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**On the Systematics of the (n,2n) Reaction Cross-Sections
at 14.5 MeV Neutrons**

Khalda T. Osman and F.I. Habbani*

Department of Physics, Faculty of Science
University of Khartoum

P.O. Box 321, Khartoum, Sudan

* E-mail: fhabbani@hotmail.com

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Department of Physics, Faculty of Science

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P.O. Box 321, Khartoum, Sudan

* E-mail: fhabbani@hotmail.com

Abstract

A systematics is proposed for the (n,2n) 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,2n) reaction cross-sections at 14.5 MeV neutrons and the target mass range $45 \leq A \leq 238$. The present formula is compared with other proposed systematics based on the statistical model and the asymmetry parameter dependence.

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1 Introduction

In continuation of our previous work on systematics studies for cross-sections of the neutron-induced reactions (n,p) and (n,α) based on the statistical model at 14.5MeV neutron energy [1,2], we are presenting here a study for the $(n,2n)$ reaction cross-sections systematics on the same basis and at the same energy. Systematics studies for the $(n,2n)$ reaction cross-sections have been carried out by several authors e.g. Qaim, Body and Csikai, Szucs, Chatterjee and Chatterjee, Lu and Fink, Adam and Jeki and Bychkov et al [3-9]. In the present work we propose systematics for the $(n,2n)$ reaction cross-sections using an empirical formula for even-A and odd-A nuclei, at 14.5MeV neutrons and the target mass range $45 \leq A \leq 238$. The formula is based on the statistical model, with dependence on the Q-value and odd-even effects. The present formula for the systematics of the $(n,2n)$ reaction cross-sections is compared with some other proposed relations based on the statistical model and asymmetry parameter dependence, as given in refs. [5-9].

2 Empirical Formulae

2.1 Present Formula

The $(n,2n)$ reaction cross-section can be expressed on the basis of the statistical model as:

$$\sigma_{n,2n} = \sigma_R (\Gamma_{2n} / \Gamma_n) \quad (1)$$

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

Γ_n = the decay width for a neutron.

Γ_{2n} = the decay width for 2n emission.

The decay width Γ_{2n} for 2n emission can be written by means of the principle of detailed balance as follows:

$$\Gamma_{2n} = \frac{(2S_{2n}+1) M_{2n}}{\pi^2 h^2 \rho_a(E_a)} \int_{E_a-B_{2n}-\delta_{2n}}^{\infty} \varepsilon_{2n} \sigma_c(\varepsilon_{2n}) \rho_b(E_b) d\varepsilon_{2n} \quad (2)$$

where S_{2n} and M_{2n} are the spin statistical factor and mass of the emitted 2n particles, respectively; B_{2n} and δ_{2n} are the separation energy of the emitted particles 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; ε_{2n} and σ_c are the emitted particles 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 for neutrons as follows:

$$\sigma_c(\varepsilon_{2n}) = \pi R^2 \quad (3)$$

where ε_{2n} is the emitted particles 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 we have:

$$S_b(E_b) - S_a(E_a) \approx (E_b - E_a)/T = -(\varepsilon_{2n} + B_{2n} + \delta_{2n})/T \quad (6)$$

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

$$\Gamma_{2n} = \frac{(2S_{2n}+1) M_{2n} R^2}{\pi h^2} \int_0^{E_a - B_{2n} - \delta_{2n}} \exp(-(\varepsilon_{2n} + B_{2n} + \delta_{2n})/T) d\varepsilon_{2n} \quad (7)$$

Integration of eq(7) gives for the decay width of 2n emission:

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

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,2n) reaction cross-section will be (substituting in eq(1)):

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

where $Q_{n,2n} = B_n - B_{2n} + \delta_n - \delta_{2n}$ is the effective Q-value of the (n,2n) reaction.

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

$$Q_{n,2n} = a_1 + a_c \left(\frac{Z^2}{A^{1/3}} - \frac{Z^2}{(A-1)^{1/3}} \right) + a_a \left(\frac{(A-2Z)^2}{A} - \frac{(A-2Z-1)^2}{A-1} \right) \quad (11)$$

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,2n) reaction:

$$\sigma_{n,2n} = \sigma_R \left(\frac{2S_{2n}+1}{2S_n+1} \right) \frac{M_{2n}}{M_n} \exp \left(\frac{a_1}{T} + a_c \left(\frac{Z^2}{A^{1/3}T} - \frac{Z^2}{(A-1)^{1/3}T} \right) + a_a \left(\frac{(A-2Z)^2}{AT} - \frac{(A-2Z-1)^2}{(A-1)T} \right) \right) \quad (12)$$

where $T = (E_n/a)^{1/2}$ MeV is the nuclear temperature, $a = (A/25) \text{ MeV}^{-1}$ is the level density parameter, $E_n(\text{MeV})$ is the incident neutron energy; $\sigma_R = \pi r_0^2 (1+A^{1/3})^2 \text{ mb}$ is the reaction cross-section and $r_0 = 1.4 \text{ fm}$.

2.2 Other Formulae

The present formula is compared with relations obtained by Szucs [5], based on the statistical model, and by Chatterjee and Chatterjee, Lu and Fink, Adam and Jeki and Bychkov et al [6-9], which are based on the asymmetry parameter dependence. The relation by Szucs is:

$$\sigma_{n,2n} = \frac{\sigma_c}{2\pi} \left[1 - \left(1 - \frac{\lambda}{R} \right)^3 \right] (N+1) \left[\left(\frac{E}{T} \right)^{1/2} + \frac{1}{2} \left(\frac{T}{E} \right)^{1/2} \exp \left(- \frac{E}{T} \right) \right] \quad (13)$$

where $R = 1.4A^{1/3}\text{fm}$ is the nuclear radius, $\lambda = 0.018(20+E)\text{fm}$ is mean free path of E energy neutron inside the nucleus, $T(\text{MeV})$ is nuclear temperature, $E(\text{MeV})$ is incident neutron energy and N is number of neutrons in target nucleus.

The relation by Chatterjee and Chatterjee is:

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

By Lu and Fink:

$$\sigma_{n,2n} = c_3 \left(A^{1/3} + 1 \right)^2 \left[1 + c_4 \exp \left(c_5 \frac{N-Z}{A} \right) \right] \quad (15)$$

By Adam and Jeki:

$$\sigma_{n,2n} = c_6 \left[1 + c_7 \left(1 + A^{1/3} \right)^2 \exp \left(c_8 \left(\frac{N-Z}{A} \right) \right) \right] \quad (16)$$

By Bychkov et al:

$$\sigma_{n,2n} = \sigma_{ne} \left(1 - a_1 \exp \left(- a_2 \frac{N-Z}{A} \right) \right) \quad (17)$$

where $c_1 - c_8$ in eqs(14 – 16) and a_1, a_2 in eq(17) are constants; $\sigma_{ne} = 8.7(100+A)$, A is mass number and $\frac{N-Z}{A}$ is asymmetry parameter.

3. Fitting Procedure

For fitting of the $(n,2n)$ reaction cross-sections relations we write eq (12) in the following form:

$$K = X + b_1 Y + b_2 Z \quad (18)$$

where $K = \ln \left(\frac{\sigma_{n,2n}}{2\pi r_0^2 (A^{1/3} + 1)^2} \right)$, $X = a_1/T + \ln(2S_{2n}+1)/(2S_n+1)$, $Y = a_c$ and $Z = a_a$.

The Legendre method of least squares is applied to eq(18) to obtain X , Y and Z . We choose X , Y and Z such that the sum of the squares of the errors is least. i.e.

$$\sum_{s=1}^n (X + b_1 Y + b_2 Z - K_s)^2 \text{ is minimum,}$$

where n = number of data points.

The input data used in the present study of the $(n,2n)$ reaction cross-sections systematics, at a neutron energy of 14.5 MeV, are given in Tables 1 and 2 for even- A and odd- A nuclides, respectively. The experimental input data used were taken from refs. [11,12]. The parameters for the best fit, given in Tables 3(a) and 3(b), have been

extracted using the iteration method [10] for the analysis and fitting of the available data of the (n,2n) reaction cross-sections at 14.5MeV neutron energy.

4. Results and Discussion

4.1 The Fitting Parameters

The proposed formula used in the present work for studying the systematics of the (n,2n) reaction cross-sections, which is based on the statistical model, contains two physical parameters related to the semiempirical mass formula , namely the coulomb parameter a_c and asymmetry parameter a_a , in addition to the constant parameter a_1 that takes into account the other terms of the semiempirical mass formula, besides the $\ln(2S_{2n}+1)/(2S_n+1)$ term.

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 level density parameter $a = A/25$ MeV¹. The best fit values for the parameters a_1 , a_c and a_a are given in Tables 3(a) and 3(b) for even-A and odd-A nuclides, respectively.

4.2 Comparison with other Systematics

The present formula is compared with some other proposed systematics for the (n,2n) reaction cross-sections, at 14.5MeV neutron energy [5-9]. The formula given by Szucs [5], based on the statistical model, allows the calculation of the (n,2n) reaction cross-sections at neutron energies around 14MeV. The empirical formulae given by Chatterjee and Chatterjee, Lu and Fink, Adam and Jeki and Bychkov et al [6-9], based on the asymmetry parameter dependence, confirm the dependence of the (n,2n) reaction cross-sections on the asymmetry parameter (N-Z)/A, and can also be used for calculations of the (n,2n) reaction cross-sections. A comparison between the 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 (n,2n) reaction cross-sections for most of the nuclides under consideration, especially in the case of odd-A nuclides.

A comparison of the ratio of the experimental to calculated (n,2n) reaction cross-sections obtained for the six systematics, for even-A and odd-A nuclides, is 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 and experimental values is observed in the following reactions:

$^{52}\text{Cr}(n,2n)^{51}\text{Cr}$, $^{74}\text{Se}(n,2n)^{73}\text{Se}$, $^{106}\text{Cd}(n,2n)^{105}\text{Cd}$, $^{232}\text{Th}(n,2n)^{231}\text{Th}$ and $^{238}\text{U}(n,2n)^{237}\text{U}$
For these reactions the experimental values of the (n ,2n) reaction cross-sections are lower than the calculated values, except for $^{106}\text{Cd}(n,2n)^{105}\text{Cd}$ where the experimental cross-section is higher than the calculated value. 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 case of $^{45}\text{Sc}(\text{n},2\text{n})^{44}\text{Sc}$ reaction, where the experimental cross-section value is lower than the calculated one.

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

$$F = \sum \left(|\sigma_{\text{exp}} - \sigma_{\text{cal}}| \right) / \sigma_{\text{cal}}$$

where n is the number of data points used.

The value of F/n can characterize the goodness of the systematics. A good fit for the cross-sections values obtained by the present systematics, taking into account the odd-even correction, is given by the following formula:

$$\sigma_{n,2n} = \alpha \left(1 + A^{1/3} \right)^2 \exp \left(\beta \frac{N - Z + \delta}{A} \right) \quad (19)$$

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

For odd-A nuclides:

$$\alpha = 23.53 \pm 0.21, \beta = 3.501 \pm 0.004 \text{ and } \delta = 0$$

For even-A nuclides:

$$\alpha = 20.82 \pm 0.23, \beta = 3.760 \pm 0.004 \text{ and } \delta = 1$$

The systematics for $\sigma_{n,2n}$ using eq(19) is shown in Fig 3, where $\sigma_{n,2n} / (A^{1/3} + 1)^2$ 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 does not exist for the $(\text{n},2\text{n})$ reaction cross-sections.

5. Conclusion

In the present work a formula is presented for the $(\text{n},2\text{n})$ reaction cross-sections systematics at 14.5MeV neutrons, based on the statistical model. Comparison is made between the present formula and five other proposed relations, based on the statistical model as well as on the asymmetry parameter dependence. The various systematics compared were found to agree with the experimental values in most cases. However, some disagreement was observed with the experimental values for a number of cases. The present formula gives good agreement with experimental data for a wide range of Z and A values, and it demonstrates clearly the absence of the odd-even effect in the $(\text{n},2\text{n})$ reaction cross-sections.

Acknowledgements

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Table1. Measured and calculated data for (n,2n) reaction cross-sections at 14.5MeV neutron energy for even-A nuclides

No.	Target nucleus	Residual nucleus	(n,2n) reaction cross-sections (mb) and ratios				
			Exp.	Present	Ratio	Szucs	Ratio
1	⁴⁸ Ca	⁴⁷ Ca	767±5	823.38	0.93	362.97	2.11
2	⁵² Cr	⁵¹ Cr	315±30	695.91	0.45	381.59	0.83
3	⁵⁶ Fe	⁵⁵ Fe	540±40	710.85	0.76	427.21	1.26
4	⁷⁰ Zn	⁶⁹ Zn	1200±120	968.48	1.24	649.14	1.85
5	⁷⁰ Ge	⁶⁹ Ge	605±40	821.74	0.74	617.45	0.98
6	⁷² Ge	⁷¹ Ge	970±75	897.90	1.08	660.58	1.47
7	⁷⁶ Ge	⁷⁵ Ge	1148±120	1058.94	1.08	749.74	1.53
8	⁷⁴ Se	⁷³ Se	320±30	831.26	0.39	671.90	0.48
9	⁷⁶ Se	⁷⁵ Se	879±70	906.43	0.97	716.42	1.23
10	⁷⁸ Se	⁷⁷ Se	993±50	984.53	1.01	761.88	1.30
11	⁸⁰ Se	⁷⁹ Se	1132±60	1065.50	1.06	808.33	1.40
12	⁸² Se	⁸¹ Se	1050±50	1149.30	0.91	855.69	1.23
13	⁸⁰ Kr	⁷⁹ Kr	810±60	914.06	0.89	773.93	1.05
14	⁸⁴ Sr	⁸³ Sr	1054±50	920.84	1.15	833.09	1.27
15	⁸⁶ Sr	⁸⁵ Sr	1000±100	996.97	1.00	881.27	1.14
16	⁹⁰ Zr	⁸⁹ Zr	730±35	1001.98	0.73	943.36	0.77
17	⁹⁶ Zr	⁹⁵ Zr	1500±90	1244.39	1.21	1097.18	1.37
18	¹⁰⁰ Mo	⁹⁹ Mo	1420±150	1245.65	1.14	1164.62	1.22
19	⁹⁶ Ru	⁹⁵ Ru	700±100	936.61	0.75	1020.18	0.69
20	⁹⁸ Ru	⁹⁷ Ru	1050±100	1009.81	1.04	1072.23	0.98
21	¹⁰⁴ Ru	¹⁰³ Ru	1440±109	1246.19	1.16	1233.54	1.17
22	¹⁰² Pd	¹⁰¹ Pd	1100±100	1012.73	1.09	1138.95	0.97
23	¹¹⁰ Pd	¹⁰⁹ Pd	1850±120	1504.17	1.23	1476.40	1.25
24	¹⁰⁶ Cd	¹⁰⁵ Cd	1350±200	1015.02	1.33	1207.17	1.12
25	¹⁰⁸ Cd	¹⁰⁷ Cd	1290±150	1089.06	1.19	1262.53	1.02
26	¹¹⁰ Cd	¹⁰⁹ Cd	1220±150	1165.84	1.05	1318.73	0.93
27	¹¹⁶ Cd	¹¹⁵ Cd	1578±100	1412.59	1.12	1492.27	1.06
28	¹¹⁴ Sn	¹¹³ Sn	1105±50	1165.56	0.95	1390.81	0.79
29	¹²⁰ Te	¹¹⁹ Te	1300±130	1242.21	1.05	1523.67	0.85
30	¹²⁸ Te	¹²⁷ Te	1690±130	1579.00	1.07	1769.05	0.96
31	¹³⁰ Te	¹²⁹ Te	1700±120	1669.94	1.02	1832.34	0.93
32	¹²⁴ Xe	¹²³ Xe	1200±100	1239.85	0.97	1599.72	0.75
33	¹²⁶ Xe	¹²⁵ Xe	1400±100	1318.97	1.06	1661.02	0.84
34	¹²⁸ Xe	¹²⁷ Xe	1550±150	1400.75	1.11	1723.10	0.90
35	¹³⁴ Xe	¹³³ Xe	1700±170	1662.17	1.02	1913.97	0.89
36	¹³⁶ Ce	¹³⁵ Ce	1600±140	1390.41	1.15	1883.74	0.85
37	¹⁴⁰ Ce	¹³⁹ Ce	1963±70	1557.62	1.26	2014.59	0.98
38	¹⁴² Ce	¹⁴¹ Ce	1900±70	1645.19	1.16	2081.14	0.91

39	^{142}Nd	^{141}Nd	1770 ± 120	1465.80	1.21	2032.17	0.87
40	^{144}Nd	^{143}Nd	1750 ± 120	1549.61	1.13	2099.04	0.83
41	^{146}Nd	^{145}Nd	1861 ± 150	1636.05	1.14	2166.65	0.86
42	^{148}Nd	^{147}Nd	1829 ± 150	1725.12	1.06	2234.99	0.82
43	^{150}Nd	^{149}Nd	1900 ± 150	1816.85	1.05	2304.07	0.83
44	^{144}Sm	^{143}Sm	1700 ± 120	1378.39	1.23	2049.65	0.83
45	^{148}Sm	^{147}Sm	1789 ± 150	1541.21	1.16	2184.77	0.82
46	^{150}Sm	^{149}Sm	1803 ± 150	1626.52	1.11	2253.43	0.80
47	^{152}Sm	^{151}Sm	1855 ± 150	1714.44	1.08	2322.82	0.80
48	^{154}Sm	^{153}Sm	1885 ± 150	1804.99	1.04	2392.93	0.79
49	^{152}Gd	^{151}Gd	1800 ± 200	1532.45	1.18	2271.77	0.79
50	^{154}Gd	^{153}Gd	1900 ± 150	1616.62	1.18	2341.47	0.81
51	^{156}Gd	^{155}Gd	1800 ± 100	1703.40	1.05	2411.89	0.75
52	^{158}Gd	^{157}Gd	1850 ± 100	1792.77	1.03	2483.02	0.75
53	^{160}Gd	^{159}Gd	1800 ± 120	1884.77	0.96	2554.87	0.71
54	^{156}Dy	^{155}Dy	1850 ± 150	1523.35	1.21	2360.02	0.78
55	^{160}Dy	^{159}Dy	2000 ± 200	1692.02	1.18	2502.19	0.79
56	^{162}Er	^{161}Er	1900 ± 130	1595.86	1.19	2521.26	0.75
57	^{164}Er	^{163}Er	1820 ± 150	1680.33	1.08	2593.72	0.70
58	^{166}Er	^{165}Er	2000 ± 150	1767.36	1.13	2666.88	0.75
59	^{170}Er	^{169}Er	1930 ± 130	1949.16	0.99	2815.28	0.69
60	^{168}Yb	^{167}Yb	1920 ± 150	1668.35	1.15	2686.46	0.72
61	^{170}Yb	^{169}Yb	1940 ± 150	1754.21	1.11	2760.61	0.70
62	^{176}Yb	^{175}Yb	2150 ± 230	2027.17	1.06	2987.21	0.72
63	^{174}Hf	^{173}Hf	1900 ± 150	1740.81	1.09	2855.55	0.67
64	^{176}Hf	^{175}Hf	2050 ± 150	1828.02	1.12	2931.37	0.70
65	^{180}W	^{179}W	1900 ± 170	1813.19	1.05	3028.46	0.63
66	^{184}W	^{183}W	2000 ± 150	1992.83	1.00	3184.09	0.63
67	^{186}W	^{185}W	1900 ± 150	2086.45	0.91	3262.90	0.58
68	^{184}Os	^{183}Os	2000 ± 150	1798.15	1.11	3126.72	0.64
69	^{186}Os	^{185}Os	2000 ± 100	1885.48	1.06	3205.15	0.62
70	^{192}Os	^{191}Os	2200 ± 150	2162.67	1.02	3444.44	0.64
71	^{192}Pt	^{191}Pt	2030 ± 100	1957.66	1.04	3385.56	0.60
72	^{198}Pt	^{197}Pt	1950 ± 120	2238.66	0.87	3629.64	0.54
73	^{196}Hg	^{195}Hg	2050 ± 180	1939.82	1.06	3488.01	0.59
74	^{198}Hg	^{197}Hg	2000 ± 150	2029.69	0.99	3569.65	0.56
75	^{204}Pb	^{203}Pb	2100 ± 150	2314.45	0.91	3818.45	0.55
76	^{206}Pb	^{205}Pb	2232 ± 130	2101.57	1.06	3757.35	0.59
77	^{208}Pb	^{207}Pb	2000 ± 100	2291.31	0.87	3925.69	0.51
78	^{232}Th	^{231}Th	1259 ± 50	2586.10	0.49	4723.93	0.23
79	^{238}U	^{237}U	745 ± 30	2659.08	0.28	4932.03	0.15

No	Chatterjee & Chatterjee	Ratio	Lu & Fink	Ratio	Adam & Jeki	Ratio	Bychkov et al	Ratio
1	895.85	0.86	-	-	-	-	988.16	0.77
2	801.62	0.39	-	-	-	-	694.49	0.45
3	825.78	0.65	-	-	423.96	1.27	683.98	0.79
4	1050.49	1.14	1111.37	1.08	1140.43	1.05	1063.34	1.12
5	952.92	0.64	640.67	0.94	664.01	0.91	824.16	0.73
6	1010.28	0.96	967.79	1.00	979.89	0.99	955.05	1.02
7	1126.54	1.02	1197.27	0.96	1171.65	0.98	1149.38	0.99
8	974.08	0.33	567.31	0.56	550.81	0.58	818.39	0.39
9	1029.79	0.85	942.89	0.93	918.68	0.96	950.87	0.92
10	1086.02	0.91	1121.26	0.89	1079.73	0.92	1059.58	0.93
11	1142.69	0.99	1213.86	0.93	1153.21	0.98	1150.19	0.98
12	1199.77	0.88	1267.66	0.83	1188.02	0.88	1226.89	0.85
13	1049.27	0.77	910.20	0.89	849.99	0.95	947.12	0.86
14	1068.66	0.99	869.99	1.21	773.99	1.36	943.74	1.12
15	1121.97	0.89	1107.66	0.90	997.76	1.00	1056.36	0.95
16	1139.98	0.64	1092.04	0.67	948.56	0.77	1054.99	0.69
17	1298.27	1.16	1375.27	1.09	1637.68	0.92	1308.65	1.15
18	1312.62	1.08	1394.38	1.02	1606.64	0.88	1313.32	1.08
19	1126.22	0.62	707.34	0.99	825.18	0.85	935.77	0.75
20	1175.95	0.89	1043.51	1.01	1133.36	0.93	1052.79	0.99
21	1327.19	1.09	1410.84	1.02	1573.05	0.92	1317.75	1.09
22	1193.86	0.92	101.85	1.09	1058.43	1.04	1051.96	1.05
23	1492.48	1.24	1542.34	1.20	1702.35	1.09	1510.60	1.23
24	1211.70	1.11	972.81	1.39	981.16	1.38	1051.30	1.28
25	1259.77	1.02	1206.79	1.07	1218.19	1.06	1154.94	1.12
26	1308.15	0.93	1347.12	0.91	1382.76	0.88	1245.77	0.98
27	1454.94	1.09	1535.37	1.03	1640.10	0.96	1461.71	1.08
28	1324.08	0.84	1344.43	0.82	1331.59	0.83	1248.08	.86
29	1386.89	0.94	1448.51	0.89	1414.59	0.92	1333.75	.98
30	1576.67	1.07	1639.9	1.03	1680.64	1.01	1592.75	1.06
31	1624.61	1.05	1663.91	1.02	1710.26	0.99	1644.03	1.03
32	1402.03	0.86	1450.60	0.83	1369.38	0.88	1337.44	0.89
33	1448.31	0.97	1532.23	0.91	1476.93	0.95	1413.61	.99
34	1494.81	1.04	1588.99	0.98	1556.43	0.99	1482.46	1.05
35	1635.53	1.04	1687.99	1.01	1694.18	1.00	1654.96	1.03
36	1522.12	1.05	1614.99	0.99	1491.44	1.07	1495.12	1.07
37	1612.63	1.22	1703.03	1.15	1616.47	1.21	1620.47	1.21
38	1658.16	1.15	1732.93	1.01	1658.03	1.15	1675.77	1.13
39	1580.36	1.12	1680.02	1.05	1533.25	1.15	1567.87	1.13
40	1624.99	1.08	1721.37	1.02	1419.46	1.2	1629.13	1.07
41	1669.80	1.12	1753.72	1.06	-	-	1685.69	1.10
42	1714.77	1.07	1780.09	1.03	-	-	1738.14	1.05
43	1759.89	1.08	1802.47	1.05	-	-	1786.99	1.06
44	1549.78	1.1	1632.74	1.04	-	-	1507.07	1.13
45	1637.49	1.09	1738.28	1.03	-	-	1637.54	1.09
46	1681.62	1.07	1773.32	1.02	-	-	1695.32	1.06

47	1725.89	1.08	1801.61	1.03	-	-	1748.95	1.06
48	1770.32	1.07	1825.34	1.03	-	-	1798.96	1.05
49	1650.13	1.09	1753.73	1.03	-	-	1645.70	1.09
50	1693.59	1.12	1791.71	1.06	-	-	1704.67	1.12
51	1737.21	1.04	1822.11	0.99	-	-	1759.47	1.02
52	1780.98	1.04	1847.35	1.00	-	-	1810.59	1.02
53	1824.89	0.99	1869.04	0.96	-	-	1858.47	.97
54	1662.86	1.11	1767.67	1.05	-	-	1658.65	1.12
55	1748.69	1.14	1841.56	1.09	-	-	1769.69	1.13
56	1717.93	1.11	1824.68	1.04	-	-	1722.64	1.10
57	1760.33	1.03	1859.93	0.98	-	-	1779.66	1.02
58	1802.87	1.11	1888.70	1.06	-	-	1832.95	1.09
59	1888.35	1.02	1934.04	0.99	-	-	1929.95	1.00
60	1772.08	1.08	1877.18	1.02	-	-	1789.37	1.07
61	1814.05	1.07	1907.98	1.02	-	-	1847.71	1.05
62	1940.73	1.11	1975.52	1.09	-	-	1988.05	1.08
63	1825.37	1.04	1926.28	0.99	-	-	1854.21	1.03
64	1866.92	1.1	1953.67	1.05	-	-	1906.19	1.08
65	1877.83	1.01	1972.75	0.96	-	-	1917.42	0.99
66	1960.24	1.02	2019.0	0.99	-	-	2014.51	0.99
67	2001.61	0.95	2038.18	0.93	-	-	2059.25	0.92
68	1888.87	1.06	1990.96	1.01	-	-	1928.38	1.04
69	1929.51	1.04	2017.14	0.99	-	-	1979.23	1.01
70	2052.09	1.07	2077.86	1.06	-	-	2116.27	1.04
71	1980.43	1.03	2059.86	0.99	-	-	2039.83	0.99
72	2101.85	0.93	2116.74	0.92	-	-	2172.60	0.89
73	1990.74	1.03	2079.26	0.99	-	-	2052.09	1.00
74	2030.64	0.99	2101.19	0.95	-	-	2099.39	0.95
75	2150.93	0.98	2154.90	0.98	-	-	2228.23	0.94
76	2080.16	1.07	2141.36	1.04	-	-	2158.03	1.03
77	2159.53	0.93	2176.67	0.92	-	-	2243.49	0.29
78	2348.64	0.54	-	-	-	-	2463.14	0.51
79	2394.52	0.311	-	-	-	-	2517.03	0.30

Table2. Measured and calculated data for (n,2n) reaction cross-sections at 14.5MeV for odd-A nuclides

No.	Target nucleus	Residual nucleus	(n,2n) reaction cross-sections (mb) and ratios				
			Exp.	Present	Ratio	Szucs	Ratio
1	⁴⁵ Sc	⁴⁴ Sc	293±20	651.71	0.45	300.51	0.98
2	⁵¹ V	⁵⁰ V	660±50	747.31	0.80	376.99	1.59
3	⁵⁵ Mn	⁵⁴ Mn	809±35	764.39	1.06	422.44	1.92
4	⁵⁹ Co	⁵⁸ Co	748±56	780.22	0.96	469.81	
5	⁶³ Cu	⁶² Cu	551±30	794.89	0.69	519.04	1.06
6	⁶⁵ Cu	⁶⁴ Cu	968±20	871.10	1.11	559.46	1.73
7	⁶⁹ Ga	⁶⁸ Ga	945±50	883.83	1.07	611.99	1.54
8	⁷¹ Ga	⁷⁰ Ga	1146±70	961.92	1.19	654.88	1.75
9	⁷⁵ As	⁷⁴ As	1061±60	972.81	1.09	710.56	1.49
10	⁷⁹ Br	⁷⁸ Br	974±50	982.78	0.99	761.93	1.27
11	⁸¹ Br	⁸⁰ Br	1026±30	1061.86	1.00	814.57	1.26
12	⁸³ Kr	⁸² Kr	1270±30	1066.09	1.19	844.54	1.50
13	⁸⁵ Rb	⁸⁴ Rb	1135±100	1070.12	1.06	974.92	1.3
14	⁸⁷ Rb	⁸⁶ Rb	1195±130	1151.00	1.04	923.81	1.29
15	⁸⁷ Sr	⁸⁶ Sr	1200±20	1073.94	1.12	905.70	1.33
16	⁸⁹ Y	⁸⁸ Y	966±100	1077.57	0.9	936.88	1.03
17	⁹³ Nb	⁹² Nb	1375±70	1084.26	1.27	1000.39	1.37
18	⁹⁹ Tc	⁹⁸ Tc	1230±120	1168.56	1.05	1118.19	1.10
19	¹⁰³ Rh	¹⁰² Rh	1325±100	1172.99	1.13	1186.02	1.12
20	¹⁰⁵ Pd	¹⁰⁴ Pd	1300±100	1174.94	1.10	1220.45	1.07
21	¹⁰⁷ Ag	¹⁰⁶ Ag	1260±120	1176.79	1.07	1255.32	1.00
22	¹⁰⁹ Ag	¹⁰⁸ Ag	1440±100	1256.00	1.15	1311.34	1.1
23	¹¹³ In	¹¹² In	1600±100	1258.32	1.27	1383.29	1.16
24	¹¹⁵ In	¹¹⁴ In	1710±80	1339.23	1.28	1441.32	1.19
25	¹²¹ Sb	¹²⁰ Sb	1500±100	1422.66	1.05	1575.85	0.95
26	¹²³ Sb	¹²² Sb	1420±140	1507.77	0.94	1636.63	0.87
27	¹²⁷ I	¹²⁶ I	1496±100	1506.27	0.99	1714.83	0.87
28	¹³³ Cs	¹³² Cs	1603±100	1590.05	1.01	1858.16	0.86
29	¹⁴¹ Pr	¹⁴⁰ Pr	1660±200	1582.70	1.05	2023.39	0.82
30	¹⁵¹ Eu	¹⁵⁰ Eu	1800±100	1658.09	1.09	2262.61	0.8
31	¹⁵³ Eu	¹⁵² Eu	1950±200	1745.06	1.12	2332.15	0.83
32	¹⁵⁵ Gd	¹⁵⁴ Gd	1850±100	1741.57	1.06	2376.59	0.78
33	¹⁵⁷ Gd	¹⁵⁶ Gd	1850±100	1830.52	1.01	2447.36	0.76
34	¹⁵⁹ Tb	¹⁵⁸ Tb	1800±120	1826.43	0.99	2492.62	0.72
35	¹⁶⁹ Tm	¹⁶⁸ Tm	2071±100	1898.08	1.09	2750.68	0.75
36	¹⁷⁵ Lu	¹⁷⁴ Lu	2030±200	1978.25	1.03	2921.19	0.69
37	¹⁸¹ Ta	¹⁸⁰ Ta	2090±100	2058.48	1.02	3095.51	0.67
38	¹⁹³ W	¹⁹² W	1900±150	2052.11	0.93	3144.93	0.60
39	¹⁸⁷ Re	¹⁸⁶ Re	1700±200	2138.74	0.8	3273.59	0.52

40	^{191}Ir	^{190}Ir	1960 ± 150	2124.60	0.92	3374.80	0.58
41	^{193}Ir	^{192}Ir	2048 ± 150	2219.01	0.92	3455.37	0.59
42	^{197}Au	^{196}Au	2254 ± 200	2203.54	1.02	3558.65	0.63
43	^{203}Tl	^{202}Tl	2065 ± 150	2282.47	0.91	3746.12	0.55
44	^{205}Tl	^{204}Tl	2006 ± 200	2379.52	0.84	3829.84	0.52
45	^{207}Pb	^{206}Pb	2000 ± 100	2370.48	0.84	3883.37	0.52
46	^{209}Bi	^{208}Bi	2261 ± 100	2361.38	0.96	3937.17	0.57

No	Chatterjee & Chatterjee	Ratio	Lu & Fink	Ratio	Adam & Jeki	Ratio	Bychkov et al	Ratio
1	730.34	0.40	-	-	-	-	611.59	0.479
2	822.59	0.73	-	-	-	-	786.36	0.76
3	845.59	0.96	-	-	809.68	1.00	775.61	1.04
4	868.42	0.86	-	-	696.07	1.08	766.09	0.98
5	891.02	0.62	485.57	1.14	570.10	0.97	757.70	0.73
6	950.86	1.02	888.57	1.09	965.06	1.03	901.86	1.07
7	971.32	0.97	856.49	1.10	894.89	1.06	895.89	1.06
8	1029.85	1.11	1059.06	1.08	1080.10	1.06	1012.48	1.13
9	1048.50	1.01	1053.09	1.01	1038.39	1.02	1009.29	1.05
10	1067.21	0.91	1040.26	0.94	990.32	0.98	1006.38	0.97
11	1122.88	0.91	1177.82	0.87	1109.66	0.93	1106.59	0.93
12	1131.49	1.12	1179.91	1.08	1094.81	1.16	1106.35	1.15
13	1140.12	0.99	1180.72	0.96	1078.81	1.05	1106.10	1.03
14	1194.73	1.00	1268.92	0.94	1148.48	1.04	1192.94	1.00
15	1148.78	1.05	1180.25	1.02	1061.66	0.13	1105.88	1.09
16	1157.45	0.84	1178.49	0.82	1043.33	0.93	1105.67	0.87
17	1174.84	1.17	1171.12	1.17	1340.84	1.03	1105.31	1.24
18	1243.06	0.99	1292.97	0.95	1439.86	0.85	1197.94	1.03
19	1259.37	1.05	1293.03	1.03	1389.03	0.95	1199.49	1.11
20	1267.55	1.03	1291.54	1.01	1362.60	0.95	1200.26	1.08
21	1275.73	0.99	1289.03	0.98	1335.53	0.94	1201.03	1.05
22	1324.75	1.09	1393.32	1.03	1467.57	0.98	1285.52	1.12
23	1340.18	1.19	1398.12	1.14	1423.05	1.12	1288.67	1.24
24	1388.51	1.23	1473.78	1.16	1525.13	1.12	1365.18	1.25
25	1450.76	1.03	1542.04	0.97	1568.47	0.96	1439.93	1.04
26	1498.65	0.95	1583.45	0.9	1627.8	0.87	1503.27	0.96
27	1511.60	0.99	1602.38	0.93	1601.85	0.93	1510.81	0.99
28	1571.14	1.02	1657.33	0.97	1628.09	0.93	1578.61	1.02
29	1596.28	1.04	1693.88	0.98	1578.15	1.05	1595.15	1.04
30	1665.67	1.08	1765.51	1.02	-	-	1671.39	1.08
31	1709.54	1.14	1798.06	1.09	-	-	1727.62	1.13
32	1715.38	1.08	1807.68	1.02	-	-	1732.56	1.07
33	1759.08	1.05	1835.26	1.01	-	-	1785.46	1.04
34	1764.64	1.02	1845.56	0.98	-	-	1790.89	1.01
35	1829.62	1.13	1911.45	1.08	-	-	1863.99	1.11
36	1882.48	1.08	1955.59	1.04	-	-	1925.08	1.06
37	1934.52	1.08	1998.12	1.05	-	-	1984.97	1.05

38	1939.59	0.98	2008.58	0.95	-	-	1991.24	0.95
39	1985.77	0.86	2039.52	0.83	-	-	2043.82	0.82
40	1995.62	0.98	2060.42	0.95	-	-	2056.92	0.95
41	2036.29	1.01	2079.79	0.99	-	-	2101.79	0.97
42	2045.81	1.10	2100.89	1.07	-	-	2115.44	1.07
43	2095.30	0.99	2140.36	0.97	-	-	2173.15	0.95
44	2135.22	0.94	2157.67	0.93	-	-	2215.48	0.91
45	2139.66	0.94	2168.38	0.92	-	-	2222.84	0.90
46	2144.14	1.06	-	-	-	-	2230.13	1.01

Table3. Values of the best fit parameters for the systematics of the (n,2n) reaction cross-sections at 14.5 MeV.

(a) For even-A nuclides:

a=level density (MeV ⁻¹)	a _l (MeV)	a _c (MeV)	a _a (MeV)	No. of data points
A/25	0.886	0.294	3.078	79

(b) For odd-A nuclides

a=level density (MeV ⁻¹)	a _l (MeV)	a _c (MeV)	a _a (MeV)	No. of data points
A/25	0.906	0.270	3.088	46

Table4. Comparison of the (n,2n) reaction cross-sections systematics at 14.5MeV

Author	Formula, σ (mb)	Mass region	n	F/n
Chatterjee & Chatterjee	$\sigma_{n,2n} = 31.39 \left(A^{1/3} + 1 \right)^2 \exp \left(1.706 \left(\frac{N - Z}{A} \right) \right)$	$45 \leq A \leq 238$	126	0.110
Lu and Fink	$\sigma_{n,2n} = 45.76 \left(A^{1/3} + 1 \right)^2 \left[1 - 7.372 \exp \left(- 32.21 \frac{N - Z}{A} \right) \right]$	$28 \leq Z \leq 82$	116	0.068
Adam and Jeki	$\sigma_{n,2n} = c_6 \left[1 + c_7 \left(A^{1/3} + 1 \right)^2 \exp \left(c_8 \frac{N - Z}{A} \right) \right]$	$28 \leq N \leq 50$ $50 \leq N \leq 82$	28 37	0.092 0.090
Szucs	$\sigma_{n,2n} = \frac{\sigma_c}{2\pi} \left[1 - \left(1 - \frac{\lambda}{R} \right)^3 \right] (N+1) \left[\left(\frac{E}{T} \right)^{1/2} + \frac{1}{2} \left(\frac{T}{E} \right)^{1/2} \exp \left(- \frac{E}{T} \right) \right]$	$45 \leq A \leq 238$	126	0.145
Bychkov et al	$\sigma_{n,2n} = \sigma_{ne} \left(1 - 0.88 \exp \left(- 7.95 \frac{N - Z}{A} \right) \right)$ $\sigma_{ne} = 8.7(100 + A)$	$45 \leq A \leq 238$	126	0.104
Present	$\sigma_{n,2n} = 23.53 \left(A^{1/3} + 1 \right)^2 \exp \left(3.50 \frac{N - Z}{A} \right)$ $\sigma_{n,2n} = 20.82 \left(A^{1/3} + 1 \right)^2 \exp \left(3.76 \frac{N - Z + 1}{A} \right)$	$45 \leq A \leq 209$ (odd-A) $48 \leq A \leq 238$ (even-A)	46 79	0.102 0.130

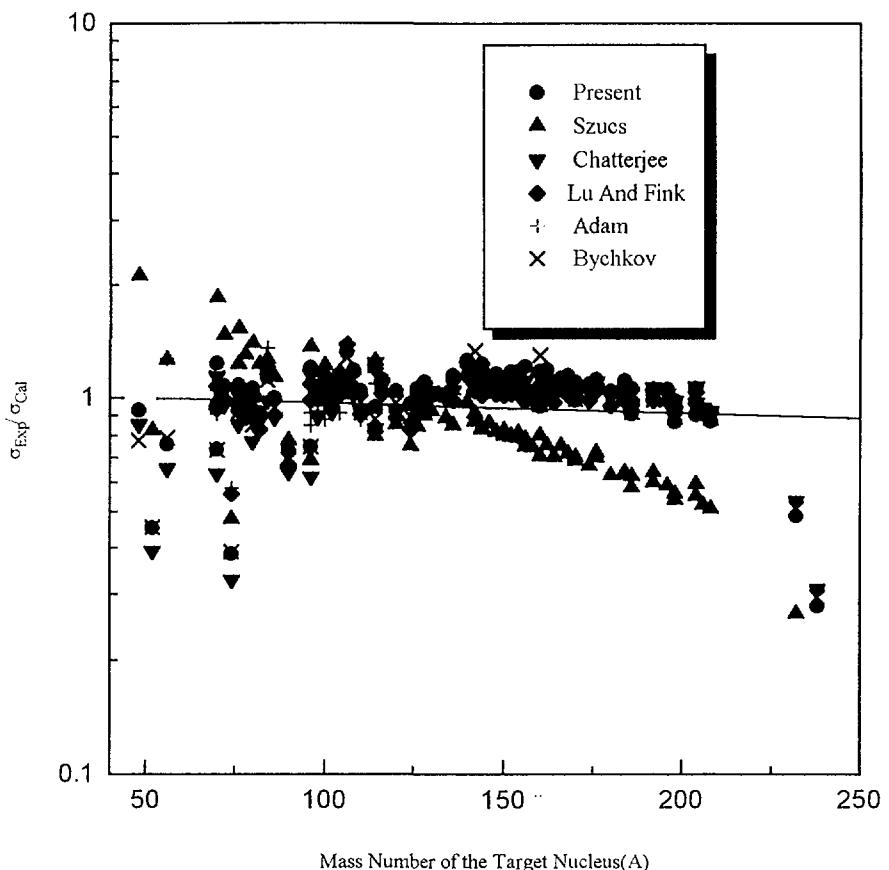


Fig.1 $\sigma_{\text{Exp}} / \sigma_{\text{Cal}}$ at 14.5MeV as a function of the mass number of the target nucleus for even- A

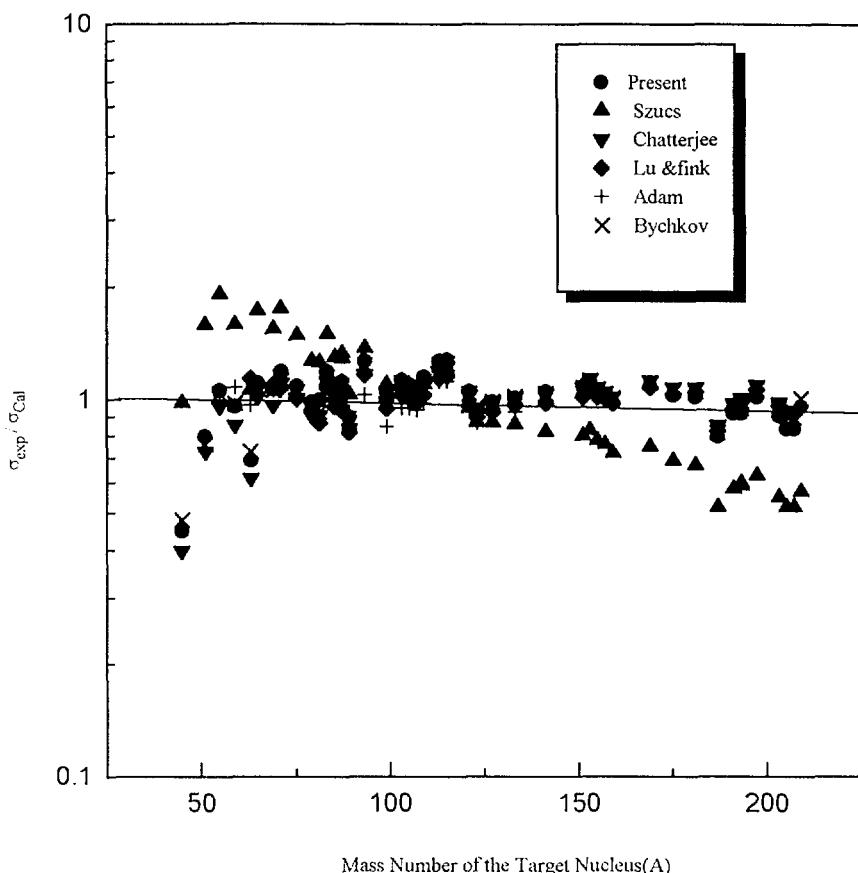


Fig.2: $\sigma_{\text{Exp}} / \sigma_{\text{Cal}}$ at 14.5MeV as a function of the mass number of the target nucleus for odd-A.

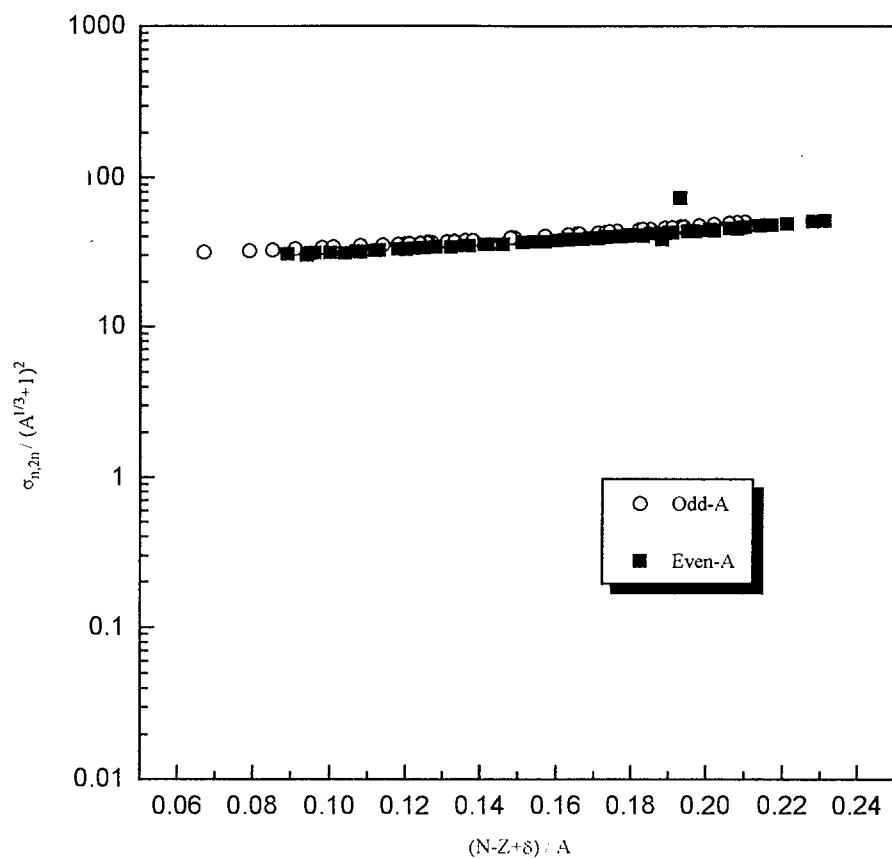


Fig.3 Systematics of $(n,2n)$ reaction cross-sections for even-A and odd-A nuclides at 14.5 MeV

Nuclear Data Section
International Atomic Energy Agency
P.O. Box 100
A-1400 Vienna
Austria

e-mail: services@iaeand.iaea.or.at
fax: (43-1) 26007
cable: INATOM VIENNA
telex: 1-12645
telephone: (43-1) 2600-2171

Online: TELNET or FTP: iaeand.iaea.or.at
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