Available online at www.sciencedirect.com
ScienceDirect
Applied Radiation and Isotopes 65 (2007) 1249–1264
Applied Radiation and Isotopes
www.elsevier.com/locate/apradiso

Systematics of (p,α) (p,nα), and (p,np) reaction cross-sections

C.H.M. Broeders, A.Yu. Konobeyev*

Institut für Reaktorsicherheit, Forschungszentrum Karlsruhe GmbH, 76021 Karlsruhe, Germany

Received 31 October 2006; received in revised form 30 March 2007; accepted 3 April 2007

Abstract

Semi-empirical systematics of (p,α) (p,nα), and (p,np) reaction cross-sections were obtained at various incident proton energies from 17.9 to 28.5 MeV. Systematics are 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 cross-sections for (p,α) (p,nα), and (p,np) reactions.

Keywords: Proton-induced reaction; Cross-section; Evaluation; Systematics; Intermediate energies

1. Introduction

Obtaining systematics is an important part of the work concerned with the prediction and calculation of nuclear reaction cross-sections. Systematics are widely used for the reaction cross-section evaluation supplementing results of measurements and calculations by theoretical models (Forrest et al., 2005).

The cross-section evaluation for materials irradiated by protons (Chadwick et al., 1999; Watanabe et al., 2004; Broeders et al., 2007) attaches special importance to the use of systematics of proton-induced reaction cross-sections (Broeders et al., 2006a). Unfortunately, the number of reactions, for which the systematic dependence of cross-sections can be investigated using experimental data, is rather small. The systematics for one of such reactions, (p,n) was discussed recently in Broeders et al. (2006a). First systematics for (p,xn) reactions cross-sections have been obtained in Röhm et al. (1973) and Münzel et al. (1974).

The present work concerns the systematics of (p,α) (p,nα), and (p,np) reaction cross-sections. Semi-empirical formulas for the evaluation of cross-sections for these reactions were derived using analytical expressions describing the equilibrium and nonequilibrium particle emission in nuclear reactions. Parameters of formulas were fitted to the data obtained from the analysis of available experimental data.

The study of the systematics' dependence of cross-sections was performed at proton incident energies with the maximal number of measurements available. The systematics for the (p,α) reaction cross-section was obtained at the incident proton energy 17.9 MeV, for the (p,nα) reaction cross-section at 24.8 and 28.5 MeV, and for the (p,np) reaction at 22.3 MeV.

2. Experimental data

Experimental cross-sections for the (p,α) reaction were taken from Levkovskij (1991), Michel et al. (1978, 1979), Kaufman (1960), Ewart and Blann (1960), Brinkman et al. (1977), Reimer and Qaim (1998), Sonck et al. (1996), Tarkanyi et al. (1991a, b, 1993, 2004, 2005a, b), Haasbroek et al. (1976), Sudar et al. (1993), Qaim et al. (1995), Cohen et al. (1954), Kastleiner et al. (1999), Nortier et al. (1991), Tarkanyi and Qaim (1989), Prescher et al. (1991), Milazzo-Colli et al. (1974), Szelecsenyi et al. (2005a); for the (p,nα) reaction from Levkovskij (1991), Michel et al. (1978, 1997), Nortier et al. (1991), Tarkanyi and Qaim (1989), Prescher et al. (1991), Tarkanyi et al. (2004, 2005b), Gadioli et al. (1981), Klein et al. (2000), Sterns (1962), Szelecsenyi et al. (2005b), Horiguchi et al. (1983), Kovacs et al. (1985), De Villiers et al. (2002), Steyn et al. (1991), Sachdev et al.

*Corresponding author. Tel.: +49 7247 82 2638; fax: +49 7247 82 3718.
E-mail address: konobeev@irs.fzk.de (A.Y. Konobeyev).

0969-8043/$ - see front matter
doi:10.1016/j.apradiso.2007.04.002

(1967), Takacs et al. (2002a), Kantelo and Hogan (1976a, b), Hilgers et al. (2003), and for the (p,np) reaction from Levkovskij (1991), Michel et al. (1979, 1997), Ewart and Blann (1960), Brinkman et al. (1977), Reimer and Qaim (1998), Haasbroek et al. (1976), Klein et al. (2000), Kovacs et al. (1985), Steyn et al. (1991), Ejnisman et al. (1996), Meadows et al. (1956), Cohen and Newman (1955), Michel and Brinkmann (1980), Gusakow et al. (1961), Jenkins and Wain (1970), Schoen et al. (1979), Sharp et al. (1956), Tarkanyi et al. (1989a, b, 1991b, c), Takacs et al. (2002b, 2003), Furukawa et al. (1990, 1991), Sonck et al. (1998), Aleksandrov et al. (1987), Meadows (1953), Ghoshal, (1950), Grutte, (1982), Meghir (1962), Colle et al. (1976), Newton et al. (1973), Szelecsenyi et al. (1998), Hassan et al. (2004), Horiguchi et al. (1980), Kastleiner et al. (2004), Sakamoto et al. (1985), Mustafa et al. (1988), Scholten et al. (1999), Diksic and Yaffe (1977), Kurenkov et al. (1989), Deptula et al. (1990), Rao and Yaffe (1963), Grant and Yaffe (1963), Kavanagh and Bell (1961), Qaim et al. (1979). Proton energies, the vicinities of which contain the maximal number of cross-section measurements for each reaction at the wide range of target nuclei, have been determined. Selected energy points are 17.9 MeV for the (p,α) reaction, 24.8 and 28.5 MeV for (p,nα), and 22.3 MeV for the (p,np) reaction. Experimental data available for the (p,α) reaction in the energy range 17.9 ± 0.5 MeV, for the (p,nα) reaction at 24.8 ± 1.0 MeV and 28.5 ± 1.0 MeV, and for the (p,np) reaction at 22.3 ± 1.0 MeV were reduced to incident proton energies 17.9, 24.8, 28.5, and 22.3 MeV, correspondingly, using excitation functions for (p,α), (p,nα), and (p,np) reactions calculated by the TALYS code (Koning et al., 2004). The calculation of excitation functions has been performed with the code options briefly described in Broeders et al. (2007). Cross-sections for individual isotopes were extracted from experimental data for natural mixtures, where it was possible.

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

Table 1
The (p,α) reaction cross-section at the incident proton energy 17.9 MeV obtained from the analysis of experimental data ($\sigma_i^{exp} \pm \Delta\sigma_i^{exp}$)

Z	*A*	$\sigma_i^{exp} \pm \Delta\sigma_i^{exp}$(mb)	Reference
22	46	42.1 ± 3.0	Levkovskij (1991)
22	47	87.5 ± 8.7	Levkovskij (1991), Michel et al. (1978)
22	49	57.8 ± 4.1	Levkovskij (1991)
26	54	46.8 ± 3.3	Levkovskij (1991)
26	57	56.6 ± 10.1	Levkovskij (1991), Michel et al. (1979)
28	58	34.7 ± 3.5	Levkovskij (1991), Kaufman (1960), Ewart and Blann (1960),Brinkman et al. (1977), Reimer and Qaim (1998), Sonck et al. (1996), Tarkanyi et al. (1991a), Haasbroek et al. (1976)
28	60	93.3 ± 6.6	Levkovskij (1991)
28	61	37.5 ± 4.7	Sudar et al. (1993)
28	64	20.5 ± 3.0	Levkovskij (1991), Qaim et al. (1995)
30	64	54.6 ± 5.5	Levkovskij (1991), Cohen et al. (1954), Szelecsenyi et al. (2005a)
30	67	27.2 ± 1.9	Levkovskij (1991)
30	70	11.0 ± 1.1	Levkovskij (1991), Kastleiner et al. (1999)
32	70	53.6 ± 9.6	Levkovskij (1991), Nortier et al. (1991)
32	76	7.57 ± 1.35	Levkovskij (1991), Nortier et al. (1991)
34	74	54.4 ± 3.8	Levkovskij (1991)
34	77	24.7 ± 1.7	Levkovskij (1991)
36	78	21.4 ± 4.2	Tarkanyi et al. (1993)
38	86	14.8 ± 2.0	Levkovskij (1991), Qaim et al. (1995)
38	87	16.0 ± 1.1	Levkovskij (1991)
40	90	14.0 ± 1.0	Levkovskij (1991)
40	91	15.5 ± 1.1	Levkovskij (1991)
42	98	10.5 ± 0.7	Levkovskij (1991)
42	100	5.19 ± 0.39	Levkovskij (1991)
48	114	5.55 ± 0.63	Tarkanyi et al. (2005a)
54	129	2.02 ± 0.45	Tarkanyi and Qaim (1989)
54	134	1.18 ± 0.25	Tarkanyi and Qaim (1989)
56	135	3.77 ± 0.45	Prescher et al. (1991)
60	150	6.40 ± 0.79	Milazzo-Colli et al. (1974)
62	147	12.7 ± 1.6	Milazzo-Colli et al. (1974)
62	152	6.30 ± 0.77	Milazzo-Colli et al. (1974)
62	154	5.23 ± 0.64	Milazzo-Colli et al. (1974)
70	176	4.01 ± 0.49	Milazzo-Colli et al. (1974)
78	195	1.20 ± 0.21	Tarkanyi et al. (2004)
79	197	1.53 ± 0.19	Milazzo-Colli et al. (1974)

Table 2
The (p,nα) reaction cross-section at the incident proton energy 24.8 MeV obtained from the analysis of experimental data ($\sigma_i^{exp} \pm \Delta\sigma_i^{exp}$)

Z	A	$(\sigma_i^{exp} \pm \Delta\sigma_i^{exp})$(mb)	Reference
22	47	35.9±2.1	Levkovskij (1991)
22	48	58.7±6.5	Levkovskij (1991), Michel et al. (1978)
22	50	33.6±2.7	Gadioli et al. (1981)
24	52	30.7±3.3	Levkovskij (1991), Klein et al. (2000)
25	55	99.0±5.7	Levkovskij (1991)
26	56	31.9±1.3	Levkovskij (1991)
26	58	88.6±5.1	Levkovskij (1991)
28	60	46.2±2.7	Levkovskij (1991)
28	62	87.8±21.3	Levkovskij (1991), Sterns (1962)
28	64	63.7±3.7	Levkovskij (1991)
30	64	45.3±2.6	Levkovskij (1991)
30	68	69.5±6.9	Levkovskij (1991), Szelecsenyi et al. (2005b), Tarkanyi et al. (2005b)
31	69	131.0±8.0	Levkovskij (1991)
32	70	81.9±8.2	Levkovskij (1991), Nortier et al. (1991), Horiguchi et al. (1983)
32	72	60.8±7.4	Levkovskij (1991), Nortier et al. (1991)
32	76	21.6±2.2	Levkovskij (1991), Nortier et al. (1991)
34	74	37.0±2.1	Levkovskij (1991)
34	76	56.6±12.3	Levkovskij (1991), Kovacs et al. (1985)
34	78	39.6±2.3	Levkovskij (1991)
34	80	19.3±1.1	Levkovskij (1991)
34	82	12.2±1.0	Levkovskij (1991)
35	79	70.0±8.6	Levkovskij (1991), De Villiers et al. (2002)
36	86	8.87±2.84	Steyn et al. (1991)
38	87	27.6±1.7	Levkovskij (1991)
38	88	13.6±1.4	Levkovskij (1991), Sachdev et al. (1967), Michel et al. (1997)
39	89	35.6±2.1	Levkovskij (1991)
40	90	12.0±1.2	Levkovskij (1991), Michel et al. (1997), Kantelo and Hogan (1976a)
40	91	28.7±1.3	Levkovskij (1991)
40	92	29.8±1.7	Levkovskij (1991)
41	93	47.7±2.8	Levkovskij (1991)
42	94	42.2±2.4	Levkovskij (1991)
42	100	12.6±1.3	Levkovskij (1991), Takacs et al. (2002a)
54	134	1.56±0.28	Tarkanyi and Qaim (1989)
56	138	4.56±2.30	Prescher et al. (1991)
78	194	1.48±0.35	Tarkanyi et al. (2004)
80	202	1.35±0.18	Kantelo and Hogan (1976b)

means" (Wollersheim, 2004; Broeders and Konobeyev, 2006).

The (p,α), (p,nα), and (p,np) reaction cross-sections obtained from the analysis of experimental data are shown in Tables 1–4. Systematics were obtained by the fitting of parameters of analytical expressions discussed in Sections 3–5 to the data from Tables 1–4 providing the minimum of the expression

$$\Sigma = \sum_{i=1}^{N} \left(\frac{(\sigma_i^{syst} - \langle \sigma_i^{exp} \rangle)}{\langle \Delta\sigma_i^{exp} \rangle} \right)^2, \quad (1)$$

where σ_i^{syst} is the cross-section calculated by systematic formula for ith target nucleus, $\langle \sigma_i^{exp} \rangle$ and $\langle \Delta\sigma_i^{exp} \rangle$ are the cross-section and its error obtained from the analysis of measured data (Tables 1–4) and N is the number of target nuclei, for which experimental data are available.

3. Systematics of the (p,α) reaction cross-section at the proton energy 17.9 MeV

The (p,α) reaction cross-section can be written in the following form:

$$\sigma_{(p,\alpha)} = \sigma_{non}(E_p) \Bigg\{ \int_0^{\beta E_p + Q_{(p,\alpha)}} W_\alpha^{pre}(\varepsilon_\alpha)\, d\varepsilon_\alpha + (1 - P_{tot}^{pre}) \int_0^{\beta E_p + Q_{(p,\alpha)}} W_\alpha^{eq}(\varepsilon_\alpha)\, d\varepsilon_\alpha \times \left[\sum_x \int_0^{\beta E_p + Q_{(p,x)}} W_x^{eq}(\varepsilon_x)\, d\varepsilon_x \right]^{-1} \Bigg\}, \quad (2)$$

where σ_{non} is the cross-section of the non-elastic interaction of the incident proton with a nucleus at the kinetic energy E_p; W_α^{pre} is the probability of the pre-equilibrium emission of the α-particle with the kinetic

Table 3
The (p,nα) reaction cross-section at the incident proton energy 28.5 MeV obtained from the analysis of experimental data ($\sigma_i^{exp} \pm \Delta\sigma_i^{exp}$)

Z	A	$\sigma_i^{exp} \pm \Delta\sigma_i^{exp}$ (mb)	Reference
22	47	41.7 ± 2.7	Levkovskij (1991)
22	48	90.5 ± 9.0	Levkovskij (1991), Michel et al. (1978)
24	52	59.1 ± 5.9	Levkovskij (1991), Klein et al. (2000)
25	55	105.0 ± 6.0	Levkovskij (1991)
26	56	66.9 ± 3.4	Levkovskij (1991)
26	58	102.0 ± 6.0	Levkovskij (1991)
28	60	64.5 ± 3.7	Levkovskij (1991)
28	62	99.6 ± 14.3	Levkovskij (1991), Sterns (1962)
28	64	55.0 ± 3.2	Levkovskij (1991)
30	64	54.4 ± 3.1	Levkovskij (1991)
30	68	47.3 ± 13.3	Levkovskij (1991), Szelecsenyi et al. (2005b), Hilgers et al. (2003)
31	69	102.0 ± 6.0	Levkovskij (1991)
32	70	101.0 ± 10.0	Levkovskij (1991), Nortier et al. (1991), Horiguchi et al. (1983)
32	72	76.3 ± 4.4	Levkovskij (1991)
32	76	23.1 ± 1.3	Levkovskij (1991)
34	74	62.7 ± 4.0	Levkovskij (1991)
34	76	80.7 ± 12.0	Levkovskij (1991), Kovacs et al. (1985)
34	78	51.3 ± 3.0	Levkovskij (1991)
34	80	23.6 ± 1.4	Levkovskij (1991)
34	82	14.4 ± 0.8	Levkovskij (1991)
35	79	77.0 ± 16.9	Levkovskij (1991), De Villiers et al. (2002)
36	86	14.7 ± 9.4	Steyn et al. (1991)
38	87	47.4 ± 2.7	Levkovskij (1991)
38	88	32.5 ± 1.9	Levkovskij (1991), Sachdev et al. (1967)
39	89	53.9 ± 3.1	Levkovskij (1991)
40	90	38.1 ± 3.8	Levkovskij (1991), Michel et al. (1997)
40	91	44.3 ± 2.1	Levkovskij (1991)
40	92	46.1 ± 2.7	Levkovskij (1991)
41	93	57.9 ± 3.3	Levkovskij (1991)
42	92	18.6 ± 2.7	Levkovskij (1991)
42	94	68.3 ± 3.9	Levkovskij (1991)
42	100	10.2 ± 1.0	Levkovskij (1991), Takacs et al. (2002a)
54	134	2.82 ± 0.89	Tarkanyi and Qaim (1989)
56	138	7.01 ± 1.72	Prescher et al. (1991)
78	194	3.26 ± 2.41	Tarkanyi et al. (2004)

energy ε_α; P_{tot}^{pre} is the integrated contribution of pre-compound processes in the particle emission; W_α^{eq} is the probability of the equilibrium emission for α-particles; $Q_{(p,\alpha)}$ is the energy of the (p,α) reaction; x refers to the particle of any type, which emission is possible; W_x^{eq} is the emission probability for the particle of the x-type; $Q_{(p,x)}$ is the energy of the reaction with the x-particle emission, $\beta = A/(A+1)$; and A is the mass number of the target nucleus.

Using the approximate expression for W_α^{pre} (Konobeyev et al., 1996), the Weisskopf and Ewing (1940) formulafor W_x^{eq} and the "constant temperature" model for evaluation of the nuclear level density (Ignatyuk and Capote, 2006), one can obtain the following expression for the (p,α) reaction cross-section:

$$\sigma_{(p,\alpha)} = \sigma_{non}\left[\frac{4}{3}\frac{(2S_\alpha+1)\mu_\alpha R^2}{\pi^2\hbar^2 g^4 E_0^4 |M|^2}(\beta E_p + Q_{(p,\alpha)} - V_\alpha)^3 \times \{0.5C_1(\beta E_p + Q_{(p,\alpha)} - V_\alpha) + C_1(V_\alpha + Q_\alpha) + C_2\} + (1 - P_{tot}^{pre})\frac{(2S_\alpha+1)\mu_\alpha}{(2S_n+1)\mu_n} \times \exp\left\{\frac{\beta E_p + Q_{(p,\alpha)} - U_{0\alpha} - V_\alpha}{T_\alpha} - \frac{\beta E_p + Q_{(p,n)} - U_{0n}}{T_n}\right\}\right], \quad (3)$$

where it is assumed that the probability of the neutron equilibrium emission predominates comparing with probabilities for other channels; S_α and μ_α are spin and reduced mass of the outgoing α-particle; ε_α is the kinetic energy of the α-particle; $|M|^2$ is the mean square of the matrix element of the residual nuclear interaction; g is the single particle level density; $E_0 = \beta E_p + Q_p$, where Q_p is the proton separation energy in a compound nucleus; R is the nucleus radius; V_α is the Coulomb potential for α-particles; C_1 and C_2 are constants in the linear approximation of the α-formation factor (Iwamoto and Harada, 1982; Sato et al., 1983): $F_{1,3} = C_1(\varepsilon_\alpha + Q_\alpha) + C_2$, where Q_α is the separation energy for the α-particle in the compound nucleus and P_{tot}^{pre} is the total probability of pre-compound

Table 4
The sum of (p,np) and (p,d) reaction cross-sections at the incident proton energy 22.3 MeV obtained from the analysis of experimental data ($\sigma_i^{exp} \pm \Delta\sigma_i^{exp}$)

Z	A	$\sigma_i^{exp} \pm \Delta\sigma_i^{exp}$ (mb)	Reference
21	45	585.0 ± 124.0	Levkovskij (1991), Ejnisman et al. (1996), Meadows et al. (1956)
22	46	336.0 ± 24.0	Levkovskij (1991)
24	50	211.0 ± 32.0	Kaufman (1960)
24	52	577.0 ± 87.0	Klein et al. (2000), Cohen and Newman (1955)
25	55	567.0 ± 60.0	Levkovskij (1991), Cohen and Newman (1955), Michel and Brinkmann (1980), Gusakow et al. (1961)
26	56	565.0 ± 126.0	Cohen and Newman (1955), Jenkins and Wain (1970)
27	59	496.0 ± 50.0	Levkovskij (1991), Michel et al. (1979), Haasbroek et al (1976), Schoen et al. (1979), Sharp et al. (1956)
28	58	213.0 ± 21.0	Levkovskij (1991), Ewart and Blann (1960), Brinkman et al (1977), Reimer and Qaim (1998), Tarkanyi et al. (1989a, b), Takacs et al. (2002b), Furukawa et al. (1990), Sonck et al. (1998), Aleksandrov et al. (1987)
28	64	210.0 ± 25.0	Furukawa et al. (1991)
29	63	571.0 ± 85.0	Cohen and Newman (1955), Meadows (1953), Ghoshal, (1950)
29	65	328.0 ± 33.0	Levkovskij (1991), Brinkman et al (1977), Michel et al. (1997), Cohen and Newman (1955), Grutte, (1982), Meghir (1962), Colle et al. (1976), Newton et al. (1973)
30	64	637.0 ± 45.0	Levkovskij (1991)
30	66	799.0 ± 80.0	Levkovskij (1991), Szelecsenyi et al. (1998)
31	69	436.0 ± 31.0	Levkovskij (1991), Cohen and Newman (1955)
32	76	179.0 ± 13.0	Levkovskij (1991)
33	75	293.0 ± 21.0	Levkovskij (1991), Cohen and Newman (1955)
34	76	429.0 ± 73.0	Kovacs et al. (1985), Hassan et al. (2004)
35	79	364.0 ± 26.0	Levkovskij (1991)
35	81	214.0 ± 11.0	Levkovskij (1991)
36	78	486.0 ± 127.0	Steyn et al. (1991)
36	80	750.0 ± 90.0	Steyn et al. (1991)
37	85	197.0 ± 37.0	Levkovskij (1991), Horiguchi et al. (1980), Kastleiner et al. (2004), Sakamoto et al. (1985)
38	86	448.0 ± 62.0	Levkovskij (1991)
39	89	208.0 ± 39.0	Levkovskij (1991), Mustafa et al. (1988)
40	96	181.0 ± 13.0	Levkovskij (1991)
42	100	105.0 ± 22.0	Levkovskij (1991), Scholten et al. (1999), Takacs et al. (2003)
53	127	85.3 ± 7.1	Diksic and Yaffe (1977)
54	124	91.7 ± 43.3	Tarkanyi et al. (1989b, c), Kurenkov et al. (1989)
55	133	75.5 ± 7.6	Sakamoto et al. (1985), Deptula et al. (1990)
73	181	76.6 ± 16.8	Rao and Yaffe (1963)
77	191	38.0 ± 7.6	Grant and Yaffe (1963)
77	193	84.2 ± 16.8	Grant and Yaffe (1963)
79	197	77.9 ± 7.8	Kavanagh and Bell (1961), Michel et al. (1997)
81	203	66.4 ± 15.9	Qaim et al. (1979)

processes, which can be evaluated using the same approximations as in (Konobeyev et al., 1996; Konobeyev and Korovin, 1999; Broeders and Konobeyev, 2006).

To obtain the systematic formula one can assume that nuclear temperatures in Eq. (3) for α-particle and neutron channels are close ($T_\alpha \approx T_n$). Making the same assumptions than in (Konobeyev et al., 1996) one can suggest the following systematic formula for the (p,α) reaction cross-section

$$\sigma_{(p,\alpha)} = \sigma_{non}[A^{-1/3}(\alpha_1 X_1 + \alpha_2) + \exp\{A^{1/2}(\alpha_3 X_2^2 + \alpha_4 X_3 + \alpha_5 + \alpha_6 f_{sh,p})\}], \quad (4)$$

where $X_1 = (N-Z-0.5)/A$, $X_2 = (N-Z-1)/A$, $X_3 = (N-Z-1.5)/A$, N, Z, and A are number of neutrons, protons, and nucleons in the target nucleus correspondingly, $f_{sh,p}$ is an empirical function describing the shell and pairing effects, and α_i are parameters.

The term $\alpha_6 f_{sh,p}$ enters in Eq. (4) as a consequence of shell and pairing effects in the reaction energy $Q_{(p,\alpha)}$, nuclear temperatures T_n and T_α and shift energies U_{0n} and $U_{0\alpha}$. Usually, the term is omitted in systematics due to problems with its parameterization. An exception was made for the systematics of the (n,t) reaction cross-section in Konobeyev et al. (1994), where $f_{sh,p}$ has been expressed as a difference between shell corrections for the target and the residual nucleus.

In the present work, the systematic formulas with and without the $\alpha_6 f_{sh,p}$ term are compared.

The fitting of Eq. (4) with $\alpha_6 = 0$ to experimental cross-sections from Table 1 results in the systematic formula with following parameters $\alpha_1 = -0.220$, $\alpha_2 = 5.1409 \times 10^{-2}$, $\alpha_3 = -38.465$, $\alpha_4 = 4.2147$, and $\alpha_5 = -0.50689$. The Σ value is equal to 352.

Various dependences on pairing and shell corrections to the mass formula (Myers and Swiatecki, 1966, 1967) were considered for the $f_{sh,p}$ function at the fitting of Eq. (4) to the data from Table 1, $f_{sh,p} = f(dW_n, \delta_n, dW_\alpha, \delta_\alpha)$, where dW_n is the shell correction for the nucleus $(Z+1, A)$ formed after the neutron emission, dW_α is for the nucleus $(Z-1, A-3)$ produced after the α-particle escape, δ_n and δ_α are pairing corrections for residuals $(Z+1, A)$ and $(Z-1, A-3)$.

Results show that the best description of experimental data is observed with the empirical $f_{sh,p}$ function defined as $f_{sh,p} = |(dW_n-\delta_n)-(dW_\alpha-\delta_\alpha)|^{1/2}$. The use of simple difference $(dW_n-\delta_n)-(dW_\alpha-\delta_\alpha)$ following from the difference of $Q_{(p,\alpha)}-Q_{(p,n)}$ (Eq. (3)) does not really change the Σ value comparing with the systematic formula with $\alpha_6 = 0$.

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

$$\sigma_{(p,\alpha)} = \sigma_{non}(17.9\,\text{MeV})[A^{-1/3}(-0.230X_1 + 5.3307\times10^{-2}) + \exp\{A^{1/2}(-40.290X_2^2 + 4.3257X_3 - 0.56099 + 5.5427\times10^{-2}\times|dW_n - dW_\alpha - \delta_n + \delta_\alpha|^{1/2}\}], \quad (5)$$

where σ_{non} is calculated by the optical model (Koning and Delaroche, 2003), $X_1 = (N-Z-0.5)/A$, $X_2 = (N-Z-1)/A$, $X_3 = (N-Z-1.5)/A$, dW_n and dW_α are shell corrections to the Myers–Swiatecki formula (Myers and Swiatecki, 1966, 1967) for the nuclei $(Z+1, A)$ and $(Z-1, A-3)$ correspondingly taken from Ignatyuk (2006), δ_n and δ_α are pairing corrections for nuclei $(Z+1, A)$ and $(Z-1, A-3)$ calculated as follows: $\delta = 12A^{-1/2}$ for even–even nuclei, $\delta = 0$ for nuclei with odd A, and $\delta = -12A^{-1/2}$ for odd–odd nuclei, N, Z, and A are number of neutrons, protons, and nucleons in the target nucleus correspondingly.

The Σ value for Eq. (5) is equal to 296, which is less than for the systematics without the shell and pairing term (Table 5).

Fig. 1 shows experimental cross-sections and cross-sections obtained by Eq. (5). The (p,α) reaction cross-section calculated using the systematics Eq. (5) are given in Table 6 for all stable nuclei with atomic numbers $18\leqslant Z\leqslant 83$. The fast evaluation of the (p,α) reaction cross-section can be done using Eq. (5) and the approximate value of the proton nonelastic cross-section

$$\sigma^{appr}_{non}(17.9\,\text{MeV}) = 1.1221\times10^{-4}A^3 - 6.7168\times10^{-2}A^2 + 11.628A + 605.99\,\text{mb}. \quad (6)$$

The use of approximate value for the nonelastic cross-section, Eq. (6) results in the Σ value equal to 294.

Table 5
The Σ value in Eq. (1) calculated using data from Tables 1–4, cross-sections predicted by systematics, Eqs. (5),(10),(12),(15) and cross-sections calculated by the TALYS code and the ALICE/ASH code with recommended code options (Koning et al., 2004; Broeders et al., 2006)

Reaction	Systematics		Code	
	With $f_{sh,p}$	Without $f_{sh,p}$	TALYS	ALICE/ASH
(p,α) at 17.9 MeV	296	352	3611	1147
(p,nα) at 24.8 MeV	231	965	3244	901
(p,nα) at 28.5 MeV	270	393	721	787
(p,np) at 22.3 MeV	155	180	191	899

See explanations in the text.

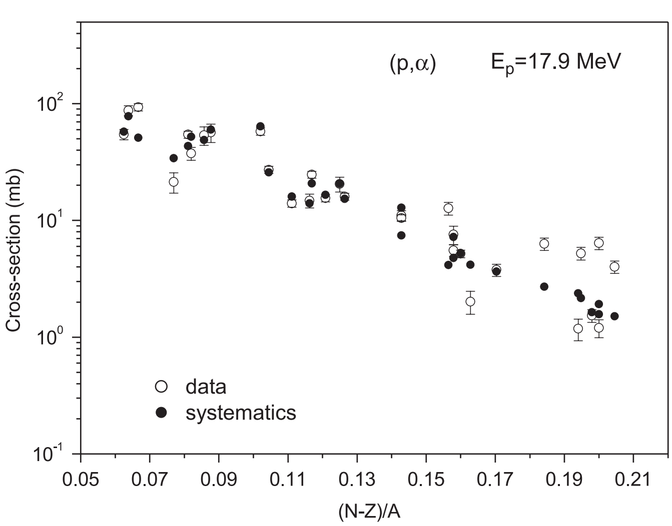

Fig. 1. The (p,α) reaction cross-sections at the incident proton energy 17.9 MeV obtained from the analysis of experimental data (Table 1) (open circle) and calculated by the systematics, Eq. (5) (black circle) depending on the $(N-Z)/A$ parameter.

4. Systematics of the (p,nα) reaction cross-section

The analytical expression for the (p,nα) reaction cross-section has the following form:

$$\sigma_{(p,n\alpha)} = \sigma_{non}(E_p)\Bigg\{\int_0^{\beta E_p+Q_{(p,n\alpha)}} W^{pre}_\alpha(\varepsilon_\alpha)\,d\varepsilon_\alpha \times \int_0^{\beta E_p+Q_{(p,n\alpha)}-\varepsilon_\alpha} W^{eq}_n(\varepsilon_n,\varepsilon_\alpha)\,d\varepsilon_n \times \left[\sum_x \int_0^{\beta E_p+Q_{(p,x\alpha)}-\varepsilon_\alpha} W^{eq}_x(\varepsilon_x,\varepsilon_\alpha)\,d\varepsilon_x\right]^{-1}$$
$$+ \int_0^{\beta E_p+Q_{(p,n\alpha)}} W^{pre}_n(\varepsilon_n)\,d\varepsilon_n \int_0^{\beta E_p+Q_{(p,n\alpha)}-\varepsilon_n} W^{eq}_\alpha(\varepsilon_\alpha,\varepsilon_n)\,d\varepsilon_\alpha \times \left[\sum_x \int_0^{\beta E_p+Q_{(p,xn)}-\varepsilon_n} W^{eq}_x(\varepsilon_x,\varepsilon_n)\,d\varepsilon_x\right]^{-1} + (1-P^{pre}_{tot})$$
$$\times\Bigg(\int_0^{\beta E_p+Q_{(p,n\alpha)}} W^{eq}_\alpha(\varepsilon_\alpha)\,d\varepsilon_\alpha\left[\sum_x\int_0^{\beta E_p+Q_{(p,x)}} W^{eq}_x(\varepsilon_x)\,d\varepsilon_x\right]^{-1} \times \int_0^{\beta E_p+Q_{(p,n\alpha)}-\varepsilon_\alpha} W^{eq}_n(\varepsilon_n,\varepsilon_\alpha)\,d\varepsilon_n \times \left[\sum_x \int_0^{\beta E_p+Q_{(p,x\alpha)}-\varepsilon_\alpha} W^{eq}_x(\varepsilon_x,\varepsilon_\alpha)\,d\varepsilon_x\right]^{-1}$$
$$+ \int_0^{\beta E_p+Q_{(p,n\alpha)}} W^{eq}_n(\varepsilon_n)d\varepsilon_n\left[\sum_x\int_0^{\beta E_p+Q_{(p,x)}} W^{eq}_x(\varepsilon_x)\,d\varepsilon_x\right]^{-1} \times \int_0^{\beta E_p+Q_{(p,n\alpha)}-\varepsilon_n} W^{eq}_\alpha(\varepsilon_\alpha,\varepsilon_n)\,d\varepsilon_\alpha \times \left[\sum_x \int_0^{\beta E_p+Q_{(p,xn)}-\varepsilon_n} W^{eq}_x(\varepsilon_x,\varepsilon_n)\,d\varepsilon_x\right]^{-1}\Bigg)\Bigg\}, \quad (7)$$

Table 6
The (p,α) reaction cross-section at the incident proton energy 17.9 MeV calculated using the systematics Eq. (5) for stable nuclei with atomic numbers from 18 to 83

Z	*A*	σ_i^{syst} (mb)
18	36	31.9
18	38	70.9
18	40	74.0
19	39	52.1
19	40	72.7
19	41	79.3
20	40	30.9
20	42	69.5
20	43	64.3
20	44	62.5
20	46	27.4
20	48	9.43
21	45	67.2
22	46	47.7
22	47	78.1
22	48	60.6
22	49	64.0
22	50	32.4
23	50	80.0
23	51	38.2
24	50	46.8
24	52	59.3
24	53	65.9
24	54	31.1
25	55	39.0
26	54	40.6
26	56	49.4
26	57	59.8
26	58	35.4
27	59	46.4
28	58	38.4
28	60	51.1
28	61	52.2
28	62	40.5
28	64	20.6
29	63	57.9
29	65	39.6
30	64	57.5
30	66	50.2
30	67	25.8
30	68	28.4
30	70	12.8
31	69	41.5
31	71	21.1
32	70	48.8
32	72	30.5
32	73	15.3
32	74	14.7
32	76	7.21
33	75	22.0
34	74	43.3
34	76	27.1
34	77	20.8
34	78	15.5
34	80	8.12
34	82	4.83
35	79	22.3
35	81	11.8
36	78	34.1
36	80	25.9
36	82	15.7

Table 6 (*continued*)

Z	*A*	σ_i^{syst} (mb)
36	83	12.7
36	84	8.59
36	86	5.25
37	85	12.0
37	87	6.75
38	84	22.1
38	86	14.0
38	87	15.3
38	88	9.58
39	89	11.0
40	90	16.0
40	91	16.6
40	92	11.6
40	94	7.00
40	96	4.74
41	93	15.1
42	92	26.9
42	94	18.3
42	95	14.1
42	96	11.6
42	97	9.03
42	98	7.44
42	100	5.21
44	96	23.9
44	98	17.3
44	99	16.8
44	100	11.3
44	101	10.6
44	102	7.58
44	104	5.46
45	103	9.76
46	102	16.9
46	104	11.4
46	105	11.5
46	106	7.71
46	108	5.83
46	110	4.51
47	107	10.0
47	109	7.06
48	106	16.6
48	108	11.1
48	110	8.20
48	111	8.17
48	112	6.08
48	113	5.78
48	114	4.78
48	116	3.80
49	113	7.31
49	115	5.55
50	112	14.2
50	114	9.56
50	115	8.22
50	116	6.76
50	117	6.00
50	118	5.17
50	119	4.65
50	120	4.22
50	122	3.27
50	124	2.49
51	121	4.86
51	123	3.84
52	120	7.65
52	122	5.61
52	123	4.87

Table 6 (*continued*)

Z	A	σ_i^{syst} (mb)
52	124	4.42
52	125	3.94
52	126	3.55
52	128	2.79
52	130	2.08
53	127	4.09
54	124	7.62
54	126	5.80
54	128	4.66
54	129	4.18
54	130	3.80
54	131	3.41
54	132	3.06
54	134	2.37
54	136	1.70
55	133	3.54
56	130	6.11
56	132	4.89
56	134	4.02
56	135	3.64
56	136	3.30
56	137	2.96
56	138	2.64
57	138	3.40
57	139	3.08
58	136	5.06
58	138	4.21
58	140	3.51
58	142	2.88
59	141	3.94
60	142	4.37
60	143	4.03
60	144	3.71
60	145	3.38
60	146	3.09
60	148	2.50
60	150	1.92
62	144	5.21
62	147	4.16
62	148	3.88
62	149	3.55
62	150	3.28
62	152	2.71
62	154	2.16
63	151	3.66
63	153	3.08
64	152	4.03
64	154	3.44
64	155	3.17
64	156	2.90
64	157	2.63
64	158	2.37
64	160	1.85
65	159	2.72
66	156	4.15
66	158	3.59
66	160	3.06
66	161	2.81
66	162	2.56
66	163	2.31
66	164	2.06
67	165	2.40
68	162	3.71
68	164	3.21

Table 6 (*continued*)

Z	A	σ_i^{syst} (mb)
68	166	2.72
68	167	2.48
68	168	2.24
68	170	1.77
69	169	2.56
70	168	3.33
70	170	2.87
70	171	2.64
70	172	2.41
70	173	2.18
70	174	1.96
70	176	1.51
71	175	2.26
71	176	2.04
72	174	2.99
72	176	2.55
72	177	2.34
72	178	2.12
72	179	1.91
72	180	1.69
73	181	1.99
74	180	2.68
74	182	2.27
74	183	2.06
74	184	1.86
74	186	1.45
75	185	2.13
75	187	1.73
76	184	2.79
76	186	2.39
76	187	2.19
76	188	2.00
76	189	1.81
76	190	1.61
76	192	1.23
77	191	1.87
77	193	1.50
78	190	2.50
78	192	2.12
78	194	1.75
78	195	1.57
78	196	1.39
78	198	1.02
79	197	1.64
80	196	2.23
80	198	1.88
80	199	1.70
80	200	1.53
80	201	1.35
80	202	1.18
80	204	0.84
81	203	1.42
81	205	1.08
82	204	1.65
82	206	1.32
82	207	1.16
82	208	0.99
83	209	1.22

where $Q_{(p,x\alpha)}$ is the energy of the reaction with the escape of the α-particle and the particle of the x-type, $Q_{(p,xn)}$ is the same for the reaction with the neutron escape,

x refers to the particle of any type, which emission is possible.

An approximate integration of Eq. (7) using expressions for pre-equilibrium and evaporation emission rates (Konobeyev et al., 1996; Weisskopf and Ewing, 1940; Ignatyuk and Capote, 2006) gives the following formula for the (p,nα) reaction cross-section:

$$\sigma_{(p,n\alpha)} = \sigma_{non}\left[\frac{(2S_\alpha+1)\mu_\alpha R^2}{\pi^2\hbar^2 g^4 E_0^4 |M|^2}\left\{-2C_1D_0^4 + \left(\frac{8}{3}\right)\right.\right.$$
$$\times(C_1D_1 - D_2)D_0^3 + 4D_1D_2D_0^2$$
$$+ (D_0+V_\alpha)^2(D_0+V_\alpha+3(Q_{(p,n)} - Q_{(p,n\alpha)}))$$
$$\left.\times\exp\left(\frac{Q_{(p,n\alpha)} - Q_{(p,2n)} - V_\alpha}{T}\right)\right\}$$
$$+ (1-P_{tot}^{pre})\frac{\mu_\alpha}{\mu_n}\frac{(2S_\alpha+1)}{(2S_n+1)}$$
$$\times\left\{\exp\left(\frac{Q_{(p,\alpha)} - Q_{(p,n)} - V_\alpha}{T}\right)\right.$$
$$\left.\left.+\exp\left(\frac{Q_{(p,n\alpha)} - Q_{(p,2n)} - V_\alpha}{T}\right)\right\}\right],$$

$$D_0 = \beta E_p + Q_{(p,n\alpha)} - V_\alpha, \quad D_1 = \beta E_p + Q_{(p,\alpha)} - V_\alpha,$$
$$D_2 = C_1(V_\alpha + Q_\alpha) + C_2, \tag{8}$$

where it is assumed that the nuclear temperature T for various reaction channels is similar, $Q_{(p,2n)}$ is the energy of the (p,2n) reaction.

Taking into account that experimental data are available for relative small number of nuclei (Tables 2 and 3) Eq. (8) has been substantially simplified to get the systematic formula for the (p,nα) reaction cross-section. As a result, the following formula for the (p,nα) reaction cross-section systematics is suggested:

$$\sigma_{(p,n\alpha)} = \sigma_{non}[A^{-1/3}\alpha_1 + \exp\{A^{1/2}(\alpha_2X_4^2 + \alpha_3X_4 + \alpha_4 + \alpha_5 f_{sh,p})\}], \tag{9}$$

where $X_4 = (N-Z-2.5)/A$, $f_{sh,p}$ corresponds to the (p,nα) reaction, α_i are free parameters.

Various dependences on pairing and shell corrections were considered for the $f_{sh,p}$ function at the fitting of Eq. (9) to the data from Tables 2 and 3. The best result was obtained for the $f_{sh,p}$ function defined as $f_{sh,p} = (dW_p - \delta_p) - (dW_{n\alpha} - \delta_{n\alpha})$, where dW_p and δ_p are taken for the target nucleus (Z,A), and $dW_{n\alpha}$ and $\delta_{n\alpha}$ refer to the residual nucleus ($Z-1, A-4$) formed after the neutron and α-particle escape from the compound nucleus. The use of $f_{sh,p} = |(dW_p - \delta_p) - (dW_{n\alpha} - \delta_{n\alpha})|^{1/2}$ and $f_{sh,p} = |(dW_p - \delta_p) - (dW_{n\alpha} - \delta_{n\alpha})|$ also improve the agreement with experimental data comparing with the systematics without the $\alpha_5 f_{sh,p}$ term.

4.1. The incident proton energy 24.8 MeV

The fitting of Eq. (9) with the $f_{sh,p}$ term discussed above to experimental data (Table 2) results in the systematics

$$\sigma_{(p,n\alpha)} = \sigma_{non}(24.8\,\text{MeV})[5.1285\times10^{-3}A^{-1/3} + \exp\{A^{1/2}(-33.081X_4^2 + 4.9310X_4 - 0.50957 + 2.3255\times10^{-2}(dW_p - dW_{n\alpha} - \delta_p + \delta_{n\alpha})\}], \tag{10}$$

where σ_{non} is calculated by the optical model (Koning and Delaroche, 2003) at the incident proton energy 24.8 MeV as discussed in Broeders and Konobeyev (2006), $X_4 = (N-Z-2.5)/A$, dW_p and $dW_{n\alpha}$ are shell corrections to the Myers–Swiatecki formula (Myers and Swiatecki, 1966, 1967) for the target nucleus (Z, A) and the residual ($Z-1, A-4$) correspondingly taken from (Ignatyuk, 2006), δ_p and $\delta_{n\alpha}$ are pairing corrections for (Z, A) and ($Z-1, A-4$) nuclei calculated as follows: $\delta = 12A^{-1/2}$ for even–even nuclei, $\delta = 0$ for nuclei with odd A, and $\delta = -12A^{-1/2}$ for odd–odd nuclei, N, Z, and A are number of neutrons, protons, and nucleons in the target nucleus correspondingly.

The value of Σ for Eq. (10) is equal to 231, which is substantially less than Σ obtained with the systematics at $\alpha_5 = 0$ (Table 5). The use of other $f_{sh,p}$ functions in Eq. (9) results in a larger value of Σ, e.g., $f_{sh,p} = |(dW_p - \delta_p) - (dW_{n\alpha} - \delta_{n\alpha})|^{1/2}$ gives the Σ value equal to 312 and $f_{sh,p} = |(dW_p - \delta_p) - (dW_{n\alpha} - \delta_{n\alpha})|$ gives $\Sigma = 270$.

Fig. 2 shows the (p,nα) reaction cross-sections obtained from the analysis of experimental data (Table 2) and cross-sections calculated by the systematic formula Eq. (10). The (p,nα) cross-section calculated by Eq. (10) are given in Table 7 for all stable nuclei with $18 \leqslant Z \leqslant 83$.

The σ_{non} calculated for the 24.8 MeV protons by optical model (Koning and Delaroche, 2003) can be evaluated

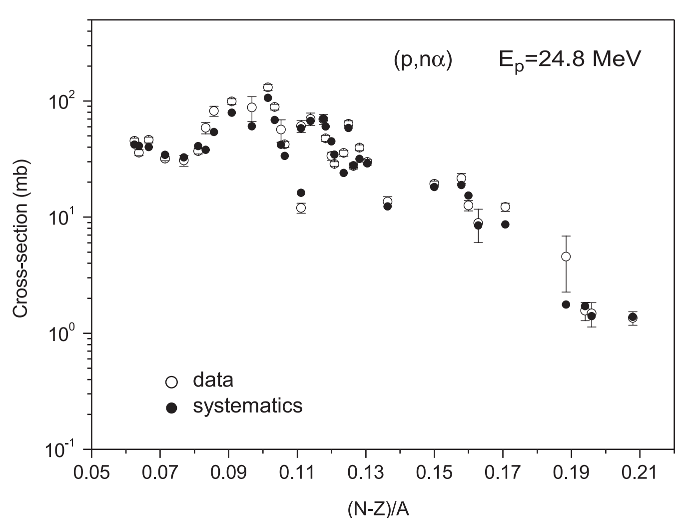

Fig. 2. The (p,nα) reaction cross-section at the incident proton energy 24.8 MeV obtained from the analysis of experimental data (Table 2) (open circle) and calculated by the systematics, Eq. (10) (black circle) depending on the $(N-Z)/A$ parameter.

Table 7
The (p,nα) reaction cross-section at the incident proton energy 24.8 MeV calculated using the systematics Eq. (10) for stable nuclei with atomic numbers from 18 to 83

Z	A	σ_i^{syst} (mb)
18	36	2.54
18	38	22.6
18	40	97.0
19	39	10.5
19	40	64.5
19	41	85.5
20	40	2.57
20	42	22.9
20	43	83.2
20	44	63.2
20	46	58.5
20	48	27.7
21	45	65.8
22	46	15.5
22	47	41.0
22	48	37.9
22	49	71.5
22	50	44.9
23	50	96.3
23	51	71.7
24	50	11.9
24	52	32.6
24	53	68.6
24	54	59.2
25	55	79.1
26	54	9.90
26	56	34.2
26	57	87.3
26	58	68.4
27	59	96.1
28	58	11.3
28	60	40.1
28	61	90.8
28	62	60.5
28	64	58.5
29	63	93.2
29	65	117.0
30	64	42.0
30	66	66.6
30	67	133.0
30	68	70.0
30	70	49.4
31	69	106.0
31	71	90.2
32	70	54.0
32	72	58.1
32	73	97.1
32	74	42.1
32	76	18.9
33	75	78.2
34	74	40.7
34	76	41.8
34	77	70.8
34	78	31.7
34	80	18.1
34	82	8.62
35	79	67.3
35	81	43.2
36	78	30.7
36	80	35.6
36	82	26.5
36	83	39.8
36	84	16.1
36	86	8.46
37	85	36.4
37	87	17.5
38	84	28.0
38	86	20.8
38	87	27.9
38	88	12.4
39	89	24.0
40	90	16.2
40	91	34.5
40	92	29.0
40	94	29.4
40	96	12.9
41	93	60.1
42	92	16.3
42	94	33.7
42	95	80.1
42	96	44.7
42	97	53.7
42	98	26.5
42	100	15.3
44	96	29.7
44	98	47.2
44	99	71.6
44	100	36.2
44	101	52.3
44	102	23.5
44	104	12.8
45	103	57.5
46	102	39.1
46	104	33.2
46	105	51.1
46	106	22.5
46	108	12.9
46	110	6.84
47	107	52.5
47	109	33.2
48	106	34.1
48	108	30.4
48	110	21.9
48	111	30.3
48	112	12.8
48	113	16.7
48	114	6.89
48	116	3.78
49	113	31.4
49	115	17.9
50	112	27.3
50	114	18.8
50	115	26.6
50	116	12.1
50	117	15.8
50	118	6.89
50	119	8.43
50	120	3.88
50	122	2.38
50	124	1.79
51	121	12.0
51	123	5.62
52	120	15.8
52	122	8.81
52	123	11.4

Table 7 (*continued*)

Z	*A*	σ_i^{syst} (mb)
52	124	4.74
52	125	5.73
52	126	2.83
52	128	1.99
52	130	1.67
53	127	5.71
54	124	12.7
54	126	8.03
54	128	4.87
54	129	6.04
54	130	3.02
54	131	3.40
54	132	2.10
54	134	1.71
54	136	1.58
55	133	3.64
56	130	8.74
56	132	5.26
56	134	3.23
56	135	3.62
56	136	2.20
56	137	2.28
56	138	1.76
57	138	4.28
57	139	2.45
58	136	5.41
58	138	3.41
58	140	2.29
58	142	2.38
59	141	4.03
60	142	3.37
60	143	5.08
60	144	3.73
60	145	5.58
60	146	2.94
60	148	2.06
60	150	1.65
62	144	5.11
62	147	10.9
62	148	5.15
62	149	5.89
62	150	3.06
62	152	2.00
62	154	1.60
63	151	7.04
63	153	3.16
64	152	5.14
64	154	2.78
64	155	2.80
64	156	1.86
64	157	1.94
64	158	1.63
64	160	1.54
65	159	2.00
66	156	4.39
66	158	2.50
66	160	1.95
66	161	2.09
66	162	1.69
66	163	1.71
66	164	1.55
67	165	1.74
68	162	2.70
68	164	2.05

Table 7 (*continued*)

Z	*A*	σ_i^{syst} (mb)
68	166	1.72
68	167	1.77
68	168	1.57
68	170	1.51
69	169	1.83
70	168	2.15
70	170	1.78
70	171	1.87
70	172	1.60
70	173	1.61
70	174	1.51
70	176	1.47
71	175	1.66
71	176	1.68
72	174	1.89
72	176	1.64
72	177	1.68
72	178	1.53
72	179	1.53
72	180	1.47
73	181	1.53
74	180	1.65
74	182	1.51
74	183	1.53
74	184	1.46
74	186	1.44
75	185	1.56
75	187	1.47
76	184	1.67
76	186	1.53
76	187	1.58
76	188	1.46
76	189	1.47
76	190	1.42
76	192	1.41
77	191	1.46
77	193	1.42
78	190	1.52
78	192	1.44
78	194	1.40
78	195	1.41
78	196	1.40
78	198	1.40
79	197	1.40
80	196	1.41
80	198	1.39
80	199	1.39
80	200	1.38
80	201	1.39
80	202	1.38
80	204	1.39
81	203	1.38
81	205	1.38
82	204	1.37
82	206	1.37
82	207	1.37
82	208	1.36
83	209	1.37

using the approximate formula

$$\sigma_{\rm non}^{\rm appr}(24.8\,{\rm MeV}) = 164.84A^{1/2}\exp(-1.986\times10^{-3}A)\,{\rm mb}. \quad (11)$$

The use of Eq. (11) for the calculation of $\sigma_{\rm non}$ from Eq. (10) results in the Σ value equal to 236.

4.2. The incident proton energy 28.5 MeV

The fitting of Eq. (9) to experimental data for the (p,nα) reaction (Table 3) gives the following systematics:

$$\sigma_{\rm (p,n\alpha)} = \sigma_{\rm non}(28.5\,{\rm MeV})[1.2492\times10^{-2}A^{-1/3} + \exp\{A^{1/2}(-38.196X_4^2 + 5.1595X_4 - 0.49023 + 9.2582\times10^{-3}({\rm d}W_{\rm p} - {\rm d}W_{\rm n\alpha} - \delta_{\rm p} + \delta_{\rm n\alpha}))\}]. \quad (12)$$

The Σ value for Eq. (12) with $\sigma_{\rm non}$ calculated by the optical model is equal to 270. The use of the approximate expression for $\sigma_{\rm non}$,

$$\sigma_{\rm non}^{\rm appr}(28.5\,{\rm MeV}) = 158.6A^{1/2}\exp(-1.3697\times10^{-3}A)\,{\rm mb}, \quad (13)$$

gives the Σ value equal to 273.

5. Systematics of the activation (p,np) reaction cross-section at the proton energy 22.3 MeV

Reaction cross-sections used to obtain the systematics (Table 4, Chapter 2) were measured by the activation method and contain contributions of (p,np) and (p,d) reaction cross-sections. The analytical expression for the (p,d) reaction cross-section is identical with Eq. (3) after the substitution of all values relating to the α-particle emission by values corresponding to the deuteron emission. The (p,np) reaction cross-section is calculated by the equation similar to Eq. (8), where "alpha" symbols are substituted by "proton" ones and with $C_1 = 1$ and $C_2 = 0$. Using the same approximations as in Sections 3 and 4, one can obtain the following systematic formula for the activation (p,np) reaction cross-section:

$$\sigma_{\rm (p,np)} = \sigma_{\rm non}[A^{-1/3}\alpha_1 + \exp\{A^{1/2}(\alpha_2X_1^2 + \alpha_3X_1 + \alpha_4 + \alpha_5f_{\rm sh,p})\}], \quad (14)$$

where $X_1 = (N-Z-0.5)/A$, $f_{\rm sh,p}$ corresponds to the (p,np) reaction, α_i are free parameters.

The following systematics were obtained after the fitting of Eq. (14) to the data from Table 4:

$$\sigma_{\rm (p,np)} = \sigma_{\rm non}(22.3\,{\rm MeV})[0.28648A^{-1/3} + \exp\{A^{1/2}(-47.495X_1^2 + 7.2876X_1 - 0.41759 + 5.1829\times10^{-3}({\rm d}W_{\rm p} - \delta_{\rm p} - {\rm d}W_{\rm n} + \delta_{\rm n})^2\}], \quad (15)$$

where $\sigma_{\rm non}$ is calculated by the optical model (Koning and Delaroche, 2003), $X_1 = (N-Z-0.5)/A$; ${\rm d}W_{\rm p}$ and ${\rm d}W_{\rm n}$ are shell corrections for the target nucleus (Z, A) and the

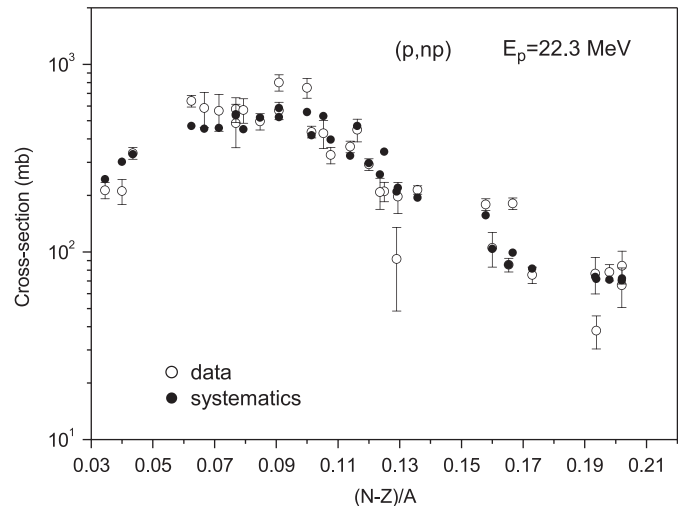

Fig. 3. The activation (p,np) reaction cross-section at the incident proton energy 22.3 MeV obtained from the analysis of experimental data (Table 4) (open circle) and calculated by the systematics, Eq. (15) (black circle) depending on the $(N-Z)/A$ parameter.

Table 8
The sum of (p,np) and (p,d) reaction cross-sections at the incident proton energy 22.3 MeV calculated using the systematics Eq. (15) for stable nuclei with atomic numbers from 18 to 83

Z	A	$\sigma_i^{\rm syst}$ (mb)
18	36	170.0
18	38	406.0
18	40	520.0
19	39	201.0
19	40	879.0
19	41	520.0
20	40	218.0
20	42	363.0
20	43	455.0
20	44	615.0
20	46	448.0
20	48	208.0
21	45	454.0
22	46	331.0
22	47	426.0
22	48	563.0
22	49	462.0
22	50	507.0
23	50	765.0
23	51	471.0
24	50	302.0
24	52	535.0
24	53	487.0
24	54	434.0
25	55	523.0
26	54	270.0
26	56	458.0
26	57	513.0
26	58	465.0
27	59	520.0
28	58	244.0
28	60	472.0
28	61	480.0
28	62	526.0
28	64	342.0
29	63	451.0

Table 8 (*continued*)

Z	A	σ_i^{syst} (mb)
29	65	396.0
30	64	470.0
30	66	584.0
30	67	414.0
30	68	415.0
30	70	212.0
31	69	418.0
31	71	266.0
32	70	621.0
32	72	517.0
32	73	282.0
32	74	299.0
32	76	156.0
33	75	297.0
34	74	608.0
34	76	530.0
34	77	312.0
34	78	363.0
34	80	188.0
34	82	111.0
35	79	325.0
35	81	195.0
36	78	541.0
36	80	555.0
36	82	413.0
36	83	209.0
36	84	222.0
36	86	118.0
37	85	219.0
37	87	134.0
38	84	566.0
38	86	469.0
38	87	236.0
38	88	267.0
39	89	259.0
40	90	536.0
40	91	257.0
40	92	209.0
40	94	133.0
40	96	98.9
41	93	299.0
42	92	586.0
42	94	347.0
42	95	285.0
42	96	236.0
42	97	177.0
42	98	149.0
42	100	104.0
44	96	415.0
44	98	365.0
44	99	314.0
44	100	257.0
44	101	203.0
44	102	164.0
44	104	113.0
45	103	221.0
46	102	382.0
46	104	277.0
46	105	223.0
46	106	181.0
46	108	123.0
46	110	95.4
47	107	240.0
47	109	151.0

Table 8 (*continued*)

Z	A	σ_i^{syst} (mb)
48	106	389.0
48	108	300.0
48	110	204.0
48	111	156.0
48	112	134.0
48	113	109.0
48	114	99.7
48	116	86.9
49	113	166.0
49	115	115.0
50	112	391.0
50	114	274.0
50	115	168.0
50	116	176.0
50	117	116.0
50	118	119.0
50	119	92.5
50	120	96.7
50	122	84.5
50	124	82.1
51	121	94.4
51	123	84.4
52	120	195.0
52	122	128.0
52	123	96.2
52	124	97.1
52	125	84.8
52	126	85.2
52	128	81.7
52	130	81.2
53	127	85.5
54	124	210.0
54	126	139.0
54	128	103.0
54	129	86.4
54	130	87.4
54	131	81.3
54	132	81.9
54	134	80.5
54	136	80.6
55	133	81.4
56	130	158.0
56	132	112.0
56	134	90.2
56	135	81.7
56	136	82.4
56	137	79.7
56	138	80.0
57	138	80.1
57	139	79.4
58	136	117.0
58	138	94.4
58	140	83.1
58	142	79.0
59	141	82.6
60	142	97.6
60	143	83.0
60	144	81.2
60	145	79.0
60	146	78.6
60	148	78.2
60	150	78.6
62	144	135.0
62	147	84.6

Table 8 (*continued*)

Z	A	σ_i^{syst} (mb)
62	148	82.3
62	149	79.1
62	150	78.5
62	152	77.7
62	154	77.8
63	151	79.4
63	153	77.4
64	152	84.1
64	154	79.3
64	155	77.2
64	156	77.2
64	157	76.8
64	158	77.0
64	160	77.4
65	159	76.5
66	156	87.9
66	158	80.0
66	160	77.0
66	161	76.2
66	162	76.3
66	163	76.3
66	164	76.5
67	165	75.8
68	162	80.9
68	164	76.9
68	166	75.7
68	167	75.4
68	168	75.6
68	170	75.9
69	169	75.0
70	168	76.8
70	170	75.0
70	171	74.6
70	172	74.7
70	173	74.7
70	174	74.9
70	176	75.3
71	175	74.3
71	176	74.4
72	174	74.4
72	176	73.8
72	177	73.8
72	178	73.9
72	179	74.1
72	180	74.3
73	181	73.6
74	180	73.0
74	182	72.9
74	183	73.0
74	184	73.2
74	186	73.6
75	185	72.5
75	187	72.9
76	184	72.3
76	186	72.0
76	187	72.0
76	188	72.2
76	189	72.3
76	190	72.5
76	192	72.9
77	191	71.8
77	193	72.2
78	190	71.0
78	192	71.1

Table 8 (*continued*)

Z	A	σ_i^{syst} (mb)
78	194	71.4
78	195	71.6
78	196	71.8
78	198	72.2
79	197	71.1
80	196	70.1
80	198	70.3
80	199	70.5
80	200	70.7
80	201	70.9
80	202	71.1
80	204	71.5
81	203	70.4
81	205	70.8
82	204	69.6
82	206	70.0
82	207	70.2
82	208	69.9
83	209	69.5

nucleus $(Z+1, A)$, δ_p and δ_n are pairing corrections for (Z, A) and $(Z+1, A)$ nuclei described above (Eqs. (5) and (10)); N, Z, and A are number of neutrons, protons, and nucleons in the target nucleus correspondingly.

The Σ value for Eq. (15) is equal to 155. The use of other $f_{sh,p}$ functions in Eq. (14) at the fitting to experimental data does not give a gain comparing with simple formula without the $f_{sh,p}$ term. The systematics with $\alpha_5 = 0$ has the Σ value equal to 180 (Table 5).

Fig. 3 shows experimental data from Table 4 and the (p,np) reaction cross-sections calculated by Eq. (15). Calculated cross-sections are presented in Table 8 for stable nuclei with atomic numbers $18 \leqslant Z \leqslant 83$. The (p,np) reaction cross-section can be evaluated using the approximate expression for the proton nonelastic cross-section at 22.3 MeV:

$$\sigma_{non}^{appr}(22.3\,\text{MeV}) = 169.8A^{1/2}\exp(-2.5451\times10^{-3}A)\ \text{mb}. \quad (16)$$

The use of Eq. (16) in the systematics formula Eq. (15) gives the Σ value equal to 159.

6. Conclusion

Analytical expressions derived using the pre-equilibrium exciton model, evaporation model, and semi-empirical mass formula were used to get systematic formulas for (p,α), (p,nα), and (p,np) reaction cross-sections. Formulas were fitted to the data obtained from the analysis of available measured cross-sections (Tables 1–4).

The systematics for the (p,α) reaction cross-section was obtained at the incident proton energy 17.9 MeV, Eq. (5); for the (p,nα) reaction cross-section at 24.8 MeV, Eq. (10); and 28.5 MeV, Eq. (12), and for the activation (p,np) reaction cross-section at the proton energy 22.3 MeV, Eq. (15). The best description of experimental data (Tables 1–4) is observed with the consideration of the term describing shell and pairing effects in equations obtained and if the proton nonelastic reaction cross-section σ_{non} is calculated by the optical model (Koning and Delaroche, 2003). Approximate expressions for σ_{non}, Eqs. (6), (11), (13) and (16) obtained in the present work can also be used to estimate (p,α), (p,nα), and (p,np) reaction cross-sections by Eqs. (5), (10), (12) and (15).

The value of Σ in Eq. (1) which quantifies the agreement of systematics with experimental data is shown in Table 5. For the comparison Σ values obtained using (p,α), (p,nα), and (p,np) reaction cross-sections calculated by nuclear models implemented in the TALYS code (Koning et al., 2004) and the ALICE/ASH code (Broeders et al., 2006b)are also given. In the last case, cross-sections calculated by codes were used instead of σ_i^{syst} values in Eq. (1). The Fermi gas model with the energy-dependent nuclear level density parameter (Ignatyuk et al., 1975) with the new set of model parameters (Koning et al., 2004) was used to obtain the nuclear level density in TALYS calculation. The generalized superfluid model (Ignatyuk et al., 1979) has been applied for nuclear level density calculations in the ALICE/ASH code. Model parameters were taken from (Ignatyuk, 1998).

Cross-sections of (p,α), (p,nα), and (p,np) reactions calculated by systematics obtained are shown for stable nuclei with atomic numbers from 18 to 83 in Tables 6–8.

Systematics obtained can be used for the evaluation of (p,α), (p,nα), and (p,np) reaction cross-sections for target nuclei with atomic numbers from 18 to 83. The best result one should expect for the mass range of nuclei, which corresponds to experimental data from Tables 1 to 4.

Cross-sections evaluated by systematics can be applied for the correction of excitation functions predicted by nuclear models for reactions on stable and unstable nuclei. Evaluated values can be used to predict the production rate of radionuclides used in medicine and industry, for the study of the activation and transmutation of materials designed for advanced nuclear energy systems.

References

Aleksandrov, V.N., Semyonova, M.P., Semyonov, V.G., 1987. Atomnaya Energiya 62, 411.

Brinkman, G.A., Helmer, J., Lindner, L., 1977. Phys. Rev. Lett. 28, 9.

Broeders, C.H.M., Konobeyev, A.Yu., 2006. Nucl. Phys. A 780, 130.

Broeders, C.H.M., Konobeyev, A.Yu., Mercatali, L., 2006a. JEF/DOC-1154.

Broeders, C.H.M., Konobeyev, A.Yu., Korovin, Yu.A., Lunev, V.P., Blann, M., 2006b. FZK 7183; 〈http://bibliothek.fzk.de/zb/berichte/FZKA7183.pdf〉.

Broeders, C.H.M., Fischer, U., Konobeyev, A.Yu., Mercatali, L., 2007. In: Proceedings of International Conference on Nuclear Data for Science and Technology, Nice, ID 352, 22–27 April 2007, in press.

Chadwick, M.B., Young, P.G., Chiba, S., Frankle, S.C., Hale, G.M., Hughes, H.G., Koning, A.J., Little, R.C., MacFarlane, R.E., Prael, R.E., Waters, L.S., 1999. Nucl. Sci. Eng. 131, 293.

Cohen, B.L., Newman, E., 1955. Phys. Rev. 99, 718.

Cohen, B.L., Newman, E., Charpie, R.A., Handley, T.H., 1954. Phys. Rev. 94, 620.

Colle, R., Kishore, R., Cumming, J.B., 1976. J. Inorg. Nucl. Chem. 38, 23.

Deptula, C., Kim, S.H., Knotek, O., Mikolajewski, S., Popinenkova, L.M., Rurarz, E., Zaitseva, N.G., 1990. Nukleonika 35, 63.

De Villiers, D., Nortier, M., Richter, W., 2002. Appl. Rad. Isot. 57, 907.

Diksic, M., Yaffe, L., 1977. J. Inorg. Nucl. Chem. 39, 1299.

Ejnisman, R., Goldman, I.D., Pascholati, P.R., da Cruz, M.T.F., Oliveira, R.M., Norman, E.B., Zlimen, I., Wietfeldt, F.E., Larimer, R.M., Chan, Y.D., Lesko, K.T., Garcia, A., 1996. Phys. Rev. C 54, 2047.

Ewart, H.A., Blann, M., 1960. EXFOR C1012.

Forrest, R.A., Kopecky, J., Sublet, J.-Ch., 2005. The European Activation File: EAF-2005 Cross Section Library, UKAEA FUS 515.

Furukawa, M., Shinohara, A., Narita, M., Kojima, S., 1990. Univ. Tokyo, Inst. Nucl. Study, Annual Report 1989, p. 32.

Furukawa, M., Shinohara, A., Narita, M., Kojima, S., 1991. Univ. Tokyo, Inst. Nucl. Study, Annual Report 1990, p. 35.

Gadioli, E., Gadioli-Erba, E., Hogan, J.J., Burns, K.I., 1981. Z. Phys. A 301, 289.

Ghoshal, S.N., 1950. Phys. Rev. 80, 939.

Grant, G.R., Yaffe, L., 1963. Can. J. Chem. 41, 2533.

Grutte, A., 1982. Nucl. Phys. A 383, 98.

Gusakow, M., Albouy, G., Poffe, N., Riehl, C., 1961. J. de Physique et le Radium 22, 636.

Haasbroek, F.J., Steyn, J., Neirinckx, R.D., Burdzik, G.F., Cogneau, M., Wanet, P., 1976. Report Council f. Scient. and Indust. Res., Pretoria, CSIR-FIS-89.

Hassan, H.E., Qaim, S.M., Shubin, Yu., Azzam, A., Morsy, M., Coenen, H.H., 2004. Appl. Rad. Isot. 60, 899.

Hilgers, K., Stoll, T., Skakun, Y., Coenen, H.H., Qaim, S.M., 2003. Appl. Rad. Isot. 59, 343.

Horiguchi, T., Noma, H., Yoshizawa, Y., Takemi, H., Hasai, H., Kiso, Y., 1980. Appl. Rad. Isot. 31, 141.

Horiguchi, T., Kumahora, H., Inoue, H., Yoshizawa, Y., 1983. Appl. Rad. Isot. 34, 1531.

Ignatyuk, A.V., 1998. In: Handbook for Calculations of Nuclear Reaction Data. IAEA-TECDOC-1034. International Atomic Energy Agency Report, p. 65, 〈http://www-nds.iaea.or.at/ripl/ripl_handbook.htm〉.

Ignatyuk, A.V., 2006. In: RIPL-2, Densities, 〈http://www-nds.iaea.org/RIPL-2/〉.

Ignatyuk, A.V., Capote, R., 2006. In: Handbook for Calculations of Nuclear Reaction Data, RIPL-2, IAEA-TECDOC-1506, p. 85, 〈http://www-nds.iaea.org/RIPL-2/handbook.html〉.

Ignatyuk, A.V., Smirenkin, G.N., Tishin, A.S., 1975. Sov. J. Nucl. Phys. 21, 255.

Ignatyuk, A.V., Istekov, K.K., Smirenkin, G.N., 1979. Yadernaja Fizika 29, 875.

Iwamoto, A., Harada, K., 1982. Phys. Rev. C 26, 1821.

Jenkins, I.L., Wain, A.G., 1970. J. Inorg. Nucl. Chem. 32, 1419.

Kantelo, M.V., Hogan, J.J., 1976a. Phys. Rev. C 14, 64.

Kantelo, M.V., Hogan, J.J., 1976b. Phys. Rev. C 13, 1095.

Kastleiner, S., Coenen, H.H., Qaim, S.M., 1999. Radiochim. Acta 84, 107.

Kastleiner, S., Shubin, Yu.N., Nortier, F.M., van der Walt, T.N., Qaim, S.M., 2004. Radiochim. Acta 92, 449.

Kaufman, S., 1960. Phys. Rev. 117, 1532.

Kavanagh, T.M., Bell, R.E., 1961. Can. J. Phys. 39, 1172.

Klein, A.T.J., Roesch, F., Qaim, S.M., 2000. Radiochim. Acta 88, 253.

Koning, A.J., Delaroche, J.P., 2003. Nucl. Phys. A 713, 231.

Koning, A.J., Hilaire, S., Duijvestijn, M.C., 2004. NRG Report 21297/04.62741/P FAI/AK/AK.

Konobeyev, A.Yu., Korovin, Yu.A., 1999. Nuovo. Cim. 112A, 1001.

Konobeyev, A.Yu., Korovin, Yu.A., Pereslavtsev, P.E., 1994. Nucl. Instrum. Meth. Phys. Res. B 93, 409.

Konobeyev, A.Yu., Lunev, V.P., Shubin, Yu.N., 1996. Nucl. Instrum. Meth. Phys. Res. B 108, 233.

Kovacs, Z., Blessing, G., Qaim, S.M., Stoecklin, G., 1985. Appl. Rad. Isot. 36, 635.

Kurenkov, N.V., Malinin, A.B., Sebyakin, A.A., Venikov, N.I., 1989. J. Radioanal. Nucl. Chem. Lett. 135, 39.
Levkovskij, V.N., 1991. Activation Cross Sections for Medium Mass Nuclei ($A = 40$–100) by Medium Energy Protons and Alpha Particles ($E = 10$–50 MeV), Moscow, 1991.
Meadows, J.W., 1953. Phys. Rev. 91, 885.
Meadows, J.W., Diamond, R.M., Sharp, R.A., 1956. Phys. Rev. 102, 190.
Meghir, S., 1962. Excitation functions of some monitor reactions. Ph.D. Thesis. McGill University, Montreal, Quebec.
Michel, R., Brinkmann, G., 1980. J. Radioanal. Chem. 59, 467.
Michel, R., Brinkmann, G., Weigel, H., Herr, W., 1978. J. Inorg. Nucl. Chem. 40, 1845.
Michel, R., Brinkmann, G., Weigel, H., Herr, W., 1979. Nucl. Phys. A 322, 40.
Michel, R., Bodemann, R., Busemann, H., Daunke, R., Gloris, M., Lange, H.-J., Klug, B., Krins, A., Leya, I., Luepke, M., Neumann, S., Reinhardt, H., Schnatz-Buettgen, M., Herpers, U., Schiekel, Th., Sudbrock, F., Holmqvist, B., Conde, H., Malmborg, P., Suter, M., Dittrich-Hannen, B., Kubik, P.-W., Sinal, H.-A., Filges, D., 1997. Nucl. Instrum. Meth. Phys. Res. B 129, 153.
Milazzo-Colli, L., Braga-Marcazzan, G.M., Milazzo, M., Signorini, C., 1974. Nucl. Phys. A 218, 274.
Münzel, H., Lange, J., Keller, K.A., 1974. Landolt-Börnstein, Numerical Data and Functional Relationships in Science and Technology, New Series I/5, Part c. Springer, Berlin.
Mustafa, M.G., West, H.I., O'Brien, H., Lanier, R.G., Benhamou, M., Tamura, T., 1988. Phys. Rev. C 38, 1624.
Myers, W.D., Swiatecki, W.J., 1966. Nucl. Phys. 81, 1.
Myers, W.D., Swiatecki, W.J., 1967. Arkiv för Fysik 36, 343.
Newton, D.A., Sarkar, S., Yaffe, L., Moore, R.B., 1973. J. Inorg. Nucl. Chem. 35, 361.
Nortier, F.M., Mills, S.J., Steyn, G.F., 1991. Appl. Rad. Isot. 42, 353.
Prescher, K., Peiffer, F., Stuek, R., Michel, R., Bodemann, R., Rao, M.N., Mathew, K.J., 1991. Nucl. Instrum. Meth. Phys. Res. B 53, 105.
Qaim, S.M., Weinreich, R., Ollig, H., 1979. Appl. Rad. Isot. 30, 85.
Qaim, S.M., Uhl, M., Rosch, F., Szelecsenyi, F., 1995. Phys. Rev. C 52, 733.
Rao, C.L., Yaffe, L., 1963. Can. J. Chem. 41, 2516.
Reimer, P., Qaim, S.M., 1998. Radiochim. Acta 80, 113.
Röhm, H.F., Münzel, H., Lange, J., 1973. Nucl. Instrum. Meth. 112, 101.
Sachdev, D.R., Porile, N.T., Yaffe, L., 1967. Can. J. Chem. 45, 1149.
Sakamoto, K., Dohniwa, M., Okada, K., 1985. Appl. Rad. Isot. 36, 481.
Sato, K., Iwamoto, A., Harada, K., 1983. Phys. Rev. C 28, 1527.
Schoen, N.C., Orlov, G., McDonald, R.J., 1979. Phys. Rev. C 20, 88.
Scholten, B., Lambrecht, R.M., Cogneau, M., Ruiz, H.V., Qaim, S.M., 1999. Appl. Rad. Isot. 51, 69.
Sharp, R.A., Diamond, R.M., Wilkinson, G., 1956. Phys. Rev. 101, 1493.
Sonck, M., van Hoyweghen, J., Hermanne, A., 1996. Appl. Rad. Isot. 47, 445.
Sonck, M., Hermanne, A., Szelecsenyi, F., Takacs, S., Tarkanyi, F., 1998. Appl. Rad. Isot. 49, 1533.
Sterns, C.M., 1962. Columbia University Report CU-34-63.
Steyn, G.F., Mills, S.J., Nortier, F.M., Haasbroek, F.J., 1991. Appl. Rad. Isot. 42, 361.
Sudar, S., Szelecsenyi, F., Qaim, S.M., 1993. Phys. Rev. C 48, 3115.
Szelecsenyi, F., Boothe, T.E., Takacs, S., Tarkanyi, F., Tavano, E., 1998. Appl. Rad. Isot. 49, 1005.
Szelecsenyi, F., Kovacs, Z., Suzuki, K., Okada, K., van der Walt, T.N., Steyn, G.F., Mukherjee, S., 2005a. J. Rad. Nucl. Chem. 263, 539.
Szelecsenyi, F., Steyn, G.F., Kovacs, Z., Vermeulen, C., Van Der Meulen, N.P., Dolley, S.G., Van Der Walt, T.N., Suzuki, K., Mukai, K., 2005b. Nucl. Instrum. Meth. Phys. Res. B 240, 625.
Takacs, S., Tarkanyi, F., Sonck, M., Hermanne, A., 2002a. Nucl. Instrum. Meth. Phys. Res. B 198, 183.
Takacs, S., Tarkanyi, F., Sonck, M., Hermanne, A., 2002b. Nucl. Instrum. Meth. Phys. Res. B 188, 106.
Takacs, S., Szucs, Z., Tarkanyi, F., Hermanne, A., Sonck, M., 2003. J. Radioanal. Nucl. Chem. 257, 195.
Tarkanyi, F., Qaim, S.M., 1989. Radiochim. Acta 47, 169.
Tarkanyi, F., Szelecsenyi, F., Kopecky, P., 1989a. Atomki Annual Report 1989, 2.
Tarkanyi, F., Qaim, S.M., Stocklin, G., 1989b. Report NEANDC(E)-302.
Tarkanyi, F., Szelecsenyi, F., Kopecky, P., 1991a. Appl. Rad. Isot. 42, 513.
Tarkanyi, F., Szelecsenyi, F., Kopecky, P., 1991b. In: Proceedings of the International Conference on Nuclear Data for Science and Technology, 13–17 May 1991, Jülich, Germany, p. 529.
Tarkanyi, F., Qaim, S.M., Stocklin, G., Sajjad, M., Lambrect, R.M., Schweickert, H., 1991c. Appl. Rad. Isot. 42, 221.
Tarkanyi, F., Kovacs, Z., Qaim, S.M., 1993. Appl. Rad. Isot. 44, 1105.
Tarkanyi, F., Ditroi, F., Takacs, S., Csikai, J., Hermanne, A., Uddin, M.S., Hagiwara, M., Baba, M., Shubin, Yu.N., Dityuk, A.I., 2004. Nucl. Instrum. Meth. Phys. Res. B 226, 473.
Tarkanyi, F., Takacs, S., Hermanne, A., Van den Winkel, P., Van der Zwart, R., Skakun, Ye.A., Shubin, Yu.N., Kovalev, S.F., 2005a. Radiochim. Acta 93, 561.
Tarkanyi, F., Ditroi, F., Csikai, J., Takacs, S., Uddin, M.S., Hagiwara, M., Baba, M., Shubin, Yu.N., Dityuk, A.I., 2005b. Appl. Rad. Isot. 62, 73.
Watanabe, Y., Fukahori, T., Kosako, K., Shigyo, N., Murata, T., Yamano, N., Hino, T., Maki, K., Nakashima, H., Odano, N., Chiba, S., 2004. In: Proceedings of the International Conference Nucl. Data Sci. Technol. September 26–October 1, 2004, Santa Fe, USA, p. 326.
Weisskopf, V.F., Ewing, D.H., 1940. Phys. Rev. 57, 472.
Wollersheim, H.J., 2004. ⟨http://www-linux.gsi.de/~wolle/⟩.