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Systematics of (n,p) and (n,α) Cross Sections for 14 MeV Neutrons on the Basis of Statistical Model

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Abstract

The systematic behaviour of (n,p) and (n,α) cross sections for 14 MeV neutrons has been investigated using Weisskopf formulation of statistical model for nuclear reactions and introducing an exponential term that takes care of the suppression of charged particle emission by Coulomb barrier. The dependence of the values of various coefficients of the physical parameters of the systematics on the level density parameter is also investigated. An intercomparison of the predictions of the present systematics with those of the systematics based on asymmetry parameter, and measured values is provided.

Contents

1. Introduction

The knowledge of the cross sections of (n,p) and (n,α) reactions induced by about 14 MeV neutrons is useful for fusion technology and development of nuclear reaction models. Therefore measurements, calculations and evaluations of these cross sections have been extensively undertaken in the past decade. The prediction of precise cross section values for these reactions requires calculations that should take into account in a proper way the contributions from compound nucleus, statistical, direct and preequilibrium modes of reactions requiring appropriate optical-model parameters and energy level densities. An alternative and less laborious though less accurate way of predicting an unknown cross section has been to bank on the systematics of nuclear reactions [1,2]. Most of these systematics use nuclear asymmetry parameter (A-2Z)/A where Z and A are the atomic number and mass number of a nuclide respectively [3-12] since the variation of these cross sections is strongly correlated with the asymmetry parameter for nuclides spread almost over the whole periodic table. A detailed summary of different systematics used for charged particle emission has been given by Forrest [12]. Mostly the systematics were based on the first order asymmetry term in the exponential. However Forrest also included the second order asymmetry term and a term which involved mass number A, and found better agreement with experimental results. Later Badikov and Pashchenko [13] reported the analysis of updated (n,p) cross sections through least squares fit using Forrest formula.

The present paper is concerned with the study of the systematic behaviour of (n,p) and (n,α) cross sections using expressions that are based on the statistical model of nuclear reactions. Previously Bychkov et al [11] had carried out similar analysis and confined themselves to the analysis of (n,p) cross sections only. The present analysis is concerned with both the (n,p) and (n,α) cross section systematics and also considers the Coulomb barrier for the suppression of the emission of charged particles from nuclei exponentially. The details of the mathematical formulation, fitting procedures and discussion are given in the following sections.

2. Mathematical Formulation

The derivation of mathematical expressions for studying the systematic behaviour of the (n,p) and (n, α) cross sections in the present work are based on the original paper of Weisskopf [14]. We consider the compound nucleus A in the excited state E_A that results from the absorption of a neutron having energy E_C in the centre-of-mass system, the binding energy of the neutron in the nucleus being E_{on}. In the compound-nucleus formalism a reaction channel i is characterized by its width Γ_i which is related to the partial decay const λ_i, defined as the probability of decay per second of the compound nucleus through channel i, as

$$\Gamma_i = \hbar\lambda_i. \tag{1}$$

The total width is given by

$$\Gamma_t = \Gamma_n + \Gamma_p + \Gamma_\alpha + \Gamma_\gamma + ... \tag{2}$$

where Γ_n, Γ_p, Γ_α, Γ_γ etc. are the widths for neutron, proton, alpha and gamma emission channels. The widths are specified in terms of energy. For heavy nuclei the residual nucleus has a high level density and the evaporated particles have almost continuous spectra. The probability of the emission of a neutron per second $W_n(\epsilon)d\epsilon$ having energy in the interval ϵ and $\epsilon + d\epsilon$ is given by

$$W_n(\epsilon)d\epsilon = \sigma(E_A, \epsilon)\frac{g_n M_n \epsilon\, \omega_B(E_B)}{\pi^2\hbar^3\omega_A(E_A)}d\epsilon, \tag{3}$$

where g_n and M_n are the spin statistical factor and the mass of the neutron respectively; $\omega_B(E_B)$ and $\omega_A(E_A)$ are energy level densities of the residual nucleus B having the excitation energy E_B and of the compound nucleus A having the excitation energy E_A respectively; $\sigma(E_A, \epsilon)$ is the cross section for the reverse process i.e. for the formation of the compound nucleus A in the energy state E_A on the bombardment of the nucleus B in the energy state E_B by a neutron of energy $\in$. Following Weisskopf, we define energy level densities in terms of entropies on the basis of the concepts of thermodynamics:

$$S_A(E) = \ln \omega_A(E),$$
$$S_B(E) = \ln \omega_B(E), \tag{4}$$

where S(E) corresponds to the entropy of the nucleus having an excitation energy between E and E+dE. Using the definition of entropy we rewrite equation (3) as

$$W_n(\in)d\in = \sigma\left(E_A,\in\right)\frac{g_n M_n}{\pi^2\hbar^3}\in \exp\left[S_B(E_A - E_{on} - \in) - S_A(E_A)\right] d\in, \tag{5}$$

The usual formula for the probability of the evaporation of a neutron can be derived from equation (5) on the assumption that E_A is much greater than both the binding energy of the neutron, E_{on}, and the kinetic energy $\in$ of the emitted particle which is valid for neutrons of 14 MeV incident energy. Further assuming that S_A and S_B are identical functions, we may put

$$S_B(E_A - E_{on} - \in) = S_A\left(E_A\right) - \left(E_{on} + \in\right)\left(\frac{dS_A\left(E_A\right)}{dE}\right). \tag{6}$$

Moreover by using the definition of the nuclear temperature T as

$$\frac{dS_A\left(E_A\right)}{dE} = \frac{1}{T_A(E)}. \tag{7}$$

We can rewrite equation (5) as

$$W_n(\in)d\in = \sigma\left(E_A,\in\right)\left(\frac{g_n M_n}{\pi^2\hbar^3}\right)\exp\left(-\frac{\in + E_{on}}{T_A\left(E_A\right)}\right)\in d\in. \tag{8}$$

The integration of equation (8) gives the total channel width for the neutron emission when multiplied by $\hbar$ resulting in

$$\Gamma_n = \bar{\sigma}\left(E_A\right)\left(\frac{g_n M_n}{\pi^2\hbar^2}\right)T_A^2\left(E_A\right)\exp\left(\frac{-E_{on}}{T_A\left(E_A\right)}\right) \tag{9}$$

where $\overline{\sigma}$ (E_A) is the mean value of $\sigma(E_{A,}\in)$ averaged over the Maxwell energy distribution. For the range of energy under discussion it is usual to take

$$\overline{\sigma}\left(E_A\right) = \pi R^2, \tag{10}$$

where R is the radius of the residual nucleus, and therefore we may write equation (9) as

$$\Gamma_n = \pi R^2 \left(\frac{g_n M_n}{\pi^2 \hbar^2}\right) T_A^2 \left(E_A\right) \exp\left(\frac{-E_{on}}{T_A\left(E_A\right)}\right). \tag{11}$$

The width of a proton emission channel differs from that of a neutron as it is charged and has to surmount Coulomb barrier. Thus the proton width can be obtained from the neutron width by its multiplication with an appropriate factor and may be written as

$$\Gamma_n \approx \pi R^2 \left(\frac{g_n M_n}{\pi^2 \hbar^2}\right) T_A^2 \left(E_A\right) \exp\left(\frac{-E_{on}}{T_A\left(E_A\right)}\right) f\left(zZE_i\right). \tag{12}$$

Some properties of the function $f(zZE_i)$ are as follows. it should be equal to 1 for the neutron emission, approach unity for large value of the incident energy E_i and approach zero for small incident energy and large Coulomb barrier values. On these grounds the function $f(zZE_i)$ has been chosen as

$$f\left(zZE_i\right) = \exp\left(-\frac{Cz(Z-1)}{E_i A^{1/3}}\right) \tag{13}$$

where C is a constant to be determined from the least-squares fit to the measured cross section data. Here z and Z are the charges of the emitted and target nuclei.

Therefore the proton width may be written as

$$\Gamma_p \approx \pi R^2 \left(\frac{g_p M_p}{\pi^2 \hbar^2}\right) T_A^2 \exp\left(\frac{-E_{op}}{T_A\left(E_A\right)} - \frac{C(Z-1)}{E_i A^{1/3}}\right). \tag{14}$$

Now on the assumption that the neutron emission is the dominant mode of the decay of the compound nucleus, we may write for the (n,p) cross section as

$$\sigma_{np} \cong \sigma_R \frac{\Gamma_p}{\Gamma_n} \tag{15}$$

where σ_R is the non-elastic or reaction cross section for 14 MeV neutrons. Using equations (11,14), we obtain

$$\begin{aligned}\sigma_{np} &\cong \sigma_R \exp\left[\left(E_{op} - E_{on}\right)/T_A\left(E_A\right) - \frac{C(Z-1)}{E_i A^{1/3}}\right] \\ \sigma_{np} &\cong \sigma_R \exp\left[Q_{np}/T_A\left(E_A\right) - \frac{C(Z-1)}{E_i A^{1/3}}\right]\end{aligned} \tag{16}$$

where Q_{np} is the Q-value for the (n,p) reaction. Using semiempirical mass formula we may write equation (16) in the form

$$\sigma_{np} \cong \sigma_R \exp\left[\frac{2a_c(Z-1)}{TA^{1/3}} - \frac{A-2Z+1}{TA} a_\tau - \frac{C(Z-1)}{E_i A^{1/3}} + a'_0\right] \tag{17}$$

where the nuclear temperature T is taken as

$$T = \left(E_X/a\right)^{1/2} \qquad a = A/10 \,. \tag{18}$$

Here E_x is the excitation energy of the compound nucleus. if one uses the temperature of the residual nucleus, E_x is taken equal to the incident energy of the neutron [11] which is the maximum energy available to the residual nucleus after emission of a neutron by the compound nucleus A. a'_o is a constant that compensates for the approximations used in deriving the expression for the Q-values in terms of the parameters of the semiempirical mass formula. The value of σ_R is taken for 14 MeV neutrons as

$$\sigma_R = 10\pi r_0^2 (1 + A^{1/3})^2 \text{ mb} \tag{19}$$

where r_o is expressed in fm and a value of 1.4 fm is, in general, used for it [11]. Here a_c and a_τ are the Coulomb energy and the asymmetry energy coefficients and have values of about 0.58 MeV and 72 MeV respectively.

For the purpose of studying the systematics of (n,p) cross sections, equation (17) is rewritten as

$$\sigma_{np} = \left(1 + A^{1/3}\right)^2 \exp\left[a_o + \frac{a_1(Z-1)}{TA^{1/3}} + \frac{a_2(A-2Z+1)}{TA} a_\tau + \frac{a_3(Z-1)}{E_i A^{1/3}}\right] \tag{20}$$

where now a_o is equal to $\left[\ln(10\,\pi r_o^2) + a'_o\right]$.

Proceeding in the similar manner and making some approximations, we can arrive at the following expression for the (n,α) cross section:

$$\sigma_{n\alpha} = 2\sigma_R \exp\left[a'_o + \frac{4a_c(Z-1.5)}{TA^{1/3}} - \frac{a_\tau(A-2Z+0.5)}{TA} - \frac{2C(Z-2)}{E_i A^{1/3}}\right] \tag{21}$$

where the factor 2 in front of the exponential comes from the fact the product of the mass and the spin statistical factor of an alpha particle is twice the same product for a proton. For the purpose of studying the systematics of (n,α) cross sections, we write equation (21) as

$$\sigma_{n\alpha} = \left(1 + A^{1/3}\right)^2 \exp\left[a_o + a_1\frac{(Z-1.5)}{TA^{1/3}} + a_2\frac{(A-2Z+0.5)}{TA} + a_3\frac{(Z-2)}{E_i A^{1/3}}\right]. \tag{22}$$

3. Fitting Procedure

The mathematical formulation of multiple regression and subroutines for computational purposes given in Ref. [15] were adopted for obtaining the best fit to the data. The previously reported data [11-44] were used in these fits. However, some data which apparently seemed inconsistent with the systematics either due to the values of cross sections or due to unrealistic quoted errors on them, were not included in the data library used for obtaining the best fits. Details of the numerical data used in the present analysis are given in tables 1 and 2. The multiple regression fit was given to the following expressions.

$$y = \ln\left[\sigma_{np} \Big/ \left(1 + A^{1/3}\right)^2\right] = a_o + a_1 \frac{(Z-1)}{TA^{1/3}} + a_2 \frac{(A-2Z+1)}{TA} + a_3 \frac{(Z-1)}{E_i A^{1/3}} \tag{23}$$

$$y = \ln\left[\sigma_{n\alpha} \Big/ \left(1 + A^{1/3}\right)^2\right] = a_o + a_1 \frac{(Z-1.5)}{TA^{1/3}} + a_2 \frac{(A-2Z+0.5)}{TA} + a_3 \frac{(Z-2)}{E_i A^{1/3}} \tag{24}$$

$$y = \ln\left[\sigma_{np} \Big/ \left(1 + A^{1/3}\right)^2\right] = a_o + a_1 \frac{(A-2Z)}{A} + a_2 \frac{(A-2Z)^2}{A} + a_3 A^{1/2} \,. \tag{25}$$

The equations (23) and (24) are the present formulae for the systematics of (n,p) and (n,α) cross sections respectively and equation (25) is the formula used by Forrest [12] for the systematics of (n,p) cross sections. Mostly the cross section data used in the fits refers to 14.6 ± 0.2 MeV incident neutron energy and where excitation function was known the cross section value at 14.6 MeV was used in the analysis. In the above formulae y was weighted by the weighting factor $\Delta\sigma/\sigma$ where $\Delta\sigma$ is the uncertainty on the reported cross section σ. The fitting programme results in the values of coefficients a_o, a_1, a_2 and a_3 and uncertainties on these coefficients.

4. Results and Discussion

4.1 The best fit parameters

The mathematical formulae used in the present work for studying the systematics of (n,p) and (n,α) cross sections are based on the statistical model of nuclear reactions. They have been expressed as a product of a factor which gives cross section for the formation of the compound nucleus, a second factor for its decay into a given channel, integrated over all possible energies of the emitted particle, and the third factor for the effect of Coulomb barrier on the emission of a charged particle. These formulae contain two physical parameters of the semi-empirical mass formula namely the Coulomb and the asymmetry energies and a third parameter expressed as a ratio of the Coulomb barrier, experienced by the emitted particle, to the incident neutron energy. The input parameters are the atomic number, the mass number, the measured cross section and its error for a given nuclide, the nuclear temperature and the incident neutron energy. The chi-square value which is a measure of the quality of a fit is highly dependent on the errors of the measured cross sections on account of their weighting power.

Therefore some data that could adversely affect the quality of fit were not included in the process of analysis. It was not possible to get a good fit to the (n,p) cross sections of nuclides having $Z \geq 18$ all taken together. A natural division of nuclides into odd-A and even-A was followed and (n,p) cross section data of these nuclides were fitted separately. However it was possible to obtain a good fit to (n,α) cross sections of all nuclides having $Z \geq 20$ taken together. The values of the coefficients a_o, a_1, a_2 and a_3 and their uncertainties obtained through least-squares fit to (n,p) cross sections along with other relevant information for even-A and odd-A nuclides are listed in tables 1 and 2 respectively. The corresponding information on the analysis of (n,α) cross sections is given in table 3. The (n,p) cross section data for 145 nuclides used in the present analysis was also fitted using the formula given by Forrest i.e equation (25) and it resulted in 4.113 ± 0.000, 36.723 ± 0.305, -30.386 ± 0.240 and -0.0356 ± 0.01 for the values of a_o, a_1, a_2 and a_3 respectively with a reduced chi-square value of 6.5.

One of the input parameters of the present analysis is the nuclear temperature which is given by the square root of the ratio of the excitation energy to the level density parameter. In order to see the effect of nuclear temperature on the nature of fit, two relevant values of excitation energy namely 14.6 MeV and 21 MeV have been used which are the average incident neutron energy and the average excitation energy of the compound nucleus respectively. For each excitation energy two values of the level density parameter namely $a=A/10$ MeV^{-1} and $a = A/15$ MeV^{-1} have been used in the analysis of the data. As may be seen from tables 1 and 2 the values of a_o, a_3, their uncertainties, the quality of fit indicated by its chi-square values and the fitted values of cross sections remain unchanged for the different values of the energy level density parameters and excitation energy. However the values of the coefficients a_1 and a_2 and errors on them do change.

The lower values of errors on the coefficients correspond to a = A/10 MeV^{-1} and E_x=14.6 MeV respectively. The values of E_x=21 MeV and a=A/15 MeV^{-1} in the analysis of (n,p) cross sections of even-A nuclides give a_c=0.5 MeV and a_τ = 73 MeV which are comparable with the values used in the semi-empirical mass formula. The value of a_o = 4.234 gives a factor exp (a_o) = 69.0 which multiplied by $(1+A^{1/3})^2$ gives, in millibarns, the cross section of compound nucleus formation and corresponds to the value r_o = 1.48 fm. On the basis of the low chi-square value and the reasonably accepted values of other physical parameters resulting from the analysis, it may be said that the (n,p) cross section data of even-A nuclides for 14 MeV incident neutron energy can be adequately explained on the basis of statistical model formulation. The fit to the (n,p) cross sections of odd-A nuclides for the same set of values of excitation energy and level density parameter results in the values of 3.794, 0.7 MeV and -50 MeV for a_o, a_1 and a_2 respectively giving a_c=0.35 MeV and, a_τ=50 MeV. Both of these values are smaller than the corresponding values used in the semi-empirical mass formula. However, it is remarkable that the values -6.254±0.519 MeV and -6.182±1.018 MeV of a_3 for the even-A and odd-A nuclides are in good agreement with each other. The value of a_o gives a measure of the compound-nucleus formation cross section and its deviation from the expected value reflects the degree of approximations made in arriving at the expression contained in the exponentials of the formulae. If we consider the value a_o=4.234 obtained from the analysis of (n,p) cross sections of even-A nuclide as the base line, the lower value of a_o=3.794 for odd-A nuclides could be attributed to a value of -0.44 resulting from the approximations made in arriving at the expression in the exponential of the formula for odd-A nuclides.

The values of coefficients a_o, a_1 and a_2 resulting from the best fit to (n,α) cross sections for both odd-A and even-A nuclides taken togather are 5.421, 1.439 MeV and -62.131 MeV respectively for a=A/15 MeV^{-1} and E_X=21 MeV. After taking into account a factor 2 in front of the exponential in equation (21) and taking as before a_o=4.234 as the base line value, we observe that the offset of about 0.494 could result due to the approximations made in arriving at the expression in the exponential of the formula for (n,α) cross sections. The value of $|a_3|$ =15.730±0.68 MeV, noting that the charge on the alpha - particle is twice the value for the proton compares well with the combined value of $|a_3|$ = 6.2±1.1 for (n,p) cross section analysis of both even-A and odd-A data. The values of a_c and a_τ obtained from a_1 and a_2 are 0.372 MeV and 62.131 MeV respectively. The values of 0.35 and 0.372 MeV for a_c, obtained from the least squares-fit to the (n,p) cross section of odd-A nuclides, and to the (n,α) cross sections of both even-A and odd-A nuclides, are in good agreement with each other but lower than the value of 0.5 MeV obtained from the analysis of (n,p) cross sections of even-A nuclides.

4.2 Comparison with previous systematics

It is very important and useful to compare the predictions of the present systematics and previous systematics with experimental results. The most extensive analysis of (n,p) and (n,α) cross sections based on systematics has been reported by Forrest [12], who obtained the following expressions on the basis of least-squares fit.

$$\sigma_{np} = 7.567\ (1+A^{1/3})^2 \exp(-28.80s - 59.24s^2 + 0.2365A^{1/2})\ \text{mb} \qquad (26)$$

$$\sigma_{n\alpha} = 10.82\ (1+A^{1/3})^2 \exp(-9.402s - 127.3s^2 + 0.00717A)\ \text{mb} \qquad Z\leq 50 \qquad (27)$$

$$\sigma_{n\alpha} = 129.4\ (1+A^{1/3})^2 \exp(-42.45s - 0.00212A^{1/2})\ \text{mb} \qquad Z>50$$

where s is the asymmetry parameter and it is equal to (A-2Z)/A. Recently Badikov and Pashchenko [13] have carried out the analysis of (n,p) cross sections using updated information and have given the following expresion.

$$\sigma_{np} = 5.2093\ (1+A^{1/3})^2 \exp(-23.486s - 85.044s^2 + 0.25406A^{1/2})\ \text{mb} \qquad (28)$$

As the equations (26, 28) represent the same systematics and essentially result in the same values of (n,p) cross sections, we only include for discussion the results of Forrest [12] under previous systematics due to their extensive nature. As it is indicated from the low chi-square values of the fits to both (n,p) and (n,α) cross sections data there is a very good agreement between the fitted values and experimental values included in the present analysis. A comparison of some fitted (n,p) cross sections is provided in table 6 and figure 1. Except for ^{54}Cr the present fitted values are in better agreement with measurements than previous systematics. As stated earlier not all the available data were included in the present analysis. The (n,p) cross section data omitted in the present analysis and included almost all of it by Forrest is given in table 7 and shown in figure 2 along with the fitted values of the previous systematics and the predictions of the present systematics. The deviations of the predictions of the present systematics from their measured values are shown in figure 3. As is evident from figure 2 there is a very good agreement between the predictions of the present systematics, the fitted values of the previous systematics and the measured (n,p) cross section values of ^{106}Cd, ^{158}Gd, ^{170}Er, ^{173}Yb, ^{176}Yb and ^{192}Os. However, the predictions of the present systematics disagree with the measurements and previously fitted values, which agree with each other, for ^{47}Ti, ^{70}Zn, ^{84}Kr, ^{95}Mo, ^{144}Sm, ^{197}Au and ^{205}Tl. The measured (n,p) cross section of ^{203}Tl agrees with the predictions of the present systematics but disagrees with its previously fitted value. The predictions of the present systematics agree with the fits of the previous systematics but disagree with the measured (n,p) cross sections of ^{84}Sr, ^{86}Sr, ^{100}Ru, ^{112}Sn, ^{128}Xe, ^{165}Ho, ^{172}Yb and ^{196}Pt. Both the systematics disagree with each other as well as with the measured cross sections of ^{64}Ni, ^{80}Se and ^{207}Pb.

We include in table 8 and show in figure 4 the measured values of (n,α) cross sections which showed rather poor agreement with fitted values of the previous systematics. It may be observed that the measurements in general are in better agreement with the present systematics. The predictions of (n,α) cross sections of the present systematics of nuclides not included in the present analysis are compared with the experimental analysis values and fitted values of the previous systematics in table 9 and figure 4. The predictions of the present systematics agree with the fitted values of the previous systematics and the measured (n, α) cross sections of ^{169}Tm and ^{176}Yb. The measured (n,α) cross sections and the predictions of the present systematics are in good agreement for ^{81}Br, ^{87}Rb, ^{89}Y, ^{95}Mo, ^{97}Mo, ^{176}Lu and ^{238}U but differ from the previously fitted values. The predictions of the present systematics differ from the measured (n,α) cross sections and the previously fitted values for ^{85}Rb, ^{108}Pd, ^{112}Cd, ^{184}W, ^{186}W, ^{190}Os and ^{209}Bi. Both systematics agree with each other but differ from the measured (n,α) cross sections of ^{127}I. Both the systematics disagree with each other as well as with the measured (n,α) cross sections of ^{114}Cd, ^{118}Sn, ^{180}Hf, ^{197}Au, ^{200}Hg and ^{230}Th. A summary of the discussion on the comparison of the predictions of the present systematics for cross sections of nuclides not included in the present analysis is provided in table 10 and it is suggested that the measurements of the cross sections of nuclides for which the predictions of the present systematics agree with the fitted values of the previous systematics but differ with the experimental values may be verified.

5. Summary and conclusions

The systematics of (n,p) and (n,α) cross sections have been studied for 14 MeV neutrons using the statistical model formulation and including the effect of Coulomb barrier on the emission of charged particles. The systematics of odd-A and even-A nuclides having Z≥18 have been studied seperately but a single formula has been used for (n,α) cross sections of all nuclides having Z≥20. The fitted values of the Coulomb and asymmetry energy parameters agree with the corresponding parameters of the conventional semiempirical mass formula for even-A nuclides but are smaller by about 28 and 30 percent respectively for odd-A nuclides in the case of (n,p) cross sections, and 15 and 30 percent respectively in the case of (n,α) cross sections for a particular choice of nuclear temperature. The most significant aspect of the present analysis has been the agreement of the values of the fitted parameter of the Coulomb barrier introduced explicitly for the first time in the systematics under discussion..

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Table 1. The (n,p) cross section library

S.No.	Nuclide	Z	A	σ	± Δσ	Ref.
1	Ar	18	40	18	3	adopted
2	K	19	41	51	8	[19]
3	Ca	20	40	470	30	[11]
4	Ca	20	42	172	20	adopted
5	Ca	20	43	92	10	[16]
6	Ca	20	44	44	8	[24]
7	Sc	21	45	58	6	[16]
8	Ti	22	46	242	30	[16]
9	Ti	22	48	64	5	adopted
10	Ti	22	49	40	7	[351
11	Ti	22	50	16	3	[11]
12	V	23	51	38	5	adopted
13	Cr	24	50	265	50	[12]
14	Cr	24	52	80	10	adopted
15	Cr	24	53	44	5	[12]
16	Cr	24	54	18	3	[19]
17	Mn	25	55	45	10	[11]
18	Fe	26	54	286	10	[27]
19	Fe	26	56	110	10	[161
20	Fe	26	57	55	8	[11]
21	Fe	26	58	23	4	adopted
22	Co	27	59	47	10	[16]
23	Ni	28	58	310	10	adopted
24	Ni	28	60	136	10	[26,27]
25	Ni	28	61	59	4	[26]
26	Ni	28	62	39	6	[12]
27	Cu	29	63	53	6	[29,30,36]
28	Cu	29	65	27	5	[11]
29	Zn	30	64	150	20	adopted
30	Zn	30	66	66	5	[16]
31	Zn	30	67	38	6	adopted
32	Zn	30	68	26	3	adopted
33	Ga	31	69	34	3	[16]
34	Ga	31	71	21	3	[12]
35	Ge	32	70	77	10	[11]
36	Ge	32	72	34	2	[26]
37	Ge	32	73	22	3	[16]
38	Ge	32	74	11	2	[11]

Table 1 Continued ...

S.No.	Nuclide	Z	A	σ	± Δσ	Ref.
39	Ge	32	76	3	1.5	[11]
40	As	33	75	30	5	[adopted,35]
41	Se	34	74	112	7	[34]
42	Se	34	76	52	5	[33,34]
43	Se	34	77	36	10	adopted
44	Se	34	78	20	2	adopted
45	Br	35	81	21	5	[16]
46	Kr	36	82	23	5	[12]
47	Kr	36	83	14	5	[12]
48	Kr	36	86	8	3	[12]
49	Rb	37	87	11	2	adopted
50	Sr	38	88	15	2	[12]
51	Y	39	89	24.6	3	[161
52	Zr	40	90	45	5	adopted
53	Zr	40	91	29	4	[19]
54	Zr	40	92	22	2	adopted
55	Zr	40	94	10	1	[24]
56	Nb	41	93	40	10	[12]
57	Mo	42	94	54	10	[30,36]
58	Mo	42	96	25	2	[37]
59	Mo	42	97	16.8	1	[16]
60	Mo	42	98	14	4	adopted
61	Mo	42	100	5.2	1	[11]
62	Tc	43	99	15	2	[19]
63	Ru	44	96	136	10	[26]
64	Ru	44	101	25	2	[25]
65	Ru	44	104	8	1	[25]
66	Rh	45	103	17	3	[19]
67	Pd	46	102	94	15	[38]
68	Pd	46	104	58	14	[11]
69	Pd	46	105	31	3	[19]
70	Pd	46	106	25	3	[161
71	Pd	46	108	9	2	[161
72	Ag	47	109	14	3	[16]
73	Cd	48	110	27	5	[16]
74	Cd	48	111	22.2	6	[16]
75	Cd	48	112	16	2	[16]
76	Cd	48	113	12	2	adopted

Table 1 Continued ...

S.No.	Nuclide	Z	A	σ	± Δσ	Ref.
77	Cd	48	114	10	2	adopted
78	Cd	48	116	2.5	0.5	adopted [24,25]
79	In	49	115	15	5	[16]
80	Sn	50	116	22	2	[16]
81	Sn	50	117	14	2	[16]
82	Sn	50	118	9	3	[11]
83	Sn	50	119	10	2	[11]
84	Sn	50	120	4.3	0.7	[11]
85	Sb	51	123	4.6	1.5	[16]
86	Te	52	122	12	2	[16]
87	Te	52	124	9	2	[16]
88	Te	52	126	5	1	[12]
89	Te	52	128	2.4	0.4	[11]
90	Te	52	130	1.8	0.3	[11]
91	I	53	127	9	3	[16]
92	Xe	54	130	9	2	[11]
93	Xe	54	131	6	1	[11]
94	Xe	54	132	3	0.5	[11]
95	Xe	54	134	2	0.5	[11]
96	Cs	55	133	10	2	[11]
97	Ba	56	136	6.3	2.0	[31]
98	Ba	56	137	6	2	adopted [31,34]
99	Ba	56	138	2.5	0.5	adopted
100	La	57	139	5	1	[12]
101	Ce	58	140	6.5	0.5	[11]
102	Ce	58	142	4	1	[11]
103	Pr	59	141	9	1	[16]
104	Nd	60	142	14	2	[11]
105	Nd	60	143	11	2	[19]
106	Nd	60	144	12	3	[12]
107	Nd	60	145	7.5	2	[12]
108	Nd	60	146	4.7	0.5	[39]
109	Sm	62	148	10	1	[16]
110	Sm	62	150	7.2	1	[11]
111	Sm	62	152	3.7	0.4	[161

Table 1 Continued ...

S.No.	Nuclide	Z	A	σ	± Δσ	Ref.
112	Sm	62	154	3.5	0.7	[16,adopted]
113	Eu	63	153	6	1	[16]
114	Gd	64	157	5.4	1.1	[16]
115	Tb	65	159	6.0	0.5	[26]
116	Dy	66	160	7.0	1.5	[12]
117	Dy	66	161	5.6	0.5	[19]
118	Dy	66	162	5	1	[16]
119	Dy	66	163	3	1	[16]
120	Dy	66	164	2.8	0.5	[19]
121	Er	68	166	6.1	1.5	adopted
122	*Er*	68	167	4	1	[11]
123	Er	68	168	2.7	1.2	adopted
124	Yb	70	174	3.5	1	[11]
125	Lu	71	175	3.7	0.5	[16]
126	Ta	73	181	4.5	0.5	[16]
127	W	74	182	6.5	0.5	[34]
128	W	74	183	4.1	0.5	[161
129	W	74	184	3.2	0.2	[34]
130	W	74	186	1.7	0.5	[16]
131	Re	75	187	4.3	0.5	[16]
132	Os	76	186	5.5	1.3	[161
133	Os	76	188	4.7	1	[261
134	Os	76	189	5	2	[16]
135	Os	76	190	2	0.5	[11]
136	Ir	77	191	4.8	0.8	[16]
137	Ir	77	193	3.8	0.5	[16]
138	Pt	78	194	4	0.5	[16]
139	Pt	78	195	2.0	0.5	[16]
140	Hg	80	198	4.6	0.3	[11]
141	Hg	80	199	3.5	0.6	[11]
142	Hg	80	200	3.6	1	[16]
143	Hg	80	201	1.8	0.3	[16]
144	Pb	82	206	2	0.4	[16]
145	Pb	82	208	1	0.5	[16]

Table 2. The (n,α) cross section library

S.No.	Nuclide	Z	A	σ	± Δσ	Ref.
1	Ca	20	44	28.6	1.5	[12]
2	SC	21	45	55	5	[11]
3	Ti	22	48	31	8	[11]
4	Ti	22	50	10	2	adopted
5	V	23	51	25	4	adopted
6	Cr	24	50	94	15	[40]
7	Cr	24	52	35	3	[16]
8	Cr	24	53	45	4	[16]
9	Cr	24	54	14	2	[16]
10	Mn	25	55	29	6	adopted
11	Fe	26	54	85	6	[27]
12	Fe	26	56	46	4	[12]
13	Fe	26	57	33	5	adopted
14	Fe	26	58	20	2	[12]
15	Co	27	59	32	2	[11]
16	Ni	28	58	120	15	[12]
17	Ni	28	60	70	10	[12]
18	Ni	28	61	45	5	[12]
19	Ni	28	62	20	3	[19]
20	Ni	28	64	9	1	[41]
21	Cu	29	63	38	8	adopted
22	Cu	29	65	18	4	[19]
23	Zn	30	68	10	2	[26]
24	Zn	30	70	4	1	[19]
25	Ga	31	69	18	2	[11]
26	Ge	32	72	15	2	[11]
27	Ge	32	74	6	1	[19]
28	As	33	75	11	1.5	[11]
29	Se	34	78	8.6	0.5	[33]
30	Se	34	80	6.6	2	[19]
31	Br	35	79	12.5	1.5	[11]
32	Zr	40	90	10	3	[12]
33	Zr	40	92	8.5	1	[12]
34	Zr	40	94	4.8	0.5	[16]
35	Zr	40	96	3	1	[11]
36	Nb	41	93	9.5	0.5	[11]
37	Mo	42	92	27	2	[12]
38	Mo	42	94	18	4	[12]
39	Mo	42	96	10	2	[12]
40	Mo	42	98	5.6	0.6	[16]
41	Mo	42	100	2.8	0.3	[16]
42	Tc	43	99	7	1	[19]
43	Ru	44	102	6.2	0.7	[19]
44	Ru	44	104	2.6	1	[42]
45	Rh	45	103	11	2	[19]

Table 2 continued ...

S.No.	Nuclide	Z	A	σ ±	Δσ	Ref.
46	Pd	46	106	5.6	0.7	[42]
47	Ag	47	107	5.5	3	[12]
48	Ag	47	109	7	3	[12]
49	Cd	48	106	100	40	[42]
50	In	49	115	3	1	adopted
51	Te	52	126	2.1	0.6	[16]
52	Te	52	128	1.1	0.3	[16]
53	Cs	55	133	2.5	0.5	adopted
54	Ba	56	138	2.0	0.2	[19]
55	La	57	139	2.0	0.3	[12]
56	Ce	58	140	4.6	2	[12]
57	Ce	58	142	3.0	0.6	[12]
58	Pr	59	141	3	1	[12]
59	Nd	60	142	7.1	0.8	[16]
60	Nd	60	144	4.7	1.5	[12]
61	Nd	60	146	3.1	0.5	[12]
62	Nd	60	148	2.4	0.5	[12]
63	Sm	62	150	3.5	0.5	[11]
64	Sm	62	152	2.1	0.5	[12]
65	Sm	62	154	1.2	0.2	[17]
66	Eu	63	151	4.2	0.5	[12]
67	Eu	63	153	2.2	0.3	[11]
68	Gd	64	156	3.1	1	[17]
69	Gd	64	158	1.2	0.4	[17]
70	Gd	64	160	2	1	[42]
71	Tb	65	159	2.5	0.6	[171
72	Dy	66	162	2.0	0.3	[17]
73	Dy	66	164	1.24	0.14	[17]
74	Ho	67	165	1.3	0.4	[17]
75	Er	68	168	2.3	0.5	[17]
76	Er	68	170	1.0	0.2	[42]
77	Tm	69	169	3.0	1.5	[12]
78	Yb	70	172	1.8	0.4	[17]
79	Yb	70	174	1.3	0.2	[17]
80	Lu	71	175	1.3	0.3	[17]
81	Hf	72	178	3.04	0.75	[26]
82	Ta	73	181	1.1	0.3	[12]
83	Re	75	187	0.94	0.3	adopted
84	Ir	77	191	2.4	0.6	[12]
85	Hg	80	202	1.0	0.3	[12]
86	Tl	81	203	2.2	1	[12]
87	Tl	81	205	0.75	0.35	[19]
88	Pb	82	206	2.8	0.4	[19]
89	Pb	82	207	1.6	0.5	[12]
90	Pb	82	209	0.7	0.3	[12]

Table 3. The values of coefficients for the best fit to (n,p) cross sections of even-A nuclides

Ex (MeV)	a (MeV^{-1})	a_0	a_1 (MeV)	a_2 (MeV)	a_3 (MeV)	R-x^2	No. of data points
21	A/10	4.234±0.00	0.820±0.002	-59.808±0.578	-6.254±0.519	2.1	85
	A/15	4.234±0.00	1.000±0.002	-73.249±0.867	-6.254±0.519	2.1	85
14.6	A/10	4.234±0.00	0.683±0.001	-49.863±0.402	-6.254±0.519	2.1	85
	A/15	4.234±0.00	0.837±0.002	-61.076±0.603	-6.254±0.519	2.1	85

Table 4. The values of coefficients for the best fit to (n,p) cross sections of odd-A nuclides

Ex (MeV)	a (MeV^{-1})	a_0	a_1 (MeV)	a_2 (MeV)	a_3 (MeV)	R-x^2	No. of data points
21	A/10	3.794±0.00	0.572±0.005	-40.863±7.74	-6.182±1.018	1.5	60
	A/15	3.794±0.00	0.700±0.008	-50.000±11.61	-6.182±1.018	1.5	60
14.6	A/10	3.794±0.00	0.477±0.004	-34.072±5.381	-6.182±1.018	1.5	60
	A/15	3.794±0.00	0.584±0.006	-41.730±8.071	-6.182±1.018	1.5	60

Table 5. The values of coefficients for the best fit to (n,α) cross sections for all A-values

Ex (MeV)	a (MeV^{-1})	a_0	a_1 (MeV)	a_2 (MeV)	a_3 (MeV)	R-x^2	No. of data points
21	A/10	5.421±0.00	1.215±0.003	-50.730±3.18	-15.730±0.678	2.6	89
	A/15	5.421±0.00	1.489±0.004	-62.131±1.978	-15.730±0.678	2.6	89
14.6	A/10	5.421±0.00	1.014±0.002	-42.306±0.917	-15.730±0.678	2.6	89
	A/15	5.421±0.00	1.241±0.003	-51.805±1.363	-15.730±0.678	2.6	89

Table 6. Comparison of measured (n,p) cross sections with the predictions of the present and previously reported systematics. All cross sections are in millibarns

Target nuclide	Experimental value	Forrest	This work
^{41}K	51 ± 8^{a}	60	62
^{40}Ca	470 ± 30^{b}	659	472
^{45}Sc	58 ± 6^{c}	86	70
^{50}Ti	16 ± 4^{d}(g) 7 ± 2^{d}(m)	12(13.5*)	22
^{54}Cr	18 ± 3^{a}	19	29
^{56}Fe	110 ± 10^{c}	98	98
^{63}Cu	53 ± 6^{e}	86(120*)	60
^{65}Cu	27 ± 5^{b}	29	33
^{67}Zn	38 ± 6^{f}	35	35
^{81}Br	21 ± 5^{c}	12	17
^{86}Kr	8 ± 3^{g}	4	6
^{103}Rh	17 ± 3^{a}	28	24
^{115}In	15 ± 5^{b} 8 ± 1^{g}	13	13
^{136}Ba	63 ± 2^{h}	4	4
^{137}B a	5.3 ± 0.7^{h}	3	5

[a]Ref. [19] [b]Ref.[11] [c]Ref. [16] [d]Ref. [43] [e]Ref. [29,30,36] [f]Ref. [26] [g]Ref. [12] [h]Ref. [31]

*Values used in the fit.

Table 7. Comparison of measured values of (n,p) cross sections of nuclides, which were not included in the analysis, with the present and previously reported systematics. All cross sections are in millibarns and taken from Ref.[12] unless specified otherwise.

Target nuclide	Experimental value	Forrest	This work
^{47}Ti	170 ± 20 116 ± 16[a]	102	74
^{64}Ni	4.5 ± 2	14	20
^{70}Zn	7 ± 0.5	7	11
^{80}Se	16 ± 4[a]	6	9
^{84}Kr	8 ± 1.5[b]	9	12
^{84}Sr	96 ± 8[a]	72	74
^{86}Sr	44 ± 4[a]	31	34
^{95}Mo	42 ± 2[b]	38	30
^{100}Ru	5 ± 6[a]	34	37
^{106}Cd	130 ± 31[a]	110	127
^{112}Sn	30 ± 10	72	83
^{128}Xe	27 ± 6	11	11
^{144}Sm	24 ± 5	29	36
^{158}Gd	3.2 ± 1.2	3	3
^{165}Ho	40 ± 15	4	5
^{170}Er	1.8 ± 0.5[c]	2.1	1.9
^{172}Yb	6.3 ± 0.8	4.4	4.5
^{173}Yb	4 ± 0.4	3.5	4.3
^{176}Yb	1.8 ± 0.3	1.8	1.6
^{192}Os	2.1 ± 0.7	1.7	1.6
^{196}Pt	1.4 ± 0.3[b]	2.3	2.2
^{197}Au	2.5 ± 0.5[b]	3.2	3.9
^{203}Tl	4.2 ± 1	2.8	3.4
^{205}Tl	1.9 ± 0.3	1.9	2.5
^{207}Pb	1.6 ± 0.3[b]	2.1	2.8
^{209}Bi	0.8 ± 0.3[b]	2.4	3.1

[a]Ref. [19] [b]Ref. [16] [c]Ref. [42]

Table 8. Comparison of measured (n,α) cross sections with predictions of the present and previously reported systematics. All cross sections are in millibarns. The measure cross sections are taken from -Ref. [I2] unless specified otherwise.

Target nuclide	Experimental value	Forrest	This work
^{51}V	25 ± 4[a]	20	24
^{64}Ni	9 ± 1[b] 3.7 ± 0.5	7	11
^{78}Se	8.6 ± 0.5[c]	6.4	8.6
^{80}Se	6.6 ± 2[d]	2.4	4.6
^{96}Zr	3 ± 1[e]	1.0	2.5
^{98}Mo	5.6 ± 0.6[f]	3 3	5.4
^{103}Rh	11 ± 2[d]	6.7	9.5
^{109}Ag	7 ± 3	4.1	6.8
^{138}Ba	2.0 ± 0.2[d]	1.2	1.4
^{142}Ce	3.0 ± 0.6	1.6	1.8
^{148}Nd	2.4 ± 0.5	1.2	1.5
^{160}Gd	2 ± 1	0.8	1.1
^{191}Ir	2.4 ± 0.6	1.1	2.6
^{203}Ti	2.2 ± 1	0.8	2.2
^{206}Pb	2.8 ± 0.4[d]	0.7	2.1

[a]adopted [b]Ref. [41] [c]Ref. [33] [d]Ref. [19] [e]Ref. [11] [f]Ref. [161

Table 9. Comparison of (n,α) cross sections of nuclides, which were omitted in the presented analysis, with the present and previously reported systematics. All cross sections are in millibarns and taken from Ref.[12] unless specified otherwise.

Target nuclide	Experimental value	Forrest	This work
^{81}Br	6.5 ± 1.2[a]	4.6	6.8
^{85}Rb	6.5 ± 1[b]	6.0	8.1
^{87}Rb	3.8 ± 0.5[a]	2.5	4.5
^{89}Y	9.3 ± 0.7[c]	7.6	9.7
^{95}Mo	13.5 ± 2	10.3	12.6
^{97}Mo	7.5 ± 2	4.9	7.2
^{107}Ag	5.5 ± 3	8.1	11.7
^{108}Pd	2.6 ± 0.4	2.5	4.8
^{112}Cd	3.15 ± 0.2[a]	3.2	5.9
^{114}Cd	0.7 ± 0.2	1.6	3.5
^{118}Sn	1.4 ± 0.2	2.0	4.4
^{127}I	1.5 ± 0.5	3.2	3.0
^{169}Tm	3 ± 1,5	1.6	2.6
^{176}Yb	0.7 ± 0.3	0.66	1.1
^{176}Lu	l.6 ± 0.2	1.1	1.9
^{180}Hf	2.8 ± 0.2[a]	0.8	1.5
^{184}W	1.2 ± 0.2[a]	1.0	2.0
^{186}W	0.6 ± 0. 1[a]	0.7	1.3
^{190}Os	0.8 ± 0 .1[a]	0.81	1.8
^{194}Pt	1.3 ± 0.4	1.0	2.4
^{196}Pt	0.6 ± 0.2	0.7	1.7
^{197}Au	0.5 ± 0.1	0.9	2.3
^{200}Hg	1.7 ± 0.3[a]	0.8	2.2
^{209}Bi	0.7 ± 0.3	0.6	2.0
^{230}Th	4.6 ± 1.2[d]	0.4	1.8
^{238}U	1.5 ± 0.3[d]	0.3	1.3

[a]Ref. [19] [b]Ref. [11] [c]Ref. [41] [d]Ref. [42]

Table 10. Classification of nuclides not included in the present analysis according to agreement and desagreement between the two systematics and measured values

Sr. No.	Classification	Listing of nuclides on the basis of (n,p) cross sections	Listing of nuclides on the basis of (n,α) cross sections
1	Present and previous systematics and measurements all agree	^{106}Cd, ^{158}Gd, ^{170}Er, ^{173}Yb, ^{176}Yb, ^{192}Os	^{169}Tm, ^{176}Yb
2	Present systematics and measurements agree but differ with previous systematics	^{203}Tl	^{81}Br, ^{87}Rb, ^{89}Y, ^{95}Mo, ^{176}Lu, ^{238}U
3	Previous systematics and measurements agree but differ with present systematics	^{47}Ti, ^{70}Zn, ^{84}Kr, ^{95}Mo, ^{144}Sm, ^{197}Au, ^{205}Tl	^{85}Rb, ^{108}Pd, ^{112}Cd, ^{184}W, ^{186}W, ^{190}Os, ^{209}Bi, ^{194}Pt
4	Previous and the present systematics agree but differ with measurements	^{84}Sr, ^{86}Sr, ^{100}Ru, ^{112}Sn, ^{128}Xe, ^{165}Ho, ^{172}Yb, ^{196}Pt	^{127}I
5	The systematics and measurements all disagree	^{64}Ni, ^{80}Se, ^{207}Pb	^{114}Cd, ^{118}Sn, ^{180}Hf, ^{197}Au, ^{200}Hg, ^{230}Th

Figures Captions

Figure 1. A comparison of measured (n,p) cross sections of some nuclides with the previous and present systematics.

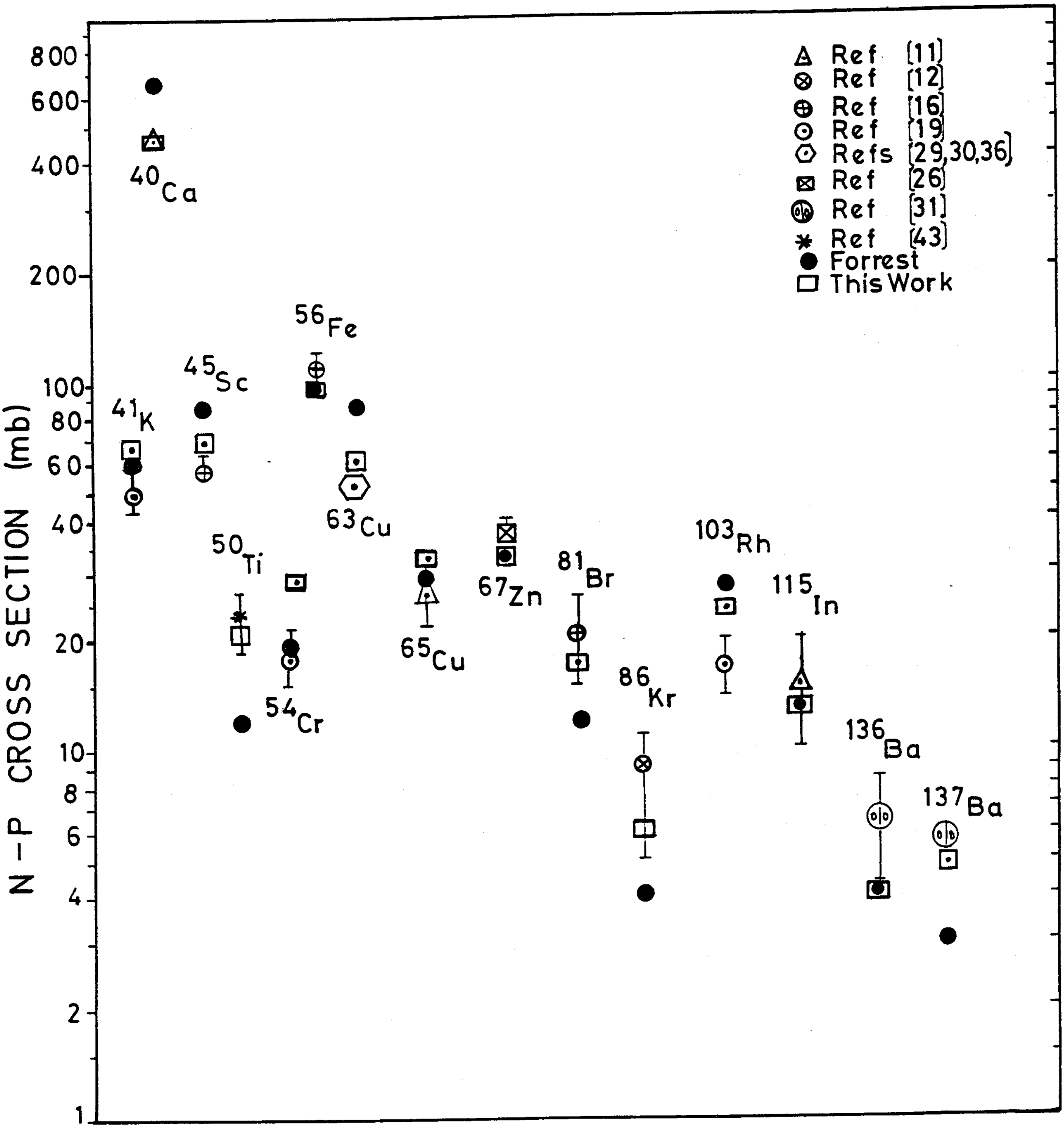
Figure 2. A comparison of predictions of the present systematics with the previously fitted and measured (n,p) cross sections of nuclides omitted in the present analysis.

Figure 3. Deviations of the predictions of (n,p) cross sections not included in the present analysis from their measured values.

Figure 4. A comparison of measured (n,α) cross sections of some nuclides with the previous and present systematics.

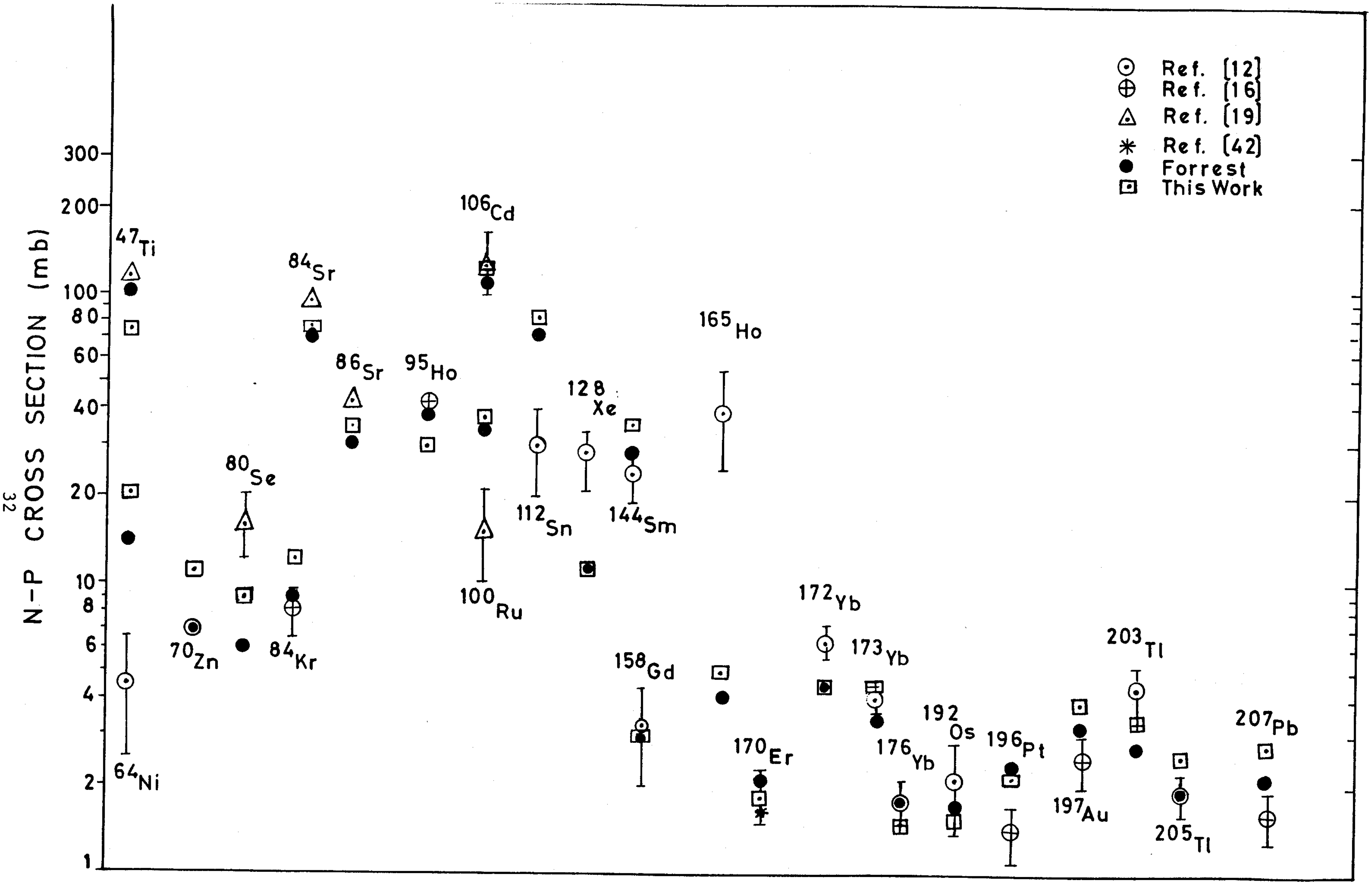
Figure 5. A comparison of the predictions of the present systematics with the previously fitted and measured (n,α) cross sections of some nuclides with the previous and present systematics.

Figure 5. Deviations of the predictions of (n,α) cross sections of omitted in the present analysis from their measured value.



N-P CROSS SECTION (mb)
800
600
400
200
100
80
60
40
20
10
8
6
4
2
1
Ref [11]
Ref [12]
Ref [16]
Ref [19]
Refs [29,30,36]
Ref [26]
Ref [31]
Ref [43]
Forrest
This Work
40Ca
41K
45Sc
56Fe
63Cu
50Ti
54Cr
65Cu
67Zn
81Br
86Kr
103Rh
115In
136Ba
137Ba

Figure-1



Ref. [12]
Ref. [16]
Ref. [19]
Ref. [42]
Forrest
This Work
N-P CROSS SECTION (mb)
300
200
100
80
60
40
20
10
8
6
4
2
1
47Ti
64Ni
70Zn
80Se
84Kr
84Sr
86Sr
95Ho
106Cd
100Ru
112Sn
128 Xe
144Sm
165Ho
158Gd
170Er
172Yb
173Yb
176Yb
192 Os
196Pt
197Au
203Tl
205Tl
207Pb

Figure-2

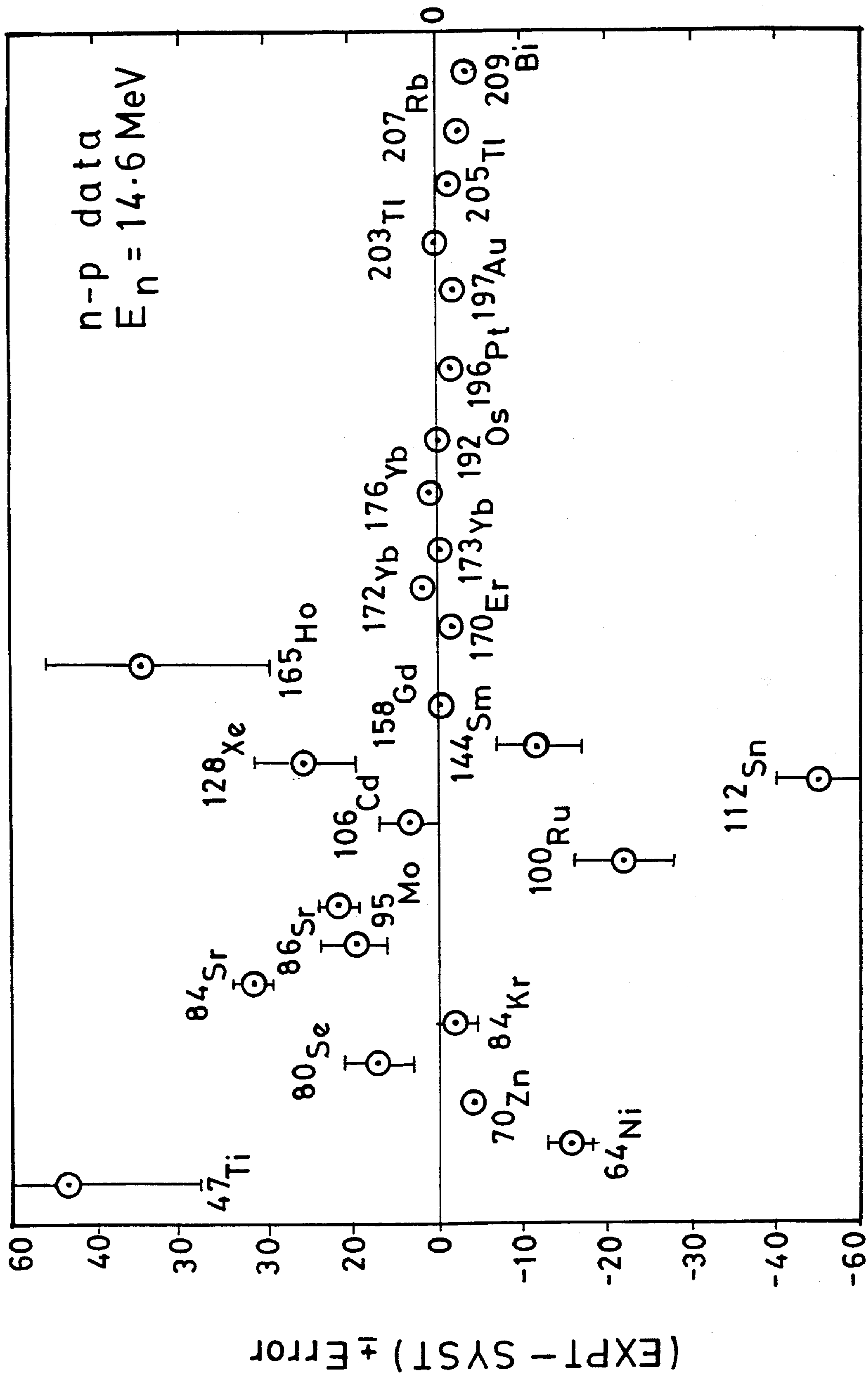
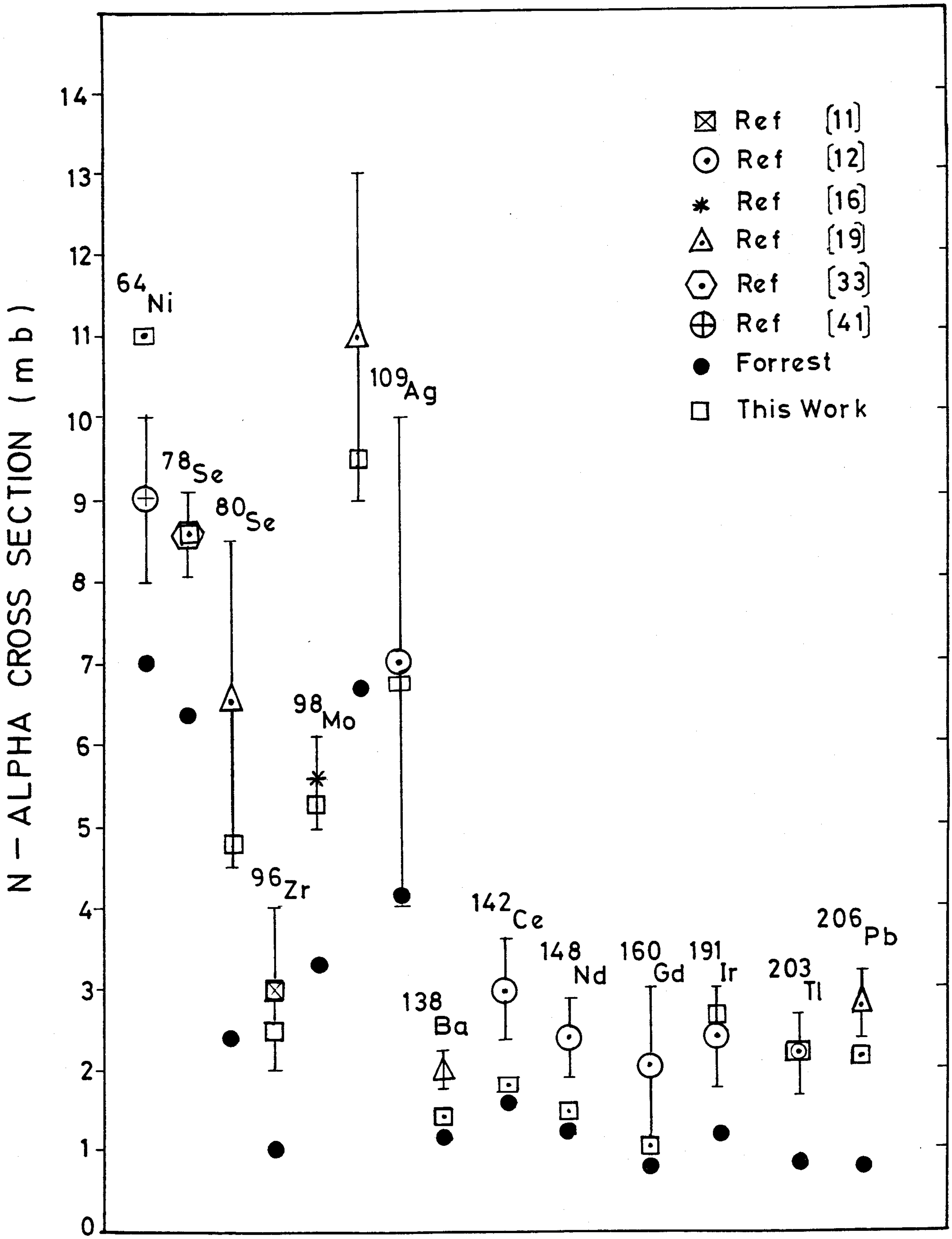

n-p data
E n = 14.6 MeV
(EXPT − SYST) ± Error
47Ti
64Ni
70Zn
80Se
84Kr
84Sr
86Sr
95Mo
100Ru
106Cd
112Sn
128Xe
144Sm
158Gd
165Ho
170Er
172Yb
173Yb
176Yb
192Os
196Pt
197Au
203Tl
205Tl
207Rb
209Bi

Figure-3



N - ALPHA CROSS SECTION (mb)
0
1
2
3
4
5
6
7
8
9
10
11
12
13
14
Ref [11]
Ref [12]
Ref [16]
Ref [19]
Ref [33]
Ref [41]
Forrest
This Work
64 Ni
78 Se
80 Se
96 Zr
98 Mo
109 Ag
138 Ba
142 Ce
148 Nd
160 Gd
191 Ir
203 Tl
206 Pb

Figure-4

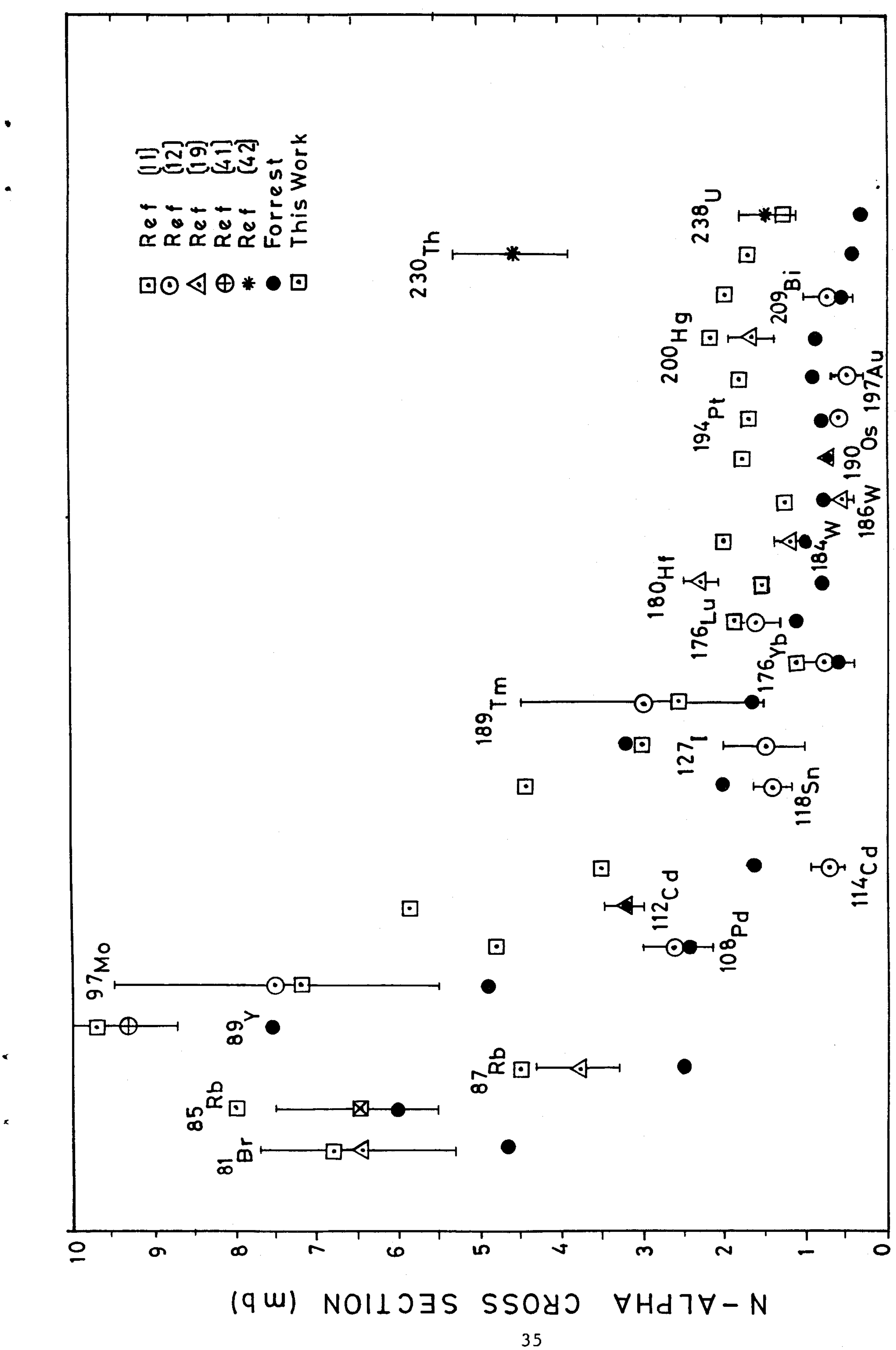

N-ALPHA CROSS SECTION (mb)
0
1
2
3
4
5
6
7
8
9
10
Ref [11]
Ref [12]
Ref [19]
Ref [41]
Ref [42]
Forrest
This Work
81Br
85Rb
87Rb
89Y
97Mo
108Pd
112Cd
114Cd
118Sn
127I
189Tm
176Yb
176Lu
180Hf
184W
186W
190Os
194Pt
197Au
200Hg
209Bi
230Th
238U

Figure-5

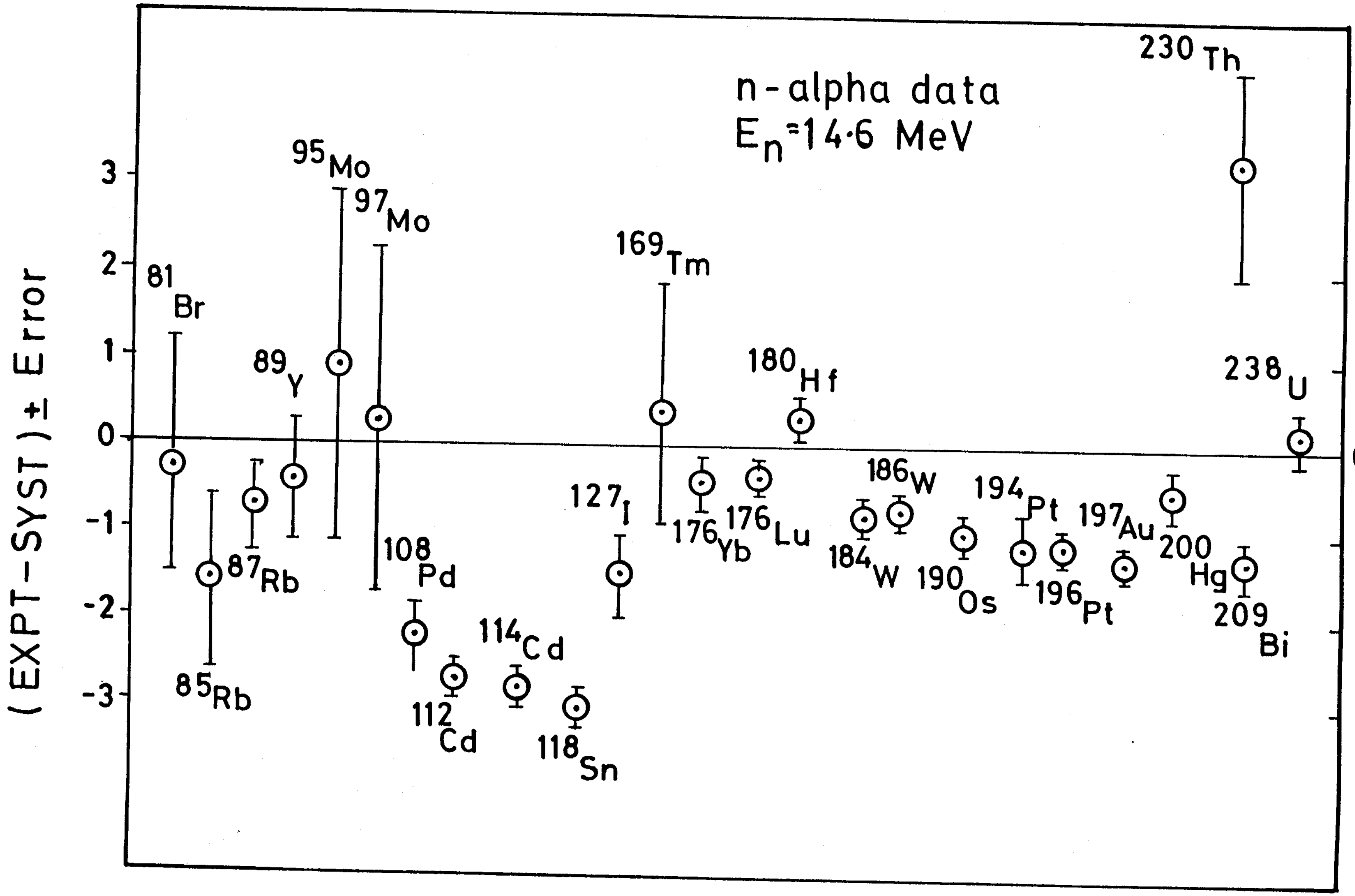


Figure-6

95-02635