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A NEW EMPIRICAL RULE FOR THE PREDICTION OF AROUND 14 MeV NEUTRON REACTION CROSS SECTIONS

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Abstract: A formula with which we can predict the values of the (n,p), (n,α) and (n,2n) reaction cross sections at around 14 MeV is found as an extension of the empirical rule by Horibe[1] for the U-235 fission neutron spectrum averaged cross sections. The grouping of experimental data according to the neutron excess number of target nuclei is essential. Cross sections thus obtained are particularly in good agreement with the experimental ones on light nuclei.

(14 MeV neutron, cross section, prediction, empirical formula, neutron excess number)

Introduction

A large number of theoretical and empirical formulae for the cross sections of reactions such as (n,p), (n,α) and (n,2n) at around 14 MeV have been proposed by many authers.[2-12]

Prediction formulae for these reactions have yielded some success, but they are inadequate for the calculations of cross sections of nuclei of which mass numbers are less than ca. 30.

We have tried to apply our empirical rule[1] for the estimation of the fission spectrum averaged (n,p) and (n,α) reaction cross sections to this problem and it was found that our formula, when modified, works well also to predict monochromatic neutron reaction cross sections.

Basis of the prediction formula

In the course of the search for the empirical rule to represent the fission neutron spectum averaged reaction cross sections, it became clear that the cross section σ_o, which was defined by Hughes[13], can be given by the following equation for outgoing charged particles with sufficient energy,

$$\sigma_o = A^{2/3}\exp[\alpha(E_T + \underline{a}A) + \beta],$$

where A is the mass-number of target nucleus, α a constant almost insensitive to neutron energy, E_T the threshold reaction energy, $\underline{a}$ a constant but takes different values when the neutron excess number of the target nucleus is changed, and β a normalization constant.

Then, a prediction formula we propose for the (n,p), (n,α) and (n,2n) reaction cross sections at around 14 MeV is,

$$\sigma = \sigma_o \exp[-c(N-Z)/A] ,$$

or

$$\ln\sigma - (2/3)\ln A + c(N-Z)/A = \alpha(E_T + \underline{a}A) + \beta, \qquad (1)$$

where c is a constant and N and Z the neutron and proton number of the target nucleus. It is to be noted that Levkovskii[8] had proposed a similar formula,

$$\sigma = \sigma_{ne}\exp[-c(N-Z)/A],$$

to predict the cross sections of (n,p) and (n,α) reactions, and the nonelastic cross section σ_{ne} in this equation corresponds to our σ_o.

Actual value of the constant $\underline{a}$ in Eq. (1) is determined from the empirical systematic relation between A and E_{eff} of nuclei with the same neutron excess number, where E_{eff} is the effective threshold energy defined by Hughes[13]. The values of a are shown in Fig. 1 as a function of (N-Z) and those for the (n,p) reaction is 0.102 MeV for target nuclei with (N-Z)=0 and decreases monotonously to 0.048 MeV for the nuclei with (N-Z)=44. Similarly for the (n,α) reaction, it changes from 0.274 MeV to 0.109 MeV. Values of $\underline{a}$ for the (n,2n) reaction are obviously zero.

Grouping of experimental data and estimation of α, β and c

There are gross accumulation of cross section data on the reactions (n,p), (n,α) and (n,2n) on various nuclei at around 14 MeV. However, those on the (n,α) and (n,2n) cross sections of even Z-odd N nuclei are rather rare. The neutron source is mostly D-T reaction neutrons, and the cross sections are measured mostly by the activation method. But regretfully, the measured values scatter very much, and one must evaluate these data and get most reliable values. Bormann et al.[14] had proposed recommended data values for these (n,p), (n,α) and (n,2n) reaction cross sections after their laborious studies. Neutron energies are 14.1, 14.5 and 14.9 MeV. We treat these recommended vaules as a basis of our prediction formula and several data were also referred to.

The grouping of these data was done so as to give linear relations in Eq. (1). E_T values

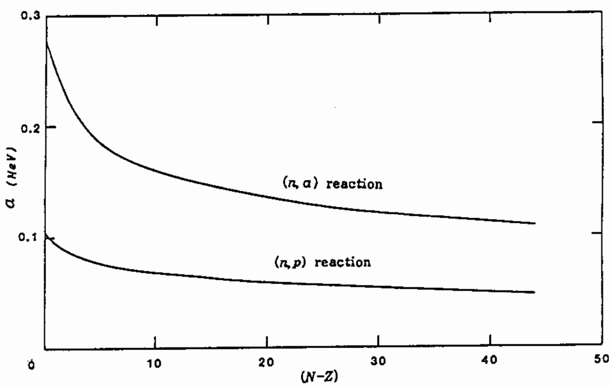

Fig. 1. Plot of values of $\underline{a}$ in Eq. (1) as a function of (N-Z) value.

Table 1. (N-Z) value of target nuclei which indicate the grouping of nuclei, and the parameter α, β and c, best fit to the linear function of (E_T+aA) value.

(a) (n,p) Reaction

N-Z	Neutron Energy(MeV)	α (MeV^{-1})	β	c	Fitting range of (E_T+aA) (MeV)		Num.of data Sampled
0	14.1	-0.170	3.98	-	11.90	4.02	5
	14.5	-0.180	4.16		11.90	4.02	4
	14.9	-0.371	5.32		14.91	4.02	5
1	14.1	0.181	4.16	80	6.07	2.61	6
	14.5	0.170	4.52	90	6.07	2.61	7
	14.9	0.301	4.29	100	11.02	3.60	7
3	14.1	0.518	12.6	190	7.28	3.23	5
	14.5	0.543	11.8	180	7.28	3.23	4
	14.9	0.610	11.4	180	7.28	3.23	4
5,7	14.1	-0.0406	6.06	50	6.77	4.10	9
	14.5	-0.0772	6.31	50	6.77	4.10	10
	14.9	-0.103	6.45	50	6.77	5.07	9
2,4, 6,8	14.1	-0.168	5.22	30	10.86	4.36	21
	14.5	-0.237	4.86	20	10.37	4.36	23
	14.9	-0.139	5.00	30	10.86	4.36	26
9,11, 13,15	14.1	0.498	11.8	120	7.41	5.27	9
	14.5	0.127	4.13	40	8.77	5.27	14
	14.9	0.424	3.54	50	7.41	4.87	13
10~54 (even)	14.1	0.0834	4.54	40	12.25	6.46	20
	14.5	-0.101	4.69	30	14.25	6.83	44
	14.9	-0.0767	5.09	40	12.25	6.46	35
17~53 (odd)	14.1	-0.900	6.40	0	10.63	7.81	8
	14.5	0.0191	5.30	40	10.73	7.31	25
	14.9	0.220	5.13	50	10.73	6.82	15

(b) (n,α) Reaction

N-Z	Neutron Energy(MeV)	α (MeV^{-1})	β	c	Fitting range of (E_T+aA) (MeV)		Num.of data Sampled
0,1,2	14.1	0.133	1.53	10	11.63	3.02	11
	14.5	-0.0952	3.22	0	11.63	7.03	7
	14.9	-0.00537	2.92	10	11.63	7.03	8
3,5, 7,9	14.1	-0.0144	4.34	40	11.68	8.58	8
	14.5	-0.0966	4.25	30	11.68	8.58	9
	14.9	0.0655	3.51	40	11.68	8.58	10
4,6, 8,10	14.1	0.263	2.30	50	12.69	10.57	6
	14.5	0.135	0.571	20	12.69	10.57	7
	14.9	0.0265	2.83	30	13.38	10.57	14
11~53 (odd)	14.1	-0.123	3.70	30	15.24	9.50	7
	14.5	-0.241	4.12	20	15.38	9.50	15
	14.9	0.00833	4.09	40	16.82	9.50	13
12~20 (even)	14.1	-0.775	5.01	-20	15.67	10.70	9
	14.5	-0.495	5.99	10	15.07	10.70	8
	14.9	-0.0708	6.57	50	14.26	10.70	11
22~54 (even)	14.1	0.410	9.24	90	15.62	11.21	5
	14.5	-0.113	8.57	50	16.61	11.89	13
	14.9	-0.382	6.53	20	15.67	11.89	11

(c) (n,2n) Reaction

N-Z	Neutron Energy(MeV)	α (MeV^{-1})	β	c	Fitting range of (E_T+aA) (MeV)		Num.of data Sampled
1	14.1	0.385	-10.7	-160	13.43	10.98	4
	14.5	0.504	-11.8	-160	13.43	10.98	4
	14.9	0.297	-7.97	-130	13.43	10.98	4
3,5	14.1	-1.06	16.0	10	11.57	10.41	4
	14.5	-1.33	20.6	30	11.57	10.41	4
	14.9	-0.832	13.6	10	11.57	10.41	4
0,2, 4,6	14.1	-0.657	6.76	-50	13.63	11.22	10
	14.5	-0.368	3.51	-50	13.63	11.22	8
	14.9	-0.276	2.58	-50	13.63	11.22	9
8,10, 12,14	14.1	-0.0597	3.22	-10	12.11	9.56	7
	14.5	0.0301	2.33	-10	12.11	9.38	11
	14.9	0.0167	2.59	-10	12.11	9.35	9
7, 9, 11,13	14.1	-0.215	6.22	0	11.60	10.05	6
	14.5	-0.183	5.95	0	11.60	10.05	6
	14.9	-0.141	5.57	0	11.60	10.05	6
15~53 (odd)	14.1	1.09	-10.8	-30	9.47	5.33	9
	14.5	0.952	-7.77	-20	9.50	6.65	12
	14.9	0.910	-7.28	-20	9.50	6.65	15
16~38 (even)	14.1	-0.162	7.20	10	10.62	7.21	12
	14.5	-0.0567	4.61	0	10.62	7.21	27
	14.9	-0.0363	4.44	0	10.62	6.92	22
40~54 (even)	14.1	1.09	-14.8	-50	8.44	6.17	5
	14.5	1.37	-21.2	-70	8.44	6.17	6
	14.9	1.43	-21.6	-70	8.44	6.17	6

on right hand side of Eq. (1) were cited from the work by Calamand[15]. Actual procedure was trial and error method. A guiding principle was that the nuclei with the same neutron excess number, or with odd excess number, or with even excess number should be classified separately into one group. The result is shown in Table 1.

In our formula, three kinds of parameters, α, β and c are used. We can estimate these parameter values simultaneously if data points which belong to the same group exceed four. In each grouped data, the best fit value of c was at first searched by varying numerical values of c from 500 to -500 in 10 steps. Fitted values of α, β and c are also presented in Table 1. The linear relation of Eq.(1) is hold as shown in Fig. 2 as an example. The neutron energy is 14.5 MeV in this case.

Estimated values of cross section

Using the best fit values of the parameters, shown in Table 1, the cross sections were calculated with Eq. (1), and then confidence intervals for the predicted values were estimated under 95% confidence level. The predicted values are shown in Table 2 (see the last page of this text) and also shown their confidence intervals as $\pm\Delta\sigma/\sigma$ in %. In the table, experimental data, cross sections of (n,p) and (n,α) reactions calculated with Levkovskii's formulae, and cross sections of the (n,2n) reaction at 14.4 MeV calculated with Lu et al.'s quick estimation formula[5], i.e.,

$$\sigma(n,2n)=61.6(A^{1/3}+1)^2\{1-1.319\exp[-8.744(N-Z)/A]\},$$

are also listed for comparison.

Discussions

Many kinds of grouping of the experimental data were tried, and the grouping shown in Table 1 proved to be the best one to keep the linear dependence of the left side of Eq. (1) on (E_T+aA). As is seen in Table 1, data are grouped into several groups referring that the neutron excess number of target nucleus is even or odd.

To stress the effect of the grouping of data according to neutron excess numbers, a factor (N-Z) were explicitly introduced in Eq. (1), and then the values of parameter c are almost independent of incident neutron energies, as shown in Table 1 with some exceptions.

The values of parameters α, β and c in Table 1 were obtained by the least squares method. Ranges of (E_T+aA) values linear to the experimental data and 95% confidence intervals in each linear fitting are shown in Fig. 2 in the case of the (n,p) reaction. Values of these parameters are valid within the ranges of (E_T+aA) in Table 1.

The cross sections thus obtained are shown in Table 2. E_T values of almost all (n,2n) reactions on even Z-odd N nuclei are too small and out of the present fitting range. Moreover, we

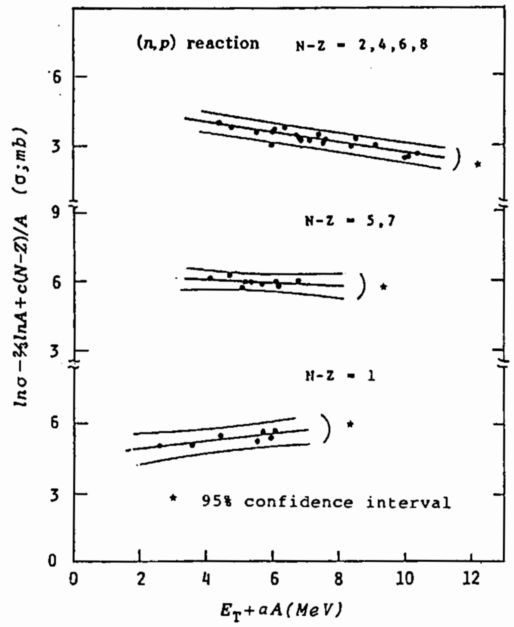

Fig. 2. Distribution of data points as a function of (E_T+aA) value. The best-fit line to the data points are also shown. Data points are grouped according to the (N-Z) values as indicated in the figure.

have no experimental data at present on the cross sections of these even Z-odd N nuclei. Therefore, no estimation of these reaction cross sections is possible in the present work.

As seen from Table 2, our estimated values are in good agreement with the data values and at the same time, the confidence intervals are usually narrow. So that, the predicted values will be reliable. The predicted value of the (n,2n) cross section of ^{11}B seems to be exceptional one. It is too large.

In Figs. 3(a), (b) and (c), scatter plots of ratios of σ_{cal}(Ho), the values estimated with our formula, to σ_{exp}, the experimental values are given. Target nucleus is indicated by its mass number. Also plotted are the ratios of σ_{cal}(Le) and σ_{cal}(Lu), the values estimated with Levkovskii's and Lu et al.'s formulae, to σ_{exp}, respectively. Incident neutron energy is 14.5 MeV. Our estimated values agree with the experimental values within 30% for most light nuclei. But both the Levkovskii's and Lu et al.'s formulae are seen to be inadequate to represent these cross section values particularly on light nuclei.

Fig. 4(a), (b) and (c) show frequency distributions of the ratios $(\sigma_{cal}(Ho)-\sigma_{exp})/\sigma_{exp}$ for respective (n,p), (n,α) and (n,2n) reaction cross sections of nuclei with A larger than 50, and also show those of the similar ratios for σ_{cal}(Le) and σ_{cal}(Lu), correspondingly. Usefulness of these formulae was evaluated by comparing full-widths at half-maximum (FWHM) in these distributions. No noticeable difference between these FWHM is seen in each figure. Therefore, the usefulness of our formula is rather comparable with those of the formulae by Levkovskii and Lu et al. as long as the nuclei with A larger than 50 are concerned.

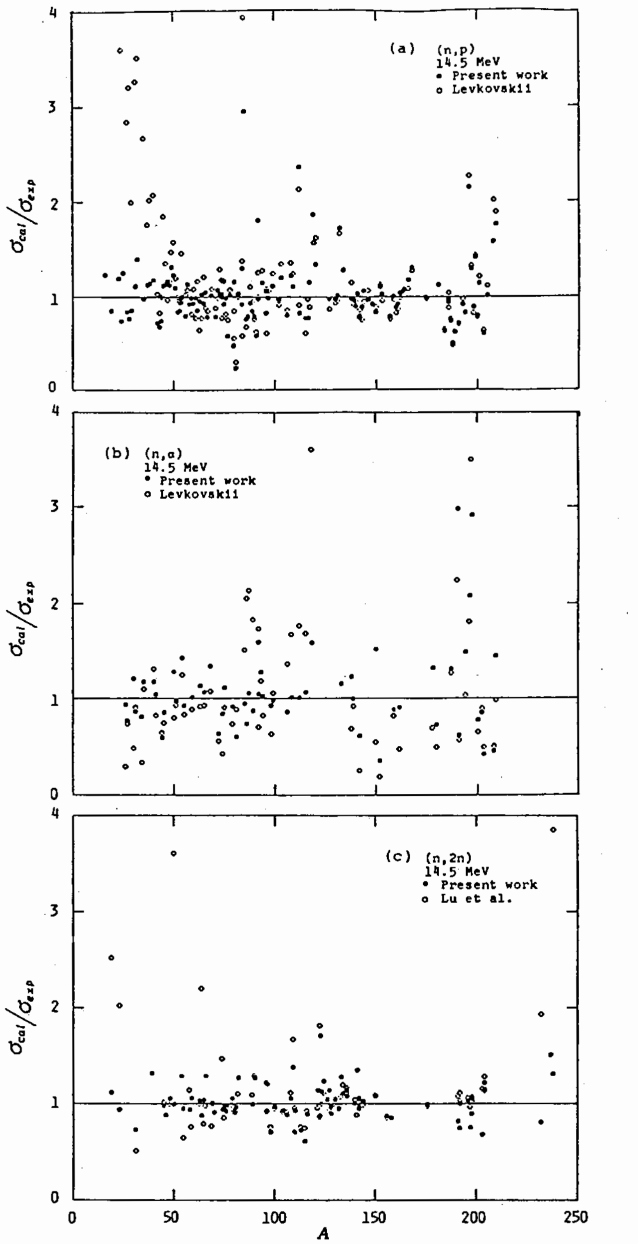

Fig. 3. (a). Plot of ratios of the values calculated with Horibe and with Levkovskii formulae to the experimental cross section data, respectively. Reaction is the (n,p). Each point corresponds to the target nucleus of mass number A. (b). Plot of ratios in the (n,α) reaction. (c). Plot of ratios in the (n,2n) reaction. The formulae are of Horibe and Lu et al. Lu et al.'s calculation is done at 14.4 MeV neutron energy.

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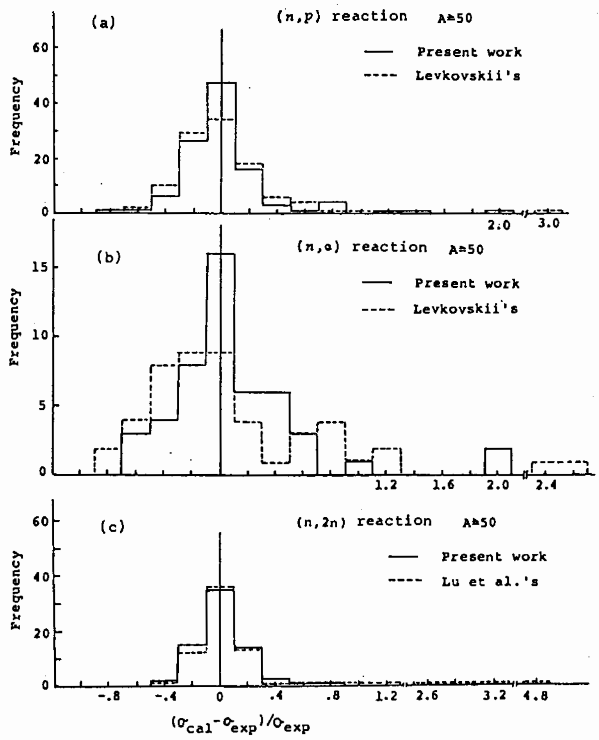

Fig. 4. (a). Frequency distribution of ratios $(\sigma_{cal}-\sigma_{exp})/\sigma_{exp}$. Values of the σ_{cal} are those calculated with our formula and with Levkovskii's. The bin width is 0.2. Raction is the (n,p) reaction. (b). Distribution similar in Fig. 4(a). Reaction is the (n,α) and the values of the σ_{cal} are those calculated with our formula and with Levkovskii's. (c). Distribution similar in Fig. 4(a). Reaction is the (n,2n) and the values σ_{cal} are those calculated with our formula and with Lu et al.'s.

Table 2. Comparison between the experimental data used and predicted values of the cross sections. Those values predicted by Levkovskii's formulae for the (n,p) and (n,α) reactions and those by Lu et al.' formula for the (n,2n) reaction are also listed.

(n,p) Reaction

Z	Target	N-Z	(E_T+aA) (MeV)	14.1 MeV Exp. (mb)	14.1 MeV Predict. (mb)	14.1 MeV $\Delta\sigma/\sigma$ (%)	14.5 MeV Exp. (mb)	14.5 MeV Predict. (mb)	14.5 MeV $\Delta\sigma/\sigma$ (%)	14.9 MeV Exp. (mb)	14.9 MeV Predict. (mb)	14.9 MeV $\Delta\sigma/\sigma$ (%)	14-15 MeV Levkovskii Predict. (mb)
6	C - 12	0	14.91	-	22.2	(+386, -79)	-	23.1	(+1713, -94)	1.93±0.25	4.23	(+3128, -97)	489
7	N - 15	1	11.02	-	13.9	(+87, -46)	-	9.06	(+189, -65)	16 ± 4	15.6	(+121, -55)	60.2
8	O - 16	0	11.90	41 ± 4	44.9	(+259, -72)	39 ± 4	48.1	(+890, -90)	34 ± 4	15.7	(+2091, -95)	560
8	O - 17	1	9.98	-	23.4	(+73, -42)	-	16.7	(+153, -61)	-	27.2	(+108, -52)	82.7
9	F - 19	1	6.07	20 ± 2	20.4	(+37, -27)	19 ± 6	16.1	(+74, -42)	18 ± 5	16.7	(+86, -46)	107
10	Ne- 20	0	8.59	-	91.4	(+191, -66)	-	101	(+576, -85)	-	62.0	(+1819, -95)	624
10	Ne- 21	1	7.14	-	39.5	(+44, -30)	-	32.5	(+87, -46)	-	40.8	(+87, -47)	133
11	Na- 23	1	5.93	43 ± 8	46.9	(+37, -27)	34 ± 15	40.8	(+72, -42)	43 ± 5	45.5	(+86, -46)	159
12	Mg- 24	0	7.36	110 ±16 [1]	127	(+183, -65)	190 ± 19	143	(+557, -85)	180 ± 18	110	(+1897, -95)	682
12	Mg- 25	1	5.52	63 ± 10	60.8	(+35, -26)	44 ± 5	55.0	(+70, -41)	40 ± 4	60.3	(+86, -46)	186
12	Mg- 26	2	10.52	27 ± 7	27.5	(+60, -38)	-	19.9	(+58, -37)	50 ± 5	29.9	(+106, -51)	56.1
13	Al- 27	1	4.43	78 ± 7	66.6	(+34, -26)	75 ± 8	62.8	(+69, -41)	75 ± 7	61.4	(+89, -47)	213
14	Si- 28	0	6.71	246 ±22 [1]	157	(+182, -65)	230 ± 30	178	(+567, -85)	210 ± 20	156	(+1979, -95)	736
14	Si- 29	1	5.69	-	108	(+36, -26)	120 ± 20	103	(+71, -41)	147 ± 18	122	(+86, -46)	240
14	Si- 30	2	10.65	-	40.3	(+61, -38)	-	26.1	(+58, -37)	-	43.9	(+106, -51)	84.5
15	P - 31	1	3.60	83 ± 8	92.0	(+36, -27)	82 ± 10 [2]	91.9	(+74, -42)	83 ± 5	84.6	(+94, -49)	267
16	S - 32	0	4.02	225 ±25	272	(+205, -67)	225 ± 12	315	(+756, -88)	212 ± 15	462	(+2683, -96)	788
16	S - 34	2	7.41	78 ± 7	95.7	(+56, -36)	-	71.7	(+53, -34)	73 ± 7	94.9	(+99, -50)	117
17	Cl- 35	1	2.61	107 ±38	112	(+41, -29)	120 ± 20	117	(+85, -46)	-	98.4	(+103, -51)	321
17	Cl- 37	3	7.28	25 ± 5	28.6	(+185, -65)	33 ± 6	37.0	(+556, -85)	41 ± 4	40.4	(+18, -15)	58.4
18	Ar- 38	2	7.51	-	122	(+56, -36)	75 ± 20	85.4	(+53, -34)	110 ± 22	121	(+99, -50)	151
18	Ar- 40	4	10.10	-	19.7	(+59, -37)	15.7 ± 2.0	18.5	(+57, -36)	20 ± 5	21.1	(+104, -51)	32.6
19	K - 39	1	3.29	-	172	(+37, -27)	-	184	(+77, -43)	-	174	(+97, -49)	374
19	K - 41	3	5.17	50 ± 5	46.2	(+135, -57)	-	52.4	(+362, -78)	48 ± 10	49.5	(+15, -13)	80.0
20	Ca- 40	0	4.21	298 ±38	305	(+202, -67)	-	353	(+734, -88)	-	499	(+2610, -96)	883
20	Ca- 42	2	6.38	175 ±10	183	(+56, -36)	182 ± 22	132	(+53, -35)	180 ± 10	177	(+100, -50)	188
20	Ca- 43	3	4.64	97 ±10	69.2	(+134, -57)	110 ± 13	74.8	(+356, -78)	-	68.3	(+15, -13)	91.7
20	Ca- 44	4	8.51	35 ± 7	36.1	(+56, -36)	46 ± 5 [3]	34.5	(+54, -35)	36 ± 7	36.9	(+100, -50)	46.2
20	Ca- 46	6	10.54	-	8.06	(+60, -38)	-	9.96	(+58, -37)	-	8.75	(+106, -51)	12.8
21	Sc- 45	3	3.23	55 ± 5	62.0	(+155, -61)	56 ± 4	62.7	(+420, -81)	53 ± 6	52.0	(+16, -14)	104
22	Ti- 46	2	5.51	290 ±20 [1]	256	(+57, -36)	166 ± 15 [3]	187	(+54, -35)	270 ± 25	240	(+102, -51)	226
22	Ti- 47	3	3.72	120 ±20	141	(+144, -59)	120 ± 20	140	(+384, -79)	120 ± 20	120	(+15, -13)	117
22	Ti- 48	4	7.09	61 ± 6	60.9	(+56, -36)	53 ± 6 [3]	59.6	(+53, -34)	61 ± 6	59.9	(+100, -50)	62.1
22	Ti- 49	5	5.07	30 ± 2	28.5	(+20, -16)	23 ± 5 [3]	30.2	(+45, -31)	39 ± 6	30.6	(+67, -40)	33.8
22	Ti- 50	6	9.98	-	12.8	(+59, -37)	12 ± 2 [3]	14.8	(+56, -36)	24 ± 5	13.7	(+103, -51)	18.9
24	Cr- 50	2	4.45	277 ±21 [1]	358	(+59, -37)	-	273	(+56, -36)	-	326	(+106, -52)	265

(n, α) Reaction

Z	Target	N-Z	(E_T+aA) (MeV)	14.1 MeV Exp. (mb)	14.1 MeV Predict. (mb)	14.1 MeV $\Delta\sigma/\sigma$ (%)	14.5 MeV Exp. (mb)	14.5 MeV Predict. (mb)	14.5 MeV $\Delta\sigma/\sigma$ (%)	14.9 MeV Exp. (mb)	14.9 MeV Predict. (mb)	14.9 MeV $\Delta\sigma/\sigma$ (%)	14-15 MeV Levkovskii Predict. (mb)
4	Be- 9	1	3.02	10 ± 1	9.80	(+147, -59)	-	81.0	(+287, -74)	-	26.0	(+641, -87)	4.38
4	Be- 10	2	10.71	-	12.0	(+112, -53)	-	41.8	(+105, -51)	-	11.0	(+178, -64)	2.45E-01
5	B - 11	1	10.18	30	35.5	(+109, -52)	-	46.8	(+101, -50)	31 ± 6	35.0	(+169, -63)	9.36
6	C - 12	0	9.90	-	89.9	(+108, -52)	80 [4]	51.0	(+100, -50)	-	92.3	(+166, -62)	196
6	C - 13	1	7.64	-	32.6	(+107, -52)	-	66.6	(+118, -54)	-	45.7	(+201, -67)	16.0
7	N - 14	0	4.43	-	48.2	(+129, -56)	100 [4]	95.0	(+215, -68)	-	105	(+438, -81)	210
8	O - 16	0	7.02	-	74.3	(+109, -52)	-	81.2	(+130, -56)	-	114	(+228, -70)	224
8	O - 18	2	9.61	-	37.3	(+107, -52)	-	68.6	(+100, -50)	-	39.9	(+165, -62)	6.06
9	F - 19	1	6.55	-	46.3	(+112, -53)	-	95.2	(+141, -59)	-	75.4	(+254, -72)	42.8
10	Ne- 20	0	6.14	-	76.7	(+114, -53)	-	102	(+153, -60)	-	132	(+281, -74)	249
10	Ne- 21	1	4.67	-	40.5	(+126, -56)	-	122	(+205, -67)	-	85.6	(+411, -80)	53.1
10	Ne- 22	2	11.16	-	64.1	(+114, -53)	-	67.7	(+110, -52)	-	55.3	(+190, -66)	13.0
11	Na- 23	1	9.78	150 ± 20	88.4	(+108, -52)	-	79.5	(+100, -50)	150 ± 20	92.2	(+166, -62)	63.6
12	Mg- 24	0	8.93	-	125	(+106, -51)	-	88.7	(+102, -51)	-	147	(+169, -63)	273
12	Mg- 25	1	5.69	-	56.2	(+117, -54)	-	124	(+167, -62)	-	103	(+315, -76)	74.4
12	Mg- 26	2	11.63	84 ± 10	87.8	(+118, -54)	77 ± 8	72.4	(+117, -54)	72 ± 10	70.9	(+207, -67)	22.4
13	Al- 27	1	9.76	121 ± 2	105	(+108, -52)	116 ± 3	88.7	(+100, -50)	111 ± 4	109	(+166, -62)	85.2
14	Si- 28	0	9.75	-	155	(+108, -52)	-	90.9	(+100, -50)	-	162	(+166, -62)	295
14	Si- 29	1	6.96	-	77.6	(+110, -52)	-	121	(+131, -57)	-	120	(+231, -70)	96.1
14	Si- 30	2	11.10	-	99.7	(+114, -53)	70 ± 10	83.7	(+109, -52)	-	86.7	(+189, -65)	33.8
15	P - 31	1	9.26	119 ± 16	113	(+106, -52)	118 ± 15	102	(+101, -50)	115 ± 12	126	(+166, -62)	107
16	S - 32	0	6.19	-	106	(+114, -53)	-	139	(+151, -60)	-	181	(+277, -73)	315
16	S - 33	1	4.13	-	60.6	(+132, -57)	-	173	(+229, -70)	-	138	(+475, -83)	118
16	S - 34	2	8.89	126 ± 7	87.4	(+106, -51)	138 ± 35	112	(+102, -51)	163 ± 15	103	(+170, -63)	46.6
16	S - 36	4	11.71	-	9.21	(+58, -37)	-	10.2	(+225, -69)	-	8.98	(+125, -56)	8.55
17	Cl- 35	1	7.03	100 ± 20	94.2	(+109, -52)	117 ± 15	137	(+130, -56)	122 ± 20	144	(+228, -69)	128
17	Cl- 36	2	5.40	-	59.0	(+120, -54)	-	163	(+177, -64)	-	113	(+339, -77)	53.5
17	Cl- 37	3	[illegible]	-	29.1	(+53, -35)	-	26.4	(+32, -24)	-	26.2	(+61, -38)	23.4
18	Ar- 36	0	6.39	-	117	(+113, -53)	-	148	(+145, -59)	-	196	(+264, -73)	335
18	Ar- 38	2	8.45	-	94.5	(+106, -51)	-	126	(+106, -52)	-	118	(+177, -64)	60.6
18	Ar- 40	4	10.57	13 ± 1.5	12.8	(+64, -39)	10 ± 1.5	11.7	(+246, -71)	10 ± 1.5	13.0	(+137, -58)	13.0
19	K - 39	1	7.27	84 ± 12	108	(+108, -52)	-	144	(+125, -55)	-	159	(+216, -68)	150
19	K - 40	2	4.68	-	60.9	(+126, -56)	-	187	(+204, -67)	-	128	(+410, -80)	67.8
19	K - 41	3	8.58	46 ± 6	43.0	(+58, -37)	39 ± 8	40.6	(+35, -26)	31 ± 5	37.2	(+66, -40)	32.0
20	Ca- 40	0	7.30	-	142	(+108, -52)	-	146	(+124, -55)	-	209	(+215, -68)	353
20	Ca- 42	2	8.53	-	107	(+106, -51)	-	134	(+105, -51)	-	133	(+176, -64)	75.3
20	Ca- 44	4	11.50	35 ± 5	27.4	(+57, -36)	29 ± 6 [5]	17.0	(+222, -69)	35 ± 8	18.7	(+126, -56)	18.5
21	Sc- 45	3	9.52	55 ± 2.8	58.6	(+50, -33)	56 ± 3	47.9	(+30, -23)	54 ± 6	54.6	(+58, -37)	41.6
22	Ti- 46	2	9.60	-	137	(+107, -52)	-	128	(+100, -50)	-	147	(+165, -62)	90.4
22	Ti- 48	4	11.42	39 ± 6	41.5	(+57, -36)	-	20.7	(+222, -69)	23 ± 6	24.8	(+126, -56)	24.8
22	Ti- 49	5	9.06	-	15.2	(+54, -35)	-	18.4	(+32, -24)	-	13.6	(+61, -38)	13.5
22	Ti- 50	6	12.69	9.4 ± 1.5	9.52	(+74, -42)	9.50 ±2.00	12.1	(+285, -74)	10 ± 2	8.79	(+135, -58)	7.56
24	Cr- 50	2	9.82	-	154	(+108, -52)	-	133	(+100, -50)	-	160	(+166, -62)	106

(n,2n) Reaction

Z	Target	N-Z	(MeV)	14.1 MeV Exp. (mb)	14.1 MeV Predict. (mb)	14.1 MeV $\Delta\sigma/\sigma$ (%)	14.5 MeV Exp. (mb)	14.5 MeV Predict. (mb)	14.5 MeV $\Delta\sigma/\sigma$ (%)	14.9 MeV Exp. (mb)	14.9 MeV Predict. (mb)	14.9 MeV $\Delta\sigma/\sigma$ (%)	14.4 MeV Lu et al. Predict. (mb)
5	B - 11	1	12.50	-	27239	(+30, -23)	- -	41629	(+341, -77)	-	9561	(+13, -12)	259
7	N - 14	0	11.30	-	2.99	(+89, -47)	-	3.02	(+64, -39)	-	3.41	(+83, -45)	-229
7	N - 15	1	11.55	-	481	(+33, -25)	-	656	(+415, -81)	-	379	(+15, -13)	195
9	F - 19	1	10.98	47 ± 4	47.8	(+38, -28)	55 ± 4	60.9	(+538, -84)	60 ± 5	60.4	(+17, -14)	139
11	Na- 22	0	11.57	-	3.39	(+86, -46)	-	3.69	(+61, -38)	-	4.28	(+79, -44)	-284
11	Na- 23	1	12.96	28 ± 2	26.9	(+30, -23)	44 ± 3	43.4	(+356, -78)	38.5±23 [6]	37.6	(+13, -12)	89.3
12	Mg- 26	2	11.52	-	184	(+86, -46)	-	197	(+61, -38)	-	228	(+79, -44)	316
13	Al- 26	0	11.81	-	3.25	(+83, -45)	-	3.79	(+59, -37)	-	4.49	(+76, -43)	-309
15	P - 31	1	12.71	5.1	4.94	(+30, -23)	10.9± 0.8	7.74	(+344, -77)	10 ± 1	9.90	(+13, -12)	5.47
16	S - 34	2	11.75	-	76.6	(+84, -46)	-	87.8	(+59, -37)	-	103	(+76, -43)	234
17	Cl- 35	1	13.01	-	3.34	(+30, -23)	-	5.42	(+360, -78)	-	7.28	(+14, -12)	-31
17	Cl- 37	3	10.59	-	556	(+52, -34)	-	667	(+61, -38)	-	598	(+24, -19)	406
18	Ar- 38	2	12.15	-	46.3	(+81, -45)	-	59.7	(+57, -36)	-	73.0	(+73, -42)	196
19	K - 39	1	13.43	2.5 ± 0.3	2.63	(+33, -25)	3.5 ± 0.3	4.49	(+406, -80)	5.9 ± 0.5	6.04	(+14, -13)	-64
20	Ca- 42	2	11.74	-	50.4	(+84, -46)	-	57.8	(+59, -37)	-	68.0	(+76, -43)	161
20	Ca- 44	4	11.39	-	570	(+88, -47)	-	590	(+63, -39)	-	673	(+81, -45)	511
20	Ca- 48	8	10.16	900 ±108	958	(+69, -41)	920 ±180	972	(+56, -36)	1070 ±360	1104	(+51, -34)	917
21	Sc- 45	3	11.57	267 ±17	256	(+61, -38)	331 ±19	314	(+72, -42)	354 ±35	346	(+28, -22)	337
22	Ti- 46	2	13.49	13.5 ± 1	13.9	(+91, -48)	30 ± 2	26.3	(+62, -38)	50 ± 4	36.3	(+80, -45)	127
22	Ti- 48	4	11.87	-	302	(+83, -45)	-	359	(+58, -37)	-	428	(+75, -43)	481
23	V - 51	5	11.27	-	281	(+52, -34)	-	200	(+61, -38)	-	354	(+24, -19)	601
24	Cr- 50	2	13.20	10 ± 1.5	14.9	(+86, -46)	26.4± 2.2	25.9	(+59, -37)	28 ± 3	34.9	(+77, -43)	95.0
24	Cr- 52	4	12.27	278 ±20	178	(+81, -45)	-	237	(+56, -36)	358 ±25	293	(+73, -42)	451
25	Mn- 55	5	10.41	855 ±60	799	(+56, -36)	890 ±60	826	(+66, -40)	850 ±60	823	(+25, -20)	575
26	Fe- 54	2	13.63	10.5 ± 1.0	10.2	(+93, -48)	15.5± 1.0	20.1	(+63, -39)	22 ± 2	28.2	(+83, -45)	64.6
26	Fe- 56	4	11.40	239 ±90	252	(+88, -47)	-	261	(+63, -39)	-	298	(+81, -45)	421
27	Co- 59	5	10.64	655 ±50	695	(+51, -34)	720 ±50	764	(+60, -37)	735 ±55	756	(+23, -19)	548
28	Ni- 58	2	12.41	24.5 ± 2.0	20.9	(+81, -45)	31.0± 2.5	29.1	(+56, -36)	34.9± 3	36.4	(+72, -42)	35.6
28	Ni- 60	4	11.58	-	185	(+85, -46)	-	202	(+61, -38)	-	234	(+78, -44)	392
28	Ni- 64	8	9.81	-	781	(+74, -42)	-	768	(+57, -36)	-	877	(+52, -34)	859
29	Cu- 63	5	11.02	480 ±20	507	(+49, -33)	522 ±20	560	(+57, -36)	585 ±25	604	(+23, -18)	521
29	Cu- 65	7	10.05	913 ±50	942	(+22, -18)	956 ±50	990	(+14, -12)	975 ±30	1027	(+16, -14)	754
30	Zn- 64	4	12.05	119 ± 9	115	(+82, -45)	165 ±13	144	(+57, -36)	204 ±16	174	(+74, -42)	364
30	Zn- 66	6	11.22	620 ±50	838	(+91, -48)	650 ±60	825	(+65, -39)	740 ±60	925	(+84, -46)	633
30	Zn- 68	8	10.35	-	732	(+67, -40)	-	755	(+55, -36)	-	856	(+50, -33)	841
30	Zn- 70	10	9.35	-	1019	(+83, -45)	-	961	(+61, -38)	1307 ±130	1104	(+55, -35)	1005
31	Ga- 69	7	10.46	850 ±80	899	(+20, -17)	957 ±80	956	(+13, -11)	1070 ±90	1009	(+15, -13)	732
32	Ge- 70	6	11.69	508 ±40	491	(+84, -46)	610 ±50	555	(+60, -37)	700 ±50	651	(+77, -43)	608

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