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

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Cross sections have been measured, deduced and adopted for 183 (n,α) reactions at (14.7±0.1) MeV incident neutron energy. Analytical expressions based on the asymmetry parameter and isotopic dependences were improved for fitting the $\sigma_{n,\alpha}$ data. Different systematics were fitted to the same data base to be able to select the best formula. Total (n,α) cross sections are given for 51 elements and compared with the $\sigma_{n,\alpha\text{-em}}$ values. Some $\sigma_{n,\alpha}$ data both for long-lived target and residual radionuclides were estimated.

1. Introduction

During the last two decades a number of helium production cross sections have been measured for elements and isotopes at around 14 MeV neutron energy for the radiation damage assessment of fusion related materials. Details of investigations as well as data obtained by accumulation measurements and double-differential alpha-particle experiments can be found e.g. in Refs. [1-29]. A series of (n,α) activation cross section measurements has also been performed [24-26,28-72] in order to check and improve the model calculations as well as to explain the observed systematics, especially the (N-Z)/A and isotopic dependence of (n,α) cross sections.

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Precise data at 14 MeV are also indispensable for the normalization of excitation functions and to predict the neutron induced activity originated mainly from the long-lived radionuclides in candidate fusion reactor materials. Some new measured, deduced and estimated $\sigma(n,\alpha)$ data are given in this paper according to the scientific scope and proposed program goal of an international collaboration organized by the IAEA Nuclear Data Section for validation of different data libraries [73-76].

2. Experimental procedure

Several types of high purity (Goodfellow) natural metal samples of disk (19 mm diam.) and rectangular (10x15 mm) shaped and oxide powders pressed in pellets were prepared for irradiation. The thicknesses of the samples were selected in most cases between 0.2 and 1 mm according to the gamma energies to be detected. For the detection of beta, X-ray and soft-gamma radiations thin (0.05-0.2 mm) samples were irradiated and measured.

Neutrons were produced via the $^3H(d,n)^4He$ reaction using 180±5 keV magnetically analyzed deuteron beam and thick TiT target in a scattering free arrangement [26]. The neutron energy could be changed by placing the sample layers sandwiched between the activation dosimetry foils at different angels to the D^+ beam. Typical values of the average neutron energy and the energy distribution profile ($\pm 1/2$ FWHM) in MeV using about 0.1 sr solid angle as irradiation geometry are as follows: 14.78±0.17, 14.68±0.15, 14.42±0.12, 14.07±0.08, 13.73±0.10, 13.49±0.12, and 13.40±0.13 for the 0^o,30^o,60^o,90^o,120^o,150^o and 180^o emission angles, respectively [26,77,78]. Data indicate that the energy spread of neutrons is between ~0.5-1% in the 14 MeV region.

The low yields of (n,α) reactions on heavy elements require the use of extended samples in which the flux density spectra $\phi(E)$ can change significantly [79]. Therefore, the activation unfolding method used for the determination of the volume averaged $\phi(E)$ functions had to be improved [80]. The spectral shape of neutrons was unfolded by using about 12 reactions of different thresholds. The cross section curves of these reactions were taken from the IRDF-90 dosimetry file.

The absolute activity of the irradiated samples was determined by Ge(Li), HPGe and NaI gamma spectrometers. The peak area analysis was based on the program ACCUSPEC developed for IBM compatible personal computers. For the measurements of soft gammas and X-rays a HPGe with Be window, a Si(Li) and a gas flow proportional counter was used. The beta-particles were detected by a 4π proportional counter and an end-window GM counter.

developed for IBM compatible personal computers. For the measurements of soft gammas and X-rays a HPGe with Be window, a Si(Li) and a gas flow proportional counter was used. The beta-particles were detected by a 4π proportional counter and an end-window GM counter. The neutron flux variation in time were recorded by a fission chamber and a BF_3 "long-counter".

Corrections were made for the following effects; variation of the flux in time, gamma-, beta- and X-ray self-absorption, true coincidence, dead time, irradiation and measuring geometries, neutron attenuation in the sample [79,81]. The errors of the cross sections contain the following principal sources: counting statistics, detector efficiency, sample mass, decay constants, energy and fluence uncertainties, effect of low energy neutrons [82], reference cross sections. The decay data of the reaction products were taken from refs.[83, 84, 113].

3. Results and conclusions

Activation cross sections have been measured and deduced in Debrecen for 115 (n,α) reactions [60, 64, 85, 86, 87, 100, 109, 110, 114, 121] in the 14 MeV region.

The recent literature was studied in order to complete the list of adopted (n,α) cross sections with some additional consistent data. Therefore, in addition to the individual papers data summarized in compilations by Jessen et al. [108], Qaim [32], Bychkov et al. [30], Kneff et al. [2], Zhao Wenrong et al. [44], Manokhin et al. [59], Forrest [28], McLane et al. [25], CINDA libraries [24] and Kopecky [29] were also taken into account. A comprehensive review of 14 MeV cross sections for different reactions based on experimental data which were published prior to January 1990 was prepared by Pashchenko [31] . From these references $\sigma_{n,\alpha}$ data were adopted for 68 reactions. It was found that our recent results for (n,α) cross sections agree well with those obtained by Ikeda et al. [34,41] and Filatenkov et al. [40] in their systematic measurements. Furthermore, the new precise data support in most cases the adopted values given by Forrest [28]. The experimental data measured around 14 MeV can be extrapolated to a given incident neutron energy by using the following expression [41] for the slopes (m_r) of the excitation functions

$$m_r\,(\,\%\,/\,\mathrm{MeV}\,) = -\,17.86 + 275.19\,S \qquad (1)$$

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

In the formula (2) given by Kasugai et al. [41] for the prediction of $\sigma_{n,\alpha}$ values at 14 MeV incident neutron energy is recommeded to complete the pre-exponential term with the absorption cross section

$$\sigma_{14}(\mathrm{mb}) = 409.1\ e^{-33.0\ S}. \qquad (2)$$

Equation(1) and the modified eq.(2) can be used for the estimation of scanty and discrepant (n,α) cross sections in the 14 MeV region.

Considering the fact that during the last decades a number of new precise data were measured it semmed to be worthwhile to carry out a critical analysis of (n,α) cross sections for the generation of some long-lived and stable residual nuclei. The adopted cross sections summarized in Table 1 can be used as standard reference data for normalization of excitation functions and to test and improve the systematic formulae for the (n,α) reactions at 14 MeV.

The new measured and evaluated data have proved the previously observed [26, 86, 109] strong isotopic dependence of (n,α) cross sections. The measured and deduced $\sigma_{n,\alpha}$ data can be well approximated by the following [28, 86] expression

$$\sigma_{n,\alpha}(A)_{Z=\mathrm{const}} = ae^{-bS-cS^2}. \qquad (3)$$

Using eq.(3) 45 unknown $\sigma_{n,\alpha}$ data could be deduced for stable target nuclei. These (n,α) cross sections are given in Table 2. The total (n,α) cross sections ($\sigma^t_{n,\alpha}$) for 51 elements given in Table 3 have been determined by averaging the $\sigma_{n,\alpha}$ values over isotopic abundances. The reevaluated total (n,α) cross sections for elements agree well in most cases both with our previous recommendations [86] and the $\sigma_{n,\alpha\text{-em}}$ values measured by direct methods [1-22, 27, 45, 112]. The ratio $\sigma_{n,\alpha\text{-em}} / \sigma^t_{n,\alpha}$ is high for Al, Cu, and Nb except of the lightest nuclei indicating a significant contribution of the (n,nα) reaction to the helium emission at 14 MeV. In the case of copper the high $\sigma_{n,\alpha\text{-em}}$ value is caused mainly by the ^{63}Cu(n,nα) reaction [5]. Data obtained for ^{63}Cu by activation [60,86] and direct [5] methods are (41.1±2.3) mb and (56±10) mb, respectively. The $\sigma_{n,\alpha\text{-em}}$ value (8.1±0.8 mb) obtained [12] for In is higher by a factor of 3 as compared to the activation data. It was found that the shapes and magnitudes of $\sigma_{n,\alpha}(A)$ and $\sigma_{n,\alpha\text{-em}}(A)$ [1, 2, 5, 7, 9] functions agree well within the limits of errors for the Cr, Fe, Ni and Mo isotopes. This observation proves the possible use of eq.(3) for the approximation of the isotopic dependence of (n,α) cross sections. Results for Cr and Ni are demonstrated in Fig. 1. A comparison of the $\sigma^t_{n,\alpha}$ values measured by activation and direct methods indicates that the ratio $\sigma^t_{n,\alpha}(\mathrm{dir}) / \sigma^t_{n,\alpha}(\mathrm{act})$ is 1.15 in average for a wide range of elements. The 15% excess in helium emission may be the contribution of the (n,n'α) process.

The fine structure in the $\sigma^t_{n,\alpha}(Z)$ function at $Z < 20$ may be caused by the individual properties of nuclei while in the $24 \leq Z \leq 64$ interval around the gross trend a fluctuation exists with a $\Delta Z \approx 8$ period. The positions of the minima and maxima are at around Z=18, 24, 36, 52 and Z=20, 28, 42, 60, respectively.

The fit of the empirical expression given by Levkovskii [115,116] to the data summarized in Tables 1 and 2 has justified that the gross trend in the (n,α) cross sections is determined by the asymmetry parameter (S). A new formula (5) which has an additional term in the exponential is able to give a substantial improvement in fitting the data [28, 86]

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

The values of a and b parameters are 15.07±0.53 and 27.55±0.754, respectively.The mass number dependence of the nonelastic cross sections, B(A) α σ_{NE} (A), at around 14 MeV is given also in Refs.[105, 106].

As shown in Fig.2 the deviations from this 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. For the selection of the systematics the following quantity was determined $F=\Sigma(|\sigma_{exp} - \sigma_{calc}|)/\sigma_{calc}$. For weighting in F neither σ_{exp} nor $\Delta\sigma$ are recomended.

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

As shown in Table 4 our present formula is successful in wide Z and A intervals without splitting the data library. The small F/n values indicate the success of some other formulae in different Z and A regions. Histograms in Figs.3a and 3b show the fit of the different formulae to the (n,α) data given in Tables 1 and 2.

It should be noted that both the experimental data libraries and the empirical formulae were improved significantly during the last decade.

Similarly to the deduced $\sigma_{n,\alpha}$ values using eq. (3) the estimated data are based also on our incomplete experiments. For example, the $\sigma_{n,\alpha}$ values could be deduced from the measured isomeric cross section ratios by accepting the isomeric or ground state production cross sections. The references in Table 1 indicate the sources of the adopted data.

It was found that the ratio $\sigma^t_{n,\alpha}$/ B(A) vs (N-Z)/A in a semi-log plot shows a smooth line if the N and A values for a given element are averaged over the isotopic abundances in eq. (5). From the fitting of eq.(5) to the $\sigma^t_{n,\alpha}$ data given in Table 3 a value of a = 18.50 ± 0.52 was obtained. Using this a and the previous b values in eq.(5) $\sigma^t_{n,\alpha}$ data were calculated for a few elements given in Table 5 together with the measured cross sections.

The measured, deduced and calculated $\sigma_{n,\alpha}$ data rendered possible to recommend (n,α) cross sections both for long-lived target and residual radionuclides. These data are summarized in Table 6.

It should be noted that the current version of the SINCROS-II system [127] is able to describe the (n,α) cross section curves up to 50 MeV. The SINCROS-II calculations [128,129] agree well with the 14 MeV data [86,109].

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Table1. Some recommended (n,α) cross sections at 14.7±0.1 MeV neutron energy

Target Element	Z	A	Residual Nucleus	$\sigma \pm \Delta\sigma$ (mb)	Ref.
Li	3	6	^{3}H	32±3	104
		7	^{4}H	< 2	100, 104
Be	4	9	^{6}He	11±1.5	97, 98
B	5	11	^{8}Li	31±4	101, 102
C	6	13	^{10}Be	0.241±0.022	107
N	7	14	^{11}B	55±10	87, 88, 89
		15	^{12}B	18	31
O	8	16^{+}	^{13}C	98.8±6.4	11
		17	^{14}C	35.4±6.5	63
		18	^{15}C	7.6±1.7	90
F	9	19	^{16}N	25±2	63
Na	11	23	^{20}F	96±0.9	63
Mg	12	26	^{23}Ne	56±4	111
Al	13	27	^{24}Na	113±1.5	26
Si	14	30	^{27}Mg	73±17	34
P	15	31	^{28}Al	116±4.7	36
S	16	34	^{31}Si	63±8	P
Cl	17	35	^{32}P	114±15	88
		37	^{34}P	67±8	63
Ar	18	40	^{37}S	11.3±3	31
K	19	39	^{36}Cl	159±10	107
		41	^{38}Cl	35±2.5	34
Ca	20	40	^{37}Ar	126±6	118
		44	^{41}Ar	28±1.3	40
		48	^{45}Ar	1.5±0.4	P
Sc	21	45	^{42}K	53.7±2.6	109
Ti	22	46^{+}	^{43}Ca	94±18	9
		48	^{45}Ca	31±2	86
		50	^{47}Ca	8.6±0.6	109

Table 1. Cont.

Tablle Target Element	Z	A	Residual Nucleus	$\sigma \pm \Delta\sigma$ (mb)	Ref.
V	23	51	^{48}Sc	17±1	109
Cr	24	50^{+}	^{47}Ti	93±10	P
		52^{+}	^{49}Ti	38±4	P
		54	^{51}Ti	13.4±1.2	126
Mn	25	55	^{52}V	22±1.6	109
Fe	26	54	^{51}Cr	86±5	109
		56^{+}	^{53}Cr	45.4±1.7	112
		58	^{55}Cr	21±2.3	P
Co	27	59	^{56}Mn	31±1	109
Ni	28	58	^{55}Fe	105±7	P
		62	^{59}Fe	20.1±1.5	86
		64	^{61}Fe	5.5±0.8	111
Cu	29	63	^{60m}Co	13.0±2.6	60
			^{60g}Co	28.1±2.0	33, 60
			^{60}Co	45±2.0	110
		65	^{62m}Co	6.44±0.7	60
			^{62g}Co	5.52±0.8	60
			^{62}Co	11.3±1.5	86, 58
Zn	30	67^{+}	^{64}Ni	14.8	31
		68	^{65}Ni	9.6±0.7	33
		70	^{67}Ni	4.0±1.0	86
Ga	31	69	^{66}Cu	21.7±1.6	111
		71	^{68}Cu	6.5±1.0	P
Ge	32	72	^{69m}Zn	6.44±0.41	33
			^{69g}Zn	6.2±0.5	86
		74	^{71m}Zn	3.3±0.28	33
			^{71g}Zn	2.8±0.4	86
		76	^{73}Zn	2.6±0.3	P
As	33	75	^{72}Ga	11.22±0.66	67

Table 1. Cont.

Target Element	Z	A	Residual Nucleus	$\sigma \pm \Delta\sigma$ (mb)	Ref.
Se	34	77⁺	^{74}Ge	11.8±2	P
		78	^{75m}Ge	4.5±0.7	109
			^{75}Ge	8.6±0.5	67
		80	^{77m}Ge	1.1±0.2	109
			^{77}Ge	3.6±0.3	109
Br	35	79	^{76}As	12.7±1.5	31
		81	^{78}As	5±2	31
Rb	37	85	^{82}Br	6.43±0.46	33
		87	^{84m}Br	0.75±0.1	111
			^{84}Br	4±1	31
Y	39	89	^{86m}Rb	2.18±0.27	64
			^{86}Rb	7.5±1.7	64
Zr	40	90	^{87m}Sr	3.8±0.2	109
			^{87}Sr	15.4±1.6	P
		92	^{89}Sr	8.9±1.0	31
		94	^{91}Sr	4.7±0.3	109
		96	^{93}Sr	2.6±0.5	86
Nb	41	93	^{90}Y	9.0±0.5	120, 69
			^{90m}Y	5.2±0.33	119
Mo	42	92	^{89}Zr	26.2±1.2	109
			^{89m}Zr	6.8±0.3	40
		96	^{93}Zr	10.6±0.9	121
		98	^{95}Zr	5.9±0.3	109
		100	^{97}Zr	3.2±0.2	109
Tc	43	99	^{96}Nb	5.6±0.4	62
Ru	44	96	^{93}Mo	38±4	P
		102	^{99}Mo	6.2±0.7	32
		104	^{101}Mo	2.6±1.0	32
Rh	45	103	^{100}Tc	11.2±1.5	114

Table 1. Cont.

Target Element	Z	A	Residual Nucleus	$\sigma \pm \Delta\sigma$ (mb)	Ref.
Pd	46	104^+	^{101}Ru	9.0±1.0	P
		106	^{103}Ru	5.4±0.5	40
		108	^{105}Ru	2.9±0.4	86
Cd	48	112	^{109m}Pd	0.6±0.16	29
			^{109}Pd	2.6±0.5	31
		114	^{111m}Pd	0.3±0.03	109
			^{111g}Pd	0.5±0.1	32
		116	^{113}Pd	0.5	31
In	49	113	^{110}Ag	4.7±0.5	P
		115	^{112}Ag	2.3±0.2	109
Sn	50	118	^{115g}Cd	1.0±0.1	109
			^{115m}Cd	0.3±0.06	116
		120	^{117m}Cd	0.24±0.09	109
			^{117g}Cd	0.3±0.03	109
		122	^{119}Cd	0.25±0.05	P
I	53	127	^{124}Sb	1.4±0.2	31
Cs	55	133	^{130g}I	1.1±0.15	32
			^{130m}I	0.5±0.1	32
Ba	56	138	^{135}Xe	2.6±0.17	40
			^{135m}Xe	0.75±0.07	119
La	57	139	^{136}Cs	2.37±0.24	120
Ce	58	136	^{133}Ba	5.3	31
		138^+	^{135}Ba	4.1±0.5	P
		140^+	^{137m}Ba	3.0±0.8	125
			^{137}Ba	3.1±0.4	P
		142	^{139}Ba	2.3±0.6	32
Nd	60	142	^{139}Ce	5.5±0.4	109
		144	^{141}Ce	4.0±0.3	109
		146	^{143}Ce	3.5±0.3	109
		148	^{145}Ce	2.1±0.15	P

Table 1. Cont.

Target Element	Z	A	Residual Nucleus	$\sigma \pm \Delta\sigma$ (mb)	Ref.
Sm	62	150	^{147}Nd	3.0±0.2	32
		152	^{149}Nd	1.7±0.7	32
		154	^{151}Nd	0.9±0.1	31
Eu	63	151	^{148m}Pm	2.2±0.3	40
			^{148g}Pm	1.3±0.2	P
		153	^{150}Pm	1.66±0.19	33
Yb	70	174	^{171}Er	1.23±0.12	122
Hf	72	178	^{175}Yb	2.0±0.2	32
		180	^{177}Yb	0.90±0.53	33
Ta	73	181	^{178}Lu	0.95±0.15	P
W	74	182^{+}	^{179}Hf	1.25±0.1	P
		184	^{181}Hf	0.85±0.09	109
		186	^{183}Hf	0.54±0.05	109
Re	75	185	^{182}Ta	0.87±0.09	123
		187	^{184}Ta	0.56±0.1	33
Os	76	190	^{187}W	0.82±0.06	124
Tl	81	203	^{200g}Au	0.37±0.06	109
			^{200}Au	1.1	31
		205	^{202}Au	0.6±0.1	P
Pb	82	204^{+}	^{201}Hg	0.88±0.06	P
		206	^{203}Hg	0.57±0.04	109
		207^{+}	^{204}Hg	0.46±0.05	P
		208	^{205}Hg	0.35±0.04	109

P: Present measured and adopted data

+: Stable residual nuclei.

Table2. Deduced (n,α) cross sections at 14.7±0.1 MeV

Target Element	Z	A	Residual Nucleus	σ ± Δσ (mb)
Ca	20	42	^{39}Ar	74.5±8
		43	^{40}Ar	48±5
		46	^{43}Ar	7.6±1
Cr	24	53	^{50}Ti	23±3
Fe	26	57	^{54}Cr	31±3
Ni	28	60	^{57}Fe	55±4
		61	^{68}Fe	35±2.5
Zn	30	64	^{61}Ni	55±5
		66	^{63}Ni	23±1.5
Ge	32	70	^{67}Zn	22±1.8
		73	^{70}Zn	9±1
Se	34	74	^{71}Ge	19±1.4
		76	^{73}Ge	15±1.2
		82	^{79}Ge	1.2±0.3
Zr	40	91	^{88}Sr	12±1.1
Mo	42	94	^{91}Zr	17±1.6
		95	^{92}Zr	14±1.2
		97	^{94}Zr	8±0.9
Ru	44	98	^{95}Mo	26.5±2
		99	^{9}Mo	20.24±1.5
		100	^{95}Mo	15±1.2
		101	^{95}Mo	10.6±1.0

Table2. Cont.

Target Element	Z	A	Residual Nucleus	$\sigma \pm \Delta\sigma$ (mb)
Pd	46	102	^{97}Ru	13±1.6
		105	^{102}Ru	7±0.6
		110	^{107}Ru	1.4±0.2
Cd	48	106	^{103}Pd	50±6
		108	^{105}Pd	19±2
		110	^{107}Pd	7±0.8
		111	^{108}Pd	4.3±0.6
		113	^{110}Pd	1.54±0.16
Sn	50	112	^{109}Cd	17.5±1.8
		114	^{111}Cd	7.6±0.8
		115	^{112}Cd	5.0±0.6
		116	^{113}Cd	3.2±0.3
		117	^{114}Cd	2.15±0.2
		119	^{116}Cd	0.95±0.1
		124	^{121}Cd	0.12±0.02
Nd	60	143	^{140}Ce	5±0.7
		145	^{142}Ce	3.4±0.4
		150	^{147}Ce	1.3±0.3
Sm	62	147	^{145}Nd	6.7±0.8
		148	^{145}Nd	5.2±0.6
		149	^{146}Nd	4±0.5
W	74	180	^{177}Hf	1.85±0.2
		183	^{180}Hf	1.0±0.3

Table 3. Total (n,α) Cross Sections for Elements at (14.7±0.1) MeV

Target Element	Z	σ (n,α) (mb)	Target Element	Z	σ (n,α) (mb)
Li	3	32.0±3	Br	35	8.9±1.6
Be	4	11.0±1.5	Rb	37	5.8±1
N	7	54.9±10	Y	39	7.5±1.7
O	8	98.6±7	Zr	40	11.7±0.5
F	9	25.0±2	Nb	41	9.0±0.6
Na	11	96.0±1	Mo	42	12±0.3
Al	13	113±1.5	Ru	44	11.3±0.3
P	15	116±5	Rh	45	11.2±1.5
Cl	17	103±10	Pd	46	5.13±0.7
Ar	18	11.3±3	Cd	48	3.3±0.2
K	19	150.6±10	In	49	2.4±0.3
Ca	20	123.3±6	Sn	50	1.46±0.2
Sc	21	53.7±2.6	I	53	1.4±0.2
Ti	22	36.1±4	Cs	55	1.6±0.15
V	23	17±1	Ba	56	2.6±0.17
Cr	24	38.4±4	La	57	2.37±0.24
Mn	25	22.0±1.6	Ce	58	3.0±0.4
Fe	26	47.4±2	Nd	60	4.1±0.2
Co	27	31.0±1	Sm	62	3.5±0.7
Ni	28	87.0±5	Eu	63	2.54±0.4
Cu	29	34.6±2	Ta	73	0.95±0.15
Zn	30	35.5±1.8	W	74	0.90±0.1
Ga	31	15.6±1.5	Re	75	0.68±0.09
Ge	32	11.3±1	Tl	81	0.75±0.1
As	33	11.2±0.7	Pb	82	0.43±0.04
Se	34	7.5±0.6			

Table 4 Copmarision of (n,α) systematics at (14.7 ± 0.1) MeV

Author	Formula , σ (mb)	Mass region	n	F/n
Levkovskii	$\sigma = 28.14\left(A^{1/3}+1\right)^2 \exp\left(-38.44\frac{N-Z}{A}\right)$	$31 \le A \le 202$	142	0.476
Forrest	$\sigma = \begin{cases} 22.08\left(A^{1/3}+1\right)^2 \exp\left\langle -14.01\frac{N-Z}{A} - 70.48\left(\frac{N-Z}{A}\right)^2 - 0.0196A \right\rangle \\ 23.24\left(A^{1/3}+1\right)^2 \exp\left\langle -2.79\left(\frac{N-Z}{A}\right) - 0.0408A \right\rangle \end{cases}$	$20 \le Z \le 50$ $50 \le A \le 82$	100 65	0.357 1.28
Kumabe & Fukuda	$\sigma = \begin{cases} 63.73A^{1/2} \exp\left(-32.2\frac{N-Z}{A}\right) \\ 66.48A^{1/2} \exp\left(-35.9\frac{N-Z}{A}\right) \\ 0.0000299A^3 \exp\left(-20.2\frac{N-Z}{A}\right) \end{cases}$	$30 \le A \le 60$ $61 \le A \le 105$ $106 \le A \le 140$	31 54 30	0.217 0.296 0.933
Ait-Tahar	$\sigma = 74.91\left(A^{1/3}+1\right) \exp\left(-42.1\frac{N-Z+1}{A}\right)$	$40 \le A \le 188$	137	0.503
Kasugai et al.	$\sigma = 434.8 \exp\left(-33.4\frac{N-Z}{A}\right)$	$19 \le A \le 188$	146	0.483

Table 4 Cont.

Author	Formula , σ (mb)	Mass region	n	F/n
Shubin et al.	$\sigma = \begin{cases} \pi r_o^2\left(A^{1/3}+1\right)^2 \exp\left(-209.11\left(\frac{N-Z+1}{A}\right)^2 + 8.4723\left(\frac{N-Z+0.5}{A}\right) - \frac{0.19253Z}{A^{1/3}} - 0.96249\right) \\ \pi r_o^2\left(A^{1/3}+1\right)^2\left(-1.6462\left(\frac{N-Z+0.5}{A}\right)+0.39951\right)^3 \end{cases}$	$Z \leq 50$ Z>50	122 41	0.409 0.321
	$r_o = 1.3$ fm			
K. Gul	$\sigma = \left(A^{1/3}+1\right)^2 \exp\left[a_0 + a_1\frac{(Z-1.5)}{TA^{1/3}} + a_2\frac{(A-2Z+0.5)}{TA} + a_3\frac{(Z-2)}{E_i A^{1/3}}\right]$	$Z \geq 20$	162	0.336
	T:nuclear temperature and E_i:excitation energy of compound nucleus			
Present	$\sigma = 15.0678\left(A^{1/3}+1\right)^2 \exp -27.55\left\{\left(\frac{N-Z}{A}\right)+\left(\frac{N-Z}{A}\right)^2\right\}$	$19 \leq A \leq 206$	163	0.322

n= Number of data points

Table 5. A comparision of the measured and calculated $\sigma^{t}_{n,\alpha}$ data.

Element	σ^{t}_{act}(mb)	σ^{t}_{dir}(mb)	σ^{t}_{calc}(mb)
Al	113±1.5	132±16	118±12
Si	-	216±11	284±24
Ti	36.1±4	38±2	33.3±3.2
V	17±1	17.8±2	20.5±2
Cr	38.4±4	39.3±6	37.3±4
Mn	22±1.6	25.3±1.5	25.4±2
Fe	47.4±2	45.3±3	47.1±2.1
Co	31±1	36.4±2	30.5±1.8
Ni	87±5	97±5	90.2±4
Cu	34.6±2	46.5±5	27.5±3
Y	7.5±1.7	8.6±2	9.3±2
Zr	11.7±0.5	10.1±0.7	9.2±1.5
Nb	9±0.6	14±1.5	11±1.0
Mo	12±0.3	14±1	8.8±2
Ag	-	7.6±0.6	7.75±1
In	2.4±0.3	8.1±0.9	4.35±0.5
Sn	1.46±0.2	1.5±0.1	3±0.3
Ta	0.95±0.15	1.1±0.1	0.91±0.1
Pt	-	0.7±0.1	0.7±0.1
Au	-	0.5±0.04	0.77±0.15
Pb	0.43±0.04	0.6±0.05	0.53±0.04

Table 6 Estimated (n,α) cross sections for long-lived target and residual nuclei at 14.7±0.1 MeV.(target $T_{1/2}$/residual $T_{1/2}$)

Reaction	Half-life	σ(mb)
^{41}Ca(n,α)^{38}Ar	1.03 10^5 y / ∞	104.35
^{45}Ca(n,α)^{42}Ar	162.6 d / 33 y	14.9
^{51}Cr(n,α)^{48}Ti	27.7 d / ∞	60.7
^{55}Fe(n,α)^{52}Cr	2.73 y /∞	63.7
^{59}Ni(n,α)^{56}Fe	7.6 10^4 y / ∞	80
^{63}Ni(n,α)^{60}Fe	100.1 y / 1.5 10^6	11
^{75}Se(n,α)^{72}Ge	119.8 d / ∞	17.8
^{79}Se(n,α)^{76}Ge	≤ 6.5 10^5 y / ∞	5.8
^{93}Zr(n,α)^{90}Sr	1.53 10^6 y / 28.8 y	6.6
^{95}Zr(n,α)^{92}Sr	64 d / 2.7 h	3.5
^{93}Mo(n,α)^{90}Zr	4.0 10^3 y / ∞	21.6
^{107}Pd(n,α)^{104}Ru	6.5 10^6 y / ∞	4
^{109}Cd(n,α)^{106}Pd	462 d / ∞	11.6
^{133}Ba(n,α)^{130}Xe	3854 d / ∞	3.65
^{145}Sm(n,α)^{142}Nd	340 d / ∞	10.7
^{146}Sm(n,α)^{143}Nd	10.3 10^7 y / ∞	9.2
^{151}Sm(n,α)^{148}Nd	90 y / ∞	4.8

Table 6 Cont.

Reaction	Half-life	σ(mb)
$^{150}Gd(n,\alpha)^{147}Sm$	$1.79\ 10^6$ y / ∞	5.8
$^{154}Gd(n,\alpha)^{151}Sm$	∞ / 90 y	2.7
$^{154}Dy(n,\alpha)^{151}Gd$	$3\ 10^3$ y / 124 d	6.8
$^{185}W(n,\alpha)^{182}Hf$	75.1 d / $9\ 10^6$ y	0.68
$^{202}Pb(n,\alpha)^{199}Hg$	$5.25\ 10^4$ y / ∞	1.36
$^{205}Pb(n,\alpha)^{202}Hg$	$1.53\ 10^7$ y / ∞	0.71
$^{210}Pb(n,\alpha)^{207}Hg$	22.3 y / 2.9 m	0.23

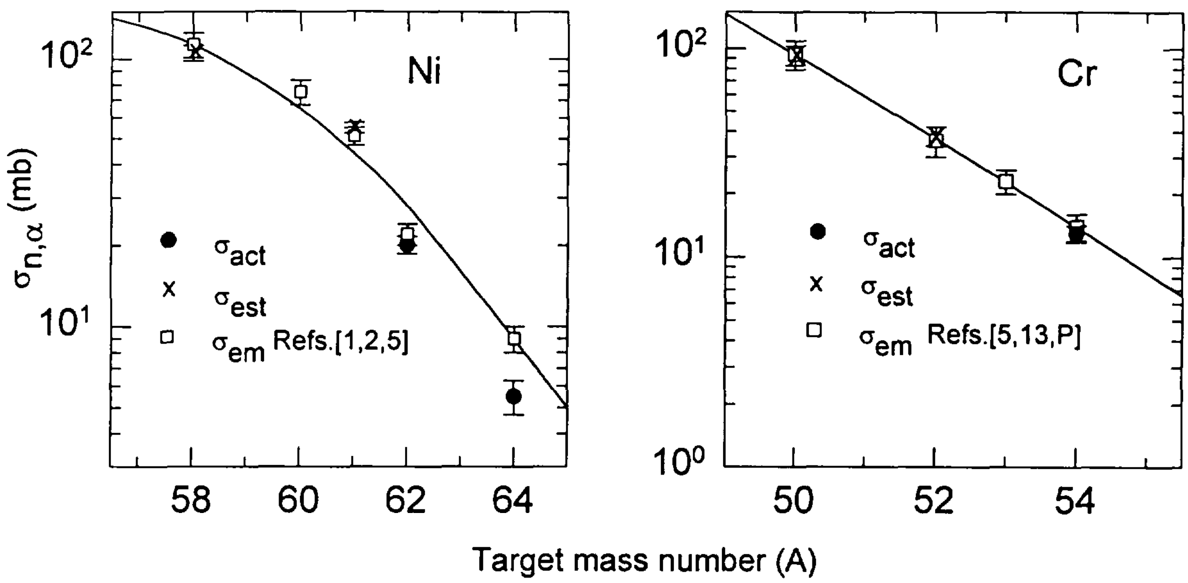

Fig.1. Isotopic dependence of $\sigma_{n,\alpha}$ data for Ni and Cr.

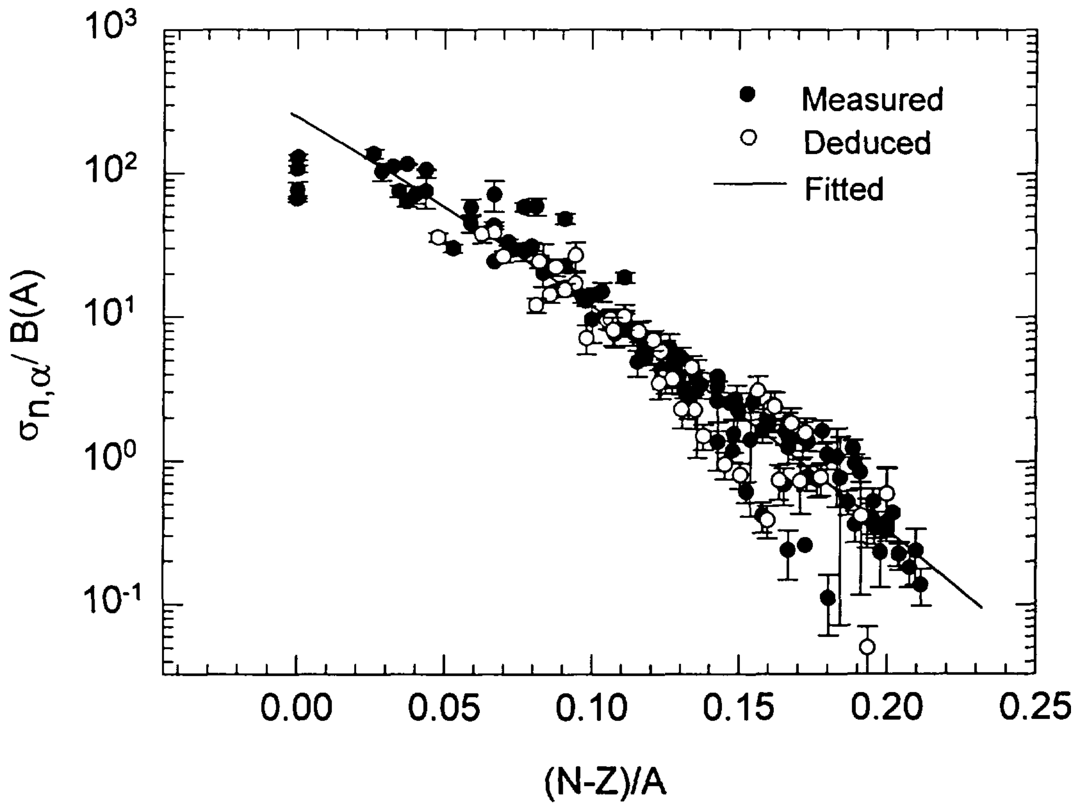

Fig.2. The value of $\sigma_{n,\alpha}/B(A)$ as a function of (N-Z)/A.

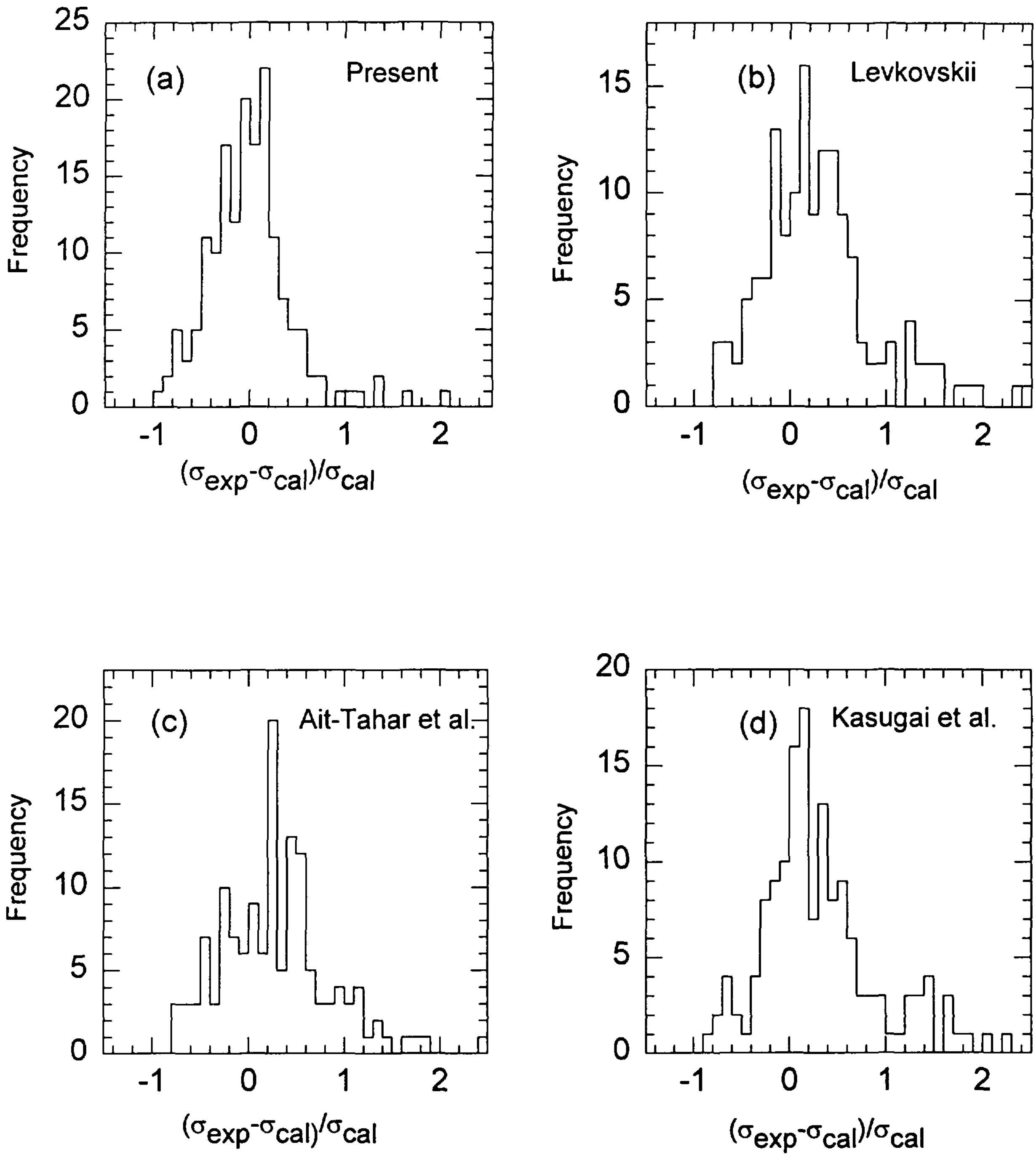

Fig.3a The distribution of the deviations $((\sigma_{exp}-\sigma_{cal})/\sigma_{cal})$ for (n,α) reactions.

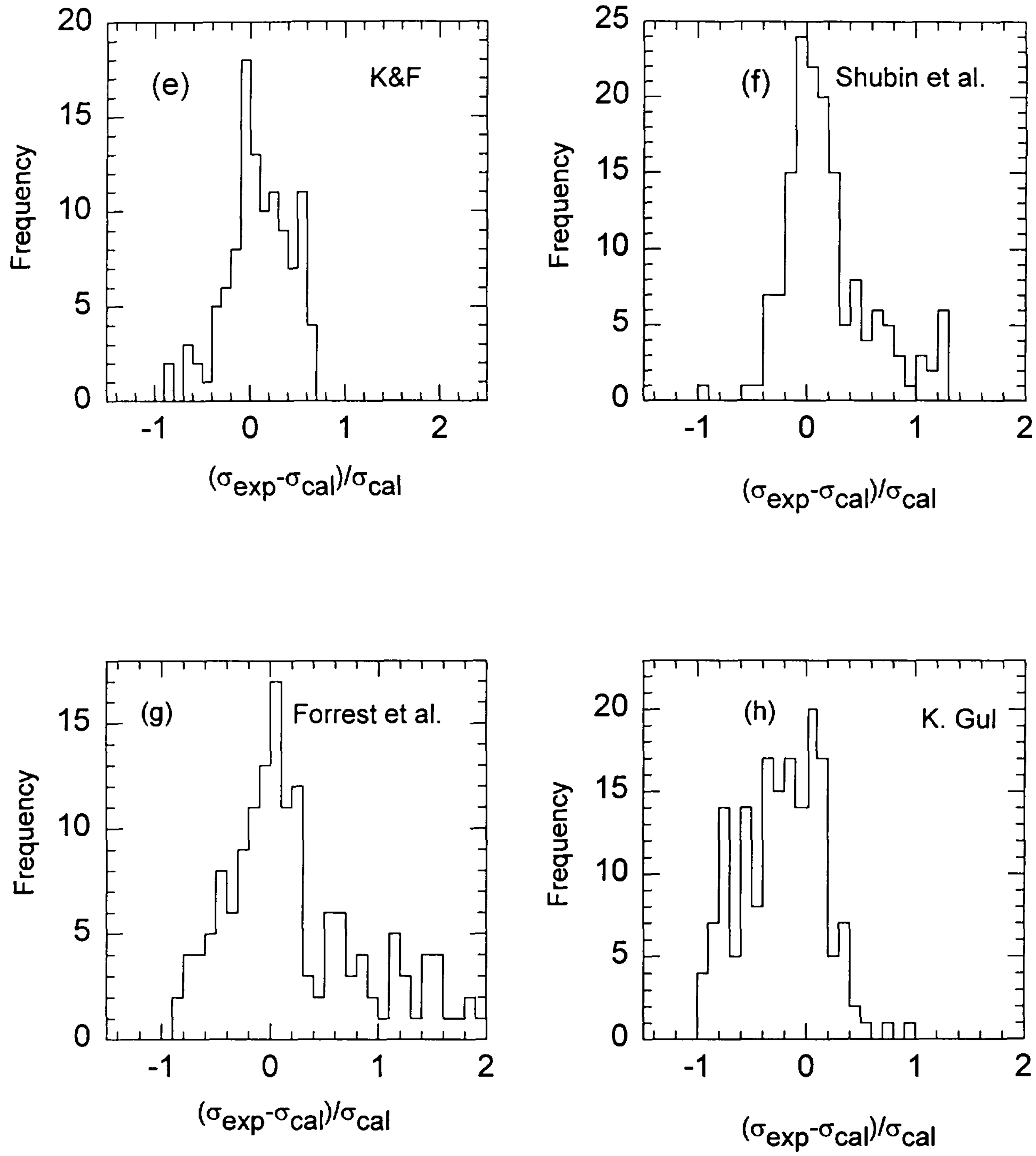

Fig.3b. The distribution of the deviations ($(\sigma_{exp}-\sigma_{cal})/\sigma_{cal}$) for (n,$\alpha$) reactions.

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