88	1.24	21.69	13.43	2.01	11.31	2.39
61	^{132}Ba(n,p)^{132}Cs	15.3 ± 3.5	13.79	1.11	12.07	1.27	1.63	9.39	15.76	0.97	15.97	0.96
62	^{136}Ba(n,p)^{136}Cs	4.8 ± 0.7	3.90	1.23	4.10	1.17	0.53	9.03	7.47	0.64	4.11	1.17
63	^{138}Ba(n,p)^{138}Cs	2.18 ± 0.15	2.12	1.03	2.43	0.90	0.29	7.42	5.17	0.42	2.11	1.03
64	^{140}Ce(n,p)^{140}La	7.05 ± 0.7	5.36	1.32	5.35	1.32	0.72	9.79	8.88	0.79	5.87	1.20
65	^{142}Ce(n,p)^{142}La	4.8 ± 0.8	2.93	1.64	3.21	1.49	0.41	11.66	6.22	0.77	3.04	1.58
66	^{142}Nd(n,p)^{142}Pr	13.7 ± 1.1	13.32	1.03	11.42	1.20	1.59	8.60	14.81	0.92	16.12	0.85
67	^{144}Nd(n,p)^{144}Pr	9.8 ± 1.5	7.27	1.35	6.88	1.42	0.95	10.29	10.44	0.94	8.34	1.17
68	^{146}Nd(n,p)^{146}Pr	4.5 ± 0.7	4.02	1.12	4.19	1.07	0.56	8.02	7.39	0.61	4.36	1.03
69	^{144}Sm(n,p)^{144}Pm	19 ± 4	32.58	0.58	23.64	0.80	3.28	5.79	24.08	0.79	43.78	0.43
70	^{148}Sm(n,p)^{148}Pm	9.8 ± 0.8	9.78	1.00	8.73	1.12	1.24	7.93	12.17	0.81	11.81	0.83
71	^{150}Sm(n,p)^{150}Pm	7 ± 0.6	5.45	1.28	5.38	1.30	0.75	9.37	8.70	0.80	6.21	1.13

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72	^{158}Gd(n,p)^{158}Eu	3.2 ± 1.2	2.38	1.34	2.71	1.18	0.35	9.05	5.33	0.60	2.53	1.26
73	^{158}Dy(n,p)^{158}Tb	10.6 ± 1.2	9.76	1.09	8.53	1.24	1.25	8.51	11.74	0.90	12.47	0.85
74	^{160}Dy(n,p)^{160}Tb	7 ± 1.5	5.58	1.25	5.42	1.29	0.78	9.01	8.56	0.82	6.70	1.04
75	^{162}Dy(n,p)^{162}Tb	4.3 ± 1	3.22	1.33	3.47	1.24	0.48	9.03	6.27	0.69	3.63	1.19
76	^{164}Dy(n,p)^{164}Tb	2.55 ± 0.5	1.88	1.36	2.24	1.14	0.28	8.97	4.60	0.55	1.98	1.29
77	^{166}Er(n,p)^{166}Ho	4.5 ± 0.7	4.32	1.04	4.38	1.03	0.63	7.18	7.31	0.62	5.17	0.87
78	^{168}Er(n,p)^{168}Ho	2.8 ± 0.4	2.54	1.10	2.86	0.98	0.39	7.27	5.41	0.52	2.84	0.99
79	^{174}Yb(n,p)^{174}Tm	3 ± 0.2	2.03	1.48	2.38	1.26	0.31	9.56	4.71	0.64	2.25	1.33
80	^{182}W(n,p)^{182}Ta	6.5 ± 0.5	3.59	1.81	3.73	1.74	0.55	11.91	6.36	1.02	4.59	1.42
81	^{184}W(n,p)^{184}Ta	2.61 ± 0.12	2.18	1.20	2.53	1.03	0.34	7.57	4.83	0.54	2.59	1.01
82	^{186}W(n,p)^{186}Ta	1.25 ± 0.25	1.34	0.93	1.72	0.72	0.21	5.90	3.67	0.34	1.47	0.85
83	^{184}Os(n,p)^{184}Re	9.30 ± 2	7.80	1.19	6.79	1.37	1.06	8.77	9.59	0.97	11.57	0.80
84	^{188}Os(n,p)^{188}Re	4 ± 0.8	2.89	1.38	3.14	1.27	0.45	8.84	5.58	0.72	3.70	1.08
85	^{190}Os(n,p)^{190}Re	2.2 ± 0.5	-	-	-	-	0.29	7.69	4.27	0.51	2.11	1.04
86	^{192}Os(n,p)^{192}Re	1 ± 0.03	-	-	-	-	0.18	5.70	3.28	0.30	1.21	0.82
87	^{196}Hg(n,p)^{196}Au	9.3 ± 1	-	-	-	-	0.74	12.61	7.32	1.27	7.48	1.24
88	^{198}Hg(n,p)^{198}Au	4.5 ± 0.8	-	-	-	-	0.49	9.23	5.67	0.79	4.31	1.04

Table 5. Measured and calculated data for reaction cross-sections at 14.7 MeV (for odd-*A* nuclides).

		(n, p) Cross-Section (mb) at 14.7 MeV										
		Experimental	Eder *et al.*	Ratio	Kasugai *et al.*	Ratio	Korovin *et al.*	Ratio	Dóczi *et al.*	Ratio	Present	Ratio
1	^{11}B(n,p)^{11}Be	4.2 ± 0.2	-	-	-	-	0.03	151.41	25.03	0.17	-	-
2	^{19}F(n,p)^{19}O	18.6 ± 0.88	29.27	0.64	17.61	1.06	3.00	6.20	88.83	0.21	-	-
3	^{23}Na(n,p)^{23}Ne	47.0 ± 2	49.50	0.95	44.55	1.06	7.16	6.56	122.90	0.38	-	-
4	^{25}Mg(n,p)^{25}Na	88.04 ± 13	62.51	1.41	63.38	1.39	9.72	9.06	139.70	0.63	-	-
5	^{27}Al(n,p)^{27}Mg	70 ± 2	77.76	0.90	85.60	0.82	12.49	5.61	156.23	0.45	-	-
6	^{29}Si(n,p)^{29}Al	135.33 ± 15	95.51	1.42	110.90	1.22	15.39	8.79	172.48	0.78	105.21	1.29
7	^{31}P(n,p)^{31}Si	91.85 ± 3.48	116.03	0.79	138.97	0.66	18.38	5.00	188.40	0.49	103.20	0.89
8	^{33}S(n,p)^{33}P	134 ± 22	139.63	0.96	169.44	0.79	21.42	6.26	204.00	0.66	101.15	1.32
9	^{35}Cl(n,p)^{35}S	110 ± 10	166.62	0.66	201.96	0.54	24.48	4.49	219.28	0.50	99.08	1.11
10	^{37}Cl(n,p)^{37}S	25.4 ± 3	30.87	0.82	30.49	0.83	4.13	6.15	58.92	0.43	75.48	0.34
11	^{39}K(n,p)^{39}Ar	314 ± 14	232.26	1.35	271.84	1.16	30.59	10.27	248.89	1.26	94.92	3.31
12	^{41}K(n,p)^{41}Ar	51.36 ± 3	48.05	1.07	52.04	0.99	6.94	7.40	76.67	0.67	73.17	0.70
13	^{43}Ca(n,p)^{43}K	99.83 ± 13	59.01	1.69	65.50	1.52	8.59	11.62	85.95	1.16	71.96	1.39
14	^{45}Sc(n,p)^{45}Ca	57 ± 8	71.84	0.79	80.78	0.71	10.40	5.48	95.45	0.60	70.73	0.81
15	^{47}Ti(n,p)^{47}Sc	136 ± 9	86.75	1.57	97.85	1.39	12.33	11.03	105.12	1.29	69.49	1.96
16	^{51}V(n,p)^{51}Ti	33.3 ± 1.7	27.69	1.20	28.19	1.18	3.51	9.49	43.91	0.76	54.11	0.62
17	^{53}Cr(n,p)^{53}V	42 ± 2.1	34.05	1.23	35.31	1.19	4.41	9.52	49.60	0.85	53.32	0.79
18	^{55}Mn(n,p)^{55}Cr	45 ± 10	41.53	1.08	43.51	1.03	5.43	8.28	55.54	0.81	52.51	0.86
19	^{57}Fe(n,p)^{57}Mn	59 ± 4	50.30	1.17	52.83	1.12	6.57	8.98	61.72	0.96	51.70	1.14

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20	$^{59}Co(n,p)^{59}Fe$	51 ± 1	60.51	0.84	63.30	0.81	7.82	6.52	68.12	0.75	50.88	1.00
21	$^{61}Ni(n,p)^{61}Co$	64 ± 4	72.36	0.88	74.96	0.85	9.18	6.97	74.71	0.86	50.06	1.28
22	$^{63}Cu(n,p)^{63}Ni$	70 ± 13	86.03	0.81	87.82	0.80	10.65	6.58	81.49	0.86	49.23	1.42
23	$^{65}Cu(n,p)^{65}Ni$	20.93 ± 4	28.45	0.74	28.55	0.73	3.45	6.07	38.18	0.55	40.06	0.52
24	$^{67}Zn(n,p)^{67}Cu$	37.9 ± 6	34.35	1.10	34.39	1.10	4.17	9.09	42.45	0.89	39.49	0.96
25	$^{69}Ga(n,p)^{69}Zn$	64 ± 5	41.24	1.55	40.99	1.56	4.98	12.85	46.91	1.36	38.92	1.64
26	$^{71}Ga(n,p)^{71}Zn$	20.5 ± 1.5	14.81	1.38	14.50	1.41	1.68	12.19	23.27	0.88	32.00	0.64
27	$^{73}Ge(n,p)^{73}Ga$	19.4 ± 1.1	17.98	1.08	17.63	1.10	2.07	9.35	26.11	0.74	31.60	0.61
28	$^{75}As(n,p)^{75}Ge$	18.7 ± 2.1	21.71	0.86	21.21	0.88	2.52	7.41	29.11	0.64	31.19	0.60
29	$^{81}Br(n,p)^{81}As$	21 ± 5	12.33	1.70	12.01	1.75	1.40	15.02	19.21	1.09	25.28	0.83
30	$^{89}Y(n,p)^{89}Sr$	22.2 ± 4.2	25.28	0.88	23.59	0.94	2.86	7.76	28.81	0.77	24.07	0.92
31	$^{91}Zr(n,p)^{91}Y$	29 ± 4	29.92	0.97	27.42	1.06	3.34	8.67	31.52	0.92	23.76	1.22
32	$^{95}Mo(n,p)^{95}Nb$	41.3 ± 2	41.43	1.00	36.33	1.14	4.46	9.26	37.31	1.11	23.14	1.78
33	$^{97}Mo(n,p)^{97}Nb$	14.6 ± 0.8	18.28	0.80	17.01	0.86	2.08	7.02	22.32	0.65	19.55	0.75
34	$^{101}Ru(n,p)^{101}Tc$	21.2 ± 1.2	25.44	0.83	22.72	0.93	2.82	7.52	26.63	0.80	19.08	1.11
35	$^{103}Rh(n,p)^{103}Ru$	17 ± 3	29.85	0.57	26.05	0.65	3.25	5.24	28.94	0.59	18.85	0.90
36	$^{105}Pd(n,p)^{105}Rh$	38 ± 2.9	34.91	1.09	29.70	1.28	3.71	10.23	31.34	1.21	18.61	2.04
37	$^{111}Cd(n,p)^{111}Ag$	23.25 ± 2.1	22.48	1.03	19.62	1.19	2.49	9.33	23.27	1.00	15.49	1.50
38	$^{115}In(n,p)^{115}Cd$	13.26 ± 2.95	12.79	1.04	11.78	1.13	1.51	8.80	16.31	0.81	13.12	1.01
39	$^{117}Sn(n,p)^{117}In$	11.7 ± 0.6	15.01	0.78	13.50	0.87	1.74	6.72	17.75	0.66	12.98	0.90
40	$^{119}Sn(n,p)^{119}In$	7.1 ± 0.8	7.49	0.95	7.29	0.97	0.93	7.63	11.63	0.61	11.16	0.64
41	$^{127}I(n,p)^{127}Ie$	11.7 ± 0.8	6.25	1.87	6.17	1.89	0.80	14.58	10.14	1.15	9.35	1.25
42	$^{131}Xe(n,p)^{131}I$	6.1 ± 0.6	3.86	1.58	4.06	1.50	0.52	11.79	7.52	0.81	8.02	0.76
43	$^{133}Cs(n,p)^{133}Xe$	10.5 ± 2	4.54	2.31	4.67	2.25	0.61	17.30	8.23	1.28	7.95	1.32
44	$^{139}La(n,p)^{139}Ba$	4.5 ± 1.1	3.37	1.33	3.62	1.24	0.47	9.64	6.80	0.66	6.79	0.66
45	$^{141}Pr(n,p)^{141}Ce$	11.5 ± 0.9	8.46	1.36	7.85	1.47	1.08	10.63	11.51	1.00	7.66	1.50
46	$^{143}Nd(n,p)^{143}Pr$	11.5 ± 2.3	9.83	1.17	8.86	1.30	1.23	9.33	12.43	0.92	7.59	1.52
47	$^{145}Nd(n,p)^{145}Pr$	7.25 ± 1.6	5.40	1.34	5.36	1.35	0.73	9.89	8.78	0.83	6.62	1.10
48	$^{153}Eu(n,p)^{153}Sm$	4.2 ± 0.4	4.75	0.88	4.79	0.88	0.66	6.32	7.98	0.53	5.64	0.75
49	$^{157}Gd(n,p)^{157}Eu$	5.4 ± 1.1	3.14	1.72	3.41	1.59	0.46	11.75	6.25	0.86	4.90	1.10
50	$^{159}Tb(n,p)^{159}Gd$	5.1 ± 0.4	3.65	1.40	3.85	1.33	0.53	9.61	6.77	0.75	4.86	1.05
51	$^{167}Er(n,p)^{167}Ho$	3.4 ± 0.3	3.31	1.03	3.54	0.96	0.49	6.90	6.29	0.54	4.18	0.81
52	$^{175}Lu(n,p)^{175}Y$	4 ± 0.7	3.03	1.32	3.28	1.22	0.46	8.67	5.88	0.68	3.60	1.11
53	$^{181}Ta(n,p)^{181}Hf$	2.94 ± 0.18	2.43	1.21	2.75	1.07	0.38	7.75	5.14	0.57	3.14	0.94
54	$^{187}Re(n,p)^{187}W$	3.73 ± 0.28	1.97	1.89	2.33	1.60	0.31	11.88	4.54	0.82	2.74	1.36
55	$^{179}Au(n,p)^{179}Pt$	2 ± 0.5	197.04	0.01	79.19	0.03	11.11	0.18	50.83	0.04	7.03	0.28
56	$^{199}Hg(n,p)^{199}Au$	2.5 ± 0.5	-	-	-	-	0.39	6.35	4.99	0.50	2.35	1.06
57	$^{203}Tl(n,p)^{203}Hg$	4.2 ± 0.8	-	-	-	-	0.29	14.52	4.16	1.01	2.08	2.02
58	$^{205}Tl(n,p)^{205}Hg$	1.9 ± 0.2	-	-	-	-	0.18	10.44	3.25	0.58	1.86	1.02
59	$^{209}Bi(n,p)^{209}Pb$	0.8 ± 0.3	-	-	-	-	0.24	3.28	3.75	0.21	-	-

a region of low *A*. The present results are closer to the experimental results at a high *A*. But in general, we can see a good agreement between the present results with the results of other authors. In **Figure 12** for the even-*A* nuclides, we can see the big difference between the author Korovin *et al.* and the present results, as we can notice that the present results are very close to the experimental results compared to the author's results.

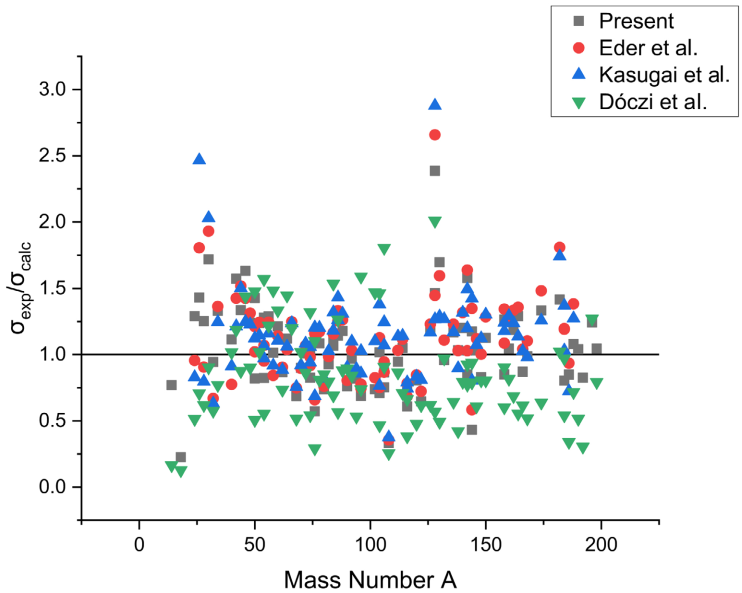

Figure 11. Comparing present with Eder *et al.*, Kasugai *et al.* and Dóczi *et al.* for the ratio of experimental to calculated σ(n, p) at 14.7 MeV versus the mass number *A* for even-*A* nuclides.

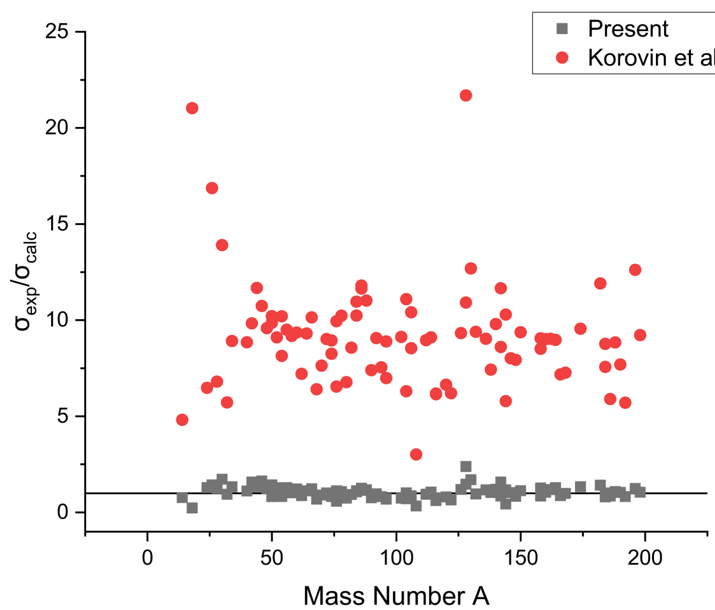

Figure 12. Comparing present and Korovin *et al.* for the ratio of experimental to calculated σ(n, p) at 14.7 MeV versus the mass number *A* for even-*A* nuclides.

As given in Table 5 the comparisons between the authors' results and the present results for odd-*A* nuclides are given and also plotted in Figure 13 for the odd-*A* nuclides, and we notice that the authors' results Eder et al and Dóczi *et al.* approach the experimental values at the middle *A* and a Scattering occurs in the low and high *A*. In other hand the author Kasugai *et al.* approaches the experimental values at the low *A* and it scatters as the mass number *A* increases. Conversely, our results are approximately equal to the experimental value at high *A*.

As shown in Figure 14, the present result is clearly closer to the experimental values compared to the results of the author Korovin *et al.* for the odd-*A* nuclides.

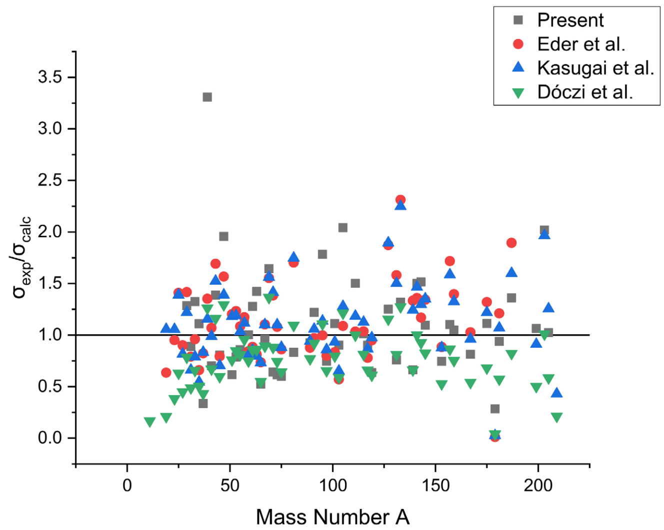

Figure 13. Comparing present with Eder *et al.*, Kasugai *et al.* and Dóczi *et al.* for the ratio of experimental to calculated σ(n, p) at 14.7 MeV versus the mass number *A* for odd-*A* nuclides.

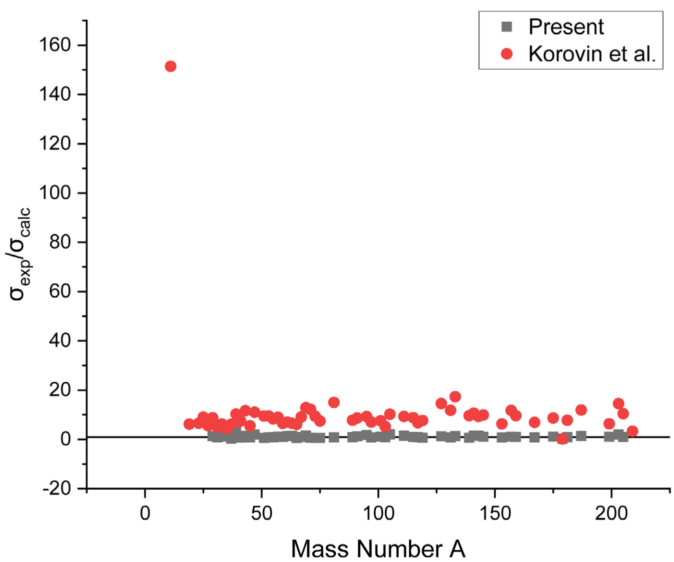

Figure 14. Comparing present and Korovin *et al.* for the ratio of experimental to calculated σ(n, p) at 14.7 MeV versus the mass number *A* for odd-*A* nuclides.

5. Conclusions

The current work's objective is to develop a semi-empirical equation for computing the reaction's cross-section at 14.7 MeV neutron energy. The findings are as follows:

- On the basis of the liquid drop model, we were able to derive a semi-empirical equation that contained the four constants ($a_0 = \ln c_3 \left(\frac{1 - V_p}{\varepsilon_p} \right)$, coulomb constant, symmetry, coulomb barrier) and the calculated (n, p) reaction cross sections based on these constants were consistent with the experimental values for both even-*A* and odd-*A* nuclides.
- The calculated (n, p) reaction cross sections using the present empirical formula for both odd and even A nuclides were compared with that obtained by other authors and it was found that there is a good agreement between the present results and that obtained by other authors.
- Also, in the present work we study the odd even effect on the (n, p) reaction cross sections at 14.7 MeV neutron energy and the present systematics shows clearly the presence of odd-even effect.
- In addition, more simple empirical formulae were obtained in this work to calculate the (n, p) reaction cross sections at 14.7 MeV neutron energy depending on odd-even character.

We suggest more studies for other interactions of neutrons, such as (n, α), (n, 2n) and (n, t) at 14.7 MeV neutron energy.

Conflicts of Interest

The authors declare no conflicts of interest regarding the publication of this paper.

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The Variables that Were Used in This Work

ε_n	The emitted neutron energy.	R	The nuclear radius.
Γ_p	The decay width for a proton.	M_n	The mass of the neutron.
Γ_n	The decay width for a neutron.	B_n	The separation energy of the neutron.
S_p, S_n	The spin statistical factors.	E_n	The incident neutron energy.
M_p	The mass of proton.	σ_R	The reaction cross-section.
B_p	The separation energy of the proton.	a_1	Coulomb constant.
δ_p, δ_n	The odd-even characters of the nucleus.	a_2	The symmetry parameter.
E_a	The excitation energy of the compound nucleus.	a_3	Coulomb barrier.
E_b	The excitation energy the residual nuclei.	A	The mass number.
V_p	The coulomb barrier of the proton.	Z	The atomic number.
ε_p	The emitted proton energy.	α, β	The fitting parameters.
σ_c	The cross-section of the reverse process.	δ	The odd-even character.
σ_R	The reaction or formation cross-section for 14 MeV neutrons.		