ISSN 1063-7788, Physics of Atomic Nuclei, 2011, Vol. 74, No. 4, pp. 551–572. © Pleiades Publishing, Ltd., 2011.
Original Russian Text © Yu.E. Titarenko, V.F. Batyaev, A.Yu. Titarenko, M.A. Butko, K.V. Pavlov, S.N. Florya, R.S. Tikhonov, V.M. Zhivun, A.V. Ignatyuk, S.G. Mashnik, S. Leray, A. Boudard, J. Cugnon, D. Mancusi, Y. Yariv, K. Nishihara, N. Matsuda, H. Kumawat, G. Mank, W. Gudowski , 2011, published in Yadernaya Fizika, 2011, Vol. 74, No. 4, pp. 574–595.

NUCLEI
Experiment

Measurement and Simulation of the Cross Sections for Nuclide Production in ^{nat}W and ^{181}Ta Targets Irradiated with 0.04- to 2.6-GeV Protons

Yu. E. Titarenko[1)*], V. F. Batyaev[1)], A. Yu. Titarenko[1)], M. A. Butko[1)], K. V. Pavlov[1)], S. N. Florya[1)], R. S. Tikhonov[1)], V. M. Zhivun[1)], A. V. Ignatyuk[2)], S. G. Mashnik[3)], S. Leray[4)], A. Boudard[4)], J. Cugnon[5)], D. Mancusi[5)], Y. Yariv[6)], K. Nishihara[7)], N. Matsuda[7)], H. Kumawat[8)], G. Mank[9)], and W. Gudowski[10)]

Received October 7, 2010

Abstract—The cross sections for nuclide production in thin ^{nat}W and ^{181}Ta targets irradiated by 0.04–2.6-GeV protons have been measured by direct γ spectrometry using two γ spectrometers with the resolutions of 1.8 and 1.7 keV in the ^{60}Co 1332-keV γ line. As a result, 1895 yields of radioactive residual product nuclei have been obtained. The ^{27}Al$(p,x)^{22}$Na reaction has been used as a monitor reaction. The experimental data have been compared with the MCNPX (BERTINI, ISABEL), CEM03.02, INCL4.2, INCL4.5, PHITS, and CASCADE07 calculations.

DOI: 10.1134/S1063778811040181

INTRODUCTION

The cross sections for nuclide production in thin ^{nat}W and ^{181}Ta targets irradiated by 0.05-, 0.07-, 0.1-, 0.15-, 0.25-, 0.4-, 0.6-, 0.8-, 1.2-, 1.6-, and 2.6-GeV protons were determined. These materials are of interest because they are considered as the main candidates for "solid-type" targets in spallation neutron sources and electronuclear facilities. They are also structural materials widely used in nuclear setups. Their advantage as compared to liquid metal targets of Pb, Hg, and Pb–Bi eutectic is the absence of Po accumulation, which is mainly responsible for the radiotoxicity of the irradiated target of electronuclear facilities. However, it is worth noting that, for ^{181}Ta and ^{nat}W targets, it is impossible to exclude completely radiotoxicity caused by α emitters produced in all heavy target materials irradiated with protons of energy above about 0.5 GeV.

At present, EXFOR contains 23 original works with the data on W and 26 works with the data on Ta, in which cumulative and independent yields of radioactive nuclides in proton-induced reactions are presented [1].

IRRADIATION AND MEASUREMENTS

Thin ^{nat}W and ^{181}Ta samples in an assembly with Al monitors were irradiated with an extracted proton beam of the ITEP U-10 synchrotron [2–4]. The samples were manufactured by cutting from a metallic foil. The total levels of chemical impurities in the ^{nat}W, ^{181}Ta, and Al samples were no more than 0.004, 0.028 and 0.05%, respectively.

The proton fluence was determined using the ^{27}Al$(p,x)^{22}$Na monitor reaction whose excitation function is well known [2]. The characteristics of the ^{nat}W and ^{181}Ta samples and the irradiation conditions are presented in Table 1.

After each irradiation, the samples and monitors were delivered to a laboratory, were repacked in a glove box, and were transferred to a room where the γ spectra of the samples and monitors were measured by calibrated HPGe detectors [2]. Examples of the measured γ spectra are shown in Figs. 1 and 2. The procedure of their processing and calculation of the cross sections is identical to that described in [3].

[1)]Institute for Theoretical and Experimental Physics, ul. Bol'shaya Cheremushkinskaya 25, Moscow, 117218 Russia.
[2)]Institute of Physics and Power Engineering, pl. Bondarenko 1, Obninsk, Kaluga oblast, 249033 Russia.
[3)]Los Alamos National Laboratory, USA.
[4)]CEA, Saclay, France.
[5)]University of Liege, Belgium.
[6)]Soreq NRC, Yavne, Israel.
[7)]JAEA, Tokai, Japan.
[8)]BARC, Mumbai, India.
[9)]IAEA, Vienna, Austria.
[10)]Royal Institute of Technology, Stockholm, Sweden.
*E-mail: Yury.Titarenko@itep.ru

Table 1. Characteristics of ^{nat}W and ^{181}Ta experimental samples and the parameters of their irradiation

^{nat}W					^{181}Ta				
Proton energy, MeV	Sample mass, mg	Monitor mass, mg	Irradiation time, min	Average proton flux, $p/(\mathrm{cm}^2\ \mathrm{s}) \times 10^{-10}$	Proton energy, MeV	Sample mass, mg	Monitor mass, mg	Irradiation time, min	Average proton flux, $p/(\mathrm{cm}^2\ \mathrm{s}) \times 10^{-10}$
2605 ± 8	256.6	59.2	28.83	6.91 ± 0.60	2605 ± 8	359.8	59.1	24.18	7.44 ± 0.64
1599 ± 4	270.9	59.2	30.68	2.93 ± 0.25	1598 ± 4	354.2	58.9	29.12	5.74 ± 0.48
1199 ± 3	265	59.3	28	7.19 ± 0.60	1199 ± 3	359.6	59.0	28	6.98 ± 0.56
799 ± 2	267	59.2	24	6.64 ± 0.58	799 ± 2	357.5	58.9	24	6.05 ± 0.49
600 ± 2	266	59.4	28	5.78 ± 0.46	599 ± 2	357.5	59.1	28	4.55 ± 0.54
400 ± 2	268	58.9	23	4.87 ± 0.42	399 ± 2	355.8	59.0	23	4.21 ± 0.38
249 ± 1	266	58.7	28	8.06 ± 0.59	248 ± 1	354.4	58.5	28	8.09 ± 0.58
149 ± 1	267	58.4	27	5.40 ± 0.42	148 ± 1	355	58.8	27	5.17 ± 0.40
99 ± 1	277	48.1	38.5	3.53 ± 0.25	97 ± 1	358.6	48.0	38.5	3.23 ± 0.27
68 ± 1	264.8	96.4	65.5	2.11 ± 0.16	66 ± 1	354.8	49.8	65.5	1.81 ± 0.13
46 ± 1	262.1	48.0	25	5.22 ± 0.37	43 ± 1	357.8	48.1	25	4.57 ± 0.34

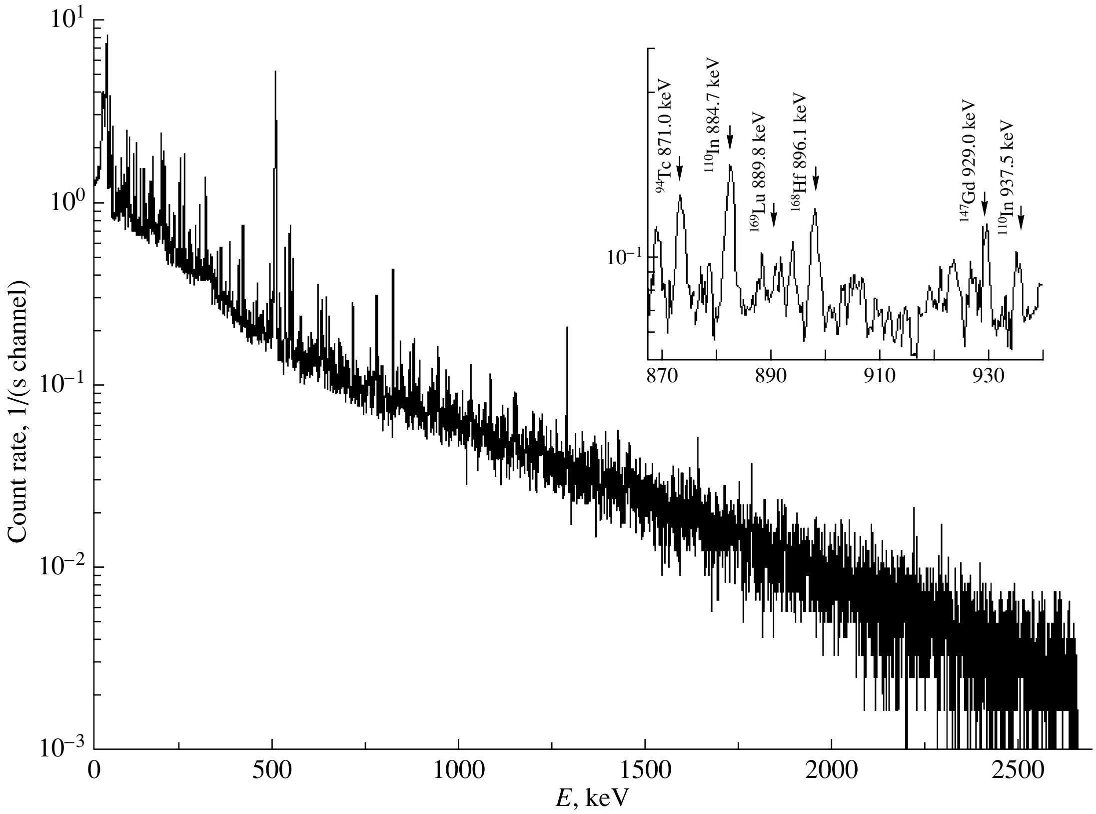

Fig. 1. Example of the γ spectrum of ^{nat}W no. 5 for $E_p = 2.6$ GeV; the measurement duration was 900 s.

Table 2. Experimental cross sections for the production of the radioactive products in the $^{nat}W(p, x)$ reactions induced by 0.04- to 2.6-GeV protons

Nuclide	Type	$T_{1/2}$	Production cross section, mb										
			$E_p = 46$ MeV	68 MeV	99 MeV	149 MeV	249 MeV	400 MeV	600 MeV	799 MeV	1199 MeV	1599 MeV	2605 MeV
^{186}Re	i	3.7183 day	3.44 (0.35)	1.95 (0.18)	0.774 (0.087)	–	–	–	–	–	–	–	–
^{184m}Re	i(m)	169 day	5.89 (0.63)	2.89 (0.32)	1.60 (0.16)	1.03 (0.20)	0.82 (0.18)	–	–	–	–	–	–
^{184}Re	i($m+g$)	38.0 day	29.1 (2.3)	16.4 (1.3)	10.50 (0.90)	6.37 (0.59)	4.13 (0.34)	2.38 (0.23)	1.90 (0.18)	1.53 (0.15)	1.66 (0.15)	1.34 (0.13)	1.46 (0.14)
^{183}Re	i	70.0 day	102.0 (9.0)	41.7 (3.4)	25.5 (2.2)	16.1 (1.5)	9.72 (0.84)	5.57 (0.57)	3.72 (0.35)	3.09 (0.30)	3.44 (0.46)	2.80 (0.27)	3.14 (0.36)
^{182m}Re	i(m)	12.7 h	150 (13)	45.7 (4.5)	27.3 (2.8)	16.3 (1.6)	9.5 (1.0)	4.90 (0.59)	3.68 (0.45)	2.65 (0.39)	2.91 (0.48)	2.54 (0.39)	2.51 (0.35)
^{182}Re	i	64.0 h	142 (12)	29.2 (2.4)	15.0 (1.3)	8.50 (0.76)	5.21 (0.45)	2.72 (0.29)	1.72 (0.60)	1.90 (0.55)	1.98 (0.75)	1.66 (0.51)	2.36 (0.52)
^{181}Re	i	19.9 h	172 (28)	96 (17)	51.2 (7.9)	28.1 (4.4)	19.9 (3.1)	10.8 (1.8)	8.4 (1.4)	6.2 (1.1)	5.80 (0.78)	–	4.94 (0.84)
^{179}Re	i	19.5 min	219 (18)	149 (12)	79.7 (7.1)	33.2 (3.3)	17.1 (2.3)	–	–	–	–	–	–
^{178}Re	i	13.2 min	78.7 (7.9)	169 (16)	98.0 (9.8)	38.9 (4.5)	19.8 (2.9)	9.5 (1.4)	5.28 (0.84)	–	–	–	–
^{177}Re	i	14.0 min	–	140 (11)	95.8 (7.8)	26.9 (2.3)	29 (16)	–	–	–	–	–	–
^{176}Re	i	5.3 min	–	28.6 (5.2)	84.0 (8.6)	34.5 (4.0)	14.2 (1.7)	–	–	–	–	–	–
^{181}W	c	121.2 day	437 (44)	377 (38)	216 (29)	–	–	–	–	–	–	–	–
^{178}W	c	21.6 day	75.3 (6.6)	198 (17)	167 (15)	102.0 (10.0)	66.0 (5.8)	40.3 (4.2)	32.6 (3.3)	23.3 (2.5)	25.2 (2.6)	18.3 (2.2)	19.2 (2.1)
^{177}W	i	135 min	–	8 (27)	20 (16)	37 (10)	27 (16)	–	–	–	–	–	–
^{177}W	c	135 min	1.39 (0.18)	141 (18)	146 (19)	99 (13)	56.3 (7.5)	45.0 (6.5)	32.2 (4.5)	24.2 (3.5)	22.6 (3.2)	17.4 (2.5)	13.1 (1.8)
^{176}W	c	2.5 h	–	35.9 (3.3)	168 (15)	127 (11)	81.0 (7.6)	46.7 (5.7)	32.6 (3.6)	25.2 (3.4)	16.1 (4.2)	17.2 (3.4)	8.8 (2.1)
^{174}W	c	31 min	–	1.23 (0.44)	47.0 (5.7)	97 (13)	61.9 (7.4)	39.6 (5.4)	31.0 (4.3)	18.0 (3.1)	20.8 (3.0)	6.1 (2.0)	6.6 (1.5)
^{184}Ta	c*	8.7 h	–	1.02 (0.11)	2.02 (0.18)	2.40 (0.50)	3.62 (0.36)	3.48 (0.63)	4.80 (0.56)	4.63 (0.54)	5.05 (0.69)	4.64 (0.47)	4.27 (0.53)
^{183}Ta	c	5.1 day	1.10 (0.13)	2.04 (0.30)	4.57 (0.45)	6.70 (0.63)	9.5 (1.0)	10.1 (1.0)	12.3 (1.2)	11.9 (1.2)	12.4 (1.3)	9.6 (1.7)	10.9 (1.1)
^{182}Ta	i(m_1+m_2+g)	114.43 day	1.02 (0.13)	3.09 (0.29)	6.36 (0.56)	9.22 (0.79)	11.80 (1.00)	12.3 (1.1)	14.2 (1.2)	13.8 (1.3)	15.1 (1.4)	12.9 (1.2)	12.8 (1.2)
^{178m}Ta	i(m)	2.36 h	2.09 (0.18)	3.92 (0.34)	6.36 (0.72)	11.0 (1.5)	13.1 (1.2)	12.3 (1.2)	10.3 (1.1)	8.48 (0.85)	11.9 (1.1)	7.61 (0.94)	9.47 (0.92)
^{177}Ta	c*	56.56 h	134 (24)	196 (25)	207 (29)	161 (25)	112 (22)	92 (23)	59 (14)	49 (12)	43 (11)	37.1 (9.1)	33.0 (8.1)
^{176}Ta	i	8.09 h	–	9.3 (1.7)	4.9 (3.5)	19.4 (4.1)	25.6 (3.5)	26.2 (4.0)	28.8 (3.7)	21.7 (3.0)	26.9 (4.2)	17.4 (3.9)	24.4 (3.4)
^{176}Ta	c	8.09 h	–	45.6 (3.8)	172 (15)	143 (13)	110.0 (9.0)	77.2 (8.0)	62.2 (5.9)	45.5 (4.8)	43.2 (4.2)	35.8 (3.7)	33.3 (3.3)
^{176}Ta	c*	8.09 h	3.27 (0.30)	–	–	–	–	–	–	–	–	–	–

Table 2. (Contd.)

Nuclide	Type	$T_{1/2}$	Production cross section, mb $E_p = 46$ MeV	68 MeV	99 MeV	149 MeV	249 MeV	400 MeV	600 MeV	799 MeV	1199 MeV	1599 MeV	2605 MeV
^{175}Ta	c	10.5 h	–	8.88	123	139	109.0	74.1	59.9	40.9	34.0	27.6	27.2
				(0.75)	(11)	(13)	(9.0)	(7.2)	(5.9)	(4.2)	(3.2)	(3.0)	(3.1)
^{174}Ta	i	1.14 h	–	4.01	4.9	5.9	28.6	25.3	19.4	18.4	8.4	17.7	14.3
				(0.77)	(1.4)	(4.1)	(3.8)	(4.0)	(3.7)	(3.8)	(2.6)	(3.4)	(2.5)
^{174}Ta	c	1.14 h	–	5.26	51.7	103	91	64.9	50.2	36.4	29.2	23.9	21.0
				(0.66)	(6.2)	(13)	(11)	(8.2)	(6.2)	(4.7)	(3.7)	(3.2)	(2.7)
^{173}Ta	c	3.14 h	–	–	19.3	90.8	97.1	73.9	59.4	44.5	30.0	25.8	22.2
					(2.3)	(8.6)	(8.8)	(7.8)	(6.1)	(5.2)	(4.9)	(5.1)	(3.4)
^{172}Ta	c*	36.8 min	–	–	–	33.1	44.2	34.6	28.3	18.9	17.4	16.6	15.4
						(4.2)	(4.0)	(3.9)	(2.9)	(2.1)	(2.4)	(2.3)	(2.2)
^{181}Hf	c	42.39 day	0.043	0.078	0.157	0.301	0.629	–	1.23	–	1.40	1.19	1.23
			(0.005)	(0.007)	(0.014)	(0.026)	(0.051)		(0.11)		(0.13)	(0.11)	(0.11)
^{180m}Hf	i(m)	5.5 h	–	–	0.69	0.76	0.67	0.572	1.01	0.86	–	–	–
					(0.16)	(0.10)	(0.10)	(0.090)	(0.16)	(0.10)			
^{179m}Hf	i(m)	25.05 day	–	0.045	0.073	0.116	0.207	0.259	0.332	0.326	–	–	–
				(0.008)	(0.007)	(0.011)	(0.028)	(0.038)	(0.040)	(0.035)			
^{175}Hf	c	70 day	0.192	9.60	122	137	116.0	83.6	70.3	53.9	48.9	39.6	36.4
			(0.018)	(0.85)	(11)	(12)	(10.0)	(8.3)	(6.6)	(5.4)	(4.7)	(3.9)	(3.6)
^{173}Hf	i	23.6 h	–	–	–	0.5	3.7	10	5.3	0.5	15.5	11	13.2
						(5.9)	(6.2)	(16)	(7.6)	(5.4)	(8.6)	(11)	(2.8)
^{173}Hf	c	23.6 h	–	–	–	101	113	88	79.9	56.0	48.3	37.7	33.4
						(12)	(13)	(12)	(8.1)	(6.8)	(5.1)	(3.8)	(3.6)
^{173}Hf	c*	23.6 h	–	0.753	22.9	–	–	–	–	–	–	–	–
				(0.084)	(2.0)								
^{172}Hf	c	1.87 yr	–	–	11.09	55.2	80.1	73.1	62.4	46.3	39.1	29.3	24.4
					(1.00)	(4.8)	(6.4)	(6.8)	(5.5)	(4.6)	(3.6)	(2.7)	(2.4)
^{171}Hf	c	12.1 h	–	–	–	24	72.0	67.7	64.6	42.6	33.9	27.9	23.6
						(16)	(7.8)	(9.4)	(7.4)	(5.9)	(4.1)	(3.5)	(3.1)
^{170}Hf	c	16.01 h	–	–	0.6	18.6	58.1	62.3	63.7	44.4	30.1	25.9	20.9
					(1.8)	(1.8)	(4.7)	(6.0)	(5.8)	(4.5)	(3.3)	(2.7)	(2.1)
^{168}Hf	c	25.95 min	–	–	–	9.3	32.8	46.4	47.6	34.0	24.8	18.3	14.3
						(1.2)	(3.9)	(4.6)	(4.4)	(3.4)	(2.5)	(1.9)	(1.7)
^{173}Lu	c	1.37 yr	–	–	18.9	83.7	98.7	83.0	73.0	55.4	43.1	36.4	31.9
					(1.7)	(7.9)	(8.9)	(8.4)	(7.0)	(5.6)	(4.3)	(3.7)	(3.2)
^{172}Lu	i	6.70 day	–	–	0.25	0.937	2.52	4.13	5.45	5.11	4.84	4.00	3.74
					(0.12)	(0.086)	(0.21)	(0.41)	(0.50)	(0.49)	(0.44)	(0.37)	(0.37)
^{172}Lu	c	6.70 day	–	–	11.6	55.5	82.4	77.7	67.7	51.9	44.1	33.3	28.4
					(3.6)	(4.9)	(6.8)	(7.3)	(6.1)	(5.1)	(4.1)	(3.2)	(2.9)
^{171}Lu	i($m+g$)	8.24 day	–	–	–	14	9.8	13.3	10.7	14.5	13.8	9.0	8.1
						(17)	(5.4)	(7.3)	(5.0)	(4.8)	(3.1)	(2.6)	(2.4)
^{171}Lu	c	8.24 day	–	–	–	39.7	85.4	84.6	79.3	60.0	49.4	37.8	33.1
						(3.4)	(6.9)	(7.9)	(7.0)	(5.7)	(4.5)	(3.5)	(3.1)
^{171}Lu	c*	8.24 day	–	–	5.31	–	–	–	–	–	–	–	–
					(0.45)								
^{170}Lu	i($m+g$)	2.012 day	–	–	1.6	3.7	4.9	1.9	2.3	3.7	11.0	4.4	4.3
					(2.6)	(1.3)	(2.3)	(2.0)	(1.8)	(2.0)	(2.5)	(2.0)	(1.4)
^{170}Lu	c	2.012 day	–	–	0.79	22.1	61.7	64.1	64.7	48.4	41.9	31.2	25.9
					(0.16)	(2.0)	(5.2)	(6.1)	(5.8)	(4.9)	(4.0)	(3.2)	(2.6)
^{169}Lu	c	34.06 h	–	–	–	11.4	45.2	54.4	57.2	43.9	36.0	26.6	22.6
						(1.1)	(3.9)	(5.4)	(5.3)	(4.2)	(3.5)	(2.6)	(2.3)

Table 2. (Contd.)

Nuclide	Type	$T_{1/2}$	Production cross section, mb										
			$E_p = 46$ MeV	68 MeV	99 MeV	149 MeV	249 MeV	400 MeV	600 MeV	799 MeV	1199 MeV	1599 MeV	2605 MeV
^{167}Lu	c	51.5 min	–	–	–	–	28.1 (3.1)	55.3 (6.5)	61.8 (7.1)	47.1 (5.6)	36.2 (4.2)	27.2 (3.2)	21.2 (2.5)
^{169}Yb	c*	32.026 day	–	–	0.403 (0.037)	14.1 (1.2)	54.9 (4.6)	73.1 (6.9)	72.6 (6.5)	58.4 (5.8)	48.1 (4.5)	36.5 (3.6)	30.3 (2.9)
^{167}Yb	i	17.5 min	–	–	–	–	0.45 (0.77)	1.14 (0.53)	0.1 (2.6)	2.81 (0.91)	0.6 (1.1)	1.2 (1.1)	0.29 (0.79)
^{167}Yb	c	17.5 min	–	–	–	–	28.4 (3.1)	56.9 (6.7)	62.6 (7.3)	50.0 (5.9)	36.9 (4.3)	28.5 (3.4)	21.4 (2.6)
^{166}Yb	c	56.7 h	–	–	–	1.21 (0.18)	20.7 (1.7)	47.0 (4.4)	61.4 (5.4)	49.3 (4.6)	41.0 (3.7)	31.6 (2.9)	24.7 (2.3)
^{162}Yb	c	18.87 min	–	–	–	–	5.31 (0.89)	13.3 (2.3)	31.9 (5.6)	28.0 (4.9)	23.4 (3.8)	13.6 (4.4)	10.5 (4.8
^{168}Tm	i	93.1 day	–	–	–	–	0.114 (0.015)	0.310 (0.044)	0.610 (0.063)	0.787 (0.081)	1.05 (0.10)	0.876 (0.099)	0.641 (0.072)
^{167}Tm	c	9.25 day	–	–	–	3.31 (0.52)	32.7 (4.5)	57.6 (8.3)	73 (10)	58.0 (8.4)	48.9 (7.0)	35.0 (5.1)	28.5 (4.1)
^{166}Tm	i	7.70 h	–	–	–	0.12 (0.91)	1.55 (0.60)	1.29 (0.62)	2.57 (0.90)	1.15 (0.33)	2.65 (0.71)	2.24 (0.63)	1.90 (0.50)
^{166}Tm	c	7.70 h	–	–	–	1.54 (0.89)	22.6 (1.9)	48.8 (4.6)	65.3 (5.8)	51.8 (5.0)	45.3 (4.2)	34.9 (3.3)	27.8 (2.6)
^{165}Tm	c	30.06 h	–	–	–	0.789 (0.083)	16.0 (1.5)	41.5 (4.1)	61.8 (5.7)	52.1 (5.2)	42.5 (4.3)	33.0 (3.4)	27.0 (2.9)
^{163}Tm	c*	1.810 h	–	–	–	–	–	37.5 (4.7)	55.2 (6.5)	53.1 (6.2)	41.2 (5.1)	29.2 (3.2)	19.4 (3.5)
^{162}Tm	i($m+g$)	21.70 min	–	–	–	–	–	17 (11)	27.5 (4.6)	24.1 (3.6)	12.4 (3.3)	18.9 (4.2)	7.2 (5.6)
^{162}Tm	c	21.70 min	–	–	–	–	–	27 (11)	56.8 (6.4)	50.2 (6.4)	34.3 (7.8)	26.9 (5.2)	18.0 (4.5)
^{161}Tm	c	33 min	–	–	–	–	1.9 (1.1)	18.3 (3.4)	33.7 (6.0)	37.5 (6.7)	34.6 (6.2)	29.8 (3.4)	22.7 (3.2)
^{161}Er	i	3.21 h	–	–	–	–	0.8 (1.3)	–	–	–	–	1.6 (2.0)	0.3 (2.3)
^{161}Er	c	3.21 h	–	–	–	–	2.68 (0.35)	–	–	–	–	32.2 (3.6)	24.9 (2.8)
^{161}Er	c*	3.21 h	–	–	–	–	–	27.6 (3.1)	57.0 (6.1)	57.1 (6.5)	50.7 (5.7)	–	–
^{160}Er	c	28.58 h	–	–	–	–	2.07 (0.37)	19.3 (2.1)	46.5 (4.8)	47.1 (5.1)	46.0 (5.0)	34.1 (3.7)	25.3 (2.7)
^{159}Er	c*	36 min	–	–	–	–	–	15.4 (2.0)	43.9 (5.5)	45.4 (5.9)	43.0 (5.5)	33.5 (4.3)	27.3 (3.2)
^{157}Er	c*	18.65 min	–	–	–	–	–	10.8 (1.7)	33.0 (4.7)	38.2 (5.4)	39.4 (5.7)	34.0 (4.8)	23.7 (3.4)
^{156}Er	c	19.5 min	–	–	–	–	–	–	23.7 (3.1)	31.6 (3.3)	33.2 (4.2)	29.2 (6.2)	22.1 (3.0)
^{160m}Ho	i(m)	5.02 h	–	–	–	–	–	1.69 (0.41)	1.91 (0.51)	1.83 (0.53)	2.60 (0.43)	2.37 (0.44)	0.94 (0.34)
^{160m}Ho	c	5.02 h	–	–	–	–	–	21.9 (2.5)	49.4 (5.3)	49.9 (5.7)	48.7 (5.7)	36.3 (4.1)	27.7 (3.1)
^{160}Ho	i($m+g$)	25.6 min	–	–	–	–	–	–	4.52 (0.72)	5.1 (1.0)	5.86 (0.91)	2.86 (0.76)	3.34 (0.60)

Table 2. (Contd.)

Nuclide	Type	$T_{1/2}$	Production cross section, mb										
			$E_p = 46$ MeV	68 MeV	99 MeV	149 MeV	249 MeV	400 MeV	600 MeV	799 MeV	1199 MeV	1599 MeV	2605 MeV
^{156}Ho	i	56 min	–	–	–	–	–	–	0.5 (2.0)	1.4 (1.4)	1.3 (3.3)	0.4 (7.0)	0.3 (2.5)
^{156}Ho	c	56 min	–	–	–	–	–	–	24.3 (3.4)	32.6 (3.2)	36.0 (4.6)	31.5 (3.4)	23.8 (2.6)
^{157}Dy	c	8.14 h	–	–	–	–	0.406 (0.059)	9.7 (1.0)	33.4 (3.3)	42.6 (4.5)	44.3 (4.4)	32.8 (3.4)	25.7 (2.7)
^{155}Dy	c*	9.9 h	–	–	–	–	–	5.81 (0.58)	25.3 (2.3)	34.1 (3.5)	40.2 (3.8)	30.9 (3.0)	23.9 (2.3)
^{152}Dy	c	2.38 h	–	–	–	–	–	1.24 (0.12)	10.02 (0.90)	16.2 (1.5)	24.4 (2.2)	20.7 (2.0)	15.0 (1.4)
^{155}Tb	c*	5.32 day	–	–	–	–	–	7.0 (1.7)	23.6 (2.2)	33.0 (3.3)	40.2 (4.2)	28.2 (3.4)	20.8 (2.7)
^{153}Tb	c*	2.34 day	–	–	–	–	–	2.43 (0.35)	16.3 (1.6)	25.6 (2.7)	33.6 (3.5)	27.6 (2.9)	19.4 (2.1)
^{152}Tb	i($m+g$)	17.5 h	–	–	–	–	–	–	2.1 (1.4)	7.9 (2.5)	0.43 (0.91)	–	–
^{152}Tb	c	17.5 h	–	–	–	–	–	–	10.7 (1.2)	20.4 (2.3)	26.6 (2.9)	27.2 (3.1)	20.3 (2.4)
^{151}Tb	c	17.609 h	–	–	–	–	–	–	8.63 (0.76)	17.9 (1.7)	25.3 (2.4)	22.8 (2.5)	16.9 (1.7)
^{150}Tb	c	3.48 h	–	–	–	–	–	–	4.87 (0.66)	9.4 (1.4)	14.9 (2.0)	11.6 (1.6)	8.4 (1.1)
^{149}Tb	c	4.118 h	–	–	–	–	–	–	3.34 (0.38)	6.69 (0.72)	9.6 (1.1)	8.81 (0.82)	6.36 (0.59)
^{148}Tb	c	60 min	–	–	–	–	–	–	4.50 (0.46)	8.85 (0.95)	13.2 (1.3)	11.1 (1.1)	8.57 (0.85)
^{147}Tb	c	1.7 h	–	–	–	–	–	–	–	–	–	–	1.83 (0.26)
^{153}Gd	c	240.4 day	–	–	–	–	–	–	–	–	22.8 (2.8)	23.5 (2.5)	18.7 (1.9)
^{151}Gd	c	124 day	–	–	–	–	–	–	14.3 (1.7)	17.2 (1.8)	24.5 (3.0)	21.4 (3.0)	16.9 (1.7)
^{149}Gd	c	9.28 day	–	–	–	–	–	1.16 (0.13)	10.6 (1.1)	20.8 (2.0)	33.8 (3.3)	28.1 (2.9)	22.1 (2.1)
^{147}Gd	c	38.06 h	–	–	–	–	–	2.36 (0.27)	7.9 (1.3)	15.9 (1.7)	27.7 (2.7)	24.9 (2.4)	18.7 (2.0)
^{146}Gd	c	48.27 day	–	–	–	–	–	0.479 (0.047)	6.37 (0.56)	15.1 (1.4)	30.4 (3.7)	26.0 (2.4)	20.0 (1.9)
^{145}Gd	c	23.0 min	–	–	–	–	–	–	–	–	16.0 (1.7)	15.2 (1.6)	11.2 (1.3)
^{149}Eu	i	93.1 day	–	–	–	–	–	–	0.1 (2.1)	0.8 (1.5)	–	–	–
^{149}Eu	c	93.1 day	–	–	–	–	–	–	10.30 (1.00)	20.1 (2.2)	–	–	–
^{149}Eu	c*	93.1 day	–	–	–	–	–	–	–	–	38.6 (3.7)	29.2 (2.8)	24.1 (2.4)
^{148}Eu	i	54.5 day	–	–	–	–	–	–	0.322 (0.041)	0.739 (0.073)	1.51 (0.16)	1.42 (0.15)	1.32 (0.12)
^{147}Eu	i	24.1 day	–	–	–	–	–	–	–	–	27 (16)	7 (16)	1.5 (7.1)

Table 2. (Contd.)

Nuclide	Type	$T_{1/2}$	Production cross section, mb										
			$E_p = 46$ MeV	68 MeV	99 MeV	149 MeV	249 MeV	400 MeV	600 MeV	799 MeV	1199 MeV	1599 MeV	2605 MeV
^{147}Eu	c*	24.1 day	–	–	–	–	–	0.734 (0.091)	7.85 (0.94)	18.5 (1.9)	34.6 (3.3)	30.9 (3.1)	23.3 (2.3)
^{146}Eu	i	4.61 day	–	–	–	–	–	0.048 (0.014)	0.738 (0.079)	2.06 (0.27)	6.07 (0.66)	5.69 (0.62)	3.74 (0.39)
^{146}Eu	c	4.61 day	–	–	–	–	–	0.530 (0.053)	7.00 (0.64)	17.5 (1.7)	35.7 (3.3)	32.1 (3.0)	23.9 (2.3)
^{145}Eu	c	5.93 day	–	–	–	–	–	0.359 (0.058)	4.09 (0.38)	10.9 (1.1)	23.6 (2.2)	22.7 (2.2)	18.1 (1.8)
^{144}Pm	i*	363 day	–	–	–	–	–	–	–	–	0.464 (0.049)	0.552 (0.055)	0.542 (0.053)
^{143}Pm	c	265 day	–	–	–	–	–	–	–	8.13 (0.91)	23.4 (2.6)	22.8 (2.5)	18.9 (2.1)
^{140m}Pm	i(m)	5.95 min	–	–	–	–	–	–	–	–	5.67 (0.81)	6.61 (0.97)	4.59 (0.72)
^{139m}Nd	i(m)	5.5 h	–	–	–	–	–	–	–	–	2.39 (0.42)	2.93 (0.51)	2.87 (0.50)
^{136}Nd	c	50.65 min	–	–	–	–	–	–	1.22 (0.17)	3.26 (0.39)	10.1 (1.1)	15.1 (1.5)	15.4 (1.8)
^{136}Pr	i	13.1 min	–	–	–	–	–	–	–	–	3.01 (0.56)	8.1 (1.3)	2.99 (0.61)
^{136}Pr	c	13.1 min	–	–	–	–	–	–	–	–	13.2 (1.5)	22.6 (3.3)	17.9 (2.1)
^{134}Pr	c*	17 min	–	–	–	–	–	–	–	1.33 (0.18)	–	–	13.0 (1.3)
^{139}Ce	c	137.640 day	–	–	–	–	–	–	0.759 (0.069)	4.63 (0.44)	17.6 (1.6)	22.3 (2.1)	20.3 (1.9)
^{135}Ce	c	17.7 h	–	–	–	–	–	–	–	–	12.7 (1.4)	17.9 (1.7)	18.3 (1.8)
^{134}Ce	c	3.16 day	–	–	–	–	–	–	1.18 (0.24)	2.40 (0.37)	10.3 (1.1)	15.8 (2.1)	16.3 (1.7)
^{133m}Ce	i(m)	4.9 h	–	–	–	–	–	–	–	–	2.52 (0.31)	3.71 (0.38)	3.08 (0.37)
^{132}Ce	c	3.51 h	–	–	–	–	–	–	–	1.01 (0.23)	7.68 (0.84)	13.0 (1.4)	14.9 (1.5)
^{130}Ce	c	25 min	–	–	–	–	–	–	–	–	3.96 (0.46)	6.50 (0.70)	7.95 (0.79)
^{132}La	i($m+g$)	4.8 h	–	–	–	–	–	–	–	0.28 (0.32)	0.78 (0.24)	0.73 (0.35)	0.31 (0.32)
^{132}La	c	4.8 h	–	–	–	–	–	–	–	1.30 (0.22)	8.5 (1.0)	13.9 (1.6)	15.6 (1.6)
^{130}La	i	8.7 min	–	–	–	–	–	–	–	–	0.53 (0.85)	5.79 (0.79)	5.02 (0.78)
^{130}La	c	8.7 min	–	–	–	–	–	–	–	–	4.51 (0.86)	12.3 (1.4)	13.0 (1.5)
^{133}Ba	c	3848.9 day	–	–	–	–	–	–	–	–	10.5 (1.0)	15.3 (1.5)	16.1 (1.6)
^{131}Ba	c	11.50 day	–	–	–	–	–	–	–	1.47 (0.14)	8.23 (0.75)	14.0 (1.3)	16.6 (1.5)
^{128}Ba	c	2.43 day	–	–	–	–	–	–	–	–	5.23 (0.55)	10.8 (1.2)	15.5 (1.7)

Table 2. (Contd.)

Nuclide	Type	$T_{1/2}$	Production cross section, mb										
			$E_p = 46$ MeV	68 MeV	99 MeV	149 MeV	249 MeV	400 MeV	600 MeV	799 MeV	1199 MeV	1599 MeV	2605 MeV
^{126}Ba	c	100 min	–	–	–	–	–	–	–	–	–	–	7.01 (0.98)
^{129}Cs	c	32.06 h	–	–	–	–	–	–	–	–	8.14 (0.85)	14.7 (1.5)	19.4 (2.0)
^{127}Cs	c	6.25 h	–	–	–	–	–	–	–	–	4.68 (0.44)	9.92 (0.95)	14.4 (1.4)
^{127}Xe	c	36.4 day	–	–	–	–	–	–	–	0.663 (0.075)	4.99 (0.60)	10.3 (1.3)	15.6 (1.5)
^{125}Xe	c	16.9 h	–	–	–	–	–	–	–	–	3.27 (0.33)	8.92 (0.85)	14.6 (1.4)
^{123}Xe	c	2.08 h	–	–	–	–	–	–	–	–	5.24 (0.53)	10.3 (1.1)	15.5 (1.5)
^{122}Xe	c	20.1 h	–	–	–	–	–	–	–	–	–	–	9.7 (1.1)
^{120}Xe	c	40 min	–	–	–	–	–	–	–	–	0.85 (0.35)	1.12 (0.47)	3.30 (0.44)
^{120}I	i	81.0 min	–	–	–	–	–	–	–	–	0.65 (0.48)	4.23 (0.73)	7.03 (0.75)
^{120}I	c	81.0 min	–	–	–	–	–	–	–	–	1.50 (0.22)	5.35 (0.54)	10.28 (1.00)
^{121m}Te	i(m)	154 day	–	–	–	–	–	–	–	0.165 (0.027)	0.322 (0.064)	0.309 (0.042)	0.621 (0.063)
^{121}Te	i($m+g$)	19.16 day	–	–	–	–	–	–	–	0.310 (0.032)	2.53 (0.24)	6.30 (0.61)	11.7 (1.1)
^{121}Te	c	19.16 day	–	–	–	–	–	–	–	0.456 (0.046)	2.82 (0.27)	6.67 (0.65)	12.3 (1.2)
^{119m}Te	i(m)	4.70 day	–	–	–	–	–	–	–	–	0.475 (0.045)	1.100 (0.100)	2.03 (0.20)
^{119}Te	c	16.05 h	–	–	–	–	–	–	–	–	13.6 (1.9)	11.9 (1.8)	10.6 (1.5)
^{117}Te	c	62 min	–	–	–	–	–	–	–	–	–	3.83 (0.41)	9.44 (0.92)
^{114}Te	c	15.2 min	–	–	–	–	–	–	–	–	–	–	2.09 (0.32)
^{120m}Sb	i(m)	5.76 day	–	–	–	–	–	–	–	–	0.060 (0.010)	0.086 (0.018)	0.168 (0.020)
^{118m}Sb	i(m)	5.00 h	–	–	–	–	–	–	–	–	–	0.74 (0.11)	1.06 (0.14)
^{115}Sb	c*	32.1 min	–	–	–	–	–	–	–	–	–	3.08 (0.36)	9.21 (0.88)
^{113}Sn	i($m+g$)	115.09 day	–	–	–	–	–	–	–	–	0.71 (0.30)	3.18 (0.47)	7.53 (0.70)
^{111}In	c	2.8047 day	–	–	–	–	–	–	–	–	1.32 (0.21)	1.73 (0.35)	7.4 (1.2)
^{110}In	i	4.9 h	–	–	–	–	–	–	–	–	–	1.71 (0.41)	3.56 (0.68)
^{109}In	c	4.2 h	–	–	–	–	–	–	–	–	–	–	4.53 (0.47)
^{108m}In	i(m)	58.0 min	–	–	–	–	–	–	–	–	–	0.87 (0.17)	3.30 (0.43)

Table 2. (Contd.)

Nuclide	Type	$T_{1/2}$	Production cross section, mb										
			$E_p = 46$ MeV	68 MeV	99 MeV	149 MeV	249 MeV	400 MeV	600 MeV	799 MeV	1199 MeV	1599 MeV	2605 MeV
^{110m}Ag	i(m)	249.76 day	–	–	–	–	–	–	–	–	–	0.108 (0.022)	0.159 (0.018)
^{106m}Ag	i(m)	8.28 day	–	–	–	–	–	–	–	–	0.373 (0.055)	0.643 (0.068)	1.79 (0.17)
^{105}Ag	c	41.29 day	–	–	–	–	–	–	0.291 (0.058)	0.325 (0.051)	0.92 (0.11)	1.97 (0.23)	5.21 (0.49)
^{100}Pd	c	3.63 day	–	–	–	–	–	–	–	–	0.147 (0.021)	0.445 (0.048)	1.65 (0.17)
^{102m}Rh	i(m)	2.9 yr	–	–	–	–	–	–	–	–	–	–	1.16 (0.12)
^{100}Rh	i($m+g$)	20.8 h	–	–	–	–	–	–	–	–	1.22 (0.13)	1.37 (0.14)	2.33 (0.34)
^{100}Rh	c	20.8 h	–	–	–	–	–	–	–	–	1.37 (0.15)	1.82 (0.18)	3.82 (0.44)
^{99m}Rh	c	4.7 h	–	–	–	–	–	–	–	–	–	0.79 (0.11)	2.42 (0.29)
^{103}Ru	c	39.26 day	–	–	–	–	–	–	–	–	0.089 (0.026)	0.074 (0.049)	0.167 (0.021)
^{97}Ru	c	2.791 day	–	–	–	–	–	–	–	–	1.76 (0.18)	–	3.72 (0.38)
^{96}Tc	i($m+g$)	4.28 day	–	–	–	–	–	–	0.156 (0.016)	0.186 (0.034)	0.442 (0.046)	0.697 (0.068)	1.83 (0.18)
^{94}Tc	c	293 min	–	–	–	–	–	–	–	–	–	0.632 (0.084)	2.00 (0.20)
^{93m}Mo	i(m)	6.85 h	–	–	–	–	–	–	–	–	–	0.397 (0.057)	1.51 (0.21)
^{90}Nb	c*	14.60 h	–	–	–	–	–	–	–	–	0.63 (0.16)	1.03 (0.11)	2.88 (0.28)
^{89}Zr	c	78.41 h	–	–	–	–	–	0.096 (0.012)	0.244 (0.032)	0.367 (0.039)	0.816 (0.075)	1.23 (0.11)	3.68 (0.34)
^{88}Zr	c	83.4 day	–	–	–	–	0.032 (0.033)	0.103 (0.009)	0.212 (0.018)	0.290 (0.027)	0.255 (0.023)	0.796 (0.073)	2.72 (0.25)
^{88}Y	i	106.65 day	–	–	–	–	0.120 (0.015)	0.149 (0.032)	0.307 (0.030)	0.52 (0.12)	0.87 (0.15)	0.94 (0.16)	1.57 (0.19)
^{88}Y	c	106.65 day	–	–	–	–	0.151 (0.025)	0.353 (0.090)	0.783 (0.085)	0.64 (0.10)	1.27 (0.12)	1.80 (0.17)	4.27 (0.40)
^{87m}Y	c*	13.37 h	–	–	–	–	–	–	–	–	0.83 (0.60)	0.89 (0.29)	2.2 (1.0)
^{87}Y	i	79.8 h	–	–	–	–	–	–	–	–	0.12 (0.69)	0.60 (0.32)	1.7 (1.2)
^{87}Y	c	79.8 h	–	–	–	–	–	–	–	–	1.24 (0.14)	1.72 (0.21)	3.88 (0.41)
^{87}Y	c*	79.8 h	–	–	–	–	–	0.178 (0.023)	0.370 (0.040)	0.587 (0.059)	–	–	–
^{86}Y	c	14.74 h	–	–	–	–	–	–	–	–	–	1.16 (0.17)	3.17 (0.38)
^{85}Sr	c	64.84 day	–	–	–	–	–	–	0.667 (0.070)	–	1.56 (0.16)	1.94 (0.20)	3.81 (0.39)

Table 2. (Contd.)

Nuclide	Type	$T_{1/2}$	Production cross section, mb										
			$E_p = 46$ MeV	68 MeV	99 MeV	149 MeV	249 MeV	400 MeV	600 MeV	799 MeV	1199 MeV	1599 MeV	2605 MeV
^{83}Sr	c	32.41 h	–	–	–	–	–	–	–	–	–	–	1.58 (0.75)
^{84}Rb	i($m+g$)	32.77 day	–	–	–	–	0.125 (0.012)	0.230 (0.024)	0.339 (0.044)	0.425 (0.046)	0.665 (0.063)	0.796 (0.077)	1.17 (0.11)
^{83}Rb	c	86.2 day	–	–	–	–	–	0.246 (0.037)	0.543 (0.070)	0.697 (0.092)	1.70 (0.68)	2.39 (0.48)	3.91 (0.45)
^{82m}Rb	i(m)	6.472 h	–	–	–	–	–	–	–	–	–	–	1.45 (0.17)
^{77}Br	c	57.036 h	–	–	–	–	–	–	–	–	–	–	2.66 (0.29)
^{75}Se	c	119.779 day	–	–	–	–	–	–	0.324 (0.035)	0.448 (0.047)	1.020 (0.100)	1.10 (0.11)	2.54 (0.25)
^{74}As	i	17.77 day	–	–	–	–	0.077 (0.009)	0.167 (0.023)	0.320 (0.036)	0.347 (0.042)	0.596 (0.070)	0.713 (0.091)	1.27 (0.15)
^{69m}Zn	i(m)	13.76 h	–	–	–	–	–	–	–	–	–	–	0.359 (0.055)
^{65}Zn	c	244.26 day	–	–	–	–	–	–	–	–	–	–	1.79 (0.17)
^{60}Co	i($m+g$)	5.2714 yr	–	–	–	–	–	–	–	–	–	–	1.40 (0.15)
^{58}Co	i($m+g$)	70.86 day	–	–	–	–	–	–	–	–	0.347 (0.083)	0.623 (0.090)	1.53 (0.14)
^{56}Co	c	77.233 day	–	–	–	–	–	–	–	–	0.094 (0.011)	–	0.213 (0.021)
^{59}Fe	c	44.472 day	–	–	–	–	0.065 (0.006)	0.104 (0.013)	0.215 (0.020)	0.273 (0.027)	0.465 (0.055)	0.538 (0.068)	0.919 (0.092)
^{54}Mn	i	312.11 day	–	–	–	–	–	–	–	0.395 (0.043)	0.687 (0.063)	0.89 (0.12)	1.95 (0.18)
^{52}Mn	c	5.591 day	–	–	–	–	–	–	–	–	0.121 (0.012)	0.161 (0.021)	0.325 (0.031)
^{48}V	c	15.9735 day	–	–	0.055 (0.005)	0.069 (0.007)	0.086 (0.007)	0.107 (0.011)	0.119 (0.013)	0.134 (0.016)	0.190 (0.017)	0.253 (0.038)	0.608 (0.058)
^{48}Sc	i	43.67 h	–	–	–	–	–	–	–	–	0.277 (0.040)	0.423 (0.041)	0.726 (0.078)
^{46}Sc	i($m+g$)	83.79 day	–	–	–	–	–	–	–	0.377 (0.038)	0.848 (0.077)	1.10 (0.11)	1.77 (0.16)
^{44m}Sc	i(m)	58.61 h	–	–	–	–	–	–	–	–	0.116 (0.018)	0.229 (0.026)	0.564 (0.056)
^{28}Mg	c	20.915 h	–	–	–	–	–	–	–	–	0.170 (0.035)	0.321 (0.034)	0.932 (0.094)
^{24}Na	c	14.9590 h	–	–	–	–	–	–	–	–	1.26 (0.12)	2.04 (0.19)	4.69 (0.44)
^{22}Na	c	2.6019 yr	–	–	–	–	–	–	–	–	–	0.487 (0.087)	0.770 (0.081)
^{7}Be	i	53.29 day	–	–	0.396 (0.058)	0.393 (0.077)	0.425 (0.040)	0.64 (0.11)	1.04 (0.10)	1.42 (0.15)	2.69 (0.25)	3.77 (0.36)	8.31 (0.79)

Note: In the i^* row, the contribution of ^{148}Eu ($\nu = 9.4 \times 10^{-7}$) was disregarded for ^{144}Pm.

Table 3. Experimental cross sections for the production of the radioactive products in the ^{nat}Ta(p, x) reactions induced by 0.04- to 2.6-GeV protons

Nuclide	Type	$T_{1/2}$	Production cross section, mb										
			$E_p = 43$ MeV	66 MeV	97 MeV	148 MeV	248 MeV	399 MeV	599 MeV	799 MeV	1199 MeV	1598 MeV	2605 MeV
^{178}W	i	21.6 day	690 (60)	102.0 (9.0)	57.4 (5.9)	30.7 (3.5)	16.7 (3.4)	11.2 (1.5)	9.7 (1.5)	7.3 (1.1)	8.2 (1.0)	6.1 (1.2)	–
^{177}W	i	135 min	366 (48)	151 (20)	64.7 (9.0)	33.3 (4.6)	16.9 (2.2)	10.8 (1.6)	8.5 (1.4)	6.06 (0.83)	4.84 (0.70)	3.47 (0.50)	2.92 (0.43)
^{176}W	i	2.5 h	–	457 (38)	95.1 (9.7)	–	–	–	15.6 (3.4)	12.5 (6.0)	5.8 (3.2)	9.2 (2.1)	4.8 (2.8)
^{174}W	i	31 min	–	–	136 (17)	41.8 (5.4)	18.6 (2.2)	11.3 (2.2)	5.7 (3.0)	5.1 (1.7)	0.6 (3.1)	1.8 (1.3)	0.11 (0.77)
^{180}Ta	i	8.152 h	114 (12)	80 (13)	78.1 (9.1)	54.9 (6.5)	76 (12)	40.6 (5.5)	–	–	–	–	–
^{178m}Ta	i(m)	2.36 h	36.5 (3.0)	59.4 (5.3)	50.1 (4.6)	32.9 (2.9)	21.4 (2.1)	22.1 (2.2)	19.9 (2.7)	15.4 (1.5)	14.1 (1.3)	13.2 (2.3)	11.5 (1.4)
^{177}Ta	c*	56.56 h	480 (62)	329 (43)	208 (28)	103 (19)	70 (17)	55 (14)	46 (12)	39.5 (9.9)	42 (10)	32.7 (8.4)	28.8 (7.2)
^{176}Ta	i	8.09 h	–	73.1 (7.7)	123 (12)	–	–	–	33.8 (5.8)	25.6 (6.3)	28.3 (6.9)	17.7 (2.4)	21.2 (3.9)
^{176}Ta	c	8.09 h	–	543 (45)	221 (21)	–	–	–	51.1 (7.0)	40.2 (4.2)	32.6 (4.1)	27.4 (2.7)	24.2 (2.4)
^{176}Ta	c*	8.09 h	0.404 (0.036)	–	–	138 (13)	78.8 (7.1)	63.0 (6.7)	–	–	–	–	–
^{175}Ta	c	10.5 h	–	224 (18)	234 (22)	137 (12)	78.6 (6.4)	61.9 (6.2)	51.3 (6.4)	32.4 (3.1)	25.9 (2.4)	20.4 (2.1)	15.6 (1.6)
^{174}Ta	i	1.14 h	–	–	105 (13)	75.1 (9.4)	46.2 (5.4)	40.4 (5.7)	34.3 (7.0)	21.1 (3.6)	20.3 (5.8)	13.7 (2.5)	15.1 (2.1)
^{174}Ta	c	1.14 h	–	–	241 (30)	117 (14)	64.8 (7.5)	51.7 (6.7)	39.9 (6.2)	26.2 (3.3)	20.8 (3.3)	15.5 (2.1)	15.2 (1.9)
^{173}Ta	c	3.14 h	–	–	221 (23)	145 (15)	81.3 (8.9)	61.8 (7.6)	42.4 (9.2)	–	22.4 (5.1)	19.7 (4.5)	20.1 (3.2)
^{172}Ta	c*	36.8 min	–	–	19.3 (6.0)	66.4 (6.4)	39.3 (3.5)	30.4 (3.4)	21.7 (2.8)	11.1 (2.1)	13.6 (1.9)	11.3 (2.3)	10.4 (1.7)
^{181}Hf	c	42.39 day	–	–	–	–	–	–	–	–	–	–	0.160 (0.017)
^{180m}Hf	i(m)	5.5 h	0.089 (0.014)	–	–	1.36 (0.36)	1.93 (0.35)	2.52 (0.32)	3.45 (0.51)	3.24 (0.33)	3.13 (0.28)	2.30 (0.35)	2.25 (0.23)
^{179m}Hf	i(m)	25.05 day	–	0.193 (0.017)	0.379 (0.036)	0.503 (0.053)	0.570 (0.069)	0.78 (0.10)	0.95 (0.12)	0.803 (0.082)	0.790 (0.072)	0.641 (0.075)	0.518 (0.056)
^{175}Hf	c	70 day	8.92 (0.88)	234 (19)	255 (24)	169 (16)	108.0 (10.0)	89.8 (9.1)	78.5 (9.9)	56.5 (5.2)	50.0 (4.8)	44.9 (5.5)	31.5 (3.1)
^{173}Hf	i	23.6 h	–	–	9 (10)	–	–	–	–	–	25.0 (5.5)	18.2 (4.4)	3.6 (2.8)
^{173}Hf	c	23.6 h	–	–	234 (22)	–	–	–	–	–	49.3 (4.4)	37.9 (3.6)	26.6 (3.0)
^{173}Hf	c*	23.6 h	–	19.1 (1.6)	–	180 (16)	123.0 (10.0)	104 (10)	87 (11)	64.3 (5.8)	–	–	–
^{172}Hf	c	1.87 yr	–	2.28 (0.20)	39.7 (3.7)	122 (11)	88.9 (7.1)	78.0 (7.7)	64.5 (7.9)	44.2 (4.1)	35.4 (3.7)	28.7 (3.8)	21.0 (2.1)
^{171}Hf	c	12.1 h	–	–	7 (12)	109 (12)	91.7 (8.1)	78.9 (9.9)	–	–	29.7 (5.1)	27.9 (3.2)	15.3 (4.0)
^{170}Hf	c	16.01 h	–	–	12.6 (1.9)	70.9 (6.6)	78.8 (6.5)	76.1 (7.4)	57.2 (7.4)	47.6 (4.9)	33.1 (3.3)	24.7 (2.4)	16.8 (1.8)

Table 3. (Contd.)

Nuclide	Type	$T_{1/2}$	Production cross section, mb										
			$E_p = 43$ MeV	66 MeV	97 MeV	148 MeV	248 MeV	399 MeV	599 MeV	799 MeV	1199 MeV	1598 MeV	2605 MeV
^{168}Hf	c	25.95 min	–	–	–	20.7	50.9	54.6	48.2	28.6	18.6	17.2	9.8
						(5.8)	(4.5)	(5.5)	(6.0)	(2.7)	(1.9)	(2.1)	(1.5)
^{173}Lu	c	1.37 yr	–	18.7	204	152	104.9	95.0	82	56.0	46.2	39.3	27.4
				(1.7)	(20)	(14)	(9.0)	(9.8)	(10)	(5.3)	(4.3)	(4.1)	(2.7)
^{172}Lu	i	6.70 day	–	0.063	3.49	4.68	7.66	12.1	13.5	10.40	9.43	8.43	6.36
				(0.006)	(0.33)	(0.42)	(0.63)	(1.2)	(1.7)	(1.00)	(0.83)	(0.79)	(0.60)
^{172}Lu	c	6.70 day	–	2.35	42.9	126	96.1	89.3	78.3	55.5	45.0	38.7	27.1
				(0.22)	(4.0)	(11)	(7.9)	(8.9)	(9.7)	(5.0)	(4.6)	(4.8)	(2.7)
^{171}Lu	i$(m+g)$	8.24 day	–	–	22	13.3	14.6	23.0	–	–	18.1	11.5	12.8
					(13)	(8.0)	(3.3)	(6.8)			(4.9)	(2.3)	(4.2)
^{171}Lu	c	8.24 day	–	–	28.8	122	111.0	106.0	–	–	50.1	40.4	29.9
					(2.7)	(11)	(9.0)	(10.0)			(4.4)	(3.7)	(2.8)
^{171}Lu	c*	8.24 day	–	–	–	–	–	–	93	63.8	–	–	–
									(11)	(5.6)			
^{170}Lu	i$(m+g)$	2.012 day	–	–	8.8	9.0	9.4	16.1	20.1	7.3	8.0	6.9	8.4
					(2.8)	(3.2)	(2.5)	(2.1)	(3.8)	(3.9)	(2.4)	(1.4)	(1.6)
^{170}Lu	c	2.012 day	–	–	20.4	79.7	88.3	92.0	78.5	53.4	43.0	32.9	25.1
					(2.1)	(7.1)	(7.1)	(9.0)	(9.7)	(4.9)	(3.9)	(3.1)	(2.4)
^{169}Lu	c	34.06 h	–	–	1.48	36.9	67.9	74.5	66.2	49.8	35.2	26.8	18.7
					(0.16)	(3.5)	(6.0)	(7.3)	(8.2)	(4.4)	(3.2)	(2.5)	(1.9)
^{167}Lu	c	51.5 min	–	–	–	21.7	55.0	81	78	49.0	35.0	24.9	16.8
						(2.6)	(6.1)	(10)	(11)	(5.7)	(4.1)	(3.0)	(2.1)
^{169}Yb	c*	32.026 day	–	–	–	48.2	88.7	103	95	60.2	48.7	39.7	24.1
						(4.4)	(7.2)	(10)	(12)	(6.0)	(4.4)	(3.6)	(2.3)
^{167}Yb	i	17.5 min	–	–	–	0.22	3.1	6.8	3.7	8.0	6.6	4.73	2.17
						(0.77)	(1.0)	(1.5)	(1.4)	(1.4)	(1.2)	(0.58)	(0.68)
^{167}Yb	c	17.5 min	–	–	–	22.0	57.9	89	83	57.1	41.7	29.5	19.0
						(2.6)	(6.5)	(11)	(12)	(6.7)	(4.9)	(3.5)	(2.3)
^{166}Yb	c	56.7 h	–	–	–	7.7	43.4	76.3	80	58.3	41.6	32.4	22.4
						(1.3)	(3.6)	(7.6)	(10)	(5.4)	(3.6)	(3.0)	(2.1)
^{162}Yb	c	18.87 min	–	–	–	–	9.5	45.9	62.3	40.7	27.2	16.7	10.9
							(1.0)	(5.3)	(8.2)	(4.9)	(2.8)	(6.7)	(2.7)
^{168}Tm	i	93.1 day	–	–	–	0.138	0.361	0.96	1.64	1.48	1.44	1.37	1.00
						(0.024)	(0.041)	(0.11)	(0.25)	(0.14)	(0.15)	(0.18)	(0.11)
^{167}Tm	c	9.25 day	–	–	–	19.1	59.0	90	91	63.0	47.0	38.1	22.8
						(2.7)	(8.0)	(13)	(15)	(8.9)	(6.6)	(5.5)	(3.3)
^{166}Tm	i	7.70 h	–	–	–	0.15	1.39	2.13	3.5	3.96	3.27	2.83	2.04
						(0.35)	(0.63)	(0.93)	(1.3)	(0.94)	(0.64)	(0.42)	(0.37)
^{166}Tm	c	7.70 h	–	–	–	7.8	45.4	81.2	86	63.1	46.0	36.7	24.8
						(1.1)	(3.8)	(8.1)	(11)	(5.7)	(4.1)	(3.4)	(2.4)
^{165}Tm	c	30.06 h	–	–	–	2.91	34.0	71.2	84	65.7	46.8	34.1	23.3
						(0.44)	(3.0)	(7.1)	(11)	(6.2)	(4.8)	(3.6)	(2.4)
^{163}Tm	c*	1.810 h	–	–	–	–	22.0	69.8	85	60.4	43.7	28.0	19.2
							(3.2)	(7.1)	(11)	(5.5)	(4.1)	(3.3)	(3.2)
^{162}Tm	i$(m+g)$	21.70 min	–	–	–	–	1.7	1.6	9.4	15.0	7.3	15.3	9.5
							(3.0)	(2.0)	(4.0)	(3.4)	(8.3)	(3.9)	(5.2)
^{162}Tm	c	21.70 min	–	–	–	–	9.6	50.3	74	54.8	37.1	25.1	12.7
							(2.1)	(6.1)	(10)	(6.1)	(7.8)	(6.8)	(4.8)
^{161}Tm	c	33 min	–	–	–	–	–	–	–	–	42.2	27.6	17.8
											(5.6)	(4.8)	(2.9)
^{161}Er	i	3.21 h	–	–	–	–	–	–	–	–	0.8	2.5	3.0
											(4.0)	(3.0)	(3.1)

Table 3. (Contd.)

Nuclide	Type	$T_{1/2}$	Production cross section, mb										
			$E_p = 43$ MeV	66 MeV	97 MeV	148 MeV	248 MeV	399 MeV	599 MeV	799 MeV	1199 MeV	1598 MeV	2605 MeV
^{161}Er	c	3.21 h	–	–	–	–	–	–	–	–	42.9 (4.6)	33.7 (3.7)	23.2 (2.6)
^{161}Er	c*	3.21 h	–	–	–	–	9.61 (0.97)	52.8 (6.1)	81 (11)	61.7 (7.3)	–	–	–
^{160}Er	c	28.58 h	–	–	–	–	5.32 (0.60)	39.1 (4.4)	68.5 (9.2)	61.8 (6.4)	44.4 (4.6)	36.7 (4.1)	23.8 (2.6)
^{159}Er	c*	36 min	–	–	–	–	3.56 (0.56)	35.0 (4.6)	67 (10)	56.3 (7.0)	44.3 (5.5)	34.5 (4.4)	21.7 (3.2)
^{157}Er	c*	18.65 min	–	–	–	–	–	23.6 (3.3)	50.4 (8.1)	44.9 (5.9)	33.6 (4.6)	31.8 (4.4)	18.7 (2.6)
^{156}Er	c	19.5 min	–	–	–	–	–	13.6 (1.4)	33.7 (4.8)	35.6 (3.3)	29.2 (2.9)	25.3 (2.6)	16.5 (1.8)
^{160m}Ho	i(m)	5.02 h	–	–	–	–	0.05 (0.26)	1.85 (0.54)	2.3 (1.1)	–	2.72 (0.56)	1.56 (0.68)	1.11 (0.24)
^{160m}Ho	c	5.02 h	–	–	–	–	5.53 (0.85)	42.9 (5.0)	71.8 (9.9)	–	46.7 (5.1)	37.3 (4.4)	24.5 (2.8)
^{160}Ho	i($m+g$)	25.6 min	–	–	–	–	–	4.1 (1.2)	6.8 (1.7)	6.8 (1.7)	4.5 (1.5)	2.68 (0.51)	3.86 (0.60)
^{156}Ho	i	56 min	–	–	–	–	–	0.64 (0.62)	6.0 (3.4)	4.26 (0.95)	6.6 (1.8)	2.8 (1.8)	0.20 (0.94)
^{156}Ho	c	56 min	–	–	–	–	–	13.9 (1.4)	40.6 (5.0)	40.3 (3.6)	35.8 (3.2)	28.9 (3.1)	16.9 (1.7)
^{157}Dy	c	8.14 h	–	–	–	–	1.25 (0.14)	21.6 (2.3)	52.7 (6.8)	53.8 (5.3)	43.7 (4.2)	34.8 (3.5)	21.2 (2.1)
^{155}Dy	c*	9.9 h	–	–	–	–	–	–	40.5 (5.0)	43.6 (4.0)	40.9 (3.7)	32.3 (3.1)	18.5 (1.8)
^{152}Dy	c	2.38 h	–	–	–	–	–	3.67 (0.37)	17.9 (2.2)	22.3 (1.9)	25.6 (2.2)	22.0 (2.0)	12.5 (1.2)
^{155}Tb	c*	5.32 day	–	–	–	–	–	10.9 (1.4)	40.3 (5.1)	42.8 (3.9)	40.1 (3.7)	28.3 (2.9)	15.6 (1.7)
^{153}Tb	c*	2.34 day	–	–	–	–	–	6.48 (0.92)	27.7 (3.7)	38.1 (3.6)	41.7 (7.8)	29.4 (3.1)	15.5 (1.6)
^{152}Tb	i($m+g$)	17.5 h	–	–	–	–	–	–	1.69 (0.92)	3.9 (2.3)	1.18 (0.94)	–	–
^{152}Tb	c	17.5 h	–	–	–	–	–	–	20.1 (2.8)	28.4 (3.1)	28.4 (3.0)	23.2 (4.1)	15.7 (1.8)
^{151}Tb	c	17.609 h	–	–	–	–	–	3.52 (0.36)	19.3 (2.5)	26.8 (2.5)	28.0 (2.5)	22.4 (2.2)	14.6 (1.5)
^{150}Tb	c	3.48 h	–	–	–	–	–	1.44 (0.26)	8.8 (1.4)	13.7 (1.8)	15.2 (2.0)	11.7 (1.6)	6.82 (0.96)
^{149}Tb	c	4.118 h	–	–	–	–	–	1.47 (0.26)	6.09 (0.92)	9.86 (0.92)	11.3 (1.1)	8.82 (0.91)	5.14 (0.50)
^{148}Tb	c	60 min	–	–	–	–	–	2.01 (0.23)	8.2 (1.1)	11.5 (1.1)	14.1 (1.3)	11.6 (1.3)	7.54 (0.73)
^{153}Gd	c	240.4 day	–	–	–	–	–	4.77 (0.74)	24.8 (3.5)	32.9 (3.7)	34.8 (3.9)	24.3 (2.8)	14.1 (2.1)
^{151}Gd	c	124 day	–	–	–	–	–	3.90 (0.74)	17.4 (2.4)	23.0 (2.2)	24.9 (2.4)	20.5 (2.9)	12.7 (1.3)
^{149}Gd	c	9.28 day	–	–	–	–	–	2.83 (0.29)	19.0 (2.4)	27.5 (2.6)	35.2 (3.3)	30.7 (3.0)	17.3 (1.7)
^{147}Gd	c	38.06 h	–	–	–	–	–	1.44 (0.17)	12.2 (1.6)	23.5 (2.4)	31.3 (2.8)	27.7 (2.6)	16.0 (1.6)

Table 3. (Contd.)

Nuclide	Type	$T_{1/2}$	Production cross section, mb										
			$E_p = 43$ MeV	66 MeV	97 MeV	148 MeV	248 MeV	399 MeV	599 MeV	799 MeV	1199 MeV	1598 MeV	2605 MeV
^{146}Gd	c	48.27 day	–	–	–	–	–	1.29 (0.13)	11.6 (1.4)	20.9 (1.8)	30.2 (2.6)	28.4 (2.6)	15.9 (1.5)
^{145}Gd	c	23.0 min	–	–	–	–	–	–	6.0 (2.0)	9.8 (1.0)	17.0 (1.6)	15.4 (1.6)	10.1 (1.2)
^{149}Eu	i	93.1 day	–	–	–	–	–	–	1.37 (0.84)	6.3 (1.2)	1.7 (2.1)		–
^{149}Eu	c	93.1 day	–	–	–	–	–	–	20.3 (2.5)	30.9 (2.7)	37.9 (3.3)	28.2 (2.9)	–
^{149}Eu	c*	93.1 day	–	–	–	–	–	2.95 (0.32)	–	–	–	–	17.8 (1.7)
^{148}Eu	i	54.5 day	–	–	–	–	–	–	0.70 (0.11)	1.18 (0.11)	1.73 (0.16)	1.65 (0.17)	1.18 (0.13)
^{147}Eu	i	24.1 day	–	–	–	–	–	–	–	–	–	–	12.8 (4.3)
^{147}Eu	c	24.1 day	–	–	–	–	0.121 (0.015)	1.78 (0.23)	15.6 (2.1)	26.8 (2.6)	38.2 (3.5)	33.4 (3.1)	20.2 (2.0)
^{146}Eu	i	4.61 day	–	–	–	–	–	0.197 (0.022)	1.90 (0.43)	3.47 (0.50)	5.51 (0.73)	5.33 (0.80)	3.25 (0.47)
^{146}Eu	c	4.61 day	–	–	–	–	–	1.43 (0.14)	14.3 (2.0)	25.6 (2.4)	37.2 (3.4)	33.0 (3.0)	20.4 (2.0)
^{145}Eu	c	5.93 day	–	–	–	–	–	0.546 (0.074)	7.81 (0.99)	16.2 (1.5)	26.7 (2.5)	24.3 (2.3)	15.3 (1.5)
^{144}Pm	i*	363 day	–	–	–	–	–	–	0.169 (0.054)	0.314 (0.032)	0.588 (0.052)	0.560 (0.063)	–
^{143}Pm	c	265 day	–	–	–	–	–	–	5.16 (0.71)	12.1 (1.3)	24.3 (2.6)	25.2 (2.8)	16.4 (1.8)
^{140m}Pm	i(m)	5.95 min	–	–	–	–	–	–	–	–	8.4 (1.1)	7.2 (1.3)	7.3 (1.4)
^{139m}Nd	i(m)	5.5 h	–	–	–	–	–	–	–	–	2.96 (0.50)	3.62 (0.64)	2.59 (0.45)
^{136}Nd	c	50.65 min	–	–	–	–	–	–	2.94 (0.42)	4.67 (0.51)	12.7 (1.5)	17.3 (1.8)	13.5 (1.3)
^{138m}Pr	i(m)	2.12 h	–	–	–	–	–	–	–	–	1.53 (0.16)	1.74 (0.19)	–
^{136}Pr	i	13.1 min	–	–	–	–	–	–	0.54 (0.19)	1.46 (0.22)	1.86 (0.59)	5.4 (1.2)	2.17 (0.35)
^{136}Pr	c	13.1 min	–	–	–	–	–	–	3.54 (0.50)	6.13 (0.67)	14.4 (1.5)	22.1 (2.8)	15.4 (1.6)
^{134}Pr	c*	17 min	–	–	–	–	–	–	–	2.39 (0.25)	10.34 (0.90)	13.8 (1.3)	12.0 (1.1)
^{139}Ce	c	137.640 day	–	–	–	–	–	0.083 (0.013)	2.16 (0.26)	7.50 (0.66)	20.8 (1.8)	25.3 (2.3)	15.6 (1.4)
^{135}Ce	c	17.7 h	–	–	–	–	–	–	–	–	15.5 (1.4)	20.5 (2.1)	15.5 (1.5)
^{134}Ce	c	3.16 day	–	–	–	–	–	–	–	–	12.6 (1.2)	16.8 (2.2)	11.8 (1.2)
^{133m}Ce	i(m)	4.9 h	–	–	–	–	–	–	–	–	2.85 (0.28)	4.59 (0.61)	3.54 (0.36)
^{132}Ce	c	3.51 h	–	–	–	–	–	–	–	1.28 (0.16)	9.53 (0.92)	15.3 (1.6)	14.9 (1.6)
^{130}Ce	c	25 min	–	–	–	–	–	–	–	–	5.07 (0.54)	8.44 (0.87)	7.51 (0.75)

Table 3. (Contd.)

Nuclide	Type	$T_{1/2}$	Production cross section, mb										
			$E_p = 43$ MeV	66 MeV	97 MeV	148 MeV	248 MeV	399 MeV	599 MeV	799 MeV	1199 MeV	1598 MeV	2605 MeV
^{132}La	i($m+g$)	4.8 h	–	–	–	–	–	–	–	0.359 (0.094)	0.29 (0.21)	0.28 (0.49)	0.41 (0.54)
^{132}La	c	4.8 h	–	–	–	–	–	–	–	1.64 (0.20)	10.0 (1.0)	15.7 (1.7)	15.3 (1.6)
^{130}La	i	8.7 min	–	–	–	–	–	–	–	–	2.39 (0.52)	4.45 (0.92)	4.8 (1.4)
^{130}La	c	8.7 min	–	–	–	–	–	–	–	–	7.54 (0.84)	12.6 (1.4)	12.3 (1.9)
^{133}Ba	c	3848.9 day	–	–	–	–	–	–	–	2.35 (0.33)	11.4 (1.0)	19.7 (1.8)	13.5 (1.3)
^{131}Ba	c	11.50 day	–	–	–	–	–	–	0.63 (0.14)	2.03 (0.19)	10.60 (0.90)	16.8 (1.5)	13.8 (1.3)
^{128}Ba	c	2.43 day	–	–	–	–	–	–	–	–	7.71 (0.77)	14.5 (1.6)	12.8 (1.4)
^{126}Ba	c	100 min	–	–	–	–	–	–	–	–	2.58 (0.44)	5.22 (0.90)	6.09 (0.83)
^{129}Cs	c	32.06 h	–	–	–	–	–	–	–	–	11.4 (1.5)	18.8 (1.9)	17.2 (1.7)
^{127}Cs	c	6.25 h	–	–	–	–	–	–	–	–	7.60 (0.73)	13.2 (1.3)	13.0 (1.2)
^{127}Xe	c	36.4 day	–	–	–	–	–	–	–	1.13 (0.11)	7.25 (0.63)	13.5 (1.2)	11.6 (1.2)
^{123}Xe	c	2.08 h	–	–	–	–	–	–	–	–	6.00 (0.56)	11.3 (1.1)	11.9 (1.2)
^{122}Xe	c	20.1 h	–	–	–	–	–	–	–	–	–	–	9.14 (0.93)
^{121m}Te	i(m)	154 day	–	–	–	–	–	–	0.098 (0.012)	0.178 (0.076)	0.235 (0.021)	0.64 (0.11)	0.493 (0.051)
^{121}Te	i($m+g$)	19.16 day	–	–	–	–	–	–	0.146 (0.018)	0.453 (0.043)	3.20 (0.29)	7.78 (0.74)	10.20 (1.00)
^{121}Te	c	19.16 day	–	–	–	–	–	–	0.233 (0.029)	0.675 (0.064)	3.45 (0.32)	8.35 (0.80)	10.70 (1.00)
^{119m}Te	i(m)	4.70 day	–	–	–	–	–	–	–	–	0.570 (0.055)	1.28 (0.12)	1.86 (0.18)
^{119}Te	c	16.05 h	–	–	–	–	–	–	–	–	2.78 (0.28)	6.09 (0.64)	9.51 (0.90)
^{117}Te	c	62 min	–	–	–	–	–	–	–	–	1.34 (0.18)	5.01 (0.57)	9.03 (0.87)
^{114}Te	c	15.2 min	–	–	–	–	–	–	–	–	–	1.32 (0.17)	2.82 (0.37)
^{120m}Sb	i(m)	5.76 day	–	–	–	–	–	–	–	–	–	0.098 (0.010)	0.139 (0.014)
^{118m}Sb	i(m)	5.00 h	–	–	–	–	–	–	–	–	0.274 (0.035)	0.665 (0.072)	0.832 (0.099)
^{115}Sb	c*	32.1 min	–	–	–	–	–	–	–	–	0.49 (0.56)	3.84 (0.39)	5.09 (0.89)
^{113}Sn	i($m+g$)	115.09 day	–	–	–	–	–	–	–	–	–	–	6.41 (0.59)
^{111}In	c	2.8047 day	–	–	–	–	–	–	–	–	1.23 (0.11)	3.50 (0.33)	6.03 (0.64)
^{110}In	i	4.9 h	–	–	–	–	–	–	–	–	1.04 (0.22)	2.77 (0.26)	3.24 (0.62)

Table 3. (Contd.)

Nuclide	Type	$T_{1/2}$	Production cross section, mb										
			$E_p = 43$ MeV	66 MeV	97 MeV	148 MeV	248 MeV	399 MeV	599 MeV	799 MeV	1199 MeV	1598 MeV	2605 MeV
^{109}In	c	4.2 h	–	–	–	–	–	–	–	–	–	1.70 (0.17)	3.84 (0.41)
^{108m}In	i(m)	58.0 min	–	–	–	–	–	–	–	–	–	1.26 (0.19)	2.31 (0.36)
^{108}In	c*	39.6 min	–	–	–	–	–	–	–	–	–	–	4.55 (0.57)
^{110m}Ag	i(m)	249.76 day	–	–	–	–	–	–	–	–	–	0.068 (0.009)	0.130 (0.013)
^{106m}Ag	i(m)	8.28 day	–	–	–	–	–	–	–	–	0.336 (0.032)	0.724 (0.073)	1.57 (0.15)
^{105}Ag	c	41.29 day	–	–	–	–	–	–	–	–	0.805 (0.099)	2.27 (0.25)	4.60 (0.43)
^{100}Pd	c	3.63 day	–	–	–	–	–	–	–	–	–	0.507 (0.053)	1.52 (0.16)
^{102}Rh	i($m+g$)	207 day	–	–	–	–	–	–	–	–	–	–	0.512 (0.079)
^{100}Rh	i($m+g$)	20.8 h	–	–	–	–	–	–	–	–	–	0.816 (0.098)	2.49 (0.31)
^{100}Rh	c	20.8 h	–	–	–	–	–	–	–	–	–	1.32 (0.14)	3.92 (0.43)
^{99m}Rh	c	4.7 h	–	–	–	–	–	–	–	–	0.446 (0.069)	0.78 (0.10)	2.11 (0.25)
^{103}Ru	c	39.26 day	–	–	–	–	–	–	–	–	–	–	0.136 (0.024)
^{97}Ru	c	2.791 day	–	–	–	–	–	–	–	–	–	–	3.02 (0.28)
^{96}Tc	i($m+g$)	4.28 day	–	–	–	–	–	0.145 (0.020)	0.188 (0.025)	0.228 (0.022)	0.445 (0.059)	0.746 (0.093)	1.63 (0.16)
^{93m}Mo	i(m)	6.85 h	–	–	–	–	–	–	–	–	–	0.449 (0.097)	1.42 (0.17)
^{90}Nb	c*	14.60 h	–	–	–	–	–	–	0.209 (0.033)	0.369 (0.073)	0.655 (0.080)	1.08 (0.11)	2.74 (0.25)
^{89}Zr	c	78.41 h	–	–	–	–	0.086 (0.012)	0.190 (0.020)	0.293 (0.043)	0.426 (0.038)	0.850 (0.076)	1.53 (0.14)	3.17 (0.29)
^{88}Zr	c	83.4 day	–	–	–	–	–	0.071 (0.008)	0.208 (0.025)	0.273 (0.024)	0.514 (0.044)	0.976 (0.087)	2.26 (0.21)
^{88}Y	i	106.65 day	–	–	–	–	–	–	0.334 (0.072)	0.468 (0.042)	0.62 (0.11)	0.89 (0.13)	1.34 (0.13)
^{88}Y	c	106.65 day	–	–	–	–	–	–	0.62 (0.15)	0.560 (0.051)	1.13 (0.10)	1.83 (0.17)	3.87 (0.36)
^{87m}Y	c*	13.37 h	–	–	–	–	–	–	–	–	–	–	1.18 (0.40)
^{87}Y	i	79.8 h	–	–	–	–	–	–	–	–	–	–	2.19 (0.49)
^{87}Y	c	79.8 h	–	–	–	–	–	–	–	–	–	–	3.34 (0.32)
^{87}Y	c	79.8 h	–	–	0.026 (0.004)	–	–	0.234 (0.028)	0.479 (0.060)	0.550 (0.066)	1.09 (0.15)	1.77 (0.18)	–
^{86}Y	c	14.74 h	–	–	–	–	–	–	–	–	0.98 (0.57)	1.43 (0.40)	2.64 (0.36)
^{85}Sr	c	64.84 day	–	–	–	–	–	–	–	–	–	–	3.07 (0.31)

Table 3. (Contd.)

Nuclide	Type	$T_{1/2}$	Production cross section, mb										
			$E_p = 43$ MeV	66 MeV	97 MeV	148 MeV	248 MeV	399 MeV	599 MeV	799 MeV	1199 MeV	1598 MeV	2605 MeV
^{83}Sr	c	32.41 h	–	–	–	–	–	–	–	–	–	–	1.61 (0.77)
^{84}Rb	i$(m+g)$	32.77 day	–	–	–	0.119 (0.014)	0.126 (0.011)	0.241 (0.025)	0.376 (0.048)	0.389 (0.036)	0.531 (0.048)	0.680 (0.064)	0.929 (0.088)
^{83}Rb	c	86.2 day	–	–	–	–	–	0.249 (0.036)	0.350 (0.057)	0.678 (0.085)	1.15 (0.15)	1.81 (0.24)	3.05 (0.33)
^{82m}Rb	i(m)	6.472 h	–	–	–	–	–	–	–	–	–	–	1.15 (0.15)
^{77}Br	c	57.036 h	–	–	–	–	–	–	–	–	–	–	2.39 (0.23)
^{75}Se	c	119.779 day	–	–	–	–	–	–	–	–	0.799 (0.082)	1.16 (0.12)	1.82 (0.18)
^{74}As	i	17.77 day	–	–	–	–	0.056 (0.008)	0.170 (0.025)	0.345 (0.050)	0.408 (0.047)	0.619 (0.068)	0.569 (0.066)	1.08 (0.12)
^{69m}Zn	i(m)	13.76 h	–	–	–	–	–	–	–	–	0.191 (0.024)	–	–
^{65}Zn	c	244.26 day	–	–	–	–	–	–	–	–	0.351 (0.037)	0.646 (0.090)	1.57 (0.14)
^{60}Co	i$(m+g)$	5.2714 yr	–	–	–	–	–	–	–	–	0.78 (0.14)	1.12 (0.13)	1.24 (0.12)
^{58}Co	i$(m+g)$	70.86 day	–	–	–	–	–	–	–	–	–	–	1.23 (0.12)
^{56}Co	c	77.233 day	–	–	–	–	–	–	–	–	–	–	0.116 (0.016)
^{59}Fe	c	44.472 day	–	–	–	–	–	0.143 (0.018)	0.235 (0.031)	0.234 (0.039)	0.364 (0.040)	0.540 (0.064)	0.764 (0.077)
^{54}Mn	i	312.11 day	–	–	–	–	–	0.099 (0.024)	0.145 (0.025)	0.270 (0.031)	0.542 (0.050)	0.879 (0.083)	1.59 (0.15)
^{52}Mn	c	5.591 day	–	–	–	–	–	–	–	–	–	–	0.271 (0.025)
^{48}V	c	15.9735 day	–	–	–	–	–	–	–	–	0.100 (0.013)	0.223 (0.022)	0.475 (0.045)
^{48}Sc	i	43.67 h	–	–	–	–	–	–	–	–	0.315 (0.083)	0.461 (0.048)	0.558 (0.068)
^{46}Sc	i$(m+g)$	83.79 day	–	–	–	–	–	–	0.201 (0.034)	0.419 (0.040)	0.377 (0.035)	0.703 (0.066)	1.60 (0.15)
^{44m}Sc	i(m)	58.61 h	–	–	–	–	–	–	–	–	–	–	0.458 (0.043)
^{28}Mg	c	20.915 h	–	–	–	–	–	–	–	–	0.164 (0.026)	0.355 (0.035)	0.814 (0.077)
^{24}Na	c	14.9590 h	–	–	–	–	–	–	–	–	1.34 (0.12)	2.03 (0.19)	4.17 (0.38)
^{22}Na	c	2.6019 yr	–	–	–	–	–	–	–	–	–	–	0.623 (0.062)
^{7}Be	i	53.29 day	0.031 (0.007)	0.161 (0.042)*	0.259 (0.036)	0.284 (0.053)	0.240 (0.037)	0.575 (0.070)	1.05 (0.27)	1.51 (0.16)	2.55 (0.22)	3.95 (0.36)	6.70 (0.63)

* At an energy of 68 MeV.

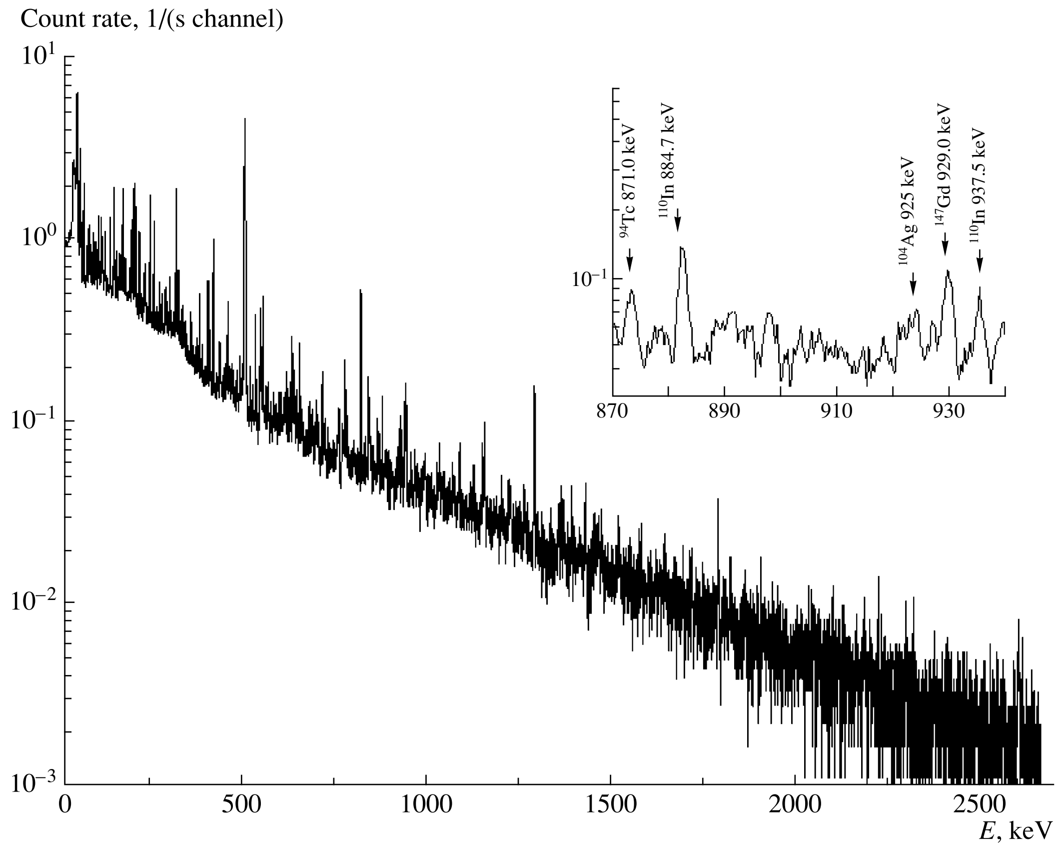

Fig. 2. Example of the γ spectrum of ^{181}Ta no. 5 for $E_p = 2.6$ GeV; the measurement duration was 1800 s.

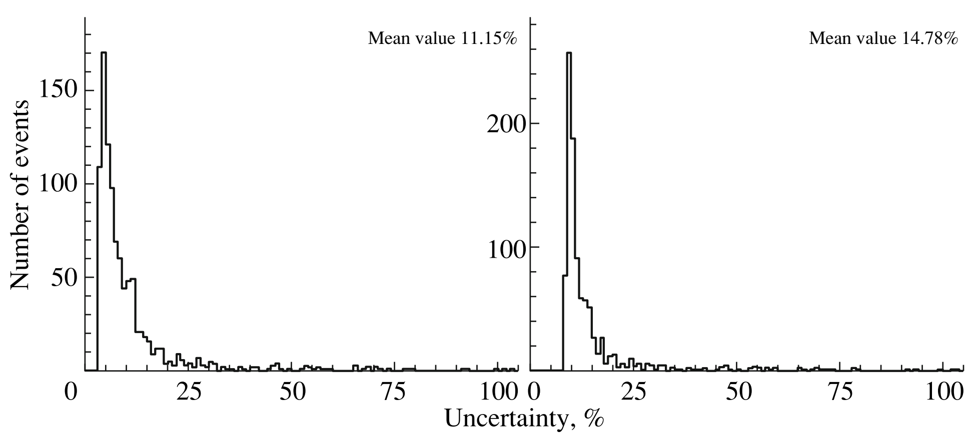

Fig. 3. Distribution of the uncertainties in reaction rates and cross sections for ^{nat}W.

RESULTS AND THEORETICAL PREDICTIONS

The cross sections for the production of radioactive nuclei in the $^{nat}W(p,x)$ and $^{181}Ta(p,x)$ reactions induced by 0.04–2.6-GeV protons are presented in Tables 2 and 3. The numbers of the measured cross sections $\sigma^{ind}(i)$ and $\sigma^{cum}(c)$ for ^{nat}W and ^{181}Ta targets are 1013 ($i = 187, i(m+g) = 76, i(m_1+m_2+g) = 11, i(m) = 82$, and $c + c^* = 657$) and 882 ($i = 165, i(m+g) = 65, i(m) = 71$, and $c + c^* = 581$), respectively. Using these data, we obtained 192 and 173 excitation functions for ^{nat}W and ^{181}Ta, respectively; among them, 99 and 76, respectively, were measured for the first time.

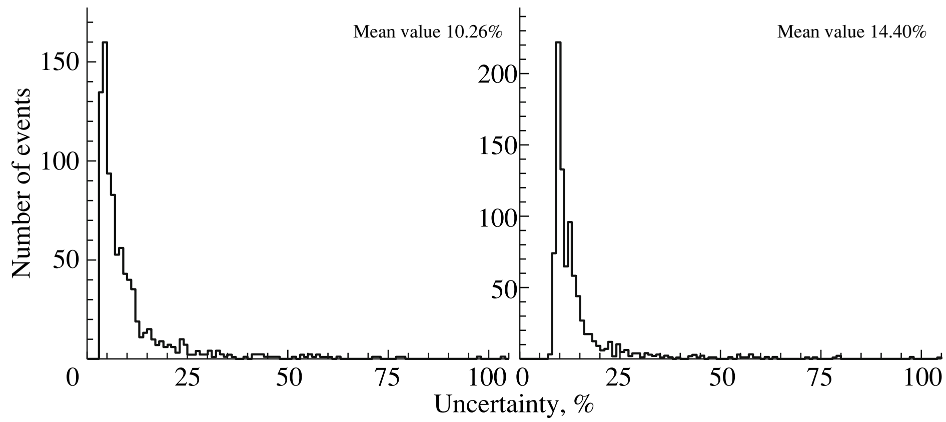

Fig. 4. As in Fig. 3, but for ^{181}Ta.

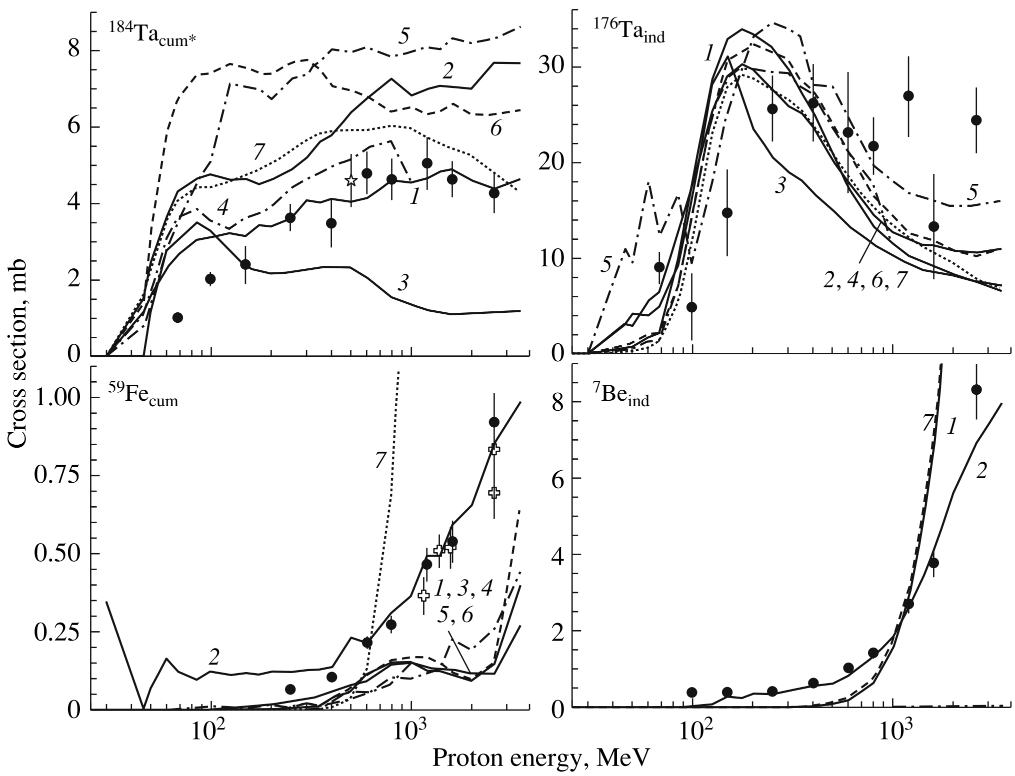

Fig. 5. Calculated and experimental cross sections for the ^{nat}W(p, x) reactions. The experimental data are taken from (●) this work, (☆) [14], and (✣) [15]. Lines *1*, *2*, *3*, *4*, *5*, *6*, and *7* represent the BERTINI, INCL4.5, CEM03.02, ISABEL, INCL4.2, PHITS, and CASCADE07 calculations, respectively.

The average accuracy of the cross sections for the observed reaction products for ^{nat}W and ^{181}Ta is 14.8 and 14.4%, respectively. The distributions of the uncertainties in the reaction rates and cross sections are presented in Figs. 3 and 4.

The resulting excitation functions were compared with the respective functions calculated by means of the BERTINI, ISABEL, CEM03.02, INCL4.2, INCL4.5, CASCADE07, and PHITS models [5–11].

The formulas for a convolution of the calculated independent yields into the cumulative ones were given in [12, 13]. Examples of the calculated and experimental excitation functions are shown in Figs. 5 and 6.

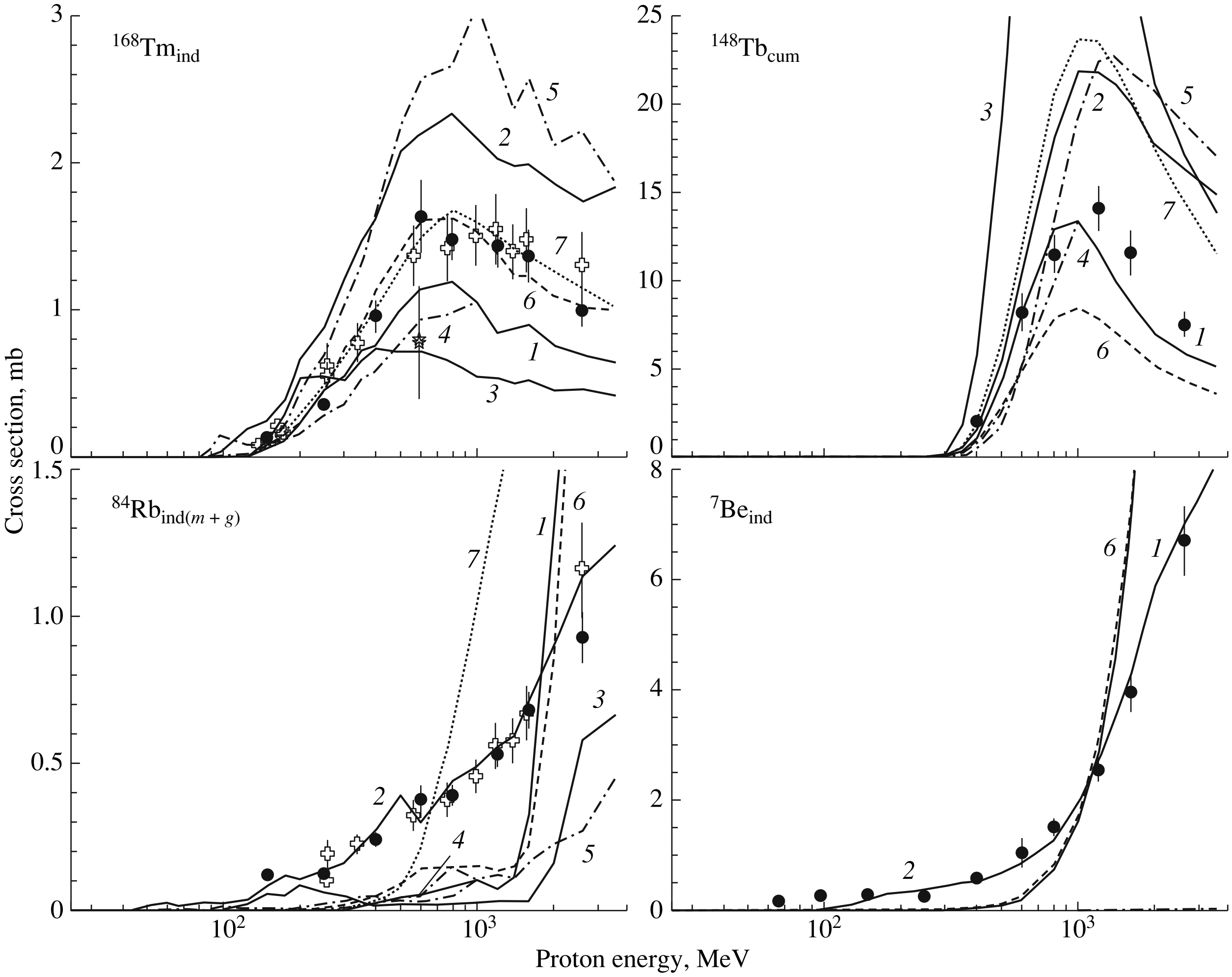

Fig. 6. As in Fig. 5, but for ^{181}Ta(p, x) reactions. The experimental data are taken from (●) this work, (☆) [16], and (✧) [17, 18]. The lines mean the same as in Fig. 5.

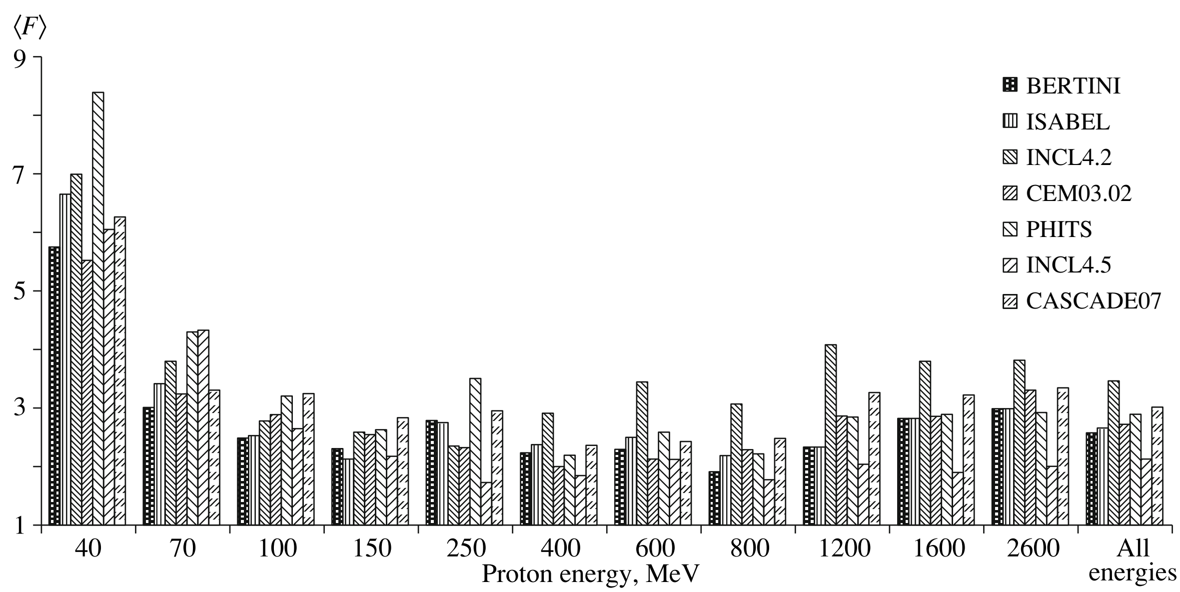

Fig. 7. Deviation coefficients $\langle F \rangle$ for ^{nat}W characterizing the predictive powers of the codes.

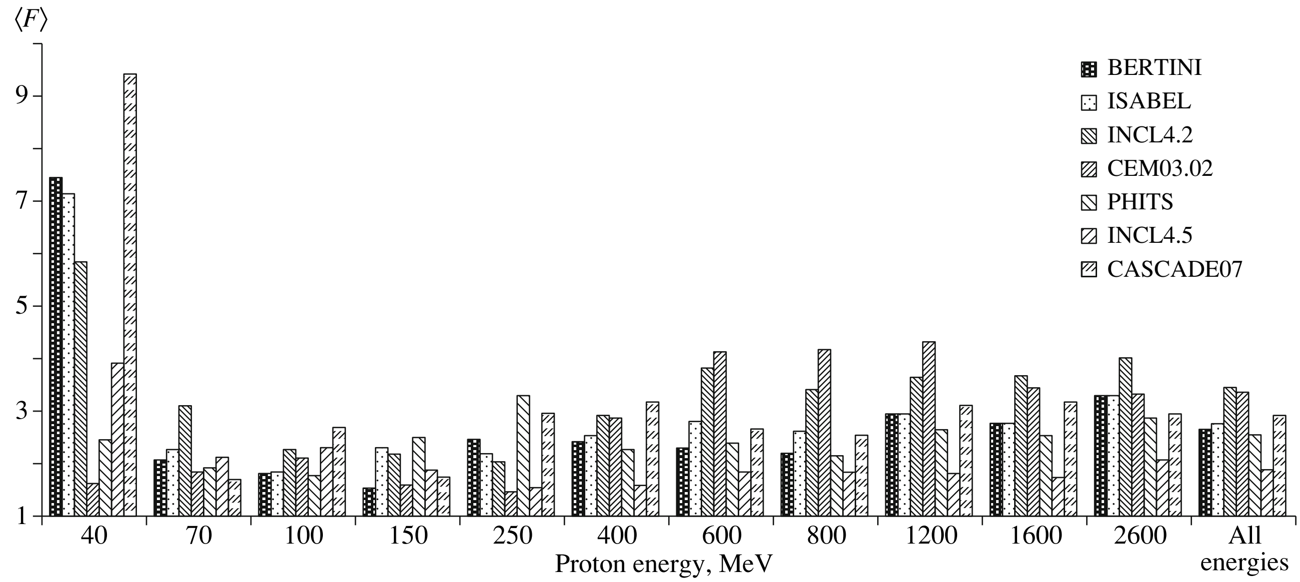

Fig. 8. As in Fig. 7, but for ^{181}Ta.

The predictive powers of the codes can be estimated in terms of the deviation coefficients $\langle F\rangle$ defined as [2–4, 12, 19]

$$F = 10^{\sqrt{\left\langle\left(\log\frac{\sigma_{\rm exp}}{\sigma_{\rm calc}}\right)^2\right\rangle}}, \qquad (1)$$

where $\sigma_{\rm exp}$ are the experimental independent or cumulative cross sections and $\sigma_{\rm calc}$ are the calculated cross sections obtained on the basis of various models.

Table 4. Deviation coefficients F for each energy and the corresponding targets of ^{nat}W and ^{181}Ta

Model	Sample	Proton energy, MeV										
		40	70	100	150	250	400	600	800	1200	1600	2600
BERTINI	W	5.75	3.02	2.49	2.26	2.78	2.30	2.28	1.94	2.34	2.82	2.96
	Ta	7.43	2.07	1.83	1.54	2.40	2.40	2.29	2.14	2.94	2.74	3.22
ISABEL	W	6.66	3.42	2.53	2.11	2.76	2.47	2.51	2.20	2.34	2.82	2.96
	Ta	7.14	2.24	1.88	2.29	2.16	2.54	2.79	2.56	2.94	2.74	3.22
CEM03.02	W	5.52	3.22	2.88	2.50	2.32	1.99	2.13	2.29	2.87	2.86	3.31
	Ta	1.61	1.85	2.21	1.59	1.42	2.86	4.17	4.19	4.30	3.43	3.33
INCL4.2	W	6.99	3.80	2.78	2.57	2.36	2.93	3.46	3.06	4.09	3.78	3.80
	Ta	5.83	3.09	2.31	2.17	2.02	2.90	3.84	3.35	3.65	3.68	3.94
INCL4.5	W	6.05	4.34	2.66	2.14	1.73	1.84	2.11	1.76	2.03	1.89	2.01
	Ta	3.89	2.09	2.33	1.81	1.48	1.59	1.85	1.75	1.80	1.73	2.01
PHITS	W	8.41	4.30	3.19	2.61	3.52	2.23	2.58	2.20	2.84	2.88	2.90
	Ta	2.44	1.91	1.83	2.49	3.25	2.27	2.37	2.08	2.64	2.51	2.81
CASCADE07	W	6.26	3.30	3.24	2.80	2.97	2.45	2.42	2.48	3.25	3.20	3.34
	Ta	9.43	1.70	2.79	1.75	2.94	3.16	2.65	2.42	3.11	3.17	2.96

The estimated predictive powers of the codes are summarized in Table 4 and in Figs. 7 and 8.

CONCLUSIONS

The deviation coefficients $\langle F \rangle$ considered here range from 1.5 to 9.4 for various models. These values correspond to the deviation of the calculations from the experimental data from 50 to 800%. Such deviations exceed significantly a required accuracy of 30% even for the most accurate code. The discrepancies are particularly large at low energies.

Thus, all intranuclear cascade codes should be further developed. The experimental data obtained in this work can be used both to improve theoretical models and to refine the design of electronuclear facilities and spallation neutron sources.

ACKNOWLEDGMENTS

This work was supported by the International Science and Technology Center, project no. 3266, and by the State Nuclear Energy Corporation Rosatom.

REFERENCES

1. Experimental Nuclear Reaction Data (EXFOR) database; http://www-nds.iaea.org/exfor/exfor.htm
2. Yu. E. Titarenko, S. P. Borovlev, M. A. Butko, et al., Yad. Fiz. **74**, 531 (2011) [Phys. Atom. Nucl. **74**, 507 (2011)].
3. Yu. E. Titarenko, V. F. Batyaev, A. Yu. Titarenko, et al., Yad. Fiz. **74**, 548 (2011) [Phys. Atom. Nucl. **74**, 523 (2011)].
4. Yu. E. Titarenko, V. F. Batyaev, A. Yu. Titarenko, et al., Yad. Fiz. **74**, 561 (2011) [Phys. Atom. Nucl. **74**, 537 (2011)].
5. J. C. Hendricks et al., Report LA-UR-05-2675, LANL (2005); http://mcnp.lanl..gov/
6. S. G. Mashnik and A. J. Sierk, J. Nucl. Sci. Technol. Suppl. **2**, 720 (2002).
7. A. Boudard, J. Cugnon, S. Leray, and C. Volant, Phys. Rev. C **66**, 044615 (2002).
8. J. Cugnon, A. Boudard, S. Leray, et al., ISBN 978-92-0-150410-4, SM/SR-02 (2010).
9. A. R. Junghans et al., Nucl. Phys. A **629**, 635 (1998).
10. H. Iwase et al., J. Nucl. Sci. Technol. **39**, 1142 (2002); http://phits.jaea.go.jp/OvPhysicalModelsJQMD.html
11. H. Kumawat et al., Nucl. Instrum. Methods Phys. Res. B **266**, 604 (2008).
12. Yu. E. Titarenko, V. F. Batyaev, V. M. Zhivun, et al., INDC(CCP)-0447, IAEA (Oct. 2009); http://www-nds.iaea.org/reports-new/indc-reports/indc-ccp/
13. Yu. E. Titarenko, V. F. Batyaev, A. Yu. Titarenko, et al., Phys. Rev. C **78**, 034615 (2008).
14. http://www-nds.iaea.org/exfor/exfor.htm; #O0296086.
15. http://www-nds.iaea.org/exfor/exfor.htm; #O1099007.
16. http://www-nds.iaea.org/exfor/exfor.htm; #O0512004.
17. http://www-nds.iaea.org/exfor/exfor.htm; #O1099130.
18. http://www-nds.iaea.org/exfor/exfor.htm; #O1099077.
19. Yu. E. Titarenko, V. F. Batyaev, E. I. Karpikhin, et al., http://www-nds.iaea.org/reports/indc-ccp-434.pdf

Translated by R. Tyapaev