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# On the Systematics for the (n,p) Reaction Cross-Sections at 14.5 MeV Neutrons

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## On the Systematics for the (n,p) Reaction Cross-Sections at 14.5 MeV Neutrons

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#### Abstract

An empirical formula for the (n,p) reaction cross-sections at 14.5 MeV neutrons is obtained on the basis of the statistical model, as a function of the effective Q-value, the formation cross-section of the reaction, the coulomb barrier encountered by the emitted proton, the probability of the barrier penetration and the nuclear temperature. The formula is compared with corresponding relations deduced from the recent works of Gul and Bychkov. The variation of the cross-sections versus the asymmetry parameter (N-Z+ $\delta$ )/A is studied and the presence of the odd-even effect is demonstrated.

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#### 1. Introduction

There were various discrepancies among the experimental (n,p) reaction crosssections and their systematics around 14 MeV neutrons[1]. Therefore further investigations of the systematics of the (n,p) reaction cross-sections were required to obtain reliable cross-sections of various nuclei around 14 MeV neutron energy. In the present work an empirical formula for even- A and odd- A target nuclei was obtained for the (n,p) reaction cross-sections at 14.5 MeV neutrons and the target mass region  $28 \le A \le 208$ . The formula is based on the statistical model, with the dependence on the Q-value and the odd-even effect taken into consideration. The systematics for the (n,p) reaction cross-sections using the present formula was compared with those deduced from the recent works of Gul [2] and Bychkov et al[3].

#### 2. Empirical Formula

On the basis of the statistical model the (n,p) reaction cross-sections can be expressed as [4]:

$$\sigma_{n,p} = \sigma_{R} \left( \Gamma_{p} / \Gamma_{n} \right) \tag{1}$$

where :  $\sigma_R$  = the reaction or formation cross-section for 14 MeV neutrons.

 $\Gamma_n$  = the decay width for a neutron.

 $\Gamma_{p}$  = the decay width for a proton.

The decay width  $\Gamma_p$  for a proton can be written by means of the principle of detailed balance as follows [5]:

$$\Gamma_{p} = \frac{E_{a} - B_{p} - \delta_{p}}{\pi^{2} h^{2} \rho_{a}(E_{a})} \int_{P} \int_{P} \frac{\delta_{p} - \delta_{p}}{\nabla_{p} \sigma_{c}(\varepsilon_{p}) \rho_{b}(E_{b}) d\varepsilon_{p}}$$
(2)

where  $S_p$  and  $M_p$  are the spin statistical factor and mass of proton, respectively ;  $B_p$  and  $\delta_p$  are the separation energy of the proton and the odd-even character of the nucleus, respectively :  $\rho_a(E_a)$  and  $\rho_b(E_b)$  are the level densities of the compound nucleus and residual nucleus, respectively ;  $E_a$  and  $E_b$  are the excitation energies of the compound and residual nuclei, respectively ;  $V_p$  is the coulomb barrier of the proton and  $\epsilon_p$  and  $\sigma_c$  are the emitted proton energy and the cross-section of the reverse process, respectively .

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

for neutrons : 
$$\sigma_{c}(\varepsilon_{n}) = \pi R^{2}$$
  
for protons :  $\sigma_{c}(\varepsilon_{p}) = \pi R^{2}(1-V_{p}/\varepsilon_{p})$  for  $\varepsilon_{p} > V_{p}$   
= 0 for  $\varepsilon_{p} < V_{p}$  (3)

where  $(1-V_p / \epsilon_p)$  is the probability for the barrier penetration for a proton in the classical limit,  $\epsilon_n$  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 [5] :

$$\rho_b(E_b)/\rho_a(E_a) \approx \exp[S_b(E_b) - S_a(E_a)]$$
(4)

with the entropy of the system given by :

$$dS/dE = 1/T$$
(5)

where T is the nuclear temperature. Thus

$$S_{b}(E_{b}) - S_{a}(E_{a}) \approx (E_{b} - E_{a})/T = -(\varepsilon_{p} + B_{p} + \delta_{p})/T$$
(6)

By substituting the relations (3 - 6) into eq(2) the following expression can be obtained:

$$\Gamma_{p} = \underbrace{(2S_{p}+1). M_{p}}_{\pi h^{2}} R^{2} \int_{\epsilon_{p}} (1 - V_{p}/\epsilon_{p}) . exp(-(\epsilon_{p}+B_{p}+\delta_{p})/T) d\epsilon_{p}$$
(7)

Integration of eq(7) gives for the decay width of a proton :

$$\Gamma_{p} \approx \frac{\left(2S_{p}+1\right)}{\pi h^{2}} M_{p} \cdot T^{2} R^{2} \left(1-V_{p} / \varepsilon_{p}\right) \cdot \exp\left[-\left(B_{p}+\delta_{p}+V_{p}\right)/T\right] (8)$$

and similarly for the decay width of a neutron :

$$\Gamma_n \approx \frac{\left(2S_n + 1\right)}{\pi h^2} M_n \cdot T^2 R^2 \cdot \exp\left[-\left(\delta_n + B_n\right)/T\right]$$
(9)

where  $S_n$  and  $M_n$  are the spin statistical factor and mass of the neutron, respectively;  $B_n$  and  $\delta_n$  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 :

$$\sigma_{n,p} = \sigma_R \left( \frac{2S_p + 1}{2S_n + 1} \right) \frac{M_p}{M_n} \left( 1 - V_p / \varepsilon_p \right) \exp \left( \frac{Q_{n,p} - V_p}{T} \right)$$
(10)

where  $Q_{n,p} = B_n - B_p + \delta_n - \delta_p$  is the effective Q-value of the (n,p) reaction.

Using the semiempirical mass formula for the effective Q-value we get:

$$Q_{n,p} = \frac{a_{a}(2Z-1)}{A^{1/3}} - 4a_{a}\left(\frac{A-2Z+1}{A}\right)$$
(11)

where  $a_c$  and  $a_a$  are the coulomb and asymmetry parameters, respectively. Inserting eq(11) into eq(10) we get for the cross-section of the (n,p) reaction :

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

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

The relation obtained by Gul [2] for the (n,p) reaction is :

$$\sigma_{n,p} = c_1 \sigma_R . \exp[2a_c \frac{(Z-1)}{TA^{1/3}} - a_\tau \frac{(A-2Z+1)}{TA} - c_2 \frac{(Z-1)}{E_n A^{1/3}} + a_o^1]$$
(13)

where all parameters are as before except for  $a_{\tau}$  = asymmetry parameter and  $c_1$ ,  $c_2$  and  $a_o^1$  which are constants.

#### 3. Fitting Procedure

For the fitting of eq(12) it can be written as:

$$\ln\left(\frac{\sigma_{n,p}}{\frac{M_p}{M_n}\sigma_R}\right) = a_0 + a_1 \frac{(2Z-1)}{TA^{1/3}} - a_2 \frac{(A-2Z+1)}{TA} - \frac{a_3}{T}$$
(14)

where  $a_0 = lnc_3 (1-V_p / \epsilon_p)$ ,  $a_1 = a_c$ ,  $a_2 = 4a_a$ ,  $a_3 = V_p$ and  $c_3 = (2S_p+1)/(2S_n+1)$ . The corresponding relation for eq(13) will be:

$$\ln\left(\frac{\sigma_{n,p}}{\left(1+A^{1/3}\right)^2}\right) = a_0 + a_1 \frac{(Z-1)}{TA^{1/3}} - a_2 \frac{(A-2Z+1)}{TA} - a_3 \frac{(Z-1)}{E_n A^{1/3}}$$
(15)

where  $a_0 = ln(c_1 \pi r_0^2) + a_o^1$ ,  $a_1 = 2a_c$ ,  $a_2 = a_\tau$  and  $a_3 = constant$ .

The Legendre method of least squares[6] and Cramer's rule can be applied to eqs(14) & (15) to obtain the values of  $a_0$ ,  $a_1$ ,  $a_2$  and  $a_3$ . The equations can be written in the following form :

$$X+aY+bZ+cF-K=0$$
 (16)

where in case of eq(14):

 $\begin{array}{l} X=a_0 = lnc_3 \left(1-V_p \ / \ \epsilon_p \ \right), \ Y=a_1 = a_c \ , \ Z=a_2 = 4a_a \ , \\ F=a_3 = V_p, \ K = ln(\sigma_{n,p} \ / (\sigma_R \ M_p \ / M_n) \ , \ a = (2Z-1) \ / TA^{1/3}, \ b = (A-2Z+1) \ / TA \ and \ c = 1 \ / T; \\ and in \ case \ of \ eq(15) : \\ \end{array}$ 

X=  $a_0 = ln(c_1\pi r_0^2) + a_o^1$ , Y =  $a_1 = 2a_c$ , Z =  $a_2 = a_\tau$ , F= $a_3$ =constant, K= $ln(\sigma_{n,p}/(1 + A^{1/3})^2)$ ,

 $a = (Z-1)/TA^{1/3}$ , b = (A-2Z+1)/TA and  $c = (Z-1)/E_n A^{1/3}$ .

We choose X, Y, Z and F such that the sum of the squares of the error is least i.e.

the quantity  $\sum_{s=1}^{n} (X + aY + bZ + cF - K)^2$  is a minimum.

The input data used in the present analysis of (n,p) reaction cross-sections at 14.5 MeV are given in Tables(1) and (2) for even-A and odd-A nuclides, respectively. All the data were taken from ref[7].

#### 4. Results and Discussion

#### 4.1 The best fit parameters

The proposed formula as given by eq(12) used in the present work for studying the systematics of the (n,p) reaction cross-sections is based on the statistical model of nuclear reactions. This formula contains two physical parameters of semiempirical mass formula, namely the coulomb and asymmetry parameters, in addition to the effective coulomb barrier  $V_p$  and the probability of the coulomb barrier penetration  $(1-V_p/\epsilon p)$  in the classical limit.

The input parameters are the atomic number, the mass number, the measured cross-section for a given nuclide at the incident neutron energy of 14.5 MeV and the level density parameter of  $a = A/15 \text{ MeV}^{-1}$ .

The values of the coefficients  $a_0$ ,  $a_1$ ,  $a_2$  and  $a_3$  and their uncertainties obtained through the least squares fit to the (n,p) reaction cross-sections for even-A and odd-A nuclides are listed in Tables(3) and (4), respectively. The corresponding values obtained for the Gul formula as given by eq(13) are also shown for comparison. The values obtained for the coulomb and asymmetry parameters using the present formula for even-A nuclides are  $a_c = 0.3$  MeV and  $a_a = 12.13$  MeV. The values obtained for odd-A nuclides at the same incident neutron energy and level density parameter are  $a_c = 0.24$  MeV and  $a_a = 4.76$  MeV. It is observed that the values for odd-A nuclides are smaller than the corresponding values obtained form the semiempirical mass formula. Also the fit of even-A and odd-A nuclides using the present formula results in the values of the effective coulomb barrier V<sub>p</sub> and the probability of coulomb barrier penetration  $lnc_3(1-V_p/\epsilon p)$  to be 5.82, 2.59MeV and 12.04, 4.33MeV for even-A and odd-A nuclides, respectively. It is to be noted that these values are smaller in the case of even-A nuclides as compared to odd-A nuclides.

#### 4.2 Comparison with other systematics

It is useful to compare the predictions of the present systematics with other systematics. Recently Bychkov et al[3] have carried out the analysis of (n,p) reaction cross-sections using updated information and the following expression for both odd-A and even-A nuclides :

$$\sigma_{n,p} = c_1 \sigma_R \exp\left(\sqrt{\frac{a}{E_n}} \left( c_2 \frac{(Z-1)}{A^{1/3}} - c_3 \frac{(N-Z+1)}{A} - \Delta \right) \right)$$
(17)

where  $c_1 = 7.06$ ,  $c_2 = 0.58 \text{MeV}$ ,  $c_3 = 50 \text{MeV}$ ,  $\Delta = 3.26$ ,  $\sigma_R = \pi r_0^2 (1 + A^{1/3})^2$ ,  $r_0 = 1.4 \text{fm}$ ,  $a = (A/10) \text{MeV}^{-1}$  and  $E_n = 14.5 \text{ MeV}$ 

We note that the shape of the Bychkov formula is similar to the present formula. The (n,p) cross-sections calculated by means of eqs(12), (13) and (17) are given in Tables(1) and (2) for even-A and odd-A nuclides, respectively.

Comparisons of the ratio of experimental to calculated (n,p) reaction crosssections obtained through the three formulae for odd-A and even-A nuclides are shown in Figs(1) and (2), respectively.

As can be seen from Fig(1) for odd-A nuclides there is good agreement between most of the predictions of the present and other two systematics and the experimental values at low and medium mass numbers of the target nuclides, while for heavy mass nuclides the Bychkov results show some disagreement. The disagreement is observed in the following reactions:

 $^{157}Cd(n,p), ^{187}Re(n,p), ^{193}Ir(n,p), ^{201}Hg(n,p) and ^{205}Tl(n,p).$ 

We see also from Fig(2) for even-A nuclides that there is good agreement between the three systematics and the experimental values for most of the crosssections. The discrepancy between the measured values and the three systematics is observed in the case of <sup>136</sup>Ba(n,p) and <sup>142</sup>Ce(n,p) reaction cross-sections, where the experimental values are much larger than those predicted by any of the three systematics.

A good fit for the cross-section values obtained by the present formula taking into account the odd-even effect correction is given by the following formula:

$$\sigma_{n,p} = (1 + A^{1/3})^2 \alpha \exp[\beta(N - Z + \delta)/A]$$
(18)

where  $\alpha$  and  $\beta$  are fitting parameters and  $\delta$  is odd-even character. They have the following values :

For odd-A nuclides :  $\alpha = 20.91$ ,  $\beta = -29.53$ ,  $\delta = 0$ and for even-A nuclides :  $\alpha = 60.34$ ,  $\beta = -34.44$ ,  $\delta = 1$ 

The systematics for the (n,p) reaction cross-sections using eq(18) is shown in Fig(3), where  $\sigma(n,p)/(1+A^{1/3})^2$  is plotted versus the asymmetry parameter (N-Z+ $\delta$ )/A for even-A and odd-A nuclides. It can be seen that the odd-even effect exists in the (n,p) reaction cross-sections. The curve of even-A nuclides is located above that of

odd-A nuclides. This trend can probably be attributed to the higher values of the (n,p) reaction cross-sections at 14.5MeV for even-A nuclides as compared to those for odd-A nuclides that have been used in this study. The trend is observed in the curves of the systematics using experimental values as shown in Fig(4). We also note that the decrease of (n,p) reaction cross-sections of even-A nuclides is faster than for odd-A nuclides.

Finally, we conclude that the results obtained using the present formula are in good agreement with those obtained by the Gul formula, especially in the case of odd-A nuclides. The present systematics show clearly the presence of the odd-even effect and the faster decrease of the cross-sections in the case of the even-A nuclides. It is to be noted that while in the present and Gul formulae different values have been obtained for the coulomb and asymmetry parameters for odd-A and even-A nuclides, in the Bychkov formula the same values have been used for both odd-A and even-A nuclides. However, the Bychkov formula led to some disagreement with both the other two formulae and the experimental values for odd-A nuclides of heavy mass numbers.

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# <u>Table (1)</u>: Measured and Calculated Data for (n,p) Reaction Cross - Sections at 14.5MeV (for Even-A Nuclides)

	Reaction	(n,p) cross - section (mb) at 14.5 Me V						
		Exp.	Bychkov	Ratio	Gul	Ratio	Present	Ratio
1.	<sup>28</sup> Si (n,p) <sup>28</sup> Al	230 ± 30	229.59	1.00	365.69	0.63	231.32	0.99
2.	$^{32}S(n,p)^{32}P$	225 ± 12	284.74	0.79	384.79	0.58	263.44	0.85
3.	<sup>38</sup> Ar (n,p) <sup>38</sup> Cl	75 ± 20	92.68	0.81	135.26	0.55	101.88	0.74
4.	<sup>40</sup> Ar (n,p) <sup>40</sup> Cl	15.7 ± 2	26.13	0.60	47.37	0.33	36.54	0.43
5.	$^{42}Ca(n,p)^{42}k$	182 ± 22	121.35	1.49	152.50	1.19	121.83	1.49
6.	<sup>46</sup> Ti (n,p) <sup>46</sup> Sc	280 ± 20	157.30	0.63	172.03	1.63	144.8	1.93
7.	<sup>48</sup> Ti (n,p) <sup>48</sup> Sc	61 ± 6	49.13	1.24	65.82	0.93	56.42	1.08
8.	${}^{52}Cr(n,p){}^{52}V$	94 ± 10	65.99	1.43	77.18	1.22	69.13	1.36
9.	<sup>54</sup> Fe (n,p) <sup>54</sup> Mn	310 ± 25	259.01	1.19	220.30	1.40	202.3	1.53
10.	<sup>56</sup> Fe(n,p) <sup>56</sup> Mn	103 ± 6	87.76	1.17	90.41	1.13	84.18	1.22
11.	<sup>58</sup> Ni (n,p) <sup>58g</sup> Co	$370 \pm 46$	330.09	1.12	250.42	1.48	238.32	1.55
12.	<sup>60</sup> Ni ( <b>n</b> , <b>p</b> ) <sup>60g</sup> Co	118 ± 8	115.81	1.02	105.90	1.11	102.01	1.16
13.	<sup>62</sup> Ni (n,p) <sup>62</sup> Co	24 ± 6	42.06	0.57	46.01	0.52	44.84	0.54
14.	<sup>64</sup> Zn (n,p) <sup>64</sup> Cu	185 ± 20	151.89	1.22	124.15	1.49	123.16	1.50
15.	<sup>66</sup> Zn (n,p) <sup>66</sup> Cu	65 ± 6	56.69	1.15	55.30	1.18	55.42	1.17
16.	<sup>74</sup> Ge (n,p) <sup>74</sup> Ga	13.2 ± 1.3	12.05	1.09	14.68	0.90	15.31	0.86
17.	<sup>76</sup> Se (n,p) <sup>76</sup> As	56 ± 5.6	40.74	1.46	37.88	1.48	39.94	1.40
18.	<sup>78</sup> Se (n,p) <sup>78</sup> <sup>g</sup> As	24 ± 2.4	16.77	1.43	18.31	1.31	19.44	1.23
19.	<sup>80</sup> Kr(n,p) <sup>80m</sup> Br	55 ± 9	55.16	0.99	46.38	1.19	49.65	1.11
20.	<sup>82</sup> Kr (n,p) <sup>82</sup> Br	23 ± 4	23.15	0.99	22.80	1.01	24.55	0.94
21.	<sup>84</sup> Kr (n,p) <sup>84</sup> Br	8.5 ± 1.5	9.91	0.86	11.39	0.75	12.34	0.69
22.	<sup>86</sup> Sr (n,p) <sup>86g</sup> Rb	42 ± 4	31.75	1.32	28.36	1.48	30.87	1.36
23.	<sup>88</sup> Sr (n,p) <sup>88</sup> Rb	17 ± 1.2	13.83	1.23	14.38	1.18	15.73	1.08
24.	<sup>90</sup> Zr (n,p) <sup>90g</sup> Y	45 ± 4	43.29	1.04	35.25	1.29	38.67	1.16
25.	<sup>92</sup> Zr (n,p) <sup>92</sup> Y	19 ± 2	19.16	0.99	18.13	1.05	19.96	0.95
26.	<sup>94</sup> Zr (n,p) <sup>94</sup> Y	8 ± 3	8.63	0.92	9.42	0.85	10.44	0.77
27.	$^{92}Mo(n,p) ^{92m}Nb$	62.5 ± 4	132.87	0.47	85.19	0.73	93.58	0.67
28.	<sup>96</sup> Mo (n,p) <sup>96</sup> Nb	21 ± 7	26.40	0.79	22.83	0.92	25.24	0.83
29.	<sup>98</sup> Mo (n,p) <sup>98g</sup> Nb	$4.1 \pm 0.5$	12.06	0.34	12.05	0.34	13.36	0.31
30.	<sup>96</sup> Ru (n,p) <sup>96</sup> Tc	146 ± 7	176.76	0.83	104.48	1.39	115.08	1.27
31.	<sup>106</sup> Pd (n,p) <sup>106g</sup> Rh	16 ± 4	23.16	0.69	19.53	0.82	21.60	0.74
32.	<sup>108</sup> Pd (n,p) <sup>108g</sup> Rh	8.3 ± 1.5	11.01	0.75	10.66	0.78	11.81	0.70
33.	<sup>112</sup> Cd (n,p) <sup>112</sup> Ag	15 ± 1.3	15.32	0.98	13.70	1.09	15.09	0.99
34.	<sup>116</sup> Cd (n,p) <sup>116</sup> Ag	5.4 ± 1.5	3.67	1.47	4.29	1.26	4.73	1.14
35.	<sup>112</sup> Sn (n,p) <sup>112</sup> In	$13 \pm 0.7$	90.95	0.14	57.29	0.23	62.59	0.21
36.	<sup>116</sup> Sn (n,p) <sup>116m</sup> In	8 ± 1	21.24	0.38	17.59	0.45	19.23	0.42
37.	<sup>118</sup> Sn (n,p) <sup>118</sup> gIn	11 ± 2	10.45	1.05	9.89	1.11	10.81	1.02
38.	$^{120}$ Sn (n,p) $^{120}$ In	4 ± 1	5.19	0.77	5.61	0.71	6.13	0.65

Table	(1):	(Continued	)
TTTTTTTTTTTTTTTTTTTTTTTTTTTTTTTTTTTTTT		•	-

	Reaction	(n,p) cross - section (mb) at 14.5 Me V				Me V		
		Exp.	Bychkov	Ratio	Gul	Ratio	Present	Ratio
39.	<sup>130</sup> Xe (n,p) <sup>130</sup> I	$6.7 \pm 0.8$	5.26	1.20	5.56	1.20	5.92	1.13
40.	$^{132}$ Xe (n,p) $^{132}$ I	$2.5 \pm 0.3$	2.72	0.90	3.26	0.77	3.47	0.72
41.	<sup>134</sup> Xe (n,p) <sup>134</sup> I	$2.2 \pm 0.5$	1.42	1.55	1.92	1.14	2.04	1.08
42.	<sup>136</sup> Ba (n,p) <sup>136</sup> Cs	38.3 ± 3.8	3.86	9.9	4.32	8.87	4.51	8.49
43.	<sup>138</sup> Ba (n,p) <sup>138</sup> Cs	$3 \pm 0.5$	2.03	1.47	2.56	1.17	2.68	1.12
44.	<sup>140</sup> Ce (n,p) <sup>140</sup> La	9.5 ± 2.5	5.46	1.74	5.71	1.66	5.86	1.62
45.	<sup>142</sup> Ce (n,p) <sup>142</sup> La	9.5 ± 0.9	2.89	3.28	3.42	2.73	3.49	2.72
46.	<sup>142</sup> Nd (n,p) <sup>142</sup> Pr	13.5 ± 2.7	14.54	0.98	12.62	1.07	12.72	1.06
47.	<sup>152</sup> Sm (n,p) <sup>152</sup> Pm	3.7 ± 0.2	3.15	1.17	3.69	1.00	3.60	1.03
48.	<sup>184</sup> W (n,p) <sup>184</sup> Ta	4.8 ± 1.0	2.61	1.84	3.46	1.39	2.77	1.73
49.	<sup>186</sup> W (n,p) <sup>186</sup> Ta	$2.3 \pm 0.5$	1.51	1.52	2.23	1.03	1.78	1.29
50.	<sup>194</sup> Pt (n,p) <sup>194</sup> Ir	$4.2 \pm 0.5$	3.09	1.36	4.15	1.01	3.07	1.37
51.	<sup>196</sup> Pt (n,p) <sup>196</sup> Ir	$1.1 \pm 0.2$	1.82	0.61	2.71	0.41	1.99	0.55
52.	<sup>198</sup> Hg (n,p) <sup>198</sup> Au	$4.5 \pm 0.5$	4.40	1.02	5.67	0.79	4.03	1.12
53.	<sup>200</sup> Hg (n,p) <sup>200</sup> Au	3.6± 0.36	2.59	1.39	3.71	0.98	2.63	1.38
54.	<sup>208</sup> Pb (n,p) <sup>208</sup> Tl	0.46± 0.06	1.32	0.35	2.23	0.21	1.49	0.31

# <u>Table (2)</u>: Measured and Calculated Data for (n,p) Reaction Cross - Sections at 14.5 Me V (for Odd-A Nuclides)

•	Reaction	(n,p) cross - section (mb) at 14.5 Me V						
		Exp.	Bychkov	Ratio	Gul	Ratio	Present	Ratio
1.	<sup>29</sup> Si (n,p) <sup>29</sup> Al	$120 \pm 26$	137.53	0.88	124.33	0.97	127.75	0.94
2.	<sup>35</sup> Cl (n,p) <sup>35</sup> S	120 ± 26	159.07	0.88	117.38	1.02	116.29	1.03
3.	<sup>37</sup> Cl (n,p) <sup>37</sup> S	33 ± 6	80.546	0.41	67.33	0.49	69.77	0.47
4.	<sup>45</sup> Sc (n,p) <sup>45</sup> Ca	56 ± 4	101.71	0.55	66.57	0.84	66.21	0.85
5.	<sup>47</sup> Ti (n,p) <sup>47</sup> Sc	$120\pm20$	108.5	1.16	66.43	1.81	65.54	1.83
6.	<sup>49</sup> Ti (n,p) <sup>49</sup> Sc	35 ± 4	55.18	0.64	41.35	0.85	42.21	0.83
7.	<sup>57</sup> Fe (n,p) <sup>57</sup> Mn	75 ± 8	73.53	1.02	42.67	1.76	42.25	1.78
8.	<sup>59</sup> Co (n,p) <sup>59</sup> Fe	80 ± 23	79.47	1.01	43.04	1.86	42.34	1.89
9.	<sup>61</sup> Ni (n,p) <sup>61g</sup> Co	$103 \pm 10$	86.11	1.20	43.42	2.37	42.47	2.43
10.	<sup>65</sup> Cu (n,p) <sup>65</sup> Ni	21 ± 5	47.89	0.44	29.19	0.72	29.14	0.72
11.	<sup>67</sup> Zn (n,p) <sup>67</sup> Cu	43 ± 10	52.16	0.82	29.65	1.45	29.43	1.46
12.	<sup>69</sup> Ga (n,p) <sup>69g</sup> Zn	17 ± 4	56.97	0.30	30.13	0.56	29.74	0.57
13.	<sup>69m</sup> Zn	21 ± 3	56.97	0.35	30.13	0.69	29.74	0.71
14.	<sup>71</sup> Ga (n,p) <sup>71m</sup> Zn	12 ± 4	29.21	0.41	20.51	0.59	20.72	0.58
15.	<sup>73</sup> Ge (n,p) <sup>73</sup> Ga	26 ± 3	32.01	0.81	20.96	1.24	21.05	1.23
16.	<sup>75</sup> As (n,p) <sup>75g</sup> Ge	20 ± 3	35.15	0.57	21.41	0.93	21.39	0.93
17.	<sup>75m</sup> Ge	16 ± 1.5	35.15	0.46	21.41	0.75	21.39	0.75
18.	<sup>77</sup> Se (n,p) <sup>77</sup> As	35 ± 10	38.68	0.96	21.88	1.59	21.76	1.61
19.	<sup>89</sup> Y (n,p) <sup>89</sup> Sr	24 ± 1.6	33.34	0.72	17.42	1.38	17.26	1.39
20.	<sup>91</sup> Zr (n,p) <sup>91g</sup> Y	40 ± 8	37.21	1.08	17.90	2.23	17.67	2.26
21.	<sup>91m</sup> Y	18.6 ± 1.9	37.21	0.50	17.90	1.04	17.67	1.05
22.	<sup>97</sup> Mo (n,p) <sup>97</sup> <sup>g</sup> Nb	15.9 ± 1.3	24.15	0.66	13.68	1.16	13.62	1.17
23.	<sup>97m</sup> Nb	$7.4 \pm 0.8$	24.15	0.31	13.68	0.54	13.62	0.54
24.	<sup>103</sup> Rh (n,p) <sup>103</sup> Ru	16.9 ± 1.5	34.49	0.49	15.04	1.12	14.79	1.14
25.	<sup>115</sup> In (n,p) <sup>115</sup> gCd	$15.5\pm4.0$	15.48	1.00	9.47	1.64	9.44	1.64
26.	<sup>115</sup> In (n,p) <sup>115m</sup> Cd	$3.5\pm0.2$	15.48	0.22	9.47	0.37	9.44	0.37
27.	<sup>115</sup> Sn (n,p) <sup>115m</sup> In	$\textbf{3.5} \pm \textbf{0.2}$	33.92	0.10	13.16	0.27	12.90	0.27
28.	<sup>117</sup> Sn (n,p) <sup>117</sup> gIn	9.8 ± 1.6	17.68	0.55	9.83	0.99	9.77	1.00
29.	<sup>117m</sup> In	4.7 ± 1.0	17.68	0.27	9.83	0.45	9.77	0.48
30.	<sup>119</sup> Sn (n,p) <sup>119</sup> gIn	$2.6 \pm 0.3$	9.21	0.28	7.83	0.35	7.43	0.35
31.	$^{127}$ I (n,p) $^{127g}$ Te	11.7 ± 1.2	7.26	1.61	6.33	1.85	6.37	1.84
32.	$^{131}$ Xe (n,p) $^{131}$ I	5.3 ± 0.6	4.37	1.21	5.04	1.05	5.11	1.04
33.	<sup>139</sup> La (n,p) <sup>139</sup> Ba	5 ± 1	3.55	1.41	4.45	1.12	4.50	1.11
34.	<sup>141</sup> Pr (n,p) <sup>141</sup> Ce	4.5 ± 1	9.18	0.49	6.33	0.71	6.29	0.71
35.	<sup>143</sup> Nd (n,p) <sup>143</sup> Pr	$11.5 \pm 2.3$	10.71	1.01	6.62	1.74	6.57	1.75
36.	<sup>153</sup> Eu (n,p) <sup>153</sup> Sm	$7.4 \pm 0.7$	4.75	1.59	4.62	1.60	4.62	1.60
37.	<sup>157</sup> Cd (n,p) <sup>157</sup> Eu	$11.3 \pm 1.7$	2.94	3.84	3.81	2.97	3.82	2.96
38.	<sup>175</sup> Lu (n,p) <sup>175</sup> Y	3.42 ± .52	2.72	1.26	3.45	0.99	3.42	1.00

	Reaction	Reaction (n,p) cross - section (mb) at 14.5 M					5 Me V	
		Exp.	Bychkov	Ratio	Gul	Ratio	Present	Ratio
39.	<sup>181</sup> Ta (n,p) <sup>181</sup> Hf	3 ± 0.5	2.06	1.46	3.07	0.98	3.05	0.98
40.	<sup>187</sup> Re (n,p) <sup>187</sup> W	$3.9 \pm 0.4$	1.58	2.47	2.76	1.41	2.74	1.42
41.	<sup>193</sup> Ir (n,p) <sup>193</sup> Os	$2.7 \pm 0.6$	1.22	2.21	2.50	1.08	2.47	1.09
42.	<sup>197</sup> Au (n,p) <sup>197</sup> Pt	$2.3 \pm 0.2$	1.79	1.28	2.81	0.82	2.67	0.83
43.	<sup>199</sup> Hg (n,p) <sup>199</sup> Au	$2.3 \pm 0.3$	2.17	1.06	2.99	0.77	2.92	0.79
44.	<sup>201</sup> Hg (n,p) <sup>201</sup> Au	$2.1 \pm 0.3$	2.17	1.79	2.42	0.87	2.37	0.88
45.	<sup>205</sup> Tl (n,p) <sup>205</sup> Hg	3 ± 1.6	0.75	4.0	2.09	1.44	2.05	1.46
46.	<sup>209</sup> Bi (n,p) <sup>209</sup> Pb	$1.3 \pm 0.3$	1.12	1.16	2.36	0.55	2.29	0.56

# <u>Table (2):</u> (Continued)

## <u>Table (3)</u>: Values of Parameters for the Best Fit for the Calculation of the (n,p) Reaction Cross - Sections at 14.5MeV ( for Even-A Nuclides )

## **Present Formula :**

$a_0 = lnc_3(1 - Vp/\epsilon_p)$	$a_1 = a_c (MeV)$	$a_2 = 4a_a(MeV)$	$a_3 = V_p (MeV)$	No. of data points
2.59 ± 1.31	$0.30\pm0.08$	48.52 ± 6.08	5.82 ± 3.70	54

Gul Formula :

$\mathbf{a}_{0} = \mathbf{In}(\mathbf{c}_{1}\pi\mathbf{r}_{0}^{2})$	$a_1 = 2a_c (MeV)$	$\mathbf{a}_2 = \mathbf{a}_{\tau} (\mathrm{MeV})$	a <sub>3</sub> = Constant	No. of data points
5.65 ± 1.02	$1.07\pm0.25$	56.49 ± 5.88	11.69 ± 3.60	54

# <u>Table (4)</u>: Values of Parameters for the Best Fit for the Calculation of the (n,p) Reaction Cross - Sections at 14.5MeV ( for Odd-A Nuclides )

## **Present Formula :**

$a_0 = Inc_3(1 - Vp/\epsilon_p)$	$a_1 = a_c (MeV)$	$a_2 = 4a_a (MeV)$	$a_3 = V_p (MeV)$	No. of data points
4.33 ± 1.25	$0.240\pm0.11$	19.03 ± 11.8	12.04 ± 3.5	46

Gul Formula :

$\mathbf{a}_{\mathrm{o}} = \mathrm{In}(\mathbf{c}_{1} \pi \mathbf{r}_{\mathrm{o}}^{2})$	$\mathbf{a}_1 = 2\mathbf{a}_c \; (\mathrm{MeV})$	$a_2 = a_\tau (MeV)$	a <sub>3</sub> = constant	No. of data points
4.91 ± 0.9	$0.63\pm0.24$	30.53 ± 13.45	10.61 ± 3.35	46



Fig(1) : The ratio of experimental to calculated  $\sigma(n,p)$  at 14.5MeV versus the mass number A for odd-A nuclides



Fig(2) : The ratio of experimental to calculated  $\sigma(n,p)$  at 14.5MeV versus the mass number A for even-A nuclides



Fig(3): Systematics of  $\sigma(n,p)$  at 14.5MeV for odd-even A nuclides



Fig(4):Systematics of  $\sigma(n,p)$  at 14 5MeV using experimental values

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