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Systematics of (*p, n*) reaction cross-section

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Summary. Semi-empirical systematics of the (p, n) reaction cross-section was obtained at incident proton energies 7.5 MeV, 12.4 MeV and 24.8 MeV. Systematics is based on analytical formulas derived using the pre-equilibrium exciton model, evaporation model and semi-empirical mass formula Parameters of systematics were fitted to the data obtained from the analysis of available measured (p, n) reaction cross-section.

1. Introduction

The use of systematics for nuclear reaction cross-section evaluation is important, if experimental data are absent and results of nuclear model calculation are not reliable.

The work performed during last years under the creation and the improvement of accuracy of systematics for neutron induced reaction cross-sections was caused by the necessity of the data testing and evaluation for activation data libraries (ADL [1], MENDL [2], EAF [3]). The method based on the use of the pre-equilibrium exciton and evaporation models has been successfully applied to obtain cross-section systematics for main neutron induced reactions at 14.5 and 20 MeV [4–8] and for the number of proton induced reactions [9].

At present the evaluation of cross-sections for proton induced reactions takes on special significance [10–12]. Evaluated data files for protons [10, 11] are used to simulate the irradiation of materials in advanced nuclear energy systems and to study ways to produce radionuclides used in nuclear medicine and industry. Systematics of cross-sections for proton induced reactions takes on special importance as an additional tool for the cross-section evaluation at intermediate energies. Obtaining systematics formulas for proton reactions with the number of measurements performed appropriate to investigate the systematic dependence of cross-sections is of undoubted interest. A list of such reactions is not large [9, 12] and (p, n) is an example of the reaction relatively well provided with experimental data.

The systematic dependence of the (p, n) reaction cross-section is investigated in the present work. Semi-empirical formulas for the evaluation of the (p, n) reaction cross-section at different energies are suggested. Formulas were obtained using analytical expressions describing the equilibrium and non-equilibrium neutron emission in nuclear reactions. The analysis of available experimental data used to obtain systematics was performed.

The study of systematics dependence of the (p, n) reaction cross-sections was performed at incident proton energies 7.5 MeV, 12.4 MeV and 24.8 MeV selected after the comparison of the number of measurements at different proton energies. The energies selected refer to different parts of the (p, n) excitation function. The energy 7.5 MeV belongs to the region, where the cross-section rises with the incident proton energy and the equilibrium neutron emission gives the main contribution to the cross-section. The energy 12.4 MeV refers approximately to the region of the maximum of excitation function. The energy 24.8 MeV belongs to the descending branch of the excitation function, where the pre-equilibrium neutron emission plays the predominant role.

2. Experimental data

Experimental data for the (p, n) reaction cross-section were taken from Refs. [13–119]. The data available in the energy range 7.5 ± 0.5 MeV, 12.4 ± 0.5 MeV and 24.8 ± 1.0 MeV were reduced to incident proton energies 7.5, 12.4 and 24.8 MeV correspondingly, using excitation functions for the (p, n) reaction calculated by the TALYS code [120]. The calculation of excitation functions has been performed with the code options briefly described in [12].

The statistical treatment of experimental cross-sections available for a single nucleus and single incident proton energy has been done using the method of "weighted means" [121]

$$\langle\sigma^{\exp}\rangle = \frac{\sum_{j=1}^{n} \sigma_j / \left(\Delta\sigma_j\right)^2}{\sum_{j=1}^{n} 1/\left(\Delta\sigma_j\right)^2}\,, \quad \langle\sigma^{\exp}\rangle = \max\left(\Delta\sigma_{\mathrm{A}}, \Delta\sigma_{\mathrm{B}}\right)\,, \tag{1}$$

and

$$\Delta\sigma_{\mathrm{A}} = \left(\frac{\sum_{j=1}^{n} \left(\sigma_j - \langle\sigma^{\exp}\rangle\right)^2 / \left(\Delta\sigma_j\right)^2}{(n-1)\sum_{j=1}^{n} 1/\left(\Delta\sigma_j\right)^2} \right)^{1/2}\,,$$

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$$\Delta\sigma_{\mathrm{B}} = \left(\sum_{j=1}^{n} 1/\left(\Delta\sigma_j\right)^2 \right)^{-1/2}, \tag{2}$$

where $\langle\sigma^{\mathrm{exp}}\rangle$ and $\langle\Delta\sigma^{\mathrm{exp}}\rangle$ are the (p,n) reaction cross-section and its error evaluated using data of different measurements; σ_i and $\Delta\sigma_i$ is the cross-section and its error, obtained in i-th experiment; n is the number of measurements available for the nucleus.

The (p,n) reaction cross-section, $\langle\sigma^{\mathrm{exp}}\rangle \pm \langle\Delta\sigma^{\mathrm{exp}}\rangle$, obtained from the analysis of experimental data for target nuclei with atomic number $17 \le Z \le 83$ at the incident proton energy 7.5 MeV is shown in Table 1 (90 nuclei), for targets with $20 \le Z \le 83$ at the proton energy 12.4 MeV in Table 2 (65 nuclei) and at the proton energy 24.8 MeV in Table 3 (45 nuclei).

Values $\langle\sigma^{\mathrm{exp}}\rangle \pm \langle\Delta\sigma^{\mathrm{exp}}\rangle$ and analytical expressions discussed below were used to obtain the systematics of the (p,n) reaction cross-section.

3. Systematics at the incident proton energy 7.5 MeV

The equilibrium neutron emission gives the main contribution in the (p,n) reaction cross-section at 7.5 MeV. According to the evaporation model the cross-section is equal to

$$\sigma_{(p,n)} = \sigma_{\mathrm{non}}(E_{\mathrm{p}}) \frac{\Gamma_{\mathrm{n}}}{\sum_x \Gamma_x}, \tag{3}$$

where σ_{non} is the cross-section of nonelastic interaction of the incident proton with a nucleus at the kinetic energy E_{p}, Γ_x is the emission width of the particle of type x, n refers to the neutron emission, the summing is for all open channels.

Using the Weisskopf–Ewing model [122] and assuming that the neutron and proton emission predominate, one can evaluate the equilibrium component of the (p,n) reaction cross-section as follows

$$\sigma_{(p,n)} = \sigma_{\mathrm{non}} \frac{\Gamma_{\mathrm{n}}}{\Gamma_{\mathrm{n}} + \Gamma_{\mathrm{p}}} \approx \frac{1}{1 + \exp\left[\dfrac{\alpha E_{\mathrm{p}} - V_{\mathrm{p}}}{T_{\mathrm{p}}} - \dfrac{\alpha E_{\mathrm{p}} + Q_{(p,n)}}{T_{\mathrm{n}}} \right]}, \tag{4}$$

where it is supposed that the nuclear level density is estimated using the "constant temperature" model, $\rho = T^{-1}\exp(U/T)$, T_{n} and T_{p} are the nuclear temperature for residuals, produced after the neutron and proton emission correspondingly, $Q_{(p,n)}$ is the energy of the (p,n) reaction, $\alpha = A/(A+1)$, A is the mass number of the target nucleus, and V_{p} is the Coulomb potential for protons.

The nuclear temperature is evaluated as follows [8]

$$T_{\mathrm{p}} \cong \sqrt{C\alpha E_{\mathrm{p}}/A}, \tag{5}$$

$$T_{\mathrm{n}} \cong \sqrt{C\left(\alpha E_{\mathrm{p}} + Q_{(p,n)}\right)/A}, \tag{6}$$

where C is the constant combining the nuclear level density parameter and the mass number of the nucleus.

Using Eqs. (4)–(5) one can obtain the following approximate expression for $\sigma_{(p,n)}$

$$\sigma_{(p,n)} = \sigma_{\mathrm{non}} \frac{1}{1 + \exp\left[\left(\frac{A}{4C\alpha E_{\mathrm{p}}}\right)^{1/2} \left(\frac{Q^2_{(p,n)}}{\alpha E_{\mathrm{p}}} - Q_{(p,n)} - 2V_{\mathrm{p}} \right) \right]}. \tag{7}$$

According to the semi-empirical mass formula the energy of the (p,n) reaction is approximately equal to

$$Q_{(p,n)} = \beta_1 \left(\frac{N - Z - 1}{A} \right) + \beta_2 Z/A^{1/3}, \tag{8}$$

where N, Z and A are the number of neutrons, protons and nucleons in the target nucleus, correspondingly; β_i are constants.

Taking into account Eqs. (7), (8), by the analogy with [8] the following 6-parametric formula can be suggested for the (p,n) reaction cross-section systematics

$$\sigma_{(p,n)} = \frac{\sigma_{\mathrm{non}}}{\exp\left(A^{\alpha_1}\left(\alpha_2 S^2 + \alpha_3 S + \alpha_4 V + \alpha_5\right)\right) + \alpha_6}, \tag{9}$$

where $S = (N - Z - 1)/A$, $V = ZA^{-1/3}$, α_i are parameters.

Fig. 1 shows the nonelastic cross-section σ_{non} calculated for all stable nuclei with the mass number $24 \le A \le 209$ using the ECIS code [123] and the optical potential from Ref. [124]. These σ_{non} values were used at the fitting of Eq. (9) to experimental cross-sections from Table 1.

The fitting provides the minimum of the expression

$$\Sigma = \sum_{i=1}^{N} \left(\left(\sigma_i^{\mathrm{syst}} - \sigma_i^{\mathrm{exp}}\right) / \Delta\sigma_i^{\mathrm{exp}} \right)^2, \tag{10}$$

where σ_i^{syst} is the cross-section calculated by systematic formula, σ_i^{exp} and $\Delta\sigma_i^{\mathrm{exp}}$ are the cross-section and its error obtained from the analysis of measured data (Sect. 2); N is the number of target nuclei, for which experimental data are available.

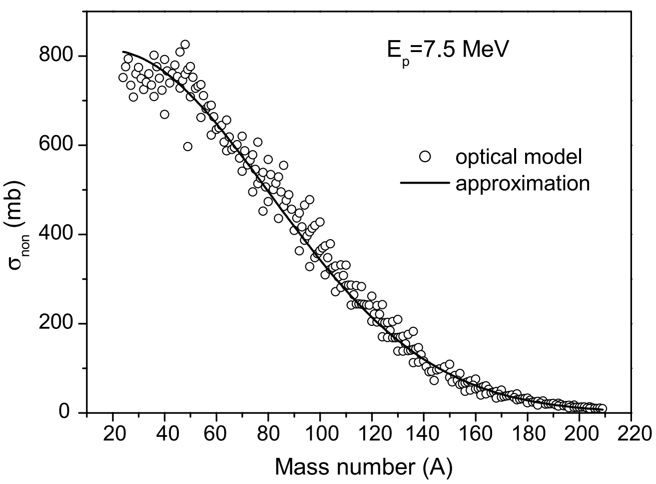

Fig. 1. The proton nonelastic cross-section σ_{non} for all stable nuclei with the mass number $24 \le A \le 209$ at the incident proton energy 7.5 MeV calculated using the optical model [124] (open circle) and evaluated by Eq. (12) (solid line).

Table 1. The (p, n) reaction cross-section at the incident neutron energy 7.5 MeV obtained from the analysis of experimental data ($\sigma_i^{\exp} \pm \Delta\sigma_i^{\exp}$), the cross-section calculated using Eq. (11) with σ_{non} obtained by the optical model with parameters from Ref. [124], and the value of $\Sigma_i = ((\sigma_i^{\text{syst}} - \sigma_i^{\exp})/\Delta\sigma_i^{\exp})^2$.

Z	A	$\sigma_i^{\exp} \pm \Delta\sigma_i^{\exp}$ (mb)	σ_i^{syst} (mb)	Σ_i	Experimental data
17	37	343.0 ± 21.0	358.0	0.502	[13]
20	43	249.0 ± 25.0	286.0	2.17	[14]
20	44	570.0 ± 55.0	494.0	1.91	[14]
21	45	294.0 ± 29.0	257.0	1.67	[14–16]
22	47	237.0 ± 24.0	225.0	0.256	[14, 17]
22	48	369.0 ± 37.0	412.0	1.37	[14, 17, 18]
23	51	393.0 ± 39.0	575.0	21.9	[14, 17, 19–25]
24	52	215.0 ± 29.0	285.0	5.84	[17, 21, 26, 27]
24	54	637.0 ± 64.0	570.0	1.09	[14, 26]
25	55	436.0 ± 39.0	531.0	5.93	[20]
26	56	155.0 ± 15.0	142.0	0.797	[14, 17, 28]
26	57	385.0 ± 38.0	497.0	8.75	[14, 17]
26	58	516.0 ± 52.0	534.0	0.126	[14, 29]
27	59	418.0 ± 42.0	448.0	0.507	[19, 20, 23]
28	60	40.3 ± 4.5	47.0	2.24	[30]
28	61	340.0 ± 34.0	371.0	0.844	[30, 31]
28	62	334.0 ± 51.0	499.0	10.5	[14, 30, 32]
28	64	462.0 ± 46.0	509.0	1.04	[14, 30, 31]
29	63	292.0 ± 29.0	259.0	1.30	[14, 19, 21, 33–36]
29	65	516.0 ± 52.0	480.0	0.490	[14, 19, 21, 24, 33, 34, 37–40]
30	66	288.0 ± 47.0	457.0	12.9	[34, 41, 42]
30	67	520.0 ± 84.0	461.0	0.495	[14, 42]
30	68	523.0 ± 52.0	466.0	1.21	[14, 34, 43]
31	69	414.0 ± 41.0	443.0	0.484	[14]
32	72	460.0 ± 46.0	431.0	0.397	[14]
32	74	761.0 ± 76.0	590.0	5.07	[14]
32	76	551.0 ± 55.0	470.0	2.15	[14]
33	75	474.0 ± 55.0	423.0	0.857	[14, 20, 44]
34	76	184.0 ± 43.0	398.0	24.8	[14, 45]
34	77	408.0 ± 63.0	408.0	0.00006	[14, 45]
34	80	591.0 ± 44.0	458.0	9.12	[14]
34	82	574.0 ± 57.0	463.0	3.83	[14]
35	79	407.0 ± 41.0	392.0	0.128	[14, 46]
36	83	351.0 ± 28.0	399.0	2.95	[47]
36	84	244.0 ± 19.0	410.0	76.2	[47]
36	86	453.0 ± 40.0	430.0	0.335	[48]
37	85	490.0 ± 49.0	384.0	4.67	[49]
38	86	269.0 ± 27.0	359.0	11.0	[14, 50]
38	87	502.0 ± 41.0	389.0	7.58	[14]
38	88	399.0 ± 127.0	379.0	0.0251	[14, 51]
39	89	347.0 ± 35.0	354.0	0.0389	[14, 20, 52]
40	96	552.0 ± 55.0	428.0	5.09	[14, 53, 54]
41	93	345.0 ± 46.0	323.0	0.224	[20, 23]
42	94	224.0 ± 39.0	300.0	3.77	[14, 54–56]
42	95	351.0 ± 41.0	308.0	1.12	[14, 54]
42	96	466.0 ± 47.0	361.0	4.97	[14]
42	100	298.0 ± 60.0	332.0	0.318	[54, 57]
44	99	361.0 ± 54.0	280.0	2.26	[58]
44	100	352.0 ± 37.0	282.0	3.58	[58]
44	102	325.0 ± 34.0	290.0	1.06	[58]
44	104	163.0 ± 23.0	294.0	32.4	[59]
45	103	290.0 ± 29.0	270.0	0.498	[19, 20, 60]
46	104	274.0 ± 27.0	249.0	0.825	[61, 62]
46	105	348.0 ± 35.0	270.0	5.00	[61, 62]
46	106	204.0 ± 21.0	255.0	5.89	[61]
46	110	333.0 ± 33.0	258.0	5.15	[61, 62]
47	107	250.0 ± 25.0	236.0	0.308	[21, 33]
47	109	231.0 ± 41.0	239.0	0.0366	[21]
48	110	226.0 ± 40.0	221.0	0.0145	[63–65]
48	111	149.0 ± 44.0	222.0	2.74	[21, 63, 66]
48	112	266.0 ± 28.0	222.0	2.48	[63, 65]
48	114	282.0 ± 24.0	221.0	6.47	[65]
48	116	323.0 ± 28.0	250.0	6.73	[65]
49	113	247.0 ± 4.0	205.0	109.0	[25]
49	115	232.0 ± 26.0	205.0	1.10	[20]
50	115	200.0 ± 9.0	189.0	1.39	[67]
50	116	170.0 ± 12.0	189.0	2.53	[67]

Table 1. Continued.

Z	A	$\sigma_i^{\exp} \pm \Delta\sigma_i^{\exp}$ (mb)	σ_i^{syst} (mb)	Σ_i	Experimental data
50	117	209.0 ± 21.0	189.0	0.950	[68, 69]
50	118	140.0 ± 10.0	188.0	22.9	[69]
50	119	260.0 ± 15.0	202.0	15.2	[68]
50	120	237.0 ± 24.0	203.0	2.03	[67, 68]
50	122	267.0 ± 27.0	207.0	4.94	[68–70]
50	124	265.0 ± 9.0	205.0	43.8	[69]
51	121	178.0 ± 19.0	172.0	0.106	[71]
52	120	140.0 ± 26.0	159.0	0.539	[72]
52	122	207.0 ± 41.0	160.0	1.29	[73]
52	124	142.0 ± 16.0	157.0	0.864	[74]
52	125	237.0 ± 38.0	184.0	1.97	[75]
52	130	75.3 ± 5.9	162.0	218.0	[37]
53	127	59.8 ± 24.7	143.0	11.4	[46, 76–78]
57	139	71.1 ± 9.7	101.0	9.64	[21]
58	140	99.4 ± 18.6	90.2	0.244	[79]
58	142	79.3 ± 18.3	93.4	0.591	[79, 80]
69	169	19.6 ± 9.9	32.0	1.58	[81]
72	178	13.0 ± 2.2	24.3	26.3	[82]
72	180	30.7 ± 1.8	25.7	7.64	[83]
73	181	31.3 ± 3.1	24.3	5.15	[23, 84, 85]
74	186	29.7 ± 3.3	23.0	4.09	[86]
79	197	10.7 ± 3.6	11.1	0.00985	[23, 84, 87]
83	209	10.4 ± 1.0	8.06	5.47	[88, 89]

The obtained systematics of the (p,n) reaction cross-section is

$$\sigma_{(p,n)} = \sigma_{\text{non}}(7.5\,\text{MeV}) \times \Big[\exp(A^{3.33}(-7.8355\times10^{-3}S^2 + 6.5548\times10^{-4}S + 1.5283\times10^{-6}V - 2.1115\times10^{-5})) + 1.29\Big]^{-1}\,, \tag{11}$$

where σ_{non} is calculated by the optical model using the potential from Ref. [124], N, Z and A are the number of neutrons, protons and nucleons in the target nucleus, correspondingly.

The value of Σ corresponding to the description of experimental data from Table 1 by Eq. (11) is equal to 823.

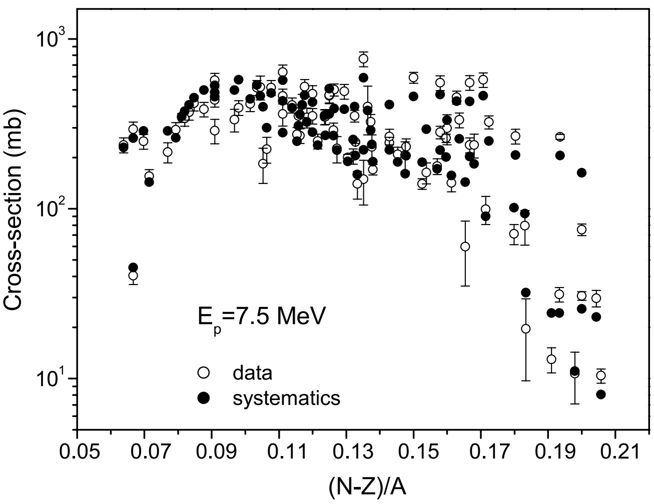

Fig. 2. The (p,n) reaction cross-sections for 90 nuclei with the mass number $37 \le A \le 209$ at the incident proton energy 7.5 MeV obtained from the analysis of experimental data (Table 1) (black circle) and calculated by the systematics, Eq. (11) (open circle) depending upon the $(N-Z)/A$ parameter.

Fig. 2 and Table 1 show experimental cross-sections and cross-sections evaluated by Eq. (11).

Eq. (11) can be used for the prediction of the (p,n) reaction cross-section at the proton energy 7.5 MeV for targets with $40 \le A \le 209$. It requires the calculation of the nonelastic cross-section σ_{non} by the optical model with the potential [124].

The fast evaluation of the (p,n) reaction cross-section can be done using Eq. (11) and the approximate formula for the proton nonelastic cross-section (Fig. 1)

$$\sigma_{\text{non}}^{\text{appr}}(7.5\,\text{MeV}) = 813.44\exp(-1.2797\times10^{-4}(A-17.878)^2)\,, \tag{12}$$

where A is the target mass number, and the cross-section is presented in mb.

In the last case the agreement with the experimental data from Table 1 is a little worse and the corresponding value of Σ is equal 976.

4. Systematics at the incident proton energy 12.4 MeV

To study the systematics dependence of the cross-section it is useful to divide nuclei on two groups with the threshold energy of the $(p,2n)$ reaction above and below 12.4 MeV assuming that the emission of the second neutron is more probable than the second proton emission. For the first group Eq. (9) can be applied to obtain the systematics of the (p,n) cross-section. Additional study is needed for the second group.

4.1 Nuclei with the threshold of the $(p,2n)$ reaction above 12.4 MeV

There are experimental data for 28 nuclei with the threshold energy of the $(p,2n)$ reaction above 12.4 MeV (Table 2).

Table 2. The (p, n) reaction cross-section at the incident neutron energy 12.4 MeV obtained from the analysis of experimental data ($\sigma_i^{\mathrm{exp}} \pm \Delta\sigma_i^{\mathrm{exp}}$), the cross-section calculated using Eqs. (13), (19) with σ_{non} obtained by the optical model with parameters from Ref. [124], and the value of $\Sigma_i = ((\sigma_i^{\mathrm{syst}} - \sigma_i^{\mathrm{exp}})/\Delta\sigma_i^{\mathrm{exp}})^2$.

Z	A	$\sigma_i^{\mathrm{exp}} \pm \Delta\sigma_i^{\mathrm{exp}}$ (mb)	σ_i^{syst} (mb)	Σ_i	Experimental data
20	43	247.0 ± 17.0	282.0	4.14	[14]
20	44	756.0 ± 49.0	737.0	0.151	[14]
21	45	361.0 ± 36.0	306.0	2.34	[14, 16, 90]
22	47	313.0 ± 49.0	334.0	0.177	[14, 17]
22	48	560.0 ± 68.0	536.0	0.126	[14, 17]
23	51	705.0 ± 71.0	846.0	3.93	[14, 17, 22, 23]
24	52	487.0 ± 49.0	422.0	1.75	[14, 17, 27]
24	54	888.0 ± 71.0	979.0	1.65	[14]
26	56	439.0 ± 44.0	376.0	2.05	[14, 17]
26	57	412.0 ± 90.0	679.0	8.83	[14, 17]
26	58	733.0 ± 73.0	763.0	0.165	[14, 29]
27	59	582.0 ± 43.0	476.0	6.10	[23]
28	60	339.0 ± 34.0	371.0	0.893	[14, 30, 90]
28	61	390.0 ± 39.0	559.0	18.9	[30, 31, 90]
28	62	604.0 ± 113.0	808.0	3.27	[14, 30, 32]
28	64	614.0 ± 96.0	754.0	2.13	[14, 17, 31, 90]
29	63	456.0 ± 46.0	503.0	1.04	[14, 33, 35, 36, 91]
29	65	631.0 ± 63.0	655.0	0.145	[14, 33, 37–40, 92–95]
30	64	358.0 ± 40.0	380.0	0.29	[34]
30	66	645.0 ± 65.0	722.0	1.40	[14, 42, 90, 91]
30	67	662.0 ± 118.0	866.0	2.98	[14, 42]
30	68	957.0 ± 96.0	643.0	10.7	[14, 42, 90, 91]
31	69	785.0 ± 79.0	553.0	8.60	[14, 90]
32	70	604.0 ± 43.0	620.0	0.13	[14]
32	72	911.0 ± 64.0	878.0	0.267	[14]
32	74	918.0 ± 65.0	518.0	37.9	[14]
32	76	237.0 ± 55.0	378.0	6.55	[14, 96]
33	75	410.0 ± 29.0	531.0	17.3	[14]
34	76	675.0 ± 110.0	834.0	2.09	[14, 45, 97]
34	77	577.0 ± 155.0	878.0	3.77	[14, 45]
34	80	743.0 ± 44.0	366.0	73.4	[14]
34	82	266.0 ± 70.0	236.0	0.178	[14, 45]
35	79	674.0 ± 73.0	489.0	6.44	[14, 46, 90]
36	83	666.0 ± 74.0	886.0	8.83	[47]
36	84	524.0 ± 58.0	361.0	7.92	[47]
37	85	677.0 ± 68.0	411.0	15.3	[49]
38	86	927.0 ± 93.0	841.0	0.852	[14, 50]
38	87	1267.0 ± 74.0	1144.0	2.75	[14]
38	88	1022.0 ± 102.0	928.0	0.856	[14, 51]
39	89	750.0 ± 75.0	850.0	1.79	[14, 52, 90]
40	90	879.0 ± 88.0	799.0	0.830	[14, 90, 98]
40	96	78.3 ± 17.7	173.0	28.4	[14, 92]
41	93	631.0 ± 47.0	412.0	21.8	[23]
42	94	650.0 ± 65.0	735.0	1.72	[14, 55]
42	95	920.0 ± 51.0	796.0	5.93	[14]
42	96	917.0 ± 89.0	380.0	36.4	[14]
45	103	256.0 ± 13.0	370.0	76.3	[60]
47	107	513.0 ± 24.0	401.0	21.7	[33]
48	111	739.0 ± 74.0	324.0	31.4	[66, 90]
48	112	708.0 ± 212.0	274.0	4.19	[63]
52	120	519.0 ± 95.0	723.0	4.63	[72]
52	123	669.0 ± 67.0	212.0	46.6	[99, 100]
52	124	505.0 ± 51.0	170.0	43.1	[74, 101, 102]
52	130	85.8 ± 16.1	33.7	10.5	[37, 99]
53	127	266.0 ± 27.0	150.0	18.5	[46, 76, 103]
58	140	976.0 ± 157.0	133.0	28.8	[79]
58	142	37.9 ± 6.8	79.2	36.8	[79, 80]
59	141	453.0 ± 91.0	192.0	8.24	[104]
67	165	129.0 ± 11.0	85.4	15.7	[105]
69	169	166.0 ± 22.0	120.0	4.35	[81]
73	181	77.3 ± 7.7	87.0	1.58	[23, 84, 85]
74	186	51.7 ± 6.0	47.0	0.606	[86]
79	197	77.5 ± 7.9	98.5	7.06	[23, 84, 87, 106]
82	206	233.0 ± 35.0	83.9	18.2	[107]
83	209	86.0 ± 6.1	78.9	1.35	[89]

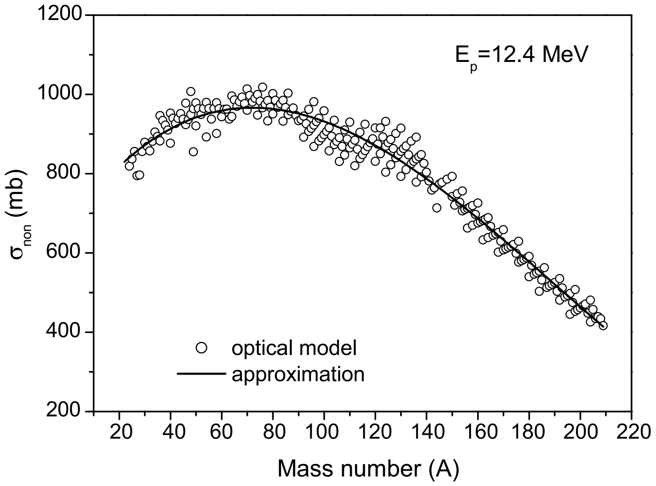

Fig. 3. The proton nonelastic cross-section σ_{non} for all stable nuclei with the mass number $24 \leq A \leq 209$ at the incident proton energy 12.4 MeV calculated using the optical model [124] (open circle) and evaluated by Eq. (14) (solid line).

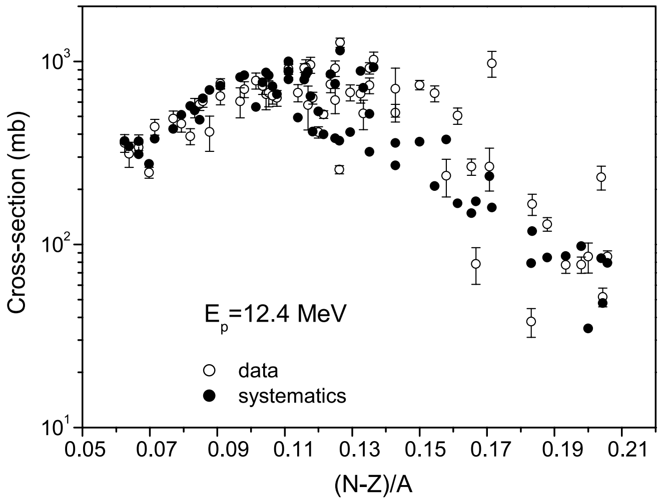

Fig. 4. The (p, n) reaction cross-sections for 65 nuclei with the mass number $43 \leq A \leq 209$ at the incident proton energy 12.4 MeV obtained from the analysis of experimental data (Table 2) (black circle) and calculated by the systematics, Eq. (13), (19) (open circle) depending upon the $(N-Z)/A$ parameter.

The fitting of Eq. (9) to the data results in the following formula for the (p, n) reaction cross-section

$$\sigma_{(p,n)} = \sigma_{\text{non}}(12.4\,\text{MeV}) \times [\exp(A^{-2.4}(-5.071119 \times 10^7 S^2 + 4.83571 \times 10^6 S + 1.904674 \times 10^2 V - 1.096068 \times 10^5)) + 1.10]^{-1}\,, \quad (13)$$

where σ_{non} is the cross-section of nonelastic interaction for the 12.4 MeV protons with the nucleus calculated using the optical potential from Ref. [124], $S = (N - Z - 1)/A$, $P = (N - Z - 1.5)/A$, $V = ZA^{-1/3}$, and Z, N, A refer to the target nucleus.

Fig. 3 shows σ_{non} values calculated using the optical model [124] for the proton incident energy 12.4 MeV and all stable nuclei with $24 \leq A \leq 209$. The obtained values can be approximated as

$$\sigma^{\text{appr}}_{\text{non}}(12.4\,\text{MeV}) = 1.346 \times 10^{-4} A^3 - 7.693 \times 10^{-2} A^2 + 8.981 A + 668.3\,, \quad (14)$$

where A is the target mass number, and the cross-section is taken in mb.

The use of Eq. (13) for the description of experimental data from Table 2 for nuclei with the $(p, 2n)$ reaction threshold above 12.4 MeV and proton nonelastic cross-sections σ_{non} calculated by the optical model [124] gives the Σ value, Eq. (10) equal to 82.7. The substitution of σ_{non} by the approximate expression, Eq. (14) results in the Σ value equal to 111.

Experimental cross-sections and cross-sections calculated using Eq. (13) are shown in Fig. 4 and Table 2.

4.2 Nuclei with the threshold of the $(p, 2n)$ reaction below 12.4 MeV

In that case, to obtain the analytical expression for the cross-section, one should take into account the probability of the emission of the second neutron. The cross-section is approximately equal to

$$\sigma_{(p,n)} = \sigma_{\text{non}} \frac{\Gamma'_{\text{n}}}{\Gamma_{\text{n}} + \Gamma_{\text{p}}} = \frac{\Gamma'_{\text{n}}/\Gamma_{\text{n}}}{1 + \Gamma_{\text{p}}/\Gamma_{\text{n}}}\,, \quad (15)$$

where Γ'_{n} is the width for the neutron emission in the energy range from $\alpha E_{\text{p}} + Q_{(p,2n)}$ to $\alpha E_{\text{p}} + Q_{(p,n)}$, $\alpha = A/(A+1)$, Γ_{n} and Γ_{p} are total neutron and proton emission widths.

The integration of neutron widths gives the following approximation expression

$$\Gamma'_{\text{n}}/\Gamma_{\text{n}} = \exp\left[-\frac{\alpha E_{\text{p}} + Q_{(p,2n)}}{T_{\text{n}}}\right]\left(1 + \frac{\alpha E_{\text{p}} + Q_{(p,2n)}}{T_{\text{n}}}\right)\,. \quad (16)$$

According to the semi-empirical mass formula the energy of the $(p, 2n)$ reaction is estimated as follows

$$Q_{(p,2n)} = \delta_1 \left(\frac{N - Z - 3}{A}\right)^2 + \delta_2 \left(\frac{N - Z - 1.5}{A}\right) + \delta_3 \frac{(Z+1)^2}{A^{4/3}} + \delta_4 \frac{Z}{A^{1/3}} + \delta_5 \frac{1}{A^{1/3}} + \delta_6\,, \quad (17)$$

where N, Z and A refer to the target nucleus, σ_i are constants.

Using Eqs. (15), (16) and (17) one can suggest the following formula for the systematics of the (p, n) reaction cross-section for nuclei with the $(p, 2n)$ reaction threshold below 12.4 MeV

$$\sigma_{(p,n)} = \sigma_{\text{non}} \exp\left[A^{1/2}(\alpha_1 R^2 + \alpha_2 P + \alpha_3 V + \alpha_4)\right] \times \left(1 + A^{1/2}(\alpha_5 R^2 + \alpha_6 P)\right)\,, \quad (18)$$

where $R = (N - Z - 3)/A$, $P = (N - Z - 1.5)/A$, $V = ZA^{-1/3}$, α_i are parameters.

Eq. (18) neglects the $\Gamma_{\text{p}}/\Gamma_{\text{n}}$ ratio comparing with unity. The additional consideration of $\Gamma_{\text{p}}/\Gamma_{\text{n}}$ in the denominator of Eq. (15) increases the number of parameters of the systematics, which is hardly reasonable taking into account the number of experimental points in Table 2. The fitting to experimental data shows that consideration of the $\Gamma_{\text{p}}/\Gamma_{\text{n}}$ ratio obtained in Sect. 4.1, did not increase the accuracy of systematics. Apparently, it indicates the high sensitivity of the (p, n) cross-section for considered group of nuclei to the energy of the $(p, 2n)$ reaction.

The fitting of Eq. (18) to experimental data for 37 nuclei from Table 2 gives the systematics of the (p, n) reaction cross-section

$$\sigma_{(p,n)} = \sigma_{\text{non}}(12.4\,\text{MeV}) \times \exp\left[A^{1/2}(-10.535R^2 + 0.2543P + 0.15407V - 3.3501)\right] \times \left(1 + A^{1/2}(1.3682 \times 10^9 R^2 + 1.6738 \times 10^7 P)\right)\,, \quad (19)$$

where $R = (N - Z - 3)/A$, $P = (N - Z - 1.5)/A$, $V = ZA^{-1/3}$, N, Z, A refer to the target nucleus.

The Σ value, which corresponds to Eq. (19) and σ_{non} cross-sections calculated by the optical model [124], is equal to 660. The use of approximate σ_{non} values, Eq. (14) gives Σ equal to 667.

Fig. 4 and Table 2 show cross-sections calculated using Eq. (19) and experimental data.

4.3 The use of systematics

The systematics of the (p, n) reaction cross-section for 12.4 MeV protons is presented by two formulas, Eqs. (13) and (19). Eq. (13) is used for nuclei with the threshold energy of the $(p, 2n)$ reaction above 12.4 MeV and Eq. (19) is applied for targets with the threshold below 12.4 MeV.

The use of Eqs. (13) and (19) for the (p, n) reaction evaluation gives the best result if the proton nonelastic cross-section, σ_{non} is calculated using the optical model with the potential from Ref. [124]. The Σ value, which corresponds to the description of experimental data for all nuclei from Table 2, is equal to 743.

The fast evaluation of the (p, n) reaction cross-section can be done using the approximate expression for σ_{non}, Eq. (14). For this case, Σ has a higher value equal to 778.

The systematics assumes that the energy of the $(p, 2n)$ reaction, $Q_{(p,2n)}$ is evaluated using the experimental mass table. Approximately, $Q_{(p,2n)}$ can be obtained by Eq. (17) with parameters $\delta_1 = -23.7$, $\delta_2 = 142.2$, $\delta_3 = -0.2367$, $\delta_4 = -1.42$, $\delta_5 = 11.867$ and $\delta_6 = -15.75$. The threshold energy of the $(p, 2n)$ reaction is equal to $-(A+1)Q_{(p,2n)}/A$. It is important to note, that the estimation of $Q_{(p,2n)}$ by Eq. (17) has the averaged error about 18% and sometimes results in incorrect determination, is the energy 12.4 MeV above or below the $(p, 2n)$ reaction threshold.

There are rare cases, when the $\sigma_{(p,n)}$ value calculated by Eq. (19) exceeds σ_{non}[1]. If it occurs, one should put $\sigma_{(p,n)}$ equal to σ_{non} for the crude evaluation of the (p, n) reaction cross-section.

5. Systematics at the incident proton energy 24.8 MeV

Pre-equilibrium neutron emission gives the main contribution to the (p, n) reaction cross-section at this proton energy. The approximate expression for the neutron spectrum obtained using the pre-equilibrium exciton model [6–8] is equal to

$$\frac{d\sigma^{\text{pre}}}{d\varepsilon_{\text{n}}} = \sigma_{\text{non}}(E_{\text{p}}) \frac{(2S_{\text{n}}+1)\mu_{\text{n}}\varepsilon_{\text{n}}\sigma_{\text{n}}^{\text{inv}}(\varepsilon_{\text{p}})}{2\pi^3\hbar^2 g^4 E_0^3\,|M|^2} \times \sum_{n=n_0} R_{\text{n}}(n)\left(\frac{\alpha E_{\text{p}} + Q_{(p,n)} - \varepsilon_{\text{n}}}{E_0}\right)^{n-2} p(n^2-1)\,, \quad (20)$$

[1] It occurs for four stable nuclei from the range $40 \leq A \leq 209$.

where ε_{n} is the kinetic energy of the outgoing neutron, S_{n} and μ_{n} are spin and reduced mass of neutron, $\sigma_{\text{n}}^{\text{inv}}$ is the inverse reaction cross-section for neutron; $|M|^2$ is the mean square of the matrix element of residual nuclear interaction; g is the single particle level density, $E_0 = \alpha E_{\text{p}} + Q_{\text{n}}$, where Q_{n} is the neutron separation energy for the compound nucleus $(Z+1, A+1)$ and $\alpha = A/(A+1)$, p is the number of particles in the n-exciton state, $R_{\text{n}}(n)$ is the factor describing the difference between the number of neutrons and protons in the n-exciton state; n_0 is the initial exciton number ($n_0 = 3$).

To evaluate the (p, n) reaction cross-section one should consider the possible particle emission from the $(Z+1, A)$ nucleus formed after the escape of the first neutron. Assuming that the neutron emission from this nucleus is the most probable, by analogy with Ref. [8], after the integration of Eq. (20) from the energy $\alpha E_{\text{p}} + Q_{(p,2n)}$ to $\alpha E_{\text{p}} + Q_{(p,n)}$, one can obtain the approximate expression for the (p, n) reaction cross-section

$$\sigma_{(p,n)} = \sigma_{\text{non}} \frac{(2S_{\text{n}}+1)\mu_{\text{n}} A^{2/3}}{\pi\hbar^2 g^4 E_0^4\,|M|^2} \times {Q'_{\text{n}}}^2\left[3(\alpha E_{\text{p}} + Q_{(p,n)}) - 2Q'_{\text{n}}\right]\,, \quad (21)$$

where Q'_{n} the is the separation energy of the neutron from the nucleus $(Z+1, A)$, which can be evaluated using the semi-empirical mass formula

$$Q'_{\text{n}} = \lambda_1\left(\frac{N-Z-3}{A}\right)^2 + \lambda_2\left(\frac{N-Z-2.5}{A}\right) + \lambda_3 Z^2/A^{4/3} + \lambda_4/A^{1/3} + \lambda_5\,, \quad (22)$$

where λ_i are constants.

It is seen that the (p, n) cross-section, Eq. (21) is expressed by polynomial functions of Q'_{n}, Eq. (22) and $Q_{(p,n)}$, Eq. (8). By analogy with Ref. [8] the following 6-parametric formula is suggested for the systematics at 24.8 MeV

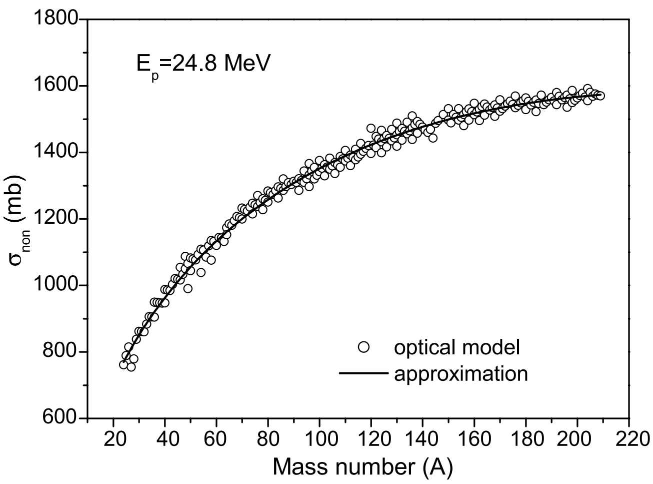

Fig. 5. The proton nonelastic cross-section σ_{non} for all stable nuclei with the mass number $24 \leq A \leq 209$ at the incident proton energy 24.8 MeV calculated using the optical model [124] (open circle) and evaluated by Eq. (25) (solid line).

Table 3. The (p,n) reaction cross-section at the incident neutron energy 24.8 MeV obtained from the analysis of experimental data ($\sigma_i^{\mathrm{exp}} \pm \Delta\sigma_i^{\mathrm{exp}}$), the cross-section calculated using Eq. (24) with σ_{non} obtained by the optical model with parameters from Ref. [124], and the value of $\Sigma_i = ((\sigma_i^{\mathrm{syst}} - \sigma_i^{\mathrm{exp}})/\Delta\sigma_i^{\mathrm{exp}})^2$.

Z	A	$\sigma_i^{\mathrm{exp}} \pm \Delta\sigma_i^{\mathrm{exp}}$ (mb)	σ_i^{syst} (mb)	Σ_i	Experimental data
20	44	57.4 ± 2.8	47.3	13.1	[14]
21	45	37.4 ± 7.1	33.8	0.258	[108]
22	48	48.2 ± 8.9	44.1	0.215	[14, 18]
23	51	56.5 ± 5.7	51.1	0.887	[14, 94, 109]
24	52	49.6 ± 2.6	41.5	9.69	[14]
24	54	57.3 ± 3.3	55.3	0.353	[14]
26	56	31.3 ± 3.2	38.8	5.55	[14, 28, 94]
26	57	35.2 ± 2.0	47.2	35.8	[14]
26	58	43.9 ± 2.5	53.0	13.1	[14]
28	60	37.6 ± 2.2	37.6	0.00007	[14]
28	64	120.0 ± 9.0	55.5	51.3	[14]
29	63	35.9 ± 3.6	43.1	4.05	[14, 33, 36]
29	65	37.9 ± 3.8	53.6	17.1	[14, 33, 39, 92, 94, 95, 110–113]
30	66	57.8 ± 5.8	48.6	2.50	[14, 41]
30	67	57.1 ± 5.7	52.6	0.610	[14, 41]
30	68	55.4 ± 12.4	55.0	0.00131	[14, 108]
32	70	59.3 ± 3.4	46.7	13.8	[14]
32	72	68.3 ± 3.9	53.4	14.6	[14]
32	74	74.2 ± 4.3	54.0	22.1	[14]
32	76	45.1 ± 2.6	47.6	0.911	[14]
33	75	42.5 ± 8.1	53.9	2.00	[14, 44]
34	76	59.8 ± 6.0	51.7	1.82	[14, 45, 97, 114]
34	77	39.4 ± 8.7	53.3	2.56	[14, 45]
34	82	52.4 ± 3.0	39.7	18.0	[14]
35	79	65.5 ± 8.1	52.7	2.51	[115]
36	83	47.7 ± 3.7	52.5	1.66	[47]
36	84	38.6 ± 3.0	50.8	16.7	[47]
36	86	38.5 ± 8.5	43.6	0.363	[48]
37	85	36.1 ± 3.6	52.3	20.3	[49]
38	86	112.0 ± 5.0	51.9	145.0	[14]
38	88	106.0 ± 20.0	51.3	7.49	[14, 51]
39	89	57.8 ± 5.8	51.8	1.06	[14, 52, 92]
40	90	100.0 ± 6.0	51.4	65.5	[14]
40	96	36.3 ± 2.4	40.4	2.93	[92]
45	103	23.8 ± 3.0	49.9	75.6	[60]
48	111	56.4 ± 5.6	48.0	2.24	[66, 116]
52	120	46.7 ± 8.4	46.8	0.00026	[72]
52	124	60.4 ± 6.0	39.6	12.0	[101, 102]
52	125	79.8 ± 13.1	36.6	10.9	[75]
52	130	11.5 ± 1.3	14.1	3.87	[117]
53	127	33.9 ± 8.8	37.7	0.184	[46, 78, 118]
60	148	26.1 ± 2.8	23.1	1.11	[119]
73	181	46.2 ± 10.2	20.1	6.56	[85]
74	186	23.4 ± 5.6	12.4	3.88	[86]
83	209	12.7 ± 1.2	11.9	0.488	[89]

$$\sigma_{(p,n)} = \sigma_{\mathrm{non}} A^{\alpha_1} (\alpha_2 S^3 + \alpha_3 S^2 + \alpha_4 S + \alpha_5 V + \alpha_6)\,, \qquad (23)$$

where $S = (N - Z - 1)/A$, $V = ZA^{-1/3}$, N, Z and A are number of neutrons, protons and nucleons in the target nucleus, α_i are parameters.

Fig. 5 shows the nonelastic cross-section σ_{non} calculated at 24.8 MeV for all stable nuclei with the mass number $24 \le A \le 209$ using the ECIS code [123] and the optical potential from Ref. [124].

The fitting of Eq. (23) to experimental data from Table 3 with σ_{non} calculated by the optical model [124] gives the formula

$$\sigma_{(p,n)} = \sigma_{\mathrm{non}}(24.8\,\mathrm{MeV}) A^{-1.0158} (-1553.4 S^3 + 161.47 S^2 + 24.371 S + 0.320 V - 1.5689)\,, \qquad (24)$$

where $S = (N - Z - 1)/A$, $V = ZA^{-1/3}$, N, Z and A are the number of neutrons, protons and nucleons in the target nucleus, correspondingly.

The Σ value for Eq. (24) is equal to 610.

Fig. 6 and Table 3 show cross-sections calculated using Eq. (24) and experimental cross-sections.

The proton nonelastic cross-section at 24.8 MeV can be approximated by the expression (Fig. 5)

$$\sigma_{\mathrm{non}}^{\mathrm{appr}}(24.8\,\mathrm{MeV}) = 164.84 A^{1/2} \exp(-1.986 \times 10^{-3} A)\,, \qquad (25)$$

where A is the target mass number, and the cross-section is taken in mb.

The use of approximate values for proton nonelastic cross-section in Eq. (24) gives Σ equal to 614.

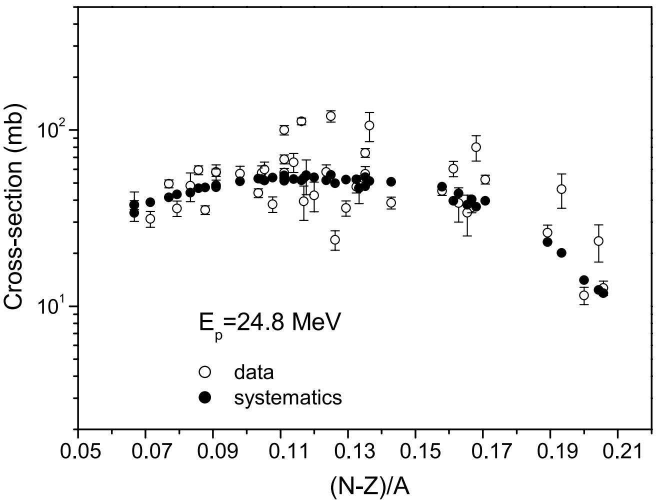

Fig. 6. The (p, n) reaction cross-sections for 45 nuclei with the mass number $44 \leq A \leq 209$ at the incident proton energy 24.8 MeV obtained from the analysis of experimental data (Table 3) (black circle) and calculated by the systematics, Eq. (24) (open circle) depending upon the $(N - Z)/A$ parameter.

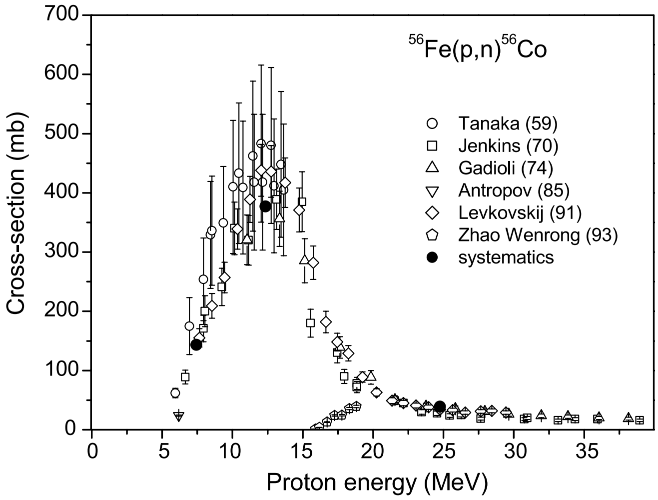

Fig. 7. The cross-section for the $^{56}Fe(p, n)^{56}Co$ reaction evaluated using the systematics obtained and available experimental data.

6. Conclusion

Systematics for the (p, n) reaction cross-section were obtained at incident proton energies 7.5 MeV, 12.4 MeV and 24.8 MeV. Analytical formulas derived using the pre-equilibrium exciton model, evaporation model and semi-empirical mass formula were used to study the systematic dependence of the (p, n) reaction cross-section on the number of neutrons and protons in nuclei. Formulas were fitted to the data obtained from the analysis of available measured (p, n) reaction cross-section.

The (p, n) reaction cross-section can be calculated for target nuclei with the mass number from 40 to 209 using Eq. (11) for the 7.5 MeV incident protons, using Eqs. (13) and (19) for the 12.4 MeV protons and Eq. (24) for the 24.8 MeV protons. The best result is obtained if the proton nonelastic reaction cross-section σ_{non} in Eqs. (11), (13), (19) and (24) is calculated using the optical model with the potential from Ref. [124]. The σ_{non} value can be evaluated also using the approximate expressions Eqs. (12), (14), (25) obtained in the present work.

The value of Σ, Eq. (10), which quantifies the description of experimental data from Tables 1–3 is shown in Table 4. For the comparison Σ values corresponding to the calculation of the (p, n) reaction cross-section using modern nuclear models [120, 125] are also given.

Fig. 7 presents the example of cross-sections evaluated by the systematics obtained. The evaluated cross-section for the $^{56}Fe(p, n)^{56}Co$ reaction and available experimental data are shown in Fig. 7.

Table 4. The Σ value, Eq. (10) calculated using the systematics obtained in the present work, Eqs. (11), (13), (19), (24) and the (p, n) cross-section calculated by the TALYS code [120] and the ALICE/ASH code [125] with recommended code options [12, 120, 125]. The experimental data are taken from Tables 1–3.

Energy (MeV)	Systematics	TALYS	ALICE/ASH
7.5	823	1620	1960
12.4	743	761	1540
24.8	610	1690	1010

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