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On the Systematics of the (n,α) Reaction Cross-Sections at 14.5 MeV Neutrons

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Abstract

A systematics is proposed for the (n,α) 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,α) reaction cross-sections at 14.5 MeV neutrons and the target mass range $26 \leq A \leq 238$. The present formula is compared with other recently proposed systematics based on the statistical model and the asymmetry parameter dependence.

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1. Introduction

Precise measurements, calculation and evaluations for the (n,α) reaction cross-sections around 14MeV neutrons are required for the improvements of model calculations and for radiation damage assessment of fusion-related structural materials. Recently a series of measurements have been carried out and a number of compilations and systematics have been presented for the (n,α) reaction cross-sections around 14MeV neutrons[1-19]. In the present work a systematics is proposed for the (n,α) reaction cross-sections based on the statistical model. An empirical formula for even-A and odd-A nuclei is presented for the (n,α) reaction cross-sections at 14.5MeV neutrons and the target mass range $26 \leq A \leq 238$. The formula is based on the statistical model, with the dependence on the Q-value and odd-even effect correction taken into consideration. The systematics for the (n,α) reaction cross-sections using the present formula is compared with other systematics based on the statistical model and asymmetry parameter dependence[13-19].

2. Empirical Formula

2.1 Present Formula:

Following a similar procedure to our previous paper[20], we have for the (n,α) reaction cross-section on the basis of the statistical model :

$$\sigma_{n,\alpha} = \sigma_R (\Gamma_\alpha / \Gamma_n) \quad (1)$$

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

Γ_α = the decay width for an alpha particle.

Γ_n = the decay width for a neutron.

The decay width Γ_α for an alpha particle can be written by means of the principle of detailed balance as follows :

$$\Gamma_\alpha = \frac{(2s_\alpha + 1)}{\pi h^2 \rho_a(E_\alpha)} M_\alpha \int_{V_\alpha}^{E_\alpha - B_\alpha - \delta_\alpha} \varepsilon_\alpha \sigma_c(\varepsilon_\alpha) \rho_b(E_b) d\varepsilon_\alpha \quad (2)$$

where S_α and M_α are the spin statistical factor and mass of alpha particle, respectively ; B_α and δ_α are the separation energy of the alpha particle 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_α is the coulomb barrier of the alpha particle and ε_α and σ_c are the emitted alpha particle energy and the cross-section of the 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 : $\sigma_c(\varepsilon_n) = \pi R^2$

$$\text{for alpha particles : } \sigma_c(\varepsilon_\alpha) = \pi R^2 (1 - V_\alpha / \varepsilon_\alpha) \quad \text{for } \varepsilon_\alpha > V_\alpha \\ = 0 \quad \text{for } \varepsilon_\alpha < V_\alpha \quad (3)$$

where $(1 - V_\alpha / \varepsilon_\alpha)$ is the probability for the barrier penetration for an alpha particle 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 :

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

with the entropy of the system given by :

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

where T is the nuclear temperature. Thus

$$S_b(E_b) - S_a(E_a) \approx (E_b - E_a)/T = -(\varepsilon_\alpha + B_\alpha + \delta_\alpha)/T \quad (6)$$

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

$$\Gamma_\alpha = \frac{(2S_\alpha + 1)}{\pi h^2} M_\alpha R^2 \int_{V_\alpha}^{E_\alpha - B_\alpha - \delta_\alpha} \varepsilon_\alpha (1 - V_\alpha / \varepsilon_\alpha) \exp[-(\varepsilon_\alpha + B_\alpha + \delta_\alpha)/T] d\varepsilon_\alpha \quad (7)$$

Integration of eq(7) gives for the decay width of an alpha particle :

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

and similarly for the decay width of a neutron :

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

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, α) reaction cross-section will be (substituting in eq(1)):

$$\sigma_{n,\alpha} = \sigma_R \left(\frac{2S_\alpha + 1}{2S_n + 1} \right) \frac{M_\alpha}{M_n} (1 - V_\alpha / \varepsilon_\alpha) \exp\left(\frac{Q_{n,\alpha} - V_\alpha}{T} \right) \quad (10)$$

where $Q_{n,\alpha} = B_n - B_\alpha + \delta_n - \delta_\alpha$ is the effective Q-value of the (n, α) reaction .

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

$$\begin{aligned} Q_{n,\alpha} = & a_1 + a_c \left(Z^2 A^{-1/3} - (Z-2)^2 (A-3)^{-1/3} - 2.519 \right) + \\ & a_a \left((A-2Z)^2 A^{-1} - (A-2Z+1)^2 (A-3)^{-1} \right) \end{aligned} \quad (11)$$

where a_c and a_a are the coulomb and asymmetry parameters, respectively, and a_1 is a constant taking into consideration the other terms of the semiempirical mass formula. Inserting eq(11) into eq(10) we get for the cross-section of the (n,α) reaction :

$$\sigma_{n,\alpha} = \sigma_R \frac{M_\alpha}{M_n} \exp \left(a_0 + \frac{Q_{n,\alpha}}{T} - \frac{V_\alpha}{T} \right) \quad (12)$$

where $a_0 = \ln(c(1-V_\alpha/\epsilon_\alpha))$ with $c=(2S_\alpha+1)/(2S_n+1)$, $T = (E_n/a)^{1/2}$, with $a = (A/15)$ MeV⁻¹ 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.

2.2 Other Formulae:

The relation obtained by Gul [15] for the (n,α) reaction on the basis of the statistical model is:

$$\sigma_{n,\alpha} = \left(A^{1/3} + 1 \right)^2 \exp \left[a_0 + a_1 \frac{(Z-1.5)}{TA^{1/3}} + a_2 \frac{(A-2Z+0.5)}{TA} + a_3 \frac{(Z-2)}{E_i A^{1/3}} \right] \quad (13)$$

where $a_1 = 4a_c$, $a_2 = a_\tau$ with a_c and a_τ coulomb and asymmetry parameters, respectively; $a_0 = \ln(c_1 \pi r_o^2) + a_0$ and c_1 , a_0 , a_3 are constants; E_i is taken as incident energy of the neutron. The present formula is compared with Gul's relation as well as with formulae based on the asymmetry parameter dependence proposed by Levkovskii, Ait-Tahars, Kasugai, Forrest and Csikai [14, 18, 17, 15, 13]. The proposed formulae are as follows: Levkovskii :

$$\sigma_{n,\alpha} = c_1 \left(A^{1/3} + 1 \right)^2 \exp \left(c_2 \frac{(N-Z)}{A} \right) \quad 31 \leq A \leq 202 \quad (14)$$

Ait-Tahars :

$$\sigma_{n,\alpha} = c_3 \left(A^{1/3} + 1 \right)^2 \exp \left(c_4 \frac{N-Z+1}{A} \right) \quad 40 \leq A \leq 188 \quad (15)$$

Kasugai :

$$\sigma_{n,\alpha} = c_5 \exp \left(c_6 \frac{N-Z}{A} \right) \quad 19 \leq A \leq 188 \quad (16)$$

Forrest :

$$\sigma_{n,\alpha} = c_7 \left(A^{1/3} + 1 \right)^2 \exp \left(c_8 \left(\frac{N-Z}{A} \right) + c_9 \left(\frac{N-Z}{A} \right)^2 + c_{10} A \right) \quad 20 \leq Z \leq 50 \quad (17)$$

$$\sigma_{n,\alpha} = c_{11} \left(A^{1/3} + 1 \right)^2 \exp \left(c_{12} \frac{N-Z}{A} + c_{13} A \right) \quad 50 \leq Z \leq 82 \quad (18)$$

Csikai :

$$\sigma_{n,\alpha} = c_{14} \left(A^{1/3} + 1 \right)^2 \exp \left(c_{15} \left(\left(\frac{N-Z}{A} \right) + \left(\frac{N-Z}{A} \right)^2 \right) \right) \quad 19 \leq A \leq 202 \quad (19)$$

3. Fitting Procedure

For fitting of the Q-value of (n,α) reaction cross-section eq(11) can be written as :

$$K = X + b_1 Y + b_2 Z \quad (20)$$

where $X = a_1$, $Y = a_c$, $Z = a_a$ and $K = Q_{n,\alpha}$

$$\text{with } b_1 = \left(Z^2 A^{-1/3} - (Z-2)^2 (A-3)^{-1/3} - 2.519 \right)$$

$$b_2 = \left((A-2Z)^2 A^{-1} - (A-2Z+1)^2 (A-3)^{-1} \right)$$

For fitting of the (n,α) reaction cross-section eq (12) can be written as :

$$K' = X' - a_1 Y' \quad (21)$$

$$\text{where } K' = \ln \left(\sigma_{n,\alpha} / (\sigma_R \frac{M_\alpha}{M_n}) \right) - Q_{n,\alpha} / T$$

$$X' = \ln c \left(1 - V_\alpha / \varepsilon_\alpha \right)$$

$$\text{with } c = (2S_\alpha + 1) / (2S_n + 1)$$

$$Y' = V_\alpha \text{ and } a_1 = (1/T)$$

The Legendre method of least squares [21] can be applied to eqs(20) and (21) to obtain X, Y, Z, X' and Y' . We choose X, Y, Z, X' and Y' such that the sum of the squares of the errors is least :

i.e.

$$\sum_{s=1}^n \left(X + b_{1s} Y + b_{2s} Z - K_s \right)^2$$

$$\text{and } \sum_{s=1}^n \left(X' - a_{1s} Y' - K'_s \right)^2$$

is minimum for eq(20) and eq(21), respectively, where n is the number of the data points.

The corresponding relation for eq(13) can be written in the following form:

$$K'' = X'' + b_1'' Y'' + b_2'' Z'' + b_3'' F \quad (22)$$

$$\text{where } K'' = \ln \left(\sigma_{n,\alpha} / (A^{1/3} + 1)^2 \right)$$

$$X'' = \ln \left(c_1 \pi r_0^2 \right) + a_0'$$

$$Y'' = 4a_c, Z'' = a_\tau, F = \text{constant}$$

$$b_1'' = \frac{(Z-1.5)}{TA^{1/3}}, b_2'' = \frac{(A-2Z+0.5)}{TA} \quad \text{and} \quad b_3'' = \frac{(Z-2)}{E_i A^{1/3}}$$

The Legendre method of least squares can be applied to eq(22) to obtain X'' , y'' , Z'' and F such that the sum of the squares of the errors is least i.e.

$$\sum_{s=1}^n \left(X'' + b_{1s}'' Y'' + b_{2s}'' Z'' + b_{3s}'' F - K_s'' \right)^2 \text{ is minimum.}$$

The input data used in the present fitting of the Q-value for the nuclides under consideration were taken from ref [22]. The input data used in the analysis of the (n,α) reaction cross-sections, taken from refs [23,24], are given in Tables 1 and 2 for even-A and odd-A nuclides, respectively. The systematics parameters for the eqs(14-19) have been extracted from the analysis and fitting of the available data of (n,α) reaction cross-sections at 14.5MeV neutron energy (given in Tables 1 and 2) using the least squares method .

4. Results and Discussion

4.1 The Fitting Parameters

The proposed formula used in the present work for studying the systematics of the (n,α) reaction cross-sections (given by eq (12)) is based on the statistical model of nuclear reactions. The formula contains two physical parameters related to the semiempirical mass formula, namely the coulomb parameter a_c and asymmetry parameter a_a . In addition, the constant a_1 is included to take into account the other terms of the semiempirical mass formula, besides the effective coulomb barrier V_α and $a_0 = \ln(1-V_\alpha / \alpha)$ which includes the probability of the barrier penetration 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 14.5MeV and the level density parameter $a = A/25$ MeV . The mass excess of the target and residual nuclei as well as the excess mass of the neutron and alpha particle are also required for the Q-value fitting .The best fit of the parameters a_0 , a_1 , a_c and a_a are given in Table3(a), for even-A and odd-A nuclides.

The corresponding values obtained for the Gul formula (given by eq(13)) are also presented in Table3(b) for comparison.The values obtained for the coulomb and asymmetry parameters using the present formula for even-A nuclides are 0.473 and 13.282MeV, respectively. The corresponding values obtained for odd-A nuclides are 0.492 and 15.995MeV. It is evident that the values for even-A nuclides are smaller than the corresponding values for odd-A nuclides. The values obtained using the present formula for the effective coulomb barrier V_α and the probability of the coulomb barrier penetration $\ln(1- V_\alpha / \alpha)$ are also smaller in the case of even-A nuclides as compared to odd-A nuclides. This indicates variations for even-A and odd-A values of the parameters involved in the cross-section determination of the present formula . It is observed that the Gul relation has the same values of the parameters for

even-A and odd-A nuclides. Also the values obtained by the Gul relation for the coulomb and asymmetry parameters are smaller than those found in the present systematics. However, the values of the parameters in the present systematics are nearer to the values given in the literature for these parameters than those obtained from Gul's relation.

4.2 Comparison with other Systematics

The predictions of the systematics based on the present formula are compared with those obtained by Gul's relation and by other systematics for the (n,α) reaction cross-sections at 14.5MeV neutron energy .

The fitting of the empirical expressions given by Levkovskii and Ait Tahars[14,18] to the measured data given in Tables 1 and 2 confirms the straight line trend of the (n,α) reaction cross-sections versus the asymmetry parameters $(N-Z)/A$ and $(N-Z+1)/A$, respectively. Other formulae given by Forrest [15] and Csikai[13], with an additional term in the exponential, are able to give substantial improvement in fitting the data . A comparison between six systematics under study is given in Table 4. As shown in Table 4 the present formula is successful in a wide range of Z and A values, with splitting of the data to even-A and odd-A nuclides, in addition to improvement in the Q-values for the reaction under consideration.

Comparisons of the ratio of the experimental to calculated (n,α) reaction cross-sections obtained through six systematics for even-A and odd-A nuclides are shown in Figs. 1 and 2 , respectively. As can be seen from Fig.1 for even-A nuclides there is good agreement between most of the predictions of the present and other systematics and experimental values. The disagreement between the six systematics is observed in the following reactions:

$^{76}\text{Ge}(n,\alpha)^{73}\text{Zn}$, $^{100}\text{Mo}(n,\alpha)^{97}\text{Zr}$, $^{110}\text{Pd}(n,\alpha)^{107}\text{Ru}$, $^{144}\text{Nd}(n,\alpha)^{141}\text{Ce}$, $^{140}\text{Ce}(n,\alpha)^{137m}\text{Ba}$, $^{142}\text{Ce}(n,\alpha)^{139}\text{Ba}$ and $^{152}\text{Sm}(n,\alpha)^{149}\text{Nd}$. In these reactions the experimental values of (n,α) reaction cross-sections are higher than calculated values.

As can be seen from Fig.2 for odd-A nuclides there is also agreement between most of the predictions of the present and other systematics and experimental values. The disagreement between the six systematics and experimental values is observed in the following reactions:

$^{81}\text{Br}(n,\alpha)^{78}\text{As}$, $^{197}\text{Au}(n,\alpha)^{194}\text{Ir}$ and $^{71}\text{Ga}(n,\alpha)^{68}\text{Cu}$. In the reactions $^{81}\text{Br}(n,\alpha)^{78}\text{As}$ and $^{71}\text{Ga}(n,\alpha)^{68}\text{Cu}$ the experimental values of the cross-sections are higher than the calculated values, while in the $^{197}\text{Au}(n,\alpha)^{194}\text{Ir}$ the experimental value of the cross-section is lower than the calculated value.

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:

$$\sigma_{n,\alpha} = \left(1 + A^{1/3}\right)^2 \chi \exp(\beta(N - Z + \delta) / A) \quad (23)$$

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

For odd-A nuclides: $\chi = 35$, $\beta = -35.714$ and $\delta = 0$.

For even-A nuclides $\chi= 3.6$, $\beta = -25$ and $\delta = -3$.

The systematics of the (n,α) reaction cross-sections using eq(23) is shown in Fig.3, where $\sigma(n,\alpha)/(1+A^{1/3})^2$ is plotted versus the asymmetry parameter $(N-Z+\delta)/A$ for odd-A and even-A nuclides. It can be seen that the odd-even effect exists in the (n,α) reaction cross-sections. The curve of odd-A-nuclides is located above that of even-A

nuclides. We also note that the slope of the curve is larger, and the decrease of the cross-sections of odd-A nuclides is faster. It is clear that with increasing $(N-Z+\delta)/A$, the odd-even effect decreases.

For comparisons between the various systematics the following quantity was proposed[13]:

$$F = \sum_{s=1}^n \left(\left| \sigma_{\text{exp}_s} - \sigma_{\text{cal}_s} \right| \right) / \sigma_{\text{cal}_s}$$

The value of F/n can characterize the goodness of the systematics ,where n is the number of data points used.

Finally, we conclude that the results obtained using the present formula are in good agreement with those obtained by other systematics , especially in the case of odd-A nuclides. It is to be noted that while in the present formula different values for the coulomb and asymmetry parameters for even-A and odd-A nuclides were obtained, in the Gul formula the same values have been used for both even-A and odd-A nuclides. It is to be noted that the present formula gives better results for the coulomb and asymmetry parameters and also shows clearly the presence of the odd-even effect and the faster decrease in the case of the odd-A nuclides.

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References

- [1] Bychkov,V.M,Manokhin,V.N.,Pashchenko,A.B. and Plyashin,V.I., " Cross-sections for the (n,p) , (n,α) and $(n,2n)$ Threshold Reactions", INDC(CCP)-146,IAEA,Vienna,1980.
- [2] QaimS.M., " 14MeV Neutron Activation Cross-Sections", in " Handbook of Spectroscopy" ,Vol.III,CRC Press Inc.,Boca Raton, Florida,1981,p.141.
- [3] Pepelnik, R ,Anders,B. and Bahal, B.M., " Measurements of 14MeV Neutron Activation Cross-Sections", Radiation Effects,92(1986)211-214.
- [4] Body,Z. and Csikai, J., " Data for 14MeV Neutron Activation Analysis" in "Handbook of Nuclear Activation Data", Tech.Rep. Series,No.273,IAEA,Vienna,1987,pp.261-203.
- [5] McLane, V. , Dunford, C.L and Rose, P.F, "Neutron Cross-Sections" Vol.2, Acad.Press Inc., New York,1988.
- [6] Katoh , T., Kawade, K. and Yamamoto,H. " Measurement of Activation Cross - Sections", IAERI-M89-083,Tokai-mura,1989.
- [7] Pashchenko, A.B, " Reaction cross-sections induced by 14.5MeV and by Cf-252 and U-235 Fission Spectrum Neutrons", INDC(CCP)-323,IAEA,Vienna,1991.
- [8] Ikeda, Y., Konno,C., Oishi,K.,Nakamara,T.,Miyade,H., Yamamoto,H. and Katoh, T. "Activation Cross-Sections Measurements for Fusion Reactor Structural Materials at Neutron Energy from 13.3 to 15.0MeV Using FNS Facility", JAERI 1312,Tokai-mura,1988.

- [9] Konno, C., Ikeda,Y., Oishi,K.,Kawade,K.,Yamamoto, H. and Maekawa, H. "Activation Cross-Sections Measurements at Neutron Energy from 13.3 to 14.9MeV Using FNS Facility", JAERI 1329,Tokai -mura,1993.
- [10]Shadad, I.A "(n,p) and (n, α) Reaction Cross-Sections Measurements and Systematics around 14MeV Neutron Energy" Ph.D Thesis,University of Khartoum,Sudan(1995)
- [11] Kapecky, J., " Experimental Data Base Compiled for Renormalizations and Validation of EAF-4.1Data",EAF-Doc-6,7,8,ECN Petten (Aug 1994, Sept1994,Jan1996).
- [12] Filatenkov,A.A.,Chuvaev, S.V, Absenov,V.N. and Jakovlev,V.A., " Systematic Measurements of Activation Cross-Sections of Neutron Energies from13.4-14.9MeV", INDC(CCP)-402,IAEA, Vienna 1997.
- [13] Csikai,J.,Semkova,V.,Doczi,R.,Majdeddin,A.D.,Varnagy,M.,Buczko' , C.M and Fenyvesi,A. " Measured, Estimated and Calculated (n, α) Cross-Sections for Fusion Applications", Fusion Engineering and Design,37(1997)65-71.
- [14] Levkovskii, V.N., " Empirical Behaviour of the (n,p) Cross-Section for 14-15MeV Neutrons", Zh.Eksp.Teor.Fiz.,45(1963)305-311.
- [15] Forrest,R.A., "Systematics of Neutron Induced Threshold Reactions with Charged Products at about 14.5MeV" AERE-R 12419,Harwell Laboratory,December,1986.
- [16] Gul,K., "Systematics of (n,p) and (n, α) Cross-Sections for 14MeV Neutrons on the Basis of the Statistical Model", INDC(PAK),009(1995).
- [17] Kasugai, Y., Ikeda, Y., Yamamoto, H. and Kawade, K., " Systematics of Activation Cross-Sections for 13.4-15.0MeV Neutrons", JAERI-Conf.95-008.
- [18] Ait-Tahar, S., "The Systematic of (n,p) Cross-sections for 14MeV Neutrons", Nucl.Phys.,13(1987)121-125.
- [19] Majdeddin,A.D., Semkova,V., Doczi,R.,Buczko,C.M and Csikai,J., "Investigations on (n, α) Cross-Sections in the 14MeV Region",INDC(HUN)-031,IAEA, Vienna,1997.
- [20] Osman, K.T and Habbani, F., " On the Systematics for the (n,p) Reaction Cross-Sections at 14.5MeV Neutrons", INDC(SUD)-002,IAEA, Vienna,1997.
- [21] J. Topping "Errors of the Observations and Their Treatment", Chapman and Hall Limited, London,W.3(1969).
- [22] Riedlnder Kenned, Macias Miller " Nuclear Radiochemistry" 3rd, Edition, John Wiley and Son ,Inc , New Yourk 100116(1980).
- [23] "Handbook on Nuclear Activation Data" Technical Reports Series No.56,IAEA, Vienna(1974).
- [24] "Handbook on Nuclear Activation Data" Technical Reports Series No.273,IAEA, Vienna(1987).

Table(1): Measured and Calculated data for (n,α) Reaction Cross-Sections at 14.5MeV Neutrons for Even -A Nuclides

No.	Reaction	Cross-sections (mb)				
		Exp	Present	Ratio	Levkovskii	Ratio
1	$^{26}\text{Mg}(n,\alpha)^{23}\text{Ne}$	77 ± 8	122.84	0.63	-	-
2	$^{30}\text{Si}(n,\alpha)^{27}\text{Mg}$	70 ± 10	104.16	0.67	-	-
3	$^{34}\text{S}(n,\alpha)^{31}\text{Si}$	138 ± 35	90.51	1.52	-	-
4	$^{40}\text{Ar}(n,\alpha)^{37}\text{S}$	10 ± 1.5	37.02	0.27	-	-
5	$^{44}\text{Ca}(n,\alpha)^{41}\text{Ar}$	35 ± 8	35.43	0.99	19.81	1.77
6	$^{40}\text{Ca}(n,\alpha)^{37}\text{Ar}$	138 ± 20	147.52	0.94	323.32	0.43
7	$^{48}\text{Ti}(n,\alpha)^{45}\text{Ca}$	31 ± 3	34.38	0.90	26.26	1.18
8	$^{50}\text{Ti}(n,\alpha)^{47}\text{Ca}$	9.5 ± 2	16.98	0.56	8.53	1.11
9	$^{54}\text{Cr}(n,\alpha)^{51}\text{Ti}$	14 ± 1.2	17.35	0.81	11.73	1.19
10	$^{54}\text{Fe}(n,\alpha)^{51}\text{Cr}$	98 ± 15	62.64	1.56	118.76	0.83
11	$^{58}\text{Fe}(n,\alpha)^{55}\text{Cr}$	21 ± 6	17.88	1.17	15.47	1.36
12	$^{62}\text{Ni}(n,\alpha)^{59}\text{Fe}$	21 ± 3	18.61	1.13	19.75	1.66
13	$^{68}\text{Zn}(n,\alpha)^{65}\text{Ni}$	9 ± 1	10.82	0.83	10.81	0.83
14	$^{76}\text{Ge}(n,\alpha)^{73}\text{Zn}$	14 ± 3	3.67	3.81	3.26	4.29
15	$^{74}\text{Ge}(n,\alpha)^{71}\text{Zn}$	10 ± 1.5	6.59	1.52	6.55	1.53
16	$^{86}\text{Kr}(n,\alpha)^{83}\text{Sc}$	1.2 ± 0.1	2.78	0.43	2.99	0.40
17	$^{90}\text{Zr}(n,\alpha)^{87\text{m}}\text{Sr}$	2.8 ± 0.4	10.67	0.26	15.42	0.18
18	$^{94}\text{Zr}(n,\alpha)^{91}\text{Sr}$	5 ± 1.0	3.84	1.30	4.84	1.03
19	$^{92}\text{Mo}(n,\alpha)^{89\text{g}}\text{Zr}$	18 ± 2	19.85	0.91	33.21	0.54
20	$^{100}\text{Mo}(n,\alpha)^{97\text{g}}\text{Zr}$	14 ± 6	2.75	5.09	3.54	3.96
21	$^{106}\text{Pd}(n,\alpha)^{103}\text{Ru}$	5.6 ± 0.7	6.40	0.87	8.76	0.64
22	$^{108}\text{Pd}(n,\alpha)^{105}\text{Ru}$	2.6 ± 0.4	3.99	0.65	5.35	0.49
23	$^{110}\text{Pd}(n,\alpha)^{107}\text{Ru}$	13.8 ± 6.2	2.47	5.59	3.33	4.14
24	$^{112}\text{Cd}(n,\alpha)^{109}\text{Pd}$	3.1 ± 0.3	4.82	0.64	6.45	0.48
25	$^{144}\text{Nd}(n,\alpha)^{141}\text{Ce}$	10 ± 1.0	3.22	3.11	3.52	2.84
26	$^{118}\text{Sn}(n,\alpha)^{115\text{g}}\text{Cd}$	1.1 ± 0.08	3.72	0.30	4.90	0.22
27	$^{138}\text{Ba}(n,\alpha)^{135\text{g}}\text{Xe}$	2 ± 0.2	1.27	1.57	1.74	1.15
28	$^{140}\text{Ce}(n,\alpha)^{137\text{m}}\text{Ba}$	11 ± 1.0	2.51	4.38	2.99	3.68
29	$^{142}\text{Ce}(n,\alpha)^{139}\text{Ba}$	6.5 ± 1.0	1.64	3.96	2.09	3.11
30	$^{146}\text{Nd}(n,\alpha)^{143}\text{Ce}$	2.6 ± 0.3	2.13	1.22	2.48	1.05
31	$^{152}\text{Sm}(n,\alpha)^{149}\text{Nd}$	9 ± 3	1.84	4.89	2.09	4.31
32	$^{162}\text{Dy}(n,\alpha)^{159}\text{Gd}$	3.56 ± 0.36	2.14	1.66	2.11	1.69
33	$^{164}\text{Dy}(n,\alpha)^{161}\text{Gd}$	0.9 ± 0.1	1.44	0.63	1.46	0.58
34	$^{178}\text{Hf}(n,\alpha)^{175}\text{Yb}$	2.1 ± 0.2	2.37	0.89	1.85	1.14
35	$^{180}\text{Hf}(n,\alpha)^{177}\text{Yb}$	2.2 ± 0.2	1.63	1.35	1.41	1.56
36	$^{186}\text{W}(n,\alpha)^{183}\text{Hf}$	0.85 ± 0.1	1.53	0.56	1.25	0.68
37	$^{190}\text{Os}(n,\alpha)^{187}\text{W}$	0.5 ± 0.1	2.09	0.24	1.45	0.35
38	$^{194}\text{Pt}(n,\alpha)^{191}\text{Os}$	1.26 ± 0.25	2.86	0.44	1.67	0.75
39	$^{196}\text{Pt}(n,\alpha)^{193}\text{Os}$	0.55 ± 0.11	1.99	0.28	2.46	0.22
40	$^{200}\text{Hg}(n,\alpha)^{197}\text{Pt}$	1.77 ± 0.4	2.75	0.64	1.49	1.19
41	$^{202}\text{Hg}(n,\alpha)^{199}\text{Pt}$	1.0 ± 0.1	1.93	0.52	2.18	0.46
42	$^{208}\text{Pb}(n,\alpha)^{205}\text{Hg}$	1.58 ± 0.2	1.89	0.84	-	-
43	$^{230}\text{Th}(n,\alpha)^{227}\text{Ra}$	4.6 ± 1.2	2.68	1.72	-	-
44	$^{238}\text{U}(n,\alpha)^{235}\text{Th}$	1.5 ± 0.3	1.98	0.76	-	-

Table 1: (continued)

Table(2): Measured and Calculated data for (n, α) Reaction Cross-Sections at 14.5MeV Neutrons (for Odd -A Nuclides)

No.	Reaction	Cross-sections (mb)				
		Exp	Present	Ratio	Levkovskii	Ratio
1	$^{19}\text{F}(\text{n},\alpha)^{16}\text{N}$	33 ± 7	-	-	-	-
2	$^{23}\text{Na}(\text{n},\alpha)^{20}\text{F}$	150 ± 15	-	-	-	-
3	$^{27}\text{Al}(\text{n},\alpha)^{24}\text{gNa}$	116 ± 3	279.56	0.41	-	-
4	$^{31}\text{P}(\text{n},\alpha)^{28}\text{Al}$	118 ± 15	229.58	0.51	103.52	1.14
5	$^{37}\text{Cl}(\text{n},\alpha)^{34}\text{P}$	112 ± 12	77.93	1.44	-	-
6	$^{41}\text{Kr}(\text{n},\alpha)^{38}\text{Cl}$	39 ± 8	72.43	0.54	33.25	1.17
7	$^{45}\text{Sc}(\text{n},\alpha)^{42}\text{K}$	56 ± 3	68.47	0.82	42.76	1.31
8	$^{51}\text{V}(\text{n},\alpha)^{48}\text{Sc}$	16 ± 3	29.98	0.53	17.12	0.94
9	$^{55}\text{Mn}(\text{n},\alpha)^{52}\text{V}$	32 ± 3	30.49	1.05	22.26	1.44
10	$^{59}\text{Co}(\text{n},\alpha)^{56}\text{Mn}$	30 ± 2	31.34	0.96	28.01	1.07
11	$^{63}\text{Cu}(\text{n},\alpha)^{60}\text{gCo}$	35.7 ± 2.5	32.57	1.09	34.32	1.02
12	$^{65}\text{Cu}(\text{n},\alpha)^{62}\text{gCo}$	20 ± 10	16.23	1.23	14.40	1.39
13	$^{75}\text{As}(\text{n},\alpha)^{72}\text{Ga}$	12 ± 2	9.93	1.21	10.58	1.13
14	$^{79}\text{Br}(\text{n},\alpha)^{76}\text{As}$	16 ± 6	11.17	1.43	13.16	1.22
15	$^{81}\text{Br}(\text{n},\alpha)^{78}\text{As}$	19 ± 2	5.89	3.22	6.73	2.82
16	$^{85}\text{Rb}(\text{n},\alpha)^{82}\text{gBr}$	4.9 ± 0.5	6.81	0.72	8.44	0.58
17	$^{87}\text{Rb}(\text{n},\alpha)^{84}\text{gBr}$	1.8 ± 0.2	3.65	0.49	4.57	0.39
18	$^{89}\text{Y}(\text{n},\alpha)^{86}\text{gRb}$	5 ± 1.0	7.91	0.63	10.38	0.48
19	$^{93}\text{Nb}(\text{n},\alpha)^{90}\text{gY}$	9 ± 1.0	9.24	0.97	12.55	0.72
20	$^{115}\text{In}(\text{n},\alpha)^{112}\text{Ag}$	2.8 ± 0.5	3.69	0.76	5.60	0.5
21	$^{133}\text{Cs}(\text{n},\alpha)^{130}\text{I}$	1.9 ± 0.3	1.59	1.19	2.77	0.69
22	$^{139}\text{La}(\text{n},\alpha)^{136}\text{Cs}$	2 ± 1.0	1.26	1.59	2.29	0.87
23	$^{187}\text{Re}(\text{n},\alpha)^{184}\text{Ta}$	0.94 ± 0.15	1.25	0.75	1.59	0.61
24	$^{191}\text{Ir}(\text{n},\alpha)^{188}\text{Re}$	2.43 ± 0.3	1.75	1.39	1.77	1.37
25	$^{197}\text{Au}(\text{n},\alpha)^{194}\text{Ir}$	0.35 ± 0.02	1.61	0.22	1.58	0.22
26	$^{203}\text{Tl}(\text{n},\alpha)^{200}\text{Au}$	2.2 ± 0.4	1.51	1.46	1.42	1.55
27	$^{209}\text{Bi}(\text{n},\alpha)^{206}\text{Tl}$	1 ± 0.05	1.43	0.7	1.28	0.78
28	$^{69}\text{Ga}(\text{n},\alpha)^{66}\text{Cu}$	34 ± 4	17.54	1.94	18.07	1.88
29	$^{71}\text{Ga}(\text{n},\alpha)^{68}\text{Cu}$	60 ± 4	8.88	6.76	8.32	7.21
30	$^{103}\text{Rh}(\text{n},\alpha)^{100}\text{Tc}$	11 ± 2	7.35	1.49	10.36	1.06
31	$^{107}\text{Ag}(\text{n},\alpha)^{104m}\text{Rh}$	11.3 ± 3.4	8.84	1.28	12.26	0.922

Table2: (continued)

No.	Forrest	Ratio	Ait-Tahar	Ratio	Csikai	Ratio	Kasugai	Ratio	Gul	Ratio
1	-	-	-	-	48.07	0.69	62.26	0.53	-	-
2	-	-	-	-	-	-	78.02	1.92	-	-
3	-	-	-	-	88.88	1.31	91.45	1.26	-	-
4	-	-	-	-	108.80	1.08	-	-	-	-
5	-	-	-	-	28.99	3.86	-	-	-	-
6	-	-	25.66	1.52	38.76	1.01	37.52	1.04	42.11	0.93
7	45.83	1.17	35.78	1.57	49.31	1.14	44.05	1.27	41.98	1.33
8	25.42	0.63	14.89	1.08	20.37	0.79	20.32	0.79	45.29	0.29
9	27.06	1.18	20.51	1.56	26.42	1.21	24.23	1.32	25.83	1.24
10	28.31	1.06	27.12	1.11	33.10	0.91	28.21	1.06	26.40	1.14
11	29.17	1.19	34.69	1.01	40.34	0.88	32.21	1.11	27.04	1.29
12	17.34	1.15	14.18	1.41	17.12	1.17	16.02	1.25	17.38	1.15
13	11.91	1.01	10.94	1.09	12.48	0.96	11.83	1.02	12.51	0.96
14	12.27	1.30	14.04	1.14	15.60	1.03	13.74	1.16	13.16	1.22
15	8.28	2.29	7.02	2.71	7.77	2.45	8.01	2.37	8.93	2.13
16	8.53	0.57	9.06	0.54	9.84	0.49	9.38	0.52	9.49	0.52
17	5.98	0.30	4.80	0.23	5.12	0.35	5.72	0.31	6.56	0.27
18	8.71	0.57	11.43	0.44	12.19	0.41	10.82	0.46	10.09	0.49
19	8.81	1.02	14.16	0.64	14.83	0.61	12.34	0.73	10.74	0.84
20	3.57	0.78	6.47	0.43	6.30	0.44	5.95	0.47	5.27	0.53
21	3.64	0.52	3.20	0.59	2.88	0.66	3.21	0.59	2.08	0.91
22	3.19	0.63	2.64	0.76	2.32	0.86	2.70	0.74	2.33	0.86
23	1.41	0.67	1.84	0.51	1.44	0.65	1.73	0.54	1.38	0.68
24	1.45	1.68	2.14	1.14	1.69	1.44	-	-	1.56	1.56
25	1.26	0.28	1.91	0.18	1.48	0.23	-	-	1.40	0.25
26	1.10	2.0	1.71	1.29	1.30	1.69	-	-	1.26	1.75
27	-	-	1.54	0.65	-	-	-	-	1.15	0.87
28	18.02	1.89	18.49	1.84	21.51	1.58	18.68	1.82	18.06	1.88
29	11.43	5.25	8.31	7.22	9.74	6.16	10.01	5.99	11.89	5.05
30	6.39	1.72	11.95	0.92	12.13	0.91	10.15	1.08	8.67	1.27
31	6.38	1.77	14.41	0.78	14.44	0.78	11.40	0.99	9.31	1.21

Table(3) : Values of Parameters for the Best Fit for the Calculation of the (n,α) Reaction Cross-Sections at 14.5MeV

(a) Present Formula

(i) For Even -A Nuclides

$a = \text{Level Density}$ (MeV^{-1})	$a_1 = \text{Constant}$ (MeV)	a_c (MeV)	a_a (MeV)	$a_0 =$ $\ln(1-V_\alpha / \alpha)$	V_α (MeV)	No.of Data Points
A/25	-7.083± 0.495	0.473± 0.059	13.282± 0.528	6.984± 0.468	25.26± 0.609	44

(ii) For Odd -A Nuclides

$a = \text{Level Density}$ (MeV^{-1})	$a_1 = \text{Constant}$ (MeV)	a_c (MeV)	a_a (MeV)	$a_0 =$ $\ln(1-V_\alpha / \alpha)$	V_α (MeV)	No.of Data Points
A/25	-6.340± 0.518	0.492± 0.084	15.995± 0.347	7.825± 0.453	27.33± 0.619	29

(b) Gul Formula

For All Even -A and Odd-A Nuclides

$a = \text{Level Density}$ (MeV^{-1})	$a_0 = \ln(c\pi r_0^2 + a_0)$ (MeV)	$a_1 = 4 a_c$ (MeV)	$a_2 = a_t$ (MeV)	$a_3 = \text{Constant}$ (MeV)	No.of Data Points
A/15	3.995± 1.233	0.613± 0.535	32.258± 0.832	9.985± 2.326	64

Table(4): Comparison of (n,α) Systematics at 14.5MeV

	Author	Formula, σ (mb)	Mass Region	n	F/n
1	Levkovskii	$\sigma_{n,\alpha} = 16.55(A^{1/3} + 1)^2 \exp\left(-31.26 \frac{N-Z}{A}\right)$	$31 \leq A \leq 202$	65	0.729
2	Forrest	$\sigma_{n,\alpha} = 24.71(A^{1/3} + 1)^2 \exp\left(-19.77 \frac{(N-Z)}{A} + 13.82 \left(\frac{N-Z}{A}\right)^2 - 0.0248A\right)$	$20 \leq Z \leq 50$	39	0.599
		$\sigma_{n,\alpha} = 11.44(A^{1/3} + 1)^2 \exp\left(-16.32 \frac{N-Z}{A} - 0.014A\right)$	$50 \leq Z \leq 82$	23	0.711
3	Ait-Tahars	$\sigma_{n,\alpha} = 31.66(A^{1/3} + 1)^2 \exp\left(-32.75 \frac{N-Z+1}{A}\right)$	$40 \leq A \leq 188$	58	0.758
4	Kasugai	$\sigma_{n,\alpha} = 227.86 \exp\left(-24.66 \frac{(N-Z)}{A}\right)$	$19 \leq A \leq 187$	61	0.647
5	Csikai	$\sigma_{n,\alpha} = 15.07(A^{1/3} + 1)^2 \exp\left(-25.98\left(\frac{(N-Z)}{A} + \left(\frac{N-Z}{A}\right)^2\right)\right)$	$19 \leq A \leq 202$	70	0.725
6	Gul	$\sigma_{n,\alpha} = (A^{1/3} + 1)^2 \exp\left(a_0 + a_1 \frac{(Z-1.5)}{TA^{1/3}} + a_2 \frac{(A-2Z+0.5)}{TA} + a_3 \frac{(Z-2)}{E_i A^{1/3}}\right)$	$19 \leq Z \leq 82$	64	0.643
7	Present	$\sigma_{n,\alpha} = 3.6(A^{1/3} + 1)^2 \exp(-25(N-Z-3)/A)$	$26 \leq A \leq 238$ (even)	44	0.728
		$\sigma_{n,\alpha} = 35(A^{1/3} + 1)^2 \exp(-35.714(N-Z)/A)$	$27 \leq A \leq 209$ (odd)	29	0.555

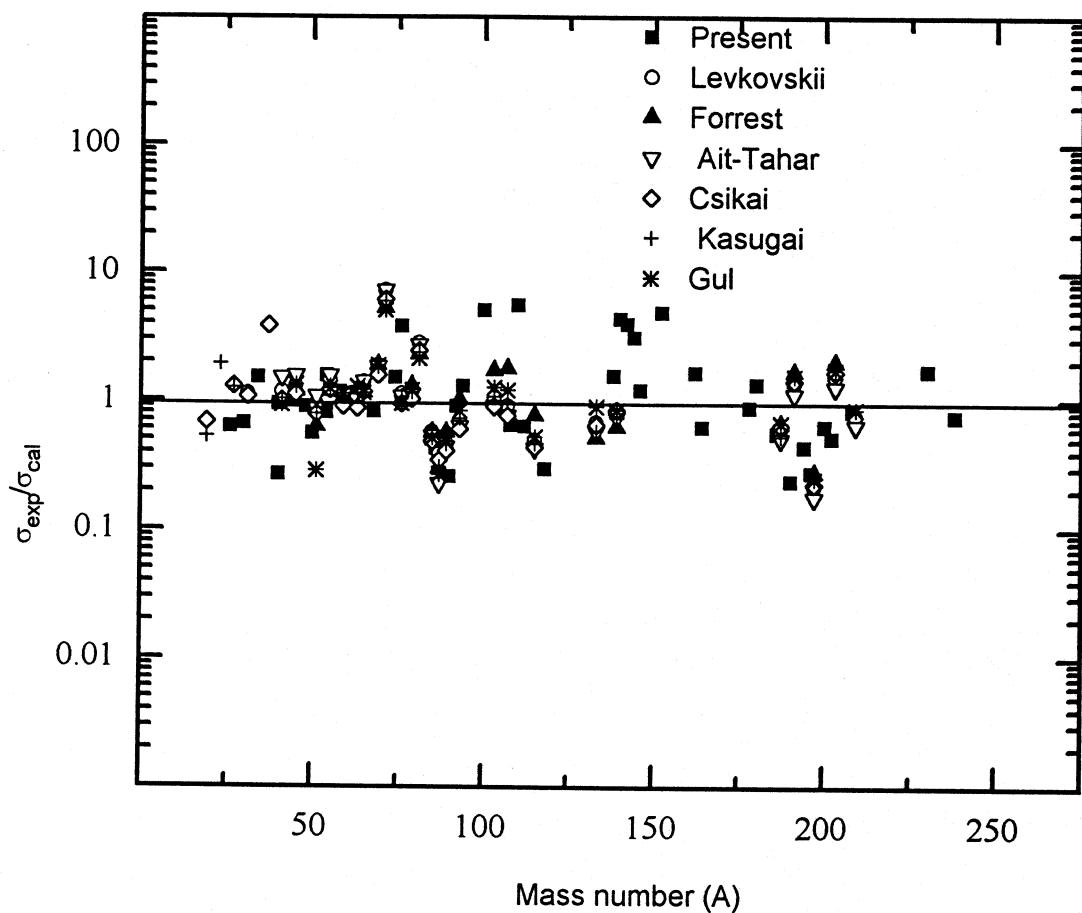


Fig.1: $\sigma_{\text{exp}}/\sigma_{\text{cal}}$ at 14.5MeV as the function of mass number of the target nucleus.
(for even-A nuclides)

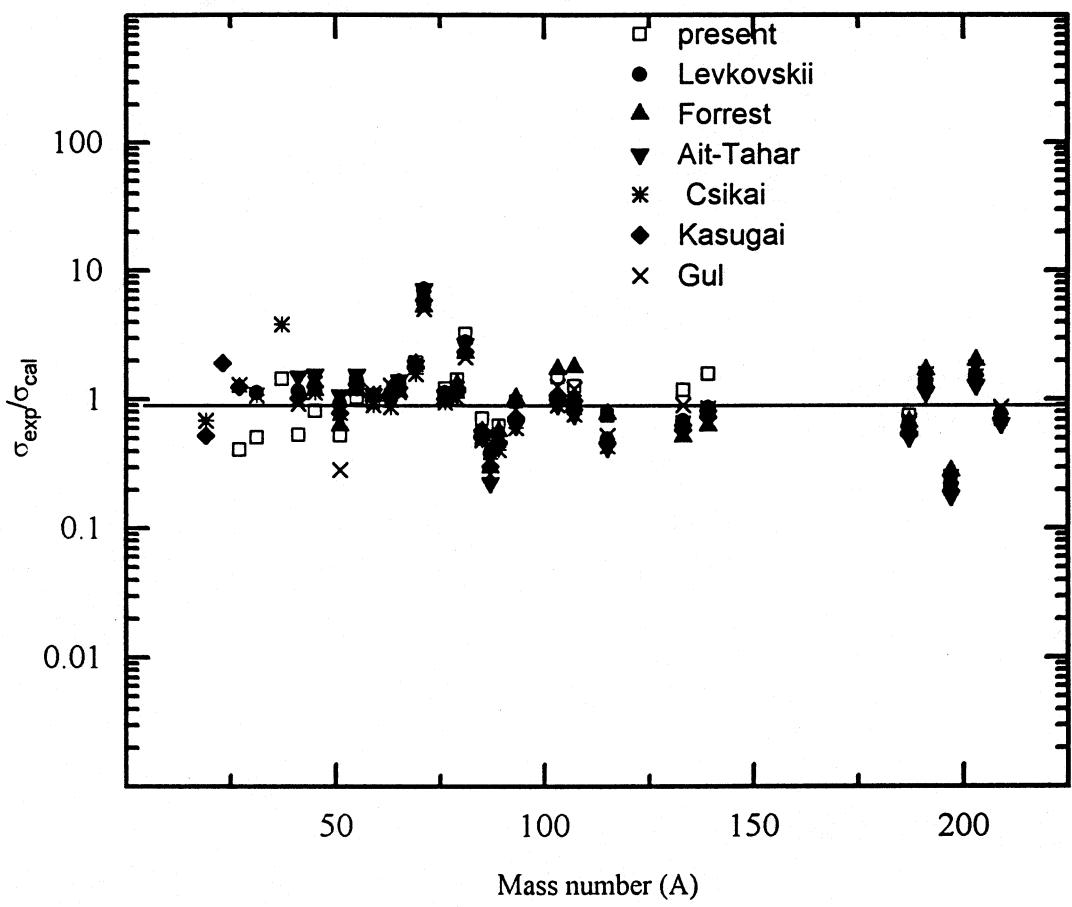


Fig. 2: $\sigma_{\text{exp}}/\sigma_{\text{cal}}$ at 14.5MeV as the function of mass number of the target nucleus.
(for Odd- A)

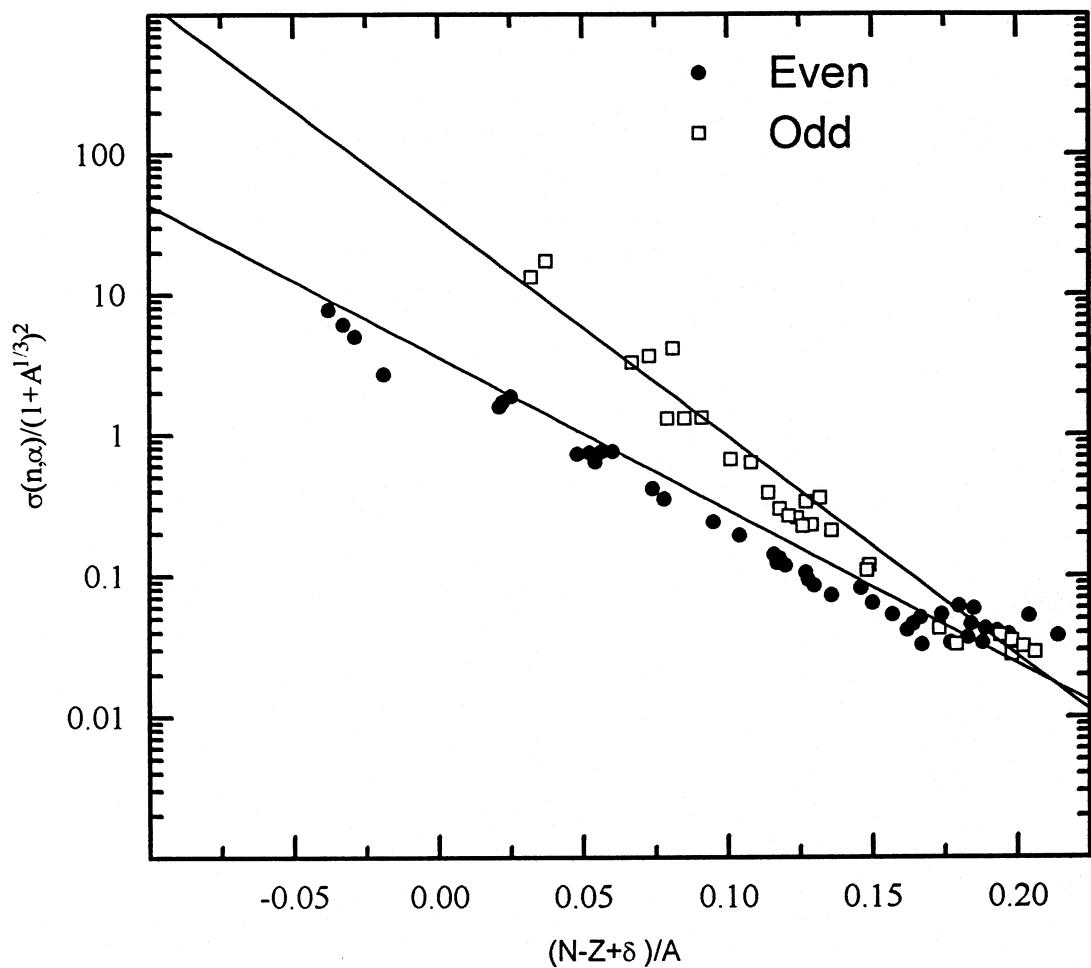


Fig.3: Systematics of (n,α) reaction cross-sections for even- A and odd- A nuclides at 14.5MeV neutrons.

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