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L. Jéki

PHENOMENOLOGICAL FORMULA FOR (n,2n), (p,2n) AND (p,3n) REACTION CROSS-SECTIONS

Hungarian Academy of Sciences

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BUDAPEST

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REACTION CROSS-SECTIONS

L. Jéki

Central Research Institute for Physics, Budapest, Hungary

Nuclear Physics Department

A strong N-Z dependence of the cross-sections for /n,2n/ reactions has been shown by several authors [1-4]. The observation of systematic trends in this reaction can be of great importance in the calculation of unknown reaction cross-sections which are of interest in various reactor and engineering applications [64].

In an earlier paper on the existence of shell effects in the /n,2n/ reaction cross-sections, it was shown that the latter could be described at constant excess energy by the following formula |4|:

$$\sigma_{emp} = \left[1 - C_1 \cdot f(A) \cdot \exp\left(-C_2 \cdot \frac{N-Z}{A}\right)\right] \cdot C_3 \qquad /1a/$$

where

$$f(A) = \left(A^{\frac{1}{3}} + 1\right)^2 \qquad /1b/$$

The agreement between measured and predicted values was very good for nuclei with $4 \leqq N-Z \leqq 21$.

In this paper the validity of this formula is extended to a broader range of nuclei and to other reaction types. According to the "independence hypothesis" of the decay of the compound nucleus [5], the formula is expected to be valid for /x,yn/ reactions in general, provided these reactions occur through a compound nucleus. Therefore an attempt has been made to describe the /n,2n/, /p,2n/ and /p,3n/ cross-sections. In the case of /x,2n/ reactions an excess energy of 3 MeV was choosen, i.e. $E_n = Q+3$ MeV. The /p,3n/ reaction cross-sections were calculated at the energies corresponding to the maximum cross-section values in the excitation curves, because very few data were available near the threshold energy.

Formula 1b had to be modified for /p,3n/ reactions. This is because in formula /1a/, f(A) is connected with the absorption cross-section

$$f(A) \sim \left(A^{\frac{1}{3}} + \frac{\lambdabar}{r_o}\right)^2$$

where $\lambdabar$ is the de Broglie wavelength and $r_o = 1.2$ fm. Now $\frac{\lambdabar}{r_o} \approx 1$ for 14 MeV neutrons and protons, but it is 0.64 for 35 MeV protons /35 MeV is the average of the energies corresponding to the maximum cross-section values/. Thus the calculations of /p,3n/ cross-sections were carried out using the modified form:

$$f(A) = \left(A^{\frac{1}{3}} + 0.64\right)^2$$

The interpretation of formulas /1a, 1b/ will be discussed elsewhere [8].

Most of the reported /n,2n/ and /p,2n/ data were measured at $E_n = Q + 3$ MeV; if not, the cross-section was obtained by extrapolation from the values measured at 14 MeV, using the Weisskopf formula [5]:

$$\sigma(n,2n) = \sigma_c \left[1 - \left(1 + \frac{E_{exc}}{T}\right) \cdot \exp\left(-\frac{E_{exc}}{T}\right)\right]$$

where

$$T = \left(\frac{E_n}{0.115 \cdot A}\right)^{\frac{1}{2}} \qquad /2/$$

σ_c was evaluated from the fit of /2/ to the excitation functions. The values of Q were taken from tables [6,7,63].

The /n,2n/ data were divided into four groups according to the neutron number of the target nuclei. For the other reaction types very few data were available and so the fit was made for all the nuclei.

The best-fit parameters are listed in Table 1. The results of the calculations are listed along with the reported data in Tables 2-7. The results show the usefulness of the empirical formula /1/ for the calculation of the three cross-sections. Using the parameters listed in Table 1, the empirical formula gives the cross-section values at the given excess energy /$E_n = Q + 3$ MeV/ for /n,2n/ and /p,2n/ reactions and at the maximum cross-section values for /p,3n/ reactions. It is possible to evaluate the cross-sections at different excitation energies from Eq.2. Further calculations for other reaction types are in progress.

Table 1.

The best-fit parameters of the empirical formula /1/ for different types of reactions

		c_1	c_2	c_3 mbarn	Ref. table
/n,2n/	$N \leq 28$	0.085	20.0	550	2
	$28 < N \leq 50$	0.06	8.45	1900	3
	$50 < N \leq 82$	0.06	9.5	2600	4
	$82 < N$	0.15	14.0	3500	5
/p,2n/	$24 \leq N \leq 124$	0.076	7.8	1800	6
/p,3n/	$28 \leq N \leq 126$	0.30	19.0	1500	7

Table 2.

Measured /σ_m/ and predicted/σ_{emp}/ values of /n,2n/ reaction cross-sections for nuclei with $N \leq 28$

target nucleus	$\frac{N-Z}{A}$	σ_m	σ_{emp}	Ref.
^{39}K	0.026	15 ± 1	20	66 M[x]
^{48}Ca	0.167	860 ± 129 707 ± 108 722 ± 184	515	9 M 10 E[x] 10 E
^{45}Sc	0.067	320 ± 48 328 ± 35 347 ± 19 316 ± 8	299	9 M 11 M 11 M 11 M
^{46}Ti	0.043	145 ± 7 135 ± 8 111 ± 3	147	65 M 11 E 11 E
^{51}V	0.098	675 ± 100	407	52 M
^{50}Cr	0.040	64 ± 3	98	11 E
^{52}Cr	0.077	317 ± 50 476 ± 33	330	11 E 12 M
^{54}Fe	0.037	50 ± 5 134 ± 3	51	53 M 9 M

[x] M measured at $E_n = Q + 3$ MeV

E extrapolated to $E_n = Q + 3$ MeV

Table 3.

Measured /σ_m/ and predicted /σ_{emp}/ values of /n,2n/ reaction cross-section for nuclei with $28 < N \leq 50$

target nucleus	$\frac{N-Z}{A}$	σ_m	σ_{emp}	Ref.
^{55}Mn	0.091	613 ± 72 750 ± 112	706	13 M 9 M
^{56}Fe	0.071	440 ± 88 500 ± 40	479	11 M 11 M
^{59}Co	0.085	570 ± 105	595	56 M
^{63}Cu	0.079	495 ± 74	486	9 M
^{65}Cu	0.108	810 ± 121	769	1 M
^{64}Zn	0.062	254 ± 50 288 ± 43	256	11 M 9 M
^{66}Zn	0.091	550 ± 83	586	9 M
^{70}Zn	0.143	1065 ± 130	1026	9 E
^{69}Ga	0.101	690 ± 65	669	56 M
^{71}Ga	0.127	780 ± 100	891	1 M
^{70}Ge	0.086	447 ± 45	483	57 M
^{76}Ge	0.158	1095 ± 120	1096	57 E
^{75}As	0.120	910 ± 40 825 ± 35	800	56 M 12 M
^{74}Se	0.081	415 ± 44 516 ± 38 565 ± 9	383	58 E 14 E 15 M
^{76}Se	0.105	745 ± 81	646	58 E
^{82}Se	0.171	1170 ± 50 1490 ± 225	1149	14 E 9 M
^{79}Br	0.114	740 ± 45	710	14 E
^{81}Br	0.136	835 ± 65 963 ± 115	897	14 E 16 E
^{78}Kr	0.077	288 ± 20	284	17 E
^{80}Kr	0.100	810 ± 60	552	17 M
^{85}Rb	0.129	887 ± 71 830 ± 125 1099 ± 55	814	12 M 9 M 65 M

Table 3. cont.

target nucleus	$\frac{N-Z}{A}$	σ_m	σ_{emp}	Ref.
^{87}Rb	0.149	1056 ± 53 1290 ± 195 1001 ± 50	972	56 M 9 M 18 E
^{84}Sr	0.095	380 ± 50 395 ± 75 380 ± 10	460	59 M 18 M 18 M
^{86}Sr	0.116	683 ± 42 570 ± 85, 701 ± 110	679	18 M 9 M 11 M
^{89}Y	0.124	751 ± 80	731	4 M
^{90}Zr	0.111	608 ± 30 885 ± 4 800 ± 120	593	11 M 15 M 9 M
^{92}Mo	0.087	280 ± 42 383 ± 6	278	9 M 15 M

Table 4

Measured /σ_m/ and predicted /σ_{emp}/ values of /n,2n/ reaction cross-sections for nuclei with 50 < N ≤ 82

target nucleus	$\frac{N-Z}{A}$	σ_m	σ_{emp}	Ref.
^{96}Zr	0.167	1197 ± 80	1628	51 E
^{100}Mo	0.160	1460 ± 200 1295 ± 180 1149 ± 85	1541	9 E 60 E 51 E
^{96}Ru	0.083	516 ± 70 494 ± 30 411 ± 90 545 ± 55	454	19 E 51 E 11 E 11 E
^{98}Ru	0.102	863 ± 110 1012 ± 96	784	19 E 51 E
^{103}Rh	0.126	642 ± 80 804 ± 80	1117	11 E 51 E
^{102}Pd	0.098	541 ± 70 559 ± 45	672	19 E 51 E
^{110}Pd	0.164	1348 ± 80 1638 ± 185	1523	20 E 51 E
^{107}Ag	0.121	782 ± 120 630 ± 141	1016	36 M 61 E
^{108}Cd	0.111	772 ± 100 490 ± 75	843	51 E 62 E
^{110}Cd	0.127	1054 ± 150	1078	51 E
^{116}Cd	0.172	1442 ± 102 1013 ± 100	1580	65 M 51 E
^{113}In	0.133	1300 ± 137 1492 ± 110 1523 ± 180	1134	21 E 20 E 22 E
^{115}In	0.148	1320 ± 166 1654 ± 119 1581 ± 110	1317	21 E 24 E 23 E
^{112}Sn	0.107	900 ± 100 1110 ± 127 1530 ± 229	739	19 M 12 M 9 M
^{114}Sn	0.123	947 ± 130 1082 ± 130 1572 ± 100	981	19 E 51 E 25 E
^{120}Sn	0.167	1240 ± 210	1502	25 E

Table 4 cont.

target nucleus	$\frac{N-Z}{A}$	σ_m	σ_{emp}	Ref.
^{121}Sb	0.157	1584 ± 115 1369 ± 93 1393 ± 80	1392	26 E 12 M 51 E
^{123}Sb	0.171	1329 ± 80 1099 ± 137 1962 ± 200	1530	51 E 12 E 23 E
^{122}Te	0.148	1422 ± 140	1272	51 E
^{128}Te	0.188	1441 ± 210	1667	51 E
^{130}Te	0.200	1270 ± 75	1764	51 E
^{127}I	0.165	1432 ± 80 1143 ± 132	1454	51 E 11 E
^{124}Xe	0.129	1021 ± 110	1002	17 E
^{126}Xe	0.143	1208 ± 165	1187	17 E
^{128}Xe	0.156	1333 ± 170	1345	17 E
^{134}Xe	0.194	1980 ± 240	1701	17 E
^{136}Xe	0.206	1501 ± 100	1790	17 E
^{133}Cs	0.173	1347 ± 75 1352 ± 250	1506	51 E 11 E
^{136}Ce	0.147	1174 ± 90	1184	51 E
^{140}Ce	0.171	1531 ± 100 1407 ± 140 1540 ± 111 1400 ± 130	1458	27 E 9 E 12 E 51 E
^{141}Pr	0.163	1450 ± 144 1231 ± 111	1360	12 E 41 M
^{142}Nd	0.155	1458 ± 120 1831 ± 200 1467 ± 125	1254	27 E 11 E 40 E
^{144}Sm	0.139	1081 ± 106 1600 ± 240 1343 ± 166 1110 ± 300	1020	12 M 9 M 29 E 29 E

Table 5.

Measured $/\sigma_m/$ and predicted $/\sigma_{emp}/$ values of /n,2n/ reaction cross-sections for nuclei with 82 < N

target nucleus	$\frac{N-Z}{A}$	σ_m	σ_{emp}	Ref.
^{142}Ce	0.183	1434 ± 300	1979	9 E
		1614 ± 160		12 E
		1756 ± 170		9 E
		1677 ± 170		27 E
		1525 ± 170		51 E
^{148}Nd	0.189	1938 ± 200	2071	11 E
^{150}Nd	0.200	1986 ± 300	2263	29 E
		1560 ± 276		29 E
^{154}Sm	0.195	2025 ± 900	2150	11 E
		1349 ± 300		11 E
^{154}Gd	0.169	1660 ± 140	1558	27 E
^{160}Gd	0.200	1345 ± 820	2218	11 E
		1327 ± 300		11 E
		1578 ± 170		11 E
^{160}Dy	0.175	1813 ± 120	1680	27 E
^{165}Ho	0.188	1904 ± 210	1954	11 E
		2503 ± 55		11 E
		1914 ± 300		2 [illegible]
^{166}Er	0.181	1778 ± 155	1786	27 E
^{170}Er	0.200	1740 ± 265	2174	11 E
		1103 ± 500		11 E
^{169}Tm	0.183	1821 ± 115	1833	27 E
^{170}Yb	0.176	1889 ± 110	1656	27 E
^{176}Yb	0.205	1681 ± 253	2231	11 E
		730 ± 80		11 E
		400 ± 100		11 E
^{175}Lu	0.189	1780 ± 170	1918	27 E
		1600 ± 300		11 E
^{176}Hf	0.182	2033 ± 115	1756	27 E
		1860 ± 100		42 E
^{181}Ta	0.193	2438 ± 200	1993	11 E
		1662 ± 300		11 E
^{182}W	0.187	1990 ± 120	1843	27 E
^{186}W	0.204	2130 ± 230	2187	43 E

Table 5. cont.

target nucleus	$\frac{Z-N}{A}$	σ_m	σ_{emp}	Ref.
^{185}Re	0.189	1666 ± 600	1882	11 E
^{187}Re	0.198	1560 ± 168	2059	11 E
		1341 ± 410		11 E
^{191}Ir	0.194	1943 ± 190	1954	27 E
^{198}Pt	0.212	2580 ± 1500	2281	11 E
^{197}Au	0.198	2158 ± 180	2018	27 E
		1601 ± 460		11 E
		2418 ± 200		11 E
		2235 ± 120		11 E
^{198}Hg	0.192	2169 ± 220	1882	27 E
^{204}Hg	0.216	2160 ± 160	2321	27 E
		2188 ± 300		30 E
^{203}Tl	0.202	2043 ± 120	2075	27 E
		1235 ± 66		11 E
		1570 ± 210		30 E
^{205}Tl	0.210	1861 ± 279	2215	11 E
^{204}Pb	0.196	1966 ± 110	1948	27 E
		1467 ± 160		9 E
^{209}Bi	0.206	2155 ± 300	2126	11 E
		2380 ± 200		11 E
^{232}Th	0.214	1940 ± 90	2166	44 M

Table 6.

Measured /σ_m/ and predicted /σ_{emp}/ values of /p,2n/ reaction cross-sections for nuclei with $24 \leq N \leq 124$

target nucleus	$\frac{N-Z}{A}$	σ_m	σ_{emp}	Ref.
^{45}Sc	0.067	12 ± 4	144	31 M
^{48}Ti	0.083	73 ± 18	297	32 E
^{51}V	0.098	231 ± 35	417	33 M
^{52}Cr	0.077	91 ± 24	153	32 E
^{56}Fe	0.071	42 ± 15	13	32 E
^{59}Co	0.085	133 ± 21	145	33 M
^{62}Ni	0.097	240 ± 57	254	32 E
^{63}Cu	0.079	50 ± 21 43 ± 15	14	34 E 32 E
^{68}Zn	0.118	410 ± 200 508 ± 117	420	31 M 32 E
^{69}Ga	0.101	237 ± 44	222	32 E
^{88}Sr	0.136	400 ± 70	432	45 E
^{89}Y	0.124	264 ± 46	280	35 E
^{93}Nb	0.118	167 ± 25	177	33 M
^{100}Mo	0.160	103 ± 14	581	46 M
^{110}Cd	0.127	425 ± 30	143	37 E
^{112}Cd	0.143	470 ± 20	318	37 E
^{140}Ce	0.171	447 ± 67	460	38 M
^{150}Nd	0.200	200 ± 30	686	39 M
^{168}Er	0.190	430 ± 200	522	50 E
^{181}Ta	0.193	417 ± 70	497	33 M
^{197}Au	0.198	232 ± 35	482	33 M
^{206}Pb	0.204	530 ± 70	510	47 M

Table 7.

Measured /σ_m/ and predicted /σ_{emp}/ values of /p,3n/ reaction cross-section for nuclei with $28 \leq N \leq 126$

target nucleus	$\frac{N-Z}{A}$	σ_m	σ_{emp}	Ref.
^{51}V	0.098	97 ± 15	208	55
^{65}Cu	0.108	165 ± 25 145 ± 23	267	34 48
^{68}Zn	0.118	120 ± 14	453	31
^{69}Ga	0.101	65 ± 10	63	49
^{71}Ga	0.127	600 ± 120	597	49
^{88}Sr	0.136	470 ± 120	649	45
^{89}Y	0.124	385 ± 46	409	35
^{112}Cd	0.143	700 ± 70	635	37
^{170}Er	0.200	620 ± 100	1127	50
^{181}Ta	0.193	1200 ± 266	1061	28
^{193}Ir	0.202	1000 ± 200	1114	54
^{206}Pb	0.204	890 ± 135	1112	47
^{208}Pb	0.212	980 ± 150	1163	47
^{209}Bi	0.206	820 ± 145	1122	47

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ABSTRACT

A phenomenological formula is suggested to calculate /n,2n/, /p,2n/ and /p,3n/ reaction cross-sections which gives good agreement between the calculated and measured values.

РЕЗЮМЕ

Предлагается феноменологическая формула для вычисления сечений реакций /n,2n/, /p,2n/ и /p,3n/, которая приводит к хорошему совпадению расчетных данных с измеренными.

KIVONAT

/n,2n/, /p,2n/ és /p,3n/ reakció-hatáskeresztmetszetek kiszámitására összefüggést adunk meg, amelynek segitségével jó egyezést kapunk a számitott és a mért értékek között.

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