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**INVESTIGATIONS ON (n,p) CROSS SECTIONS
IN THE 14 MeV REGION**

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Cross sections have been measured, deduced, and adopted for 208 (n,p) reactions at (14.7±0.2) MeV incident neutron energy. Systematics based on asymmetry parameter dependence and isotopic effects have been confirmed. Recommended formulae were fitted to the same data base to be able to test their applicability. Total (n,p) cross sections are given for 54 elements and compared with the results of direct methods. Some $\sigma_{n,p}$ data both for long-lived target and residual radionuclides were estimated.

1. Introduction

Recently, a number of hydrogen production cross section have been measured and calculated for elements and isotopes at around 14 MeV neutron energy [1-14], mainly for the radiation damage assessment of fusion related materials, to complete the data base of neutron activation cross sections for environmental protection, and to estimate the potential radiation hazards connected with the nuclear techniques. Cross sections for the generation of long-lived radionuclides, of importance in fusion reactor technology and accelerator based neutron

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sources, have a high priority. Precise data at 14 MeV are needed for validation and testing of different data libraries and for the normalization of excitation functions.

Recently, on the basis of precise cross section measurements a number of investigations [11,27,81,83-87] were devoted to improve the systematics based on the isotopic and asymmetry parameter dependences. The reliable theoretical and empirical formulae are indispensable to estimate cross sections if experimental data are not available.

2. Experimental procedure

The description of the sample preparation, the properties of neutron sources, the irradiation conditions as well as the absolute activity determination were summarized in our recent paper [15] on the investigations of (n, α) activation cross sections around 14 MeV.

3. Results and conclusions

Activation cross sections of (n,p) reactions, measured and deduced in Debrecen, were completed with the recent literature data in order to prepare a recommended library of the consistent data. A systematic study of the cross sections has shown that some data are discrepant due to the different measuring procedures, the adopted reference reactions and decay parameters. The recommended cross sections are given as the average of the most recent data [8-12, 16-80] by omitting those which show unrealistic deviations from the mean. The recommended (n,p) cross sections are summarized in Table 1.

The experimental data measured around 14 MeV can be extrapolated to a given incident neutron energy by using the following expression [27] for the slopes (m_T) of the excitation functions

$$\sigma_r (\%/MeV) = -19.1 + 137.8S + 1207S^2, \quad (1)$$

where $S = (N-Z)/A$ is the asymmetry parameter.

Kasugai et al. [27] have given the empirical formula, Eq. 2, to determine the σ_{14} values in a wide mass number region ($A=19-187$)

$$\sigma_{14} (\text{mb}) = 1830(N-Z+1)\exp(-50.7(N-Z+1)/A). \quad (2)$$

Equations (1) and (2) can be used for the estimation of the cross sections in the 14 MeV region. It was found in Ref. 15, that similarly to the (n,α) reactions, the isotopic dependence of the measured and deduced (n,p) cross sections can be well approximated by the following expression

$$\sigma_{n,p}(A)_{Z=\text{const}} = ae^{-bS-cS^2}, \quad (3)$$

where a , b , and c are fitting parameters. Some examples for the $\sigma_{n,p}(A)$ functions are shown in Fig. 1.

As shown in Fig. 1 the isotopic dependence of $\sigma_{n,p}$ values is not linear in a semi-log plot.

Using Eq. 3 61 unknown $\sigma_{n,p}$ data were deduced for nuclei having unfavourable decay properties. These cross sections are given in Table 2.

Total (n,p) cross sections were determined for 54 elements by averaging the $\sigma_{n,p}$ values over isotopic abundances. These data are summarized in Table 3.

The analyses of the available $\sigma_{n,p-em}$ values [1-14] and the recommended $\sigma_{n,p}$ data indicate that the (n,np) and (n,d) reactions are significant even for medium and heavy nuclei.

The fit of the empirical expression given by Levkovskii [81,82] to the data summarized in Tables 1 and 2 proved that the gross trend in the (n,p) cross sections is determined by the

asymmetry parameter S . A new formula (Eq. 5), with an additional term in the exponential, gives a substantial improvement in fitting the data [15]

$$\sigma_{n,p} = a(A^{1/3} + 1)^2 e^{-b(S + S^2)} = aB(A)e^{-b(S + S^2)} . \quad (5)$$

The values of a and b parameters are 23.659 ± 1.128 and 23.041 ± 0.507 , respectively.

In order to eliminate the two parameter dependence in Eq. 5, the $\sigma_{n,p}$ values were divided by the absorption term B .

$$R = \sigma_{n,p} / (A^{1/3} + 1)^2 = e^{-bS + cS^2} \quad (6)$$

Fitted R ratios and the values of a , b , and c parameters are given in Fig.2. This figure shows that the deviations from the gross trend are significant for magic Z numbers and deformed nuclei. The fits of the formulae to the data were based on the weighted least-squares method. To judge on the systematics quality the following quantity was determined $F = \Sigma(|\sigma_{\text{exp}} - \sigma_{\text{calc}}|) / \sigma_{\text{calc}}$. For weighting in F neither σ_{exp} nor $\Delta\sigma$ are recommended.

The quantity F/n , where n is the number of data points available in the intervals covered by the given systematics, can characterize the goodness of the formulae.

As shown in Table 4, the empirical formulae given by Eder et al. [83], Bychkov et al. [84], Forrest [11], Ait-Tahar [85], and Kasugai et al. [27] agree well with the recommended (n,p) cross sections in wide Z and A intervals without splitting the data library. It should be noted, however, that the formulae consisting of different parts for different regions of Z or A give better fits to the data. Histograms in Figs.3a, 3b and 3c show the fit of the different formulae to the (n,p) data given in Tables 1 and 2.

The systematic studies of the $\sigma_{n,p}$ data rendered possible to estimate some (n,p) cross sections both for long-lived target and residual radionuclides. These data are summarized in Table 5.

It should be noted, that the current version of the SINCROS-II system [88] is able to describe the (n,p) cross section curves up to 50 MeV. The SINCROS-II calculations [89-91] agree well with the 14 MeV data.

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Table 1. Some recommended (n,p) cross sections at 14.7 ± 0.2 MeV neutron energy

Target Element	Z	A	$\sigma \pm \Delta\sigma$ (mb)
B	5	11	4.2 ± 0.2
N	7	14	45.2 ± 6
O	8	18	2.3 ± 0.5
F	9	19	18.6 ± 0.88
Na	11	23	47.0 ± 2
Mg	12	24	183.6 ± 9
		25	88.04 ± 13
		26	39 ± 11
Al	13	27	70 ± 2
Si	14	28	238.7 ± 30
		29	135.33 ± 15
		30	70.04 ± 20
P	15	31	91.85 ± 3.48
S	16	32	237 ± 25
		33	134 ± 22
		34	78 ± 8
Cl	17	35	110 ± 10
		37	25.4 ± 3
K	19	39	314 ± 14
		41	51.36 ± 3
Ca	20	40	470.01 ± 50
		42	178.25 ± 12
		43	99.83 ± 13
		44	43.27 ± 6
Sc	21	45	57 ± 8
Ti	22	46	251 ± 13
		47	136 ± 9
		48	57.2 ± 2.7
		50	11.9 ± 6
V	23	51	33.3 ± 1.7
Cr	24	50	294 ± 30
		52	80 ± 4
		53	42 ± 2.1
		54	17.4 ± 1
Mn	25	55	45 ± 10
Fe	26	54	350 ± 15
		56	115 ± 6
		57	59 ± 4

Table 1. Cont.

Co	27	59	51±1
Ni	28	58	366±19
		60	148±8
		61	64±4
		62	37±4
Cu	29	63	70±13
		65	20.93±4
Zn	30	64	185±10
		66	73.3±8
		67	37.9±6
		68	15.2±2.5
Ga	31	69	64±5
		71	20.5±1.5
Ge	32	70	74±8
		72	31.6±1.4
		73	19.4±1.1
		74	10.1±0.5
		76	2.8±0.4
As	33	75	18.7±2.1
Se	34	74	112±7
		76	49±3
		78	19±1.1
Br	35	81	21±5
Kr	36	80	45±6
		82	23±5
		84	11±2
		86	5±1.5
Sr	38	84	95±8
		86	44±4
		88	17.4±2
Y	39	89	22.2±4.2
Zr	40	90	37±5
		91	29±4
		92	20.23±2.5
		94	7.5±1.1
Mo	42	95	41.3±2
		96	21.3±1.1
		97	14.6±0.8
Ru	44	96	146±8
		101	21.2±1.2
		104	6±0.7
Rh	45	103	17±3
Pd	46	102	93.6±15
		104	58±15
		105	38±2.9

Table 1. Cont.

Pd	46	106 108	22.5±6 4±1
Cd	48	106	130±24
		111	23.25±2.1
		112	16.1±3
		114	8.5±1.3
		116	2.96±0.3
In	49	115	13.26±2.95
Sn	50	116	14.6±2
		117	11.7±0.6
		119	7.1±0.8
		120	4.5±0.5
Te	52	122	10.5±1.5
		126	4.7±0.2
		128	2.9±0.1
		130	1.7±0.1
I	53	127	11.7±2
Xe	54	128	27±4
		131	6.1±0.6
Cs	55	133	10.5±2
Ba	56	132	15.3±3.5
		136	4.8±0.7
		138	2.18±0.15
La	57	139	4.5±1.1
Ce	58	140	7.05±0.7
		142	4.8±0.8
Pr	59	141	11.5±0.9
Nd	60	142	13.7±1.1
		143	11.5±2.3
		144	9.8±1.5
		145	7.25±1.6
		146	4.5±0.7
Sm	62	144	19±4
		148	9.8±0.8
		150	7±0.6
Eu	63	153	4.2±0.4
Gd	64	157	5.4±1.1
		158	3.2±1.2
Tb	65	159	5.1±0.4
Dy	66	158	10.6±1.2
		160	7±1.5
		162	4.3±1
		164	2.55±0.5
Er	68	166	4.5±0.7
		167	3.4±0.3

Table 1. Cont.

Er	68	168	2.8 ± 0.4
Yb	70	174	3 ± 0.2
Lu	71	175	4 ± 0.7
Ta	73	181	2.94 ± 0.18
W	74	182	6.5 ± 0.5
		184	2.61 ± 0.12
		186	1.25 ± 0.25
Re	75	187	3.73 ± 0.28
Os	76	184	9.30 ± 2
		188	4 ± 0.8
		190	2.2 ± 0.5
		192	1 ± 0.03
Au	79	179	2 ± 0.5
Hg	80	196	9.3 ± 1
		198	4.5 ± 0.8
		199	2.5 ± 0.5
Tl	81	203	4.2 ± 0.8
		205	1.9 ± 0.2
Bi	83	209	0.8 ± 0.3

Table 2. Deduced (n,p) cross sections using Eq. 3 at 14.7 ± 0.2 MeV

Target Element	Z	A	σ (mb)
S	16	36	28.6
Ca	20	46	9.2
		48	1.5
Ti	22	49	23.1
Fe	26	58	28.4
Ni	28	64	3.75
Zn	30	70	2.15
Se	34	77	30.9
		80	6.7
		82	2.16
Kr	36	78	81.4
		83	16
Sr	38	87	28.4
Zr	40	96	1.93
Mo	42	92	186.7
		94	69.4
		98	7
		100	1.96
Ru	44	98	68.1
		99	46.3
		100	31.3
		102	14.1
Pd	46	110	0.82
Cd	48	108	66.7
		110	33.3
		113	11.3
Sn	50	112	41.6
		114	25
		115	19.3
		118	8.7
		122	2.9
		124	1.68

Target Element	Z	A	σ (mb)
Te	52	120	14.3
		123	8.8
		124	7.2
		125	5.9
Ba	56	130	24.8
		134	8.7
		135	6.4
Ba	56	137	3.3
Nd	60	148	3.3
		150	1.9
Sm	62	147	11.6
		149	8.3
		152	5
		154	3.5
Dy	66	156	15.2
		161	5.5
		163	3.3
Er	68	162	11.4
		164	7.2
		170	1.66
W	74	180	15.2
		183	4.2
Os	76	186	5.96
		187	4.7
		189	2.9
Hg	80	200	1.85
		201	1.22
		202	0.8
		204	0.34

Table 3. Total (n,p) cross sections for elements at (14.7±0.2) MeV

Element	Z	σ_{tot} (mb)
N	7	45.2±6
O	8	2.3±0.5
F	9	18.6±0.9
Na	11	47.0±2
Mg	12	158.0±10
Al	13	70.0±2
Si	14	231.4±30
P	15	91.9±3.5
S	16	229.5±25
Cl	17	89.5±10
K	19	296.3±14
Ca	20	457.8±50
Sc	21	57.0±8
Ti	22	74.9±12
V	23	33.3±1.7
Cr	24	84.2±18
Mn	25	45.0±10
Fe	26	127.3±15
Co	27	51.0±1
Ni	28	290.1±19
Cu	29	54.9±13
Zn	30	114.7±10
Ga	31	46.6±5
Ge	32	29.8±8
As	33	18.7±2.1
Se	34	16.0±4
Kr	36	13.0±3

Element	Z	σ_{tot} (mb)
Sr	38	21.2±5
Y	39	22.2±4.2
Zr	40	27.1±5
Mo	42	47.5±2
Ru	44	28.3±4
Rh	45	17.0±3
Pd	46	23.2±4
Cd	48	17.2±5
Sn	50	8.1±2
Te	52	3.5±1
I	53	11.7±2
Cs	55	10.5±2
Ba	56	3.0±0.7
La	57	4.5±1.1
Pr	59	11.5±0.9
Nd	60	9.1±1.5
Sm	62	7.2±1
Tb	65	5.1±0.4
Dy	66	3.9±1
Er	68	3.4±0.7
Ta	73	2.9±0.2
W	74	3.5±0.5
Os	76	2.2±0.6
Au	79	2.0±0.5
Hg	80	1.7±0.5
Tl	81	2.6±0.3
Bi	83	0.8±0.3

Table 4. Comparison of (n,p) systematics at (14.7±0.2) MeV.

Author	Formula, σ (mb)	Mass region	n*	F/n
Levkovskii	$\sigma = \begin{cases} 55.3(A^{1/3} + 1)^2 \exp\left(-34.8 \frac{N-Z+1}{A+1}\right) \\ 49.4(A^{1/3} + 1)^2 \exp\left(-35.1 \frac{N-Z}{A}\right) \end{cases}$	19≤A≤40	17	0.468
		40≤A≤188	175	0.399
Eder et al.	$\sigma = \exp\left(1.31 + 0.806A^{1/2} - 10.3 \frac{N-Z}{A^{2/3}}\right)$	19≤A≤188	191	0.29
Bychkov et al.	$\sigma = 46.6(A^{1/3} + 1)^2 \exp\left\{\sqrt{\frac{A}{140}}\left(-53.3 \frac{N-Z+1}{A} + 0.622 \frac{Z-1}{A^{1/3}} - 3.20\right)\right\}$	40≤A≤188	175	0.307
Forrest	$\sigma = 11.23(A^{1/3} + 1)^2 \exp\left(-32.73 \frac{N-Z}{A} - 46.57\left(\frac{N-Z}{A}\right)^2 + 0.218A^{1/2}\right)$	40≤A≤188	175	0.254
Kumabe and Fukuda	$\sigma = \begin{cases} 27.9A \exp\left(-39.1 \frac{N-Z}{A}\right) \\ 0.58A^2 \exp\left(-42.3 \frac{N-Z}{A}\right) \\ 0.94A^2 \exp\left(-47.8 \frac{N-Z}{A}\right) \end{cases}$	40≤A≤62	25	0.200
		63≤A≤89	28	0.336
		90≤A≤188	113	0.289
Ait-Tahar	$\sigma = 140.2(A^{1/3} + 1)^2 \exp\left(-39.1 \frac{N-Z+1}{A}\right)$	40≤A≤188	175	0.309

Table 4. Cont.

Author	Formula, σ (mb)	Mass region	n*	F/n
Kasugai et al.	$\sigma = 1830(N - Z + 1)\exp\left(-50.7\frac{N - Z + 1}{A}\right)$	$19 \leq A \leq 188$	191	0.280
Korovin et al.	$\sigma = \pi r_0^2 (A^{1/3} + 1)^2$ $\times \left\{ A^{1.1128} \left(1.1242 \left(\frac{N - Z + 1}{A} \right)^2 - 0.73212 \left(\frac{N - Z + 1}{A} \right) + 0.11707 \right)^3 \right.$ $\left. + 0.4936 \exp \left(-194.69 \left(\frac{N - Z + 1}{A} \right)^2 - 5.3778 \left(\frac{N - Z + 1}{A} \right) \right) \right\}$	$11 \leq A \leq 209$	207	0.331
Present	$23.659(A^{1.3} + 1)^2 \exp\left(-23.041\left(\left(\frac{N - Z}{A}\right) + \left(\frac{N - Z}{A}\right)^2\right)\right)$	$11 \leq A \leq 209$	207	0.351

*Number of data points

Table 5. Estimated (n,p) cross sections for long-lived target and residual nuclei at 14.7 ± 0.2 MeV.

$T_{1/2}$ gives target $T_{1/2}$ /residual $T_{1/2}$ in years (if not stated otherwise).

Reaction	$T_{1/2}$	σ (mb)
$^{40}\text{Ca}(n,p)^{40}\text{K}$	$\infty/1.28 \cdot 10^9$	470 ± 50
$^{50}\text{Cr}(n,p)^{50}\text{V}$	$\infty/1.4 \cdot 10^{17}$	294 ± 50
$^{60}\text{Ni}(n,p)^{60}\text{Co}$	$\infty/5.27$	148 ± 8
$^{63}\text{Cu}(n,p)^{63}\text{Ni}$	$\infty/100.1$	70 ± 13
$^{92}\text{Mo}(n,p)^{92}\text{Nb}$	$\infty/3.47 \cdot 10^7$	186.7
$^{94}\text{Mo}(n,p)^{94}\text{Nb}$	$\infty/2.03 \cdot 10^4$	69.4
$^{108}\text{Cd}(n,p)^{108}\text{Ag}$	$\infty/2.37\text{m} + 418$	66.7
$^{134}\text{Ba}(n,p)^{134}\text{Cs}$	$\infty/2.062$	8.7
$^{135}\text{Ba}(n,p)^{135}\text{Cs}$	$\infty/2.3 \cdot 10^6 + 53\text{m}$	6.4
$^{137}\text{Ba}(n,p)^{137}\text{Cs}$	$\infty/30.07$	3.3
$^{158}\text{Dy}(n,p)^{158}\text{Tb}$	$\infty/180$	10.6 ± 1.2
$^{180}\text{W}(n,p)^{180}\text{Ta}$	$\infty/8.15\text{h} + >1.2 \cdot 10^{15}$	15.2
$^{32}\text{Si}(n,p)^{32}\text{Al}$	172/33ms	16
$^{41}\text{Ca}(n,p)^{41}\text{K}$	$1.03 \cdot 10^5/\infty$	263
$^{55}\text{Fe}(n,p)^{55}\text{Mn}$	2.73/ ∞	145
$^{59}\text{Ni}(n,p)^{59}\text{Co}$	$7.6 \cdot 10^4/\infty$	165
$^{60}\text{Fe}(n,p)^{60}\text{Mn}$	$1.5 \cdot 10^6/51\text{s} + 1.77\text{s}$	17
$^{63}\text{Ni}(n,p)^{63}\text{Co}$	100.1/27.4s	34
$^{79}\text{Se}(n,p)^{79}\text{As}$	$\leq 6.5 \cdot 10^4/9.01\text{m}$	17
$^{81}\text{Kr}(n,p)^{81}\text{Br}$	$2.29 \cdot 10^5/\infty$	39
$^{85}\text{Kr}(n,p)^{85}\text{Br}$	10.756/2.90m	12
$^{90}\text{Sr}(n,p)^{90}\text{Rb}$	28.78/158s+258s	11
$^{93}\text{Zr}(n,p)^{93}\text{Y}$	$1.53 \cdot 10^6/10.18\text{h} + 0.82\text{s}$	18
$^{93}\text{Mo}(n,p)^{93}\text{Nb}$	$4.0 \cdot 10^3/\infty + 16.13\text{y}$	63
$^{107}\text{Pd}(n,p)^{107}\text{Rh}$	$6.5 \cdot 10^6/21.7\text{m}$	20
$^{126}\text{Sn}(n,p)^{126}\text{In}$	$\approx 1 \cdot 10^5/1.6\text{s}$	2.7
$^{133}\text{Ba}(n,p)^{133}\text{Cs}$	10.52/ ∞	13
$^{146}\text{Sm}(n,p)^{146}\text{Pm}$	$10.3 \cdot 10^8/5.53$	17
$^{151}\text{Sm}(n,p)^{151}\text{Pm}$	90/28.40h	7.4
$^{154}\text{Dy}(n,p)^{154}\text{Tb}$	$3.0 \cdot 10^6/21.5\text{h} + 9.4\text{h} + 22.7\text{h}$	22
$^{194}\text{Hg}(n,p)^{194}\text{Au}$	520/38.02h+600ms+420ms	9.5

Fig 1. Isotopic dependence of $\sigma_{n,p}$ data

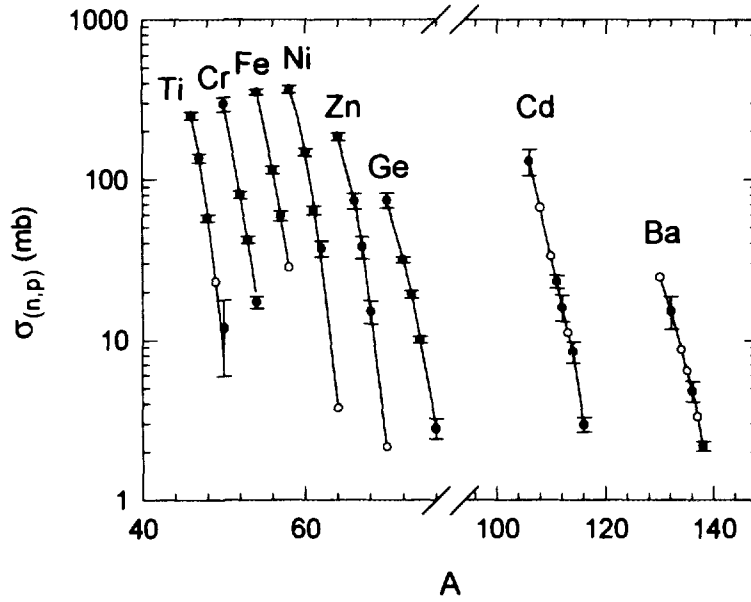
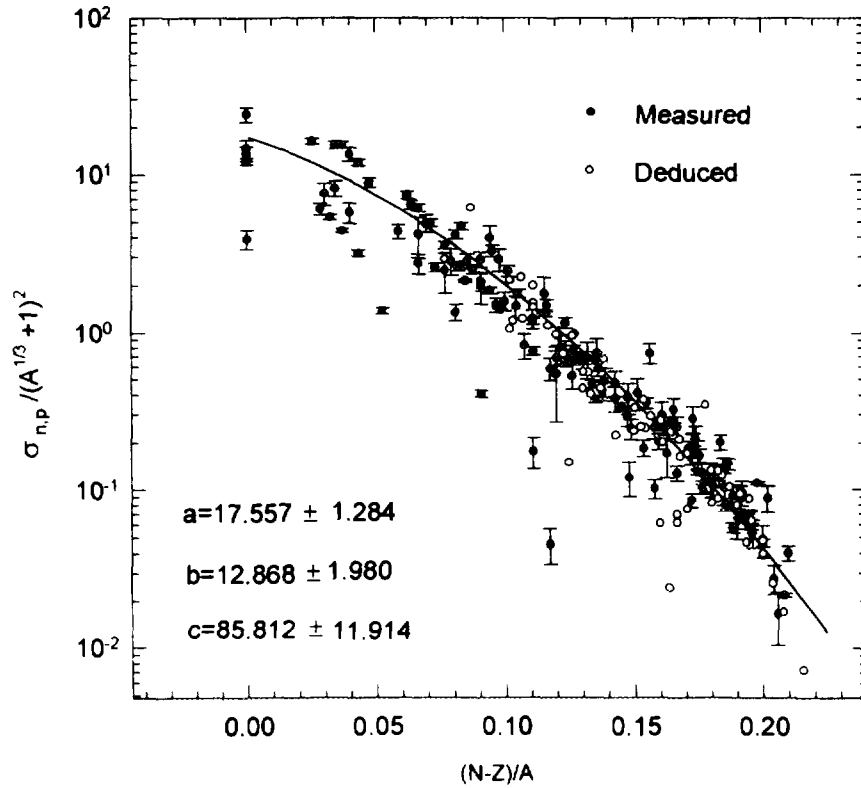


Fig 2. The value of $\sigma_{n,p}/(A^{1/3} + 1)^2$ as a function of $(N-Z)/A$



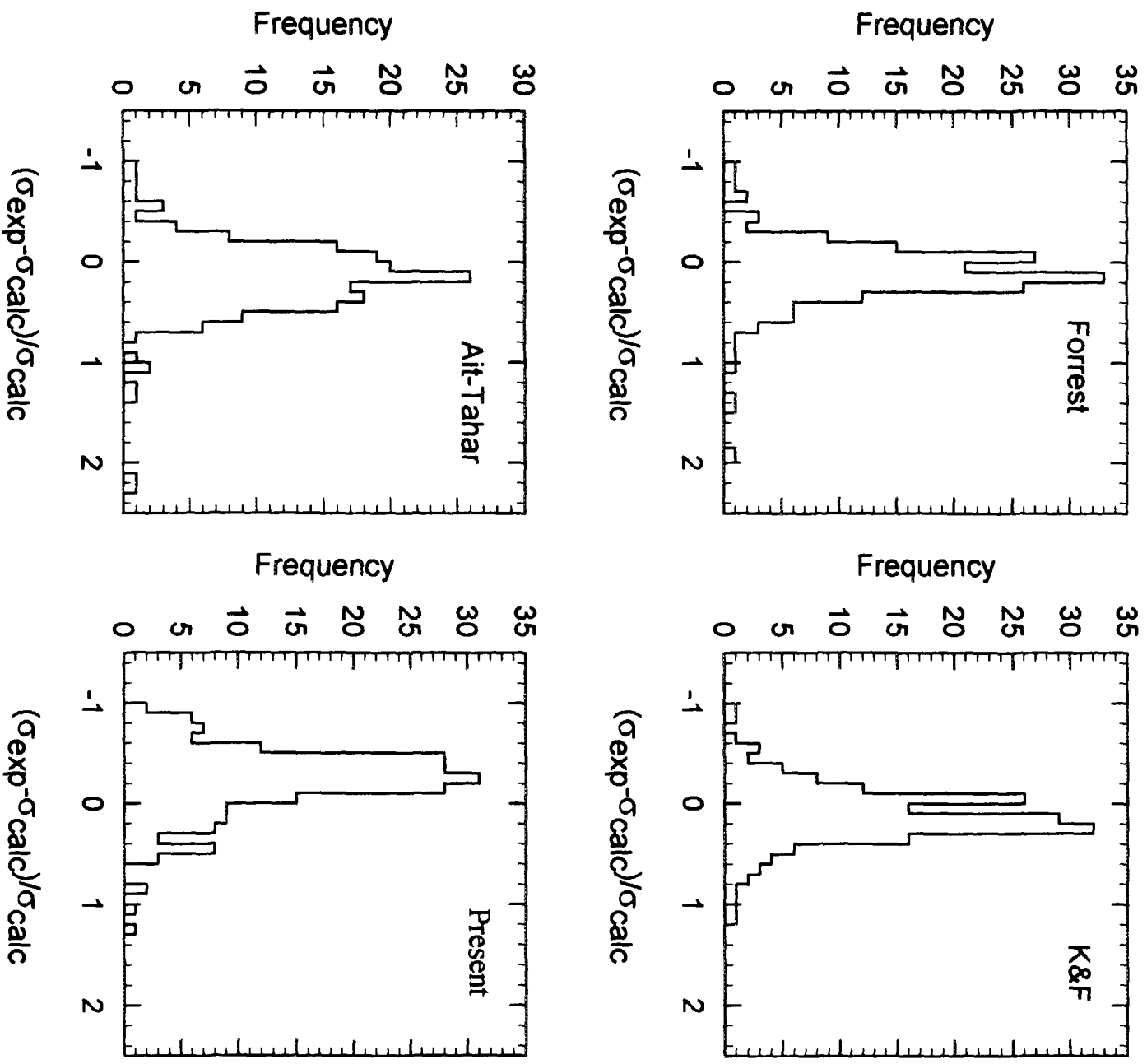


Fig. 3a The distribution of the deviations $((\sigma_{\text{exp}} - \sigma_{\text{calc}}) / \sigma_{\text{calc}})$ for (n,p) reactions.

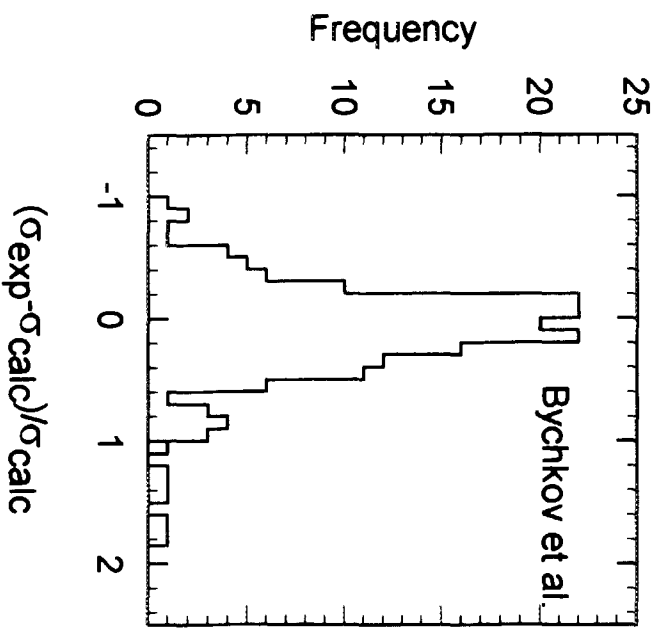
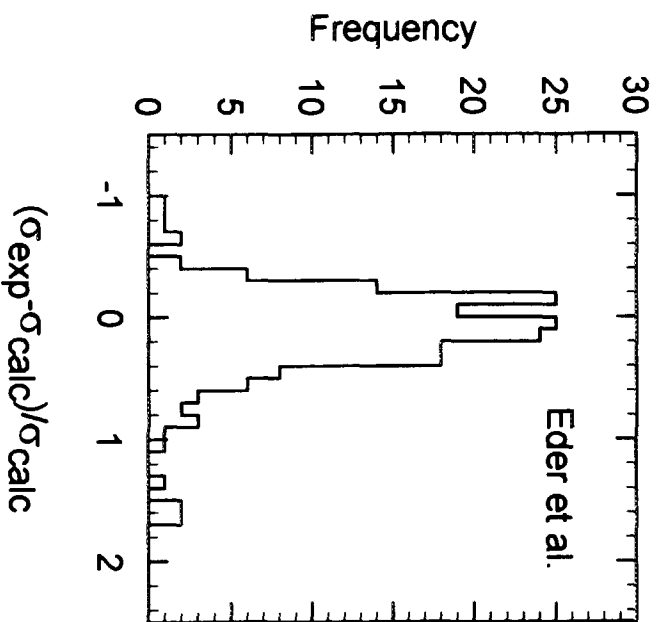
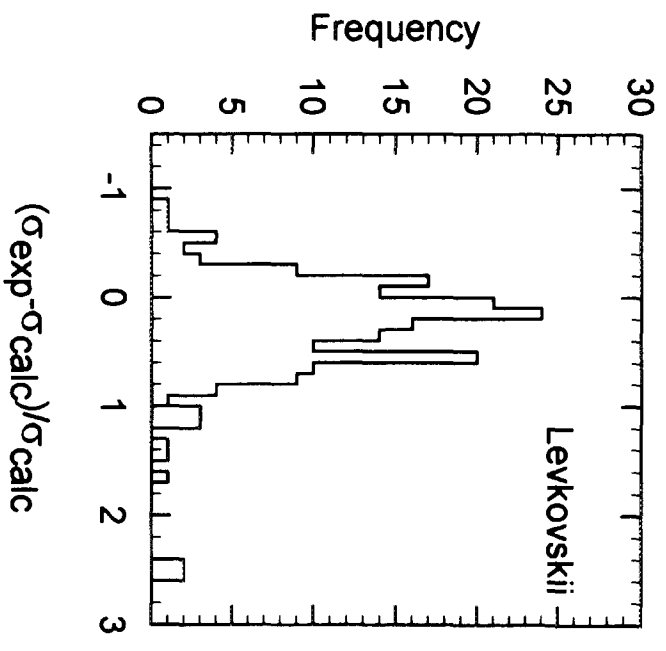
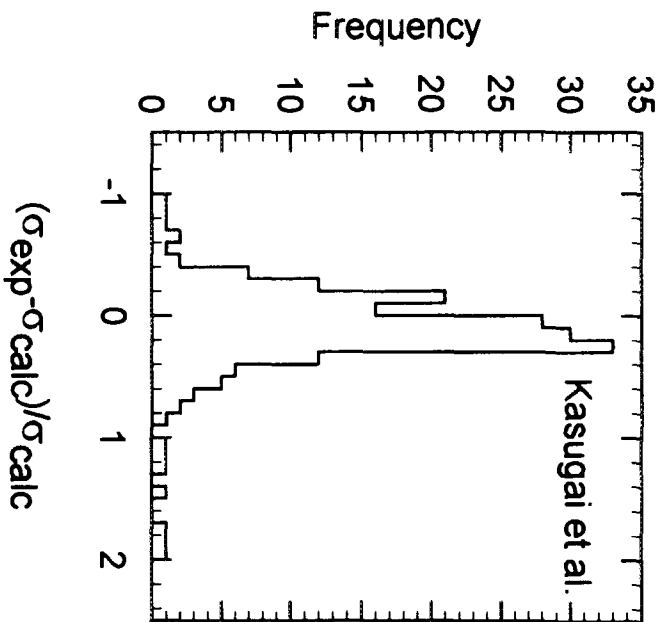


Fig. 3b The distribution of the deviations $((\sigma_{\text{exp}} - \sigma_{\text{calc}}) / \sigma_{\text{calc}})$ for (n,p) reactions.

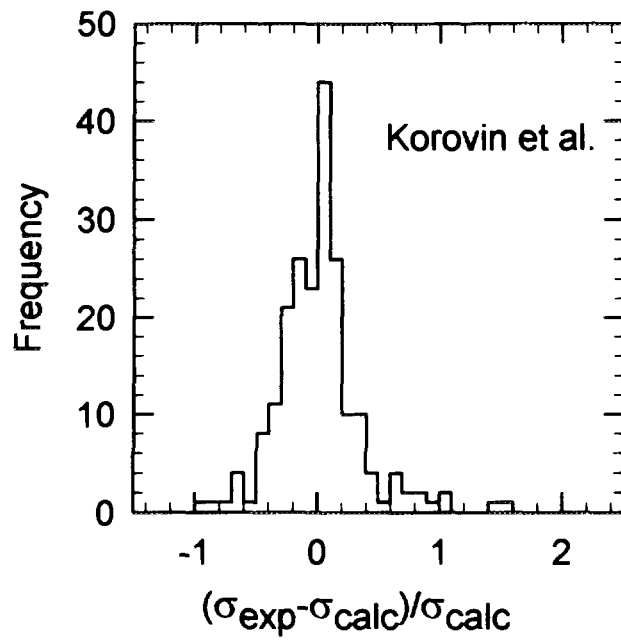


Fig. 3c The distribution of the deviations $((\sigma_{\text{exp}} - \sigma_{\text{calc}}) / \sigma_{\text{calc}})$ for (n,p) reactions.

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