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Measurement and Simulation of the Cross Sections for Nuclide Production in ^{93}Nb and $^{\mathrm{nat}}$Ni Targets Irradiated with 0.04- to 2.6-GeV Protons

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Abstract—The cross sections for nuclide production in thin ^{93}Nb and $^{\mathrm{nat}}$Ni targets irradiated by 0.04- to 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, 1112 yields of radioactive residual 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.

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INTRODUCTION

The aims of this work are to experimentally determine and simulate the independent and cumulative yields of radioactive residual nuclei that are produced in structural materials (^{93}Nb, $^{\mathrm{nat}}$Ni), used in electronuclear facilities and spallation neutron sources based on a high-current proton accelerator. Interest in these materials is stimulated by the possibility of their use both in accelerator (superconducting magnets) and in reactor (capability to increase the high-temperature strength and heat resistance of steels) technologies.

Alloys based on Zr with addition of Nb (N-1.1 and N-2.5 alloys containing 1 and 2.5% Nb) are widely used in the nuclear industry as structural elements of nuclear reactor cores [1].

Traditional type-II superconductors (Nb—Ti and Nb$_3$Sn alloys) are used in superconducting magnetic systems as composites in the matrix of normal metals to increase their heat and electrical conductivities. Stainless steels and alloys based on Ni and Cr are used as shells of absorbing elements, spring elements of fuel assemblies, and sometimes for spacing lattices of fuel assemblies.

It is expected that the application of these materials in future electronuclear facilities and spallation neutron sources will be quite wide.

At present, EXFOR contains 23 original works with the data on Nb and 84 works with the data on Ni, in which cumulative and independent cross sections for nuclide production in proton-induced reactions samples are presented [2].

IRRADIATION AND MEASUREMENTS

Thin ^{93}Nb and $^{\mathrm{nat}}$Ni samples in assembly with Al monitors were irradiated by an extracted proton beam

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Table 1. Characteristics of the ^{nat}Ni and ^{93}Nb samples and conditions of their irradiation

^{nat}Ni					^{93}Nb				
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	205.9	58.9	27	6.45 ± 0.56	2605 ± 8	189.2	59.2	27.42	6.96 ± 0.61
1598 ± 4	205.4	59.3	29.25	5.30 ± 0.44	1599 ± 4	189.5	59.0	31.37	6.00 ± 0.50
1199 ± 3	205.4	59.0	55	3.39 ± 0.27	1199 ± 3	190.1	59.0	55	3.66 ± 0.29
799 ± 2	205.4	58.9	30	3.06 ± 0.26	799 ± 2	189.3	59.0	30	3.09 ± 0.27
599 ± 2	206.7	58.8	24	7.19 ± 0.68	600 ± 2	189.5	58.4	24	8.17 ± 0.75
399 ± 2	206.8	58.2	22	4.01 ± 0.38	400 ± 2	189.9	58.3	22	4.26 ± 0.40
249 ± 1	206.5	49.1	22	7.10 ± 0.55	249 ± 1	189	49.0	22	7.58 ± 0.57
148 ± 1	206.6	24.7	24	5.31 ± 0.45	149 ± 1	190.9	48.0	24	5.67 ± 0.45
97 ± 1	203.5	48.5	33.5	4.36 ± 0.32	99 ± 1	189.7	49.7	33.5	4.67 ± 0.35
66 ± 1	205.6	49.8	67.5	1.85 ± 0.14	68 ± 1	186.9	48.3	67.5	1.97 ± 0.15
43 ± 1	205.7	48.0	25	4.43 ± 0.32	46 ± 1	189.4	48.3	25	4.86 ± 0.34

of the ITEP U-10 synchrotron [3, 4]. The samples were manufactured by cutting from a metallic foil. The total levels of chemical impurities in Ni, Nb, and Al samples were no more than 0.013, 0.026, and 0.05%, respectively.

The proton fluence is determined using the ${}^{27}\mathrm{Al}(p,x){}^{22}\mathrm{Na}$ monitor reaction whose excitation function is well known [3]. The characteristics of the ^{nat}Ni and ^{93}Nb samples and the conditions of irradiation 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 preliminarily calibrated HPGe detectors [3].

Table 2. Experimental cross sections for radioactive-nuclide production in the $^{\rm nat}$Ni(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	249 MeV	399 MeV	599 MeV	799 MeV	1199 MeV	1599 MeV	2605 MeV
^{61}Cu	i	3.333 h	1.92 (0.24)	0.91 (0.15)	0.486 (0.082)	0.338 (0.060)	0.251 (0.047)	–	–	–	–	–	–
^{60}Cu	i	23.7 min	5.25 (0.42)	2.24 (0.19)	1.45 (0.13)	0.814 (0.079)	0.474 (0.042)	0.340 (0.036)	0.309 (0.041)	0.252 (0.031)	0.296 (0.032)	0.211 (0.025)	0.197 (0.033)
^{57}Ni	c	35.60 h	91.4 (9.4)	72.0 (8.5)	57.8 (5.8)	47.3 (5.3)	32.3 (3.2)	32.1 (3.9)	29.9 (3.4)	25.0 (2.7)	26.5 (2.6)	21.2 (2.4)	19.0 (2.3)
^{56}Ni	c	6.075 day	11.70 (1.00)	7.21 (0.60)	5.98 (0.51)	4.62 (0.42)	3.16 (0.27)	2.85 (0.29)	2.57 (0.26)	2.14 (0.19)	2.10 (0.18)	1.64 (0.15)	1.44 (0.14)
^{62m}Co	i(m)	13.91 min	–	–	–	–	–	–	–	0.092 (0.015)	0.106 (0.023)	0.079 (0.019)	0.079 (0.027)
^{60}Co	i$(m+g)$	5.2714 yr	1.90 (0.20)	1.64 (0.21)	1.67 (0.20)	1.68 (0.18)	2.03 (0.23)	1.93 (0.34)	2.03 (0.26)	1.73 (0.19)	1.92 (0.22)	1.79 (0.17)	1.46 (0.14)
^{58}Co	i$(m+g)$	70.86 day	69.6 (6.4)	32.9 (2.8)	25.9 (2.5)	21.1 (2.0)	15.9 (1.5)	17.1 (1.7)	18.1 (1.9)	16.9 (1.5)	18.4 (1.7)	13.6 (1.3)	11.1 (1.2)
^{57}Co	i	271.74 day	89.7 (9.1)	58.0 (6.3)	65.1 (6.4)	43.5 (4.2)	38.6 (3.8)	37.9 (4.3)	46.0 (4.8)	43.2 (4.4)	50.7 (4.9)	34.8 (8.9)	35 (11)
^{57}Co	c	271.74 day	213 (17)	172 (14)	132 (11)	100.9 (9.0)	72.8 (6.1)	75.5 (7.6)	78.5 (7.8)	71.3 (6.4)	74.9 (6.4)	56.8 (5.1)	50.3 (4.6)
^{56}Co	i	77.233 day	208 (17)	93.9 (7.9)	76.9 (6.9)	57.8 (5.3)	40.8 (3.5)	38.8 (3.9)	37.5 (3.8)	32.3 (2.9)	32.0 (3.5)	25.7 (2.4)	21.9 (2.2)
^{56}Co	c	77.233 day	223 (18)	105.0 (8.0)	82.9 (7.0)	62.8 (5.7)	43.5 (3.6)	41.5 (4.2)	39.3 (3.9)	33.1 (3.0)	33.3 (2.8)	27.5 (2.5)	24.2 (2.2)
^{55}Co	c	17.53 h	11.80 (1.00)	34.3 (2.9)	26.9 (2.4)	20.5 (1.9)	15.3 (1.3)	13.9 (1.4)	13.4 (1.5)	10.4 (1.0)	10.41 (0.90)	8.59 (0.79)	7.47 (0.71)
^{59}Fe	c	44.472 day	0.082 (0.048)	0.155 (0.037)	0.183 (0.020)	0.210 (0.033)	0.267 (0.038)	0.309 (0.047)	0.374 (0.050)	0.342 (0.038)	0.372 (0.034)	0.298 (0.030)	0.252 (0.026)
^{53}Fe	c*	8.51 min	17.1 (1.8)	8.24 (0.96)	12.8 (1.4)	10.8 (1.4)	9.2 (1.0)	10.1 (1.3)	9.6 (1.3)	8.06 (0.98)	7.75 (0.98)	5.35 (0.66)	3.44 (0.42)
^{52}Fe	c	8.275 h	0.020 (0.004)	2.75 (0.24)	2.13 (0.19)	2.16 (0.21)	1.90 (0.17)	1.96 (0.20)	2.01 (0.27)	1.50 (0.14)	1.46 (0.13)	1.17 (0.21)	0.86 (0.11)
^{56}Mn	c	2.5789 h	0.025 (0.006)	0.249 (0.023)	0.570 (0.051)	0.615 (0.059)	0.606 (0.053)	0.776 (0.080)	0.924 (0.095)	0.856 (0.080)	0.901 (0.080)	0.748 (0.070)	0.601 (0.058)
^{54}Mn	i	312.11 day	–	22.3 (1.8)	23.6 (2.0)	21.2 (1.9)	17.1 (1.4)	18.7 (1.9)	18.8 (1.9)	16.1 (1.4)	15.8 (1.3)	12.4 (1.1)	10.39 (0.90)
^{52m}Mn	i(m)	21.1 min	0.321 (0.028)	11.16 (0.93)	10.0 (1.4)	10.4 (1.3)	9.47 (0.86)	10.4 (1.1)	10.0 (1.0)	8.80 (0.91)	7.94 (0.83)	6.68 (0.62)	5.19 (0.54)
^{52m}Mn	c	21.1 min	0.347 (0.030)	14.0 (1.3)	12.5 (1.4)	12.8 (1.5)	11.3 (1.0)	12.3 (1.3)	12.3 (1.3	10.27 (1.00)	9.60 (0.95)	8.08 (0.74)	6.31 (0.64)
^{52}Mn	c	5.591 day	0.631 (0.051)	20.9 (1.7)	18.2 (1.6)	19.5 (1.8)	16.8 (1.4)	18.4 (1.9)	18.2 (1.8)	15.3 (1.4)	14.6 (1.3)	11.3 (1.0)	9.11 (0.86)
^{51}Cr	c	27.7025 day	0.985 (0.097)	–	31.5 (2.7)	38.0 (3.5)	36.7 (3.1)	44.2 (4.4)	45.8 (4.5)	38.7 (3.5)	36.4 (3.1)	26.8 (2.4)	21.7 (2.0)
^{49}Cr	c	42.3 min	0.018 (0.013)	2.99 (0.29)	3.68 (0.34)	7.15 (0.74)	8.08 (0.75)	10.8 (1.2)	11.9 (1.3)	10.50 (1.00)	9.72 (0.92)	7.09 (0.91)	5.38 (0.73)
^{48}Cr	c	21.56 h	–	0.036 (0.004)	0.483 (0.042)	0.898 (0.083)	1.19 (0.10)	1.75 (0.18)	2.08 (0.21)	1.81 (0.17)	1.80 (0.16)	1.32 (0.12)	1.070 (0.100)
^{48}V	c	15.9735 day	–	0.592 (0.048)	4.69 (0.40)	10.7 (1.0)	14.7 (1.2)	22.3 (2.2)	26.4 (2.6)	23.5 (2.1)	22.5 (1.9)	18.0 (1.6)	14.3 (1.3)
^{48}Sc	i	43.67 h	–	–	–	–	0.055 (0.007)	0.114 (0.015)	0.221 (0.024)	0.183 (0.045)	0.281 (0.043)	0.241 (0.025)	0.238 (0.037)

Table 2. (Contd.)

Nuclide	Type	$T_{1/2}$	Production cross section, mb										
			$E_p = 43$ MeV	66 MeV	97 MeV	148 MeV	249 MeV	399 MeV	599 MeV	799 MeV	1199 MeV	1599 MeV	2605 MeV
^{47}Sc	c	3.3492 day	–	–	–	–	0.524 (0.045)	1.01 (0.10)	1.53 (0.15)	1.56 (0.14)	1.76 (0.15)	1.23 (0.11)	1.020 (0.090)
^{46}Sc	i$(m+g)$	83.79 day	–	–	0.091 (0.011)	0.771 (0.092)	1.82 (0.15)	3.99 (0.40)	5.74 (0.58)	5.82 (0.54)	6.10 (0.53)	4.95 (0.46)	4.00 (0.38)
^{44m}Sc	i(m)	58.61 h	–	–	0.219 (0.019)	0.868 (0.079)	2.25 (0.19)	5.28 (0.53)	8.33 (0.83)	8.56 (0.77)	9.43 (0.81)	7.08 (0.63)	5.65 (0.52)
^{44}Sc	i	3.97 h	–	–	0.295 (0.042)	1.040 (0.100)	2.49 (0.21)	5.54 (0.56)	8.65 (0.90)	8.73 (0.80)	9.23 (0.83)	8.01 (0.81)	6.5 (1.0)
^{44}Sc	i$(m+g)$	3.97 h	–	–	0.539 (0.058)	1.90 (0.19)	4.69 (0.39)	10.7 (1.1)	16.9 (1.7)	17.1 (1.5)	18.4 (1.6)	15.3 (1.4)	12.5 (1.1)
^{43}Sc	c	3.891 h	–	–	–	0.581 (0.058)	1.64 (0.15)	4.00 (0.42)	6.70 (0.70)	7.09 (0.68)	7.61 (0.69)	5.87 (0.56)	4.66 (0.45)
^{47}Ca	c	4.536 day	–	–	–	–	0.015 (0.004)	–	–	–	–	0.023 (0.005)	0.021 (0.005)
^{43}K	c	22.3 h	–	–	–	–	0.059 (0.005)	0.230 (0.024)	0.491 (0.049)	0.563 (0.051)	0.755 (0.064)	0.651 (0.058)	0.541 (0.050)
^{42}K	i	12.360 h	–	–	–	–	0.299 (0.031)	1.05 (0.11)	2.14 (0.21)	2.47 (0.22)	3.10 (0.27)	2.78 (0.25)	2.40 (0.23)
^{38}K	i	7.636 min	–	–	–	–	0.071 (0.020)	0.359 (0.056)	0.771 (0.095)	1.05 (0.12)	1.39 (0.16)	1.24 (0.14)	0.85 (0.10)
^{41}Ar	c	109.34 min	–	–	–	–	–	0.094 (0.011)	0.219 (0.023)	0.311 (0.029)	0.433 (0.039)	0.411 (0.037)	0.324 (0.030)
^{39}Cl	c	55.6 min	–	–	–	–	–	–	0.129 (0.020)	0.192 (0.027)	0.277 (0.026)	0.281 (0.028)	0.234 (0.024)
^{38}Cl	i$(m+g)$	37.24 min	–	–	–	–	–	–	–	–	–	1.25 (0.12)	0.972 (0.099)
^{38}Cl	c	37.24 min	–	–	–	–	0.026 (0.014)	0.214 (0.025)	0.572 (0.059)	0.812 (0.074)	1.18 (0.10)	1.29 (0.12)	1.050 (0.100)
^{34m}Cl	i(m)	32.00 min	–	–	–	–	0.032 (0.009)	0.214 (0.035)	0.545 (0.056)	0.804 (0.074)	1.27 (0.11)	1.15 (0.14)	1.06 (0.13)
^{38}S	c	170.3 min	–	–	–	–	–	–	–	–	–	0.021 (0.009)	0.034 (0.007)
^{29}Al	c	6.56 min	–	–	–	–	–	–	–	0.654 (0.075)	1.35 (0.16)	1.57 (0.17)	1.37 (0.14)
^{28}Mg	c	20.915 h	–	–	–	–	–	–	0.043 (0.016)	0.065 (0.007)	0.163 (0.015)	0.190 (0.017)	0.232 (0.022)
^{27}Mg	c	9.458 min	–	–	–	–	–	–	0.164 (0.025)	0.337 (0.036)	0.696 (0.067)	0.899 (0.086)	0.884 (0.085)
^{24}Na	c	14.9590 h	–	–	–	–	–	–	–	1.020 (0.090)	2.14 (0.18)	2.61 (0.23)	3.08 (0.28)
^{22}Na	c	2.6019 yr	–	–	–	–	–	–	0.462 (0.086)	0.86 (0.10)	1.74 (0.15)	2.31 (0.21)	2.86 (0.26)
^{7}Be	i	53.29 day	–	–	–	–	0.71 (0.11)	1.54 (0.20)	2.89 (0.32)	3.96 (0.38)	6.94 (0.59)	7.60 (0.68)	9.25 (0.86)

Table 3. Experimental cross sections for radioactive-nuclide production in the $^{93}\mathrm{Nb}(p,x)$ 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
^{93m}Mo	i(m)	6.85 h	1.37 (0.13)	0.845 (0.095)	0.651 (0.069)	0.392 (0.043)	0.270 (0.049)	0.222 (0.066)	0.236 (0.059)	0.228 (0.073)	0.209 (0.033)	0.216 (0.028)	0.196 (0.030)
^{91}Mo	i($m+g$)	15.49 min	94 (22)	–	–	–	–	–	–	–	–	–	–
^{90}Mo	i	5.56 h	61.3 (5.3)	25.7 (2.4)	12.1 (1.3)	6.07 (0.60)	3.30 (0.32)	2.10 (0.24)	1.36 (0.36)	0.94 (0.10)	0.808 (0.099)	0.663 (0.095)	0.555 (0.076)
^{92m}Nb	i(m)	10.15 day	54.8 (4.4)	44.0 (4.1)	33.9 (2.9)	25.0 (2.1)	18.9 (1.5)	19.9 (2.0)	20.3 (2.0)	18.6 (1.7)	19.8 (1.7)	19.1 (1.7)	17.8 (1.7)
^{91m}Nb	c	60.86 day	34.9 (3.2)	22.0 (2.0)	17.6 (1.7)	11.6 (1.2)	7.63 (0.83)	8.0 (1.3)	7.5 (1.1)	5.3 (1.1)	5.1 (1.2)	5.5 (1.3)	5.44 (0.66)
^{90}Nb	i($m+g$)	14.60 h	302 (25)	179 (17)	108 (11)	71.4 (6.4)	44.1 (4.5)	36.7 (3.7)	30.9 (3.7)	24.4 (2.4)	21.8 (2.1)	20.2 (1.9)	18.3 (1.8)
^{90}Nb	c	14.60 h	364 (29)	200 (17)	123 (11)	79.2 (6.9)	48.9 (4.3)	39.8 (4.0)	33.2 (3.4)	26.7 (2.5)	24.5 (2.2)	22.5 (2.1)	20.0 (1.9)
^{89m}Nb	i(m)	66 min	0.39 (0.18)	18.0 (1.7)	9.27 (0.92)	6.41 (0.66)	4.41 (0.49)	3.78 (0.49)	3.09 (0.39)	1.88 (0.37)	2.38 (0.29)	1.94 (0.22)	1.47 (0.16)
^{89}Nb	c	2.03 h	–	176 (21)	87 (11)	54.9 (6.7)	27.9 (3.4)	24.9 (3.4)	20.6 (2.8)	14.6 (2.0)	12.9 (1.7)	11.9 (1.6)	9.5 (1.3)
^{88}Nb	c*	14.5 min	–	4.13 (0.38)	21.0 (2.0)	12.4 (1.2)	7.52 (0.71)	5.52 (0.65)	4.28 (0.45)	3.29 (0.33)	2.76 (0.29)	2.27 (0.27)	2.07 (0.20)
^{89}Zr	c	78.41 h	12.40 (1.00)	268 (23)	164 (14)	117.0 (10.0)	81.9 (6.8)	72.7 (7.2)	61.5 (6.0)	50.8 (4.7)	47.1 (4.1)	42.7 (3.9)	37.3 (3.5)
^{88}Zr	c	83.4 day	61.2 (4.8)	44.7 (3.8)	125 (11)	90.4 (7.7)	64.2 (5.2)	57.6 (5.6)	47.4 (4.6)	37.3 (3.4)	33.3 (2.9)	29.6 (2.7)	25.1 (2.3)
^{87}Zr	c	1.68 h	7.76 (0.77)	26.9 (2.2)	73.6 (6.3)	56.6 (4.8)	43.0 (3.5)	40.3 (4.0)	31.5 (3.0)	26.6 (2.4)	20.7 (1.8)	17.6 (1.6)	14.8 (1.4)
^{86}Zr	c	16.5 h	4.0 (1.0)	13.8 (1.3)	7.6 (1.4)	22.4 (2.0)	17.8 (1.5)	16.0 (1.6)	10.9 (1.4)	10.2 (1.0)	6.93 (0.71)	7.31 (0.70)	5.80 (0.55)
^{85}Zr	c	7.86 min	–	–	2.94 (0.36)	–	5.76 (0.56)	7.58 (0.81)	7.86 (0.82)	7.09 (0.73)	5.31 (0.73)	–	–
^{90m}Y	i(m)	3.19 h	–	0.553 (0.093)	0.635 (0.071)	0.865 (0.092)	0.90 (0.11)	1.43 (0.16)	1.81 (0.20)	1.73 (0.23)	1.86 (0.17)	1.66 (0.16)	1.45 (0.15)
^{88}Y	i	106.65 day	13.4 (1.2)	7.77 (0.70)	18.1 (1.6)	17.5 (1.5)	16.0 (1.3)	18.2 (1.9)	17.8 (1.8)	15.7 (1.5)	15.4 (1.4)	14.1 (1.3)	12.1 (1.2)
^{88}Y	c	106.65 day	74.6 (6.2)	53.3 (4.6)	145 (13)	110.0 (10.0)	81.3 (6.9)	76.6 (7.6)	66.8 (6.7)	53.6 (5.1)	49.0 (4.5)	44.0 (4.1)	37.6 (3.6)
^{87m}Y	i(m)	13.37 h	6.56 (0.70)	20.3 (2.5)	22.3 (3.4)	27.2 (2.5)	24.3 (2.5)	24.6 (2.9)	23.2 (2.4)	18.0 (1.8)	18.1 (1.7)	16.6 (1.5)	13.8 (1.4)
^{87m}Y	c	13.37 h	14.3 (1.1)	46.7 (4.0)	94.7 (8.4)	83.6 (7.2)	66.9 (5.6)	64.7 (6.4)	54.6 (5.3)	44.5 (4.1)	38.6 (3.4)	34.1 (3.1)	28.5 (2.7)
^{87}Y	c	79.8 h	19.1 (1.5)	59.7 (5.1)	97.1 (8.4)	107.0 (9.0)	84.8 (6.9)	82.4 (8.1)	70.8 (6.9)	57.4 (5.3)	50.9 (4.4)	44.9 (4.1)	37.8 (3.5)
^{86m}Y	i(m)	48 min	–	17.3 (1.6)	17.0 (1.6)	23.6 (2.1)	19.0 (1.9)	21.9 (2.2)	19.6 (2.0)	–	13.8 (1.2)	11.8 (1.1)	10.02 (0.99)
^{86}Y	i($m+g$)	14.74 h	22 (51)	32.7 (3.0)	30.4 (2.9)	41.0 (3.7)	36.0 (3.1)	39.5 (4.0)	34.4 (3.4)	27.7 (2.6)	25.0 (2.2)	18.2 (2.0)	17.6 (1.7)
^{86}Y	c	14.74 h	25 (27)	46.0 (4.2)	44.9 (4.0)	63.2 (5.7)	54.0 (4.6)	56.3 (5.7)	47.4 (4.7)	38.0 (3.6)	33.2 (2.9)	27.9 (2.6)	23.3 (2.2)
^{85m}Y	c	4.86 h	–	1.94 (0.39)	17.7 (1.9)	20.6 (2.0)	18.9 (2.1)	21.3 (2.3)	17.4 (2.3)	14.7 (1.9)	11.9 (1.4)	9.29 (0.96)	7.81 (0.85)
^{85}Y	c	2.68 h	–	–	7.53 (0.68)	9.1 (1.0)	8.64 (0.83)	8.9 (1.1)	7.42 (0.95)	6.15 (0.66)	5.43 (0.55)	4.35 (0.43)	3.73 (0.39)

Table 3. (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
^{84}Y	c	39.5 min	–	–	9.64 (0.85)	12.9 (1.2)	14.6 (1.3)	16.3 (1.7)	14.4 (1.5)	11.3 (1.1)	9.13 (0.83)	7.68 (0.73)	6.21 (0.62)
^{85m}Sr	i(m)	67.63 min	–	–	1.19 (0.13)	1.51 (0.28)	1.46 (0.13)	1.84 (0.20)	2.08 (0.30)	1.82 (0.20)	1.61 (0.16)	1.46 (0.15)	1.22 (0.14)
^{85m}Sr	c	67.63 min	–	0.144 (0.087)	8.54 (0.79)	10.0 (1.0)	9.90 (0.86)	10.9 (1.2)	9.6 (1.1)	7.92 (0.80)	6.93 (0.70)	5.76 (0.61)	4.89 (0.58)
^{85}Sr	c	64.84 day	–	–	–	–	–	–	–	47.6 (4.9)	40.8 (3.9)	33.8 (3.4)	29.5 (3.0)
^{83}Sr	c	32.41 h	–	2.4 (2.4)	3.74 (0.89)	22.2 (3.6)	28.6 (4.6)	37.6 (6.8)	31.9 (5.9)	26.1 (4.9)	25.3 (4.6)	21.8 (4.0)	17.1 (3.3)
^{82}Sr	c	25.55 day	–	–	2.30 (0.20)	10.10 (0.90)	15.7 (1.3)	21.9 (2.2)	21.7 (2.1)	17.8 (1.6)	14.9 (1.3)	12.5 (1.1)	9.77 (0.91)
^{81}Sr	c	22.3 min	–	–	0.44 (0.14)	2.27 (0.30)	4.18 (0.59)	7.23 (0.87)	7.47 (0.90)	6.75 (0.83)	4.94 (0.83)	3.83 (0.55)	3.29 (0.50)
^{80}Sr	c	106.3 min	–	–	–	–	–	–	–	2.06 (0.78)	1.37 (0.34)	1.33 (0.30)	1.10 (0.20)
^{86}Rb	i($m+g$)	18.631 day	–	–	–	–	0.24 (0.12)	0.36 (0.29)	0.30 (0.37)	0.58 (0.55)	0.535 (0.087)	0.561 (0.095)	0.524 (0.071)
^{84m}Rb	i(m)	20.26 min	–	–	0.71 (0.33)	1.63 (0.16)	2.05 (0.20)	3.07 (0.33)	3.34 (0.37)	3.15 (0.31)	2.95 (0.30)	2.42 (0.24)	1.98 (0.21)
^{84}Rb	i($m+g$)	32.77 day	–	0.554 (0.049)	1.060 (0.100)	2.38 (0.21)	3.38 (0.30)	4.98 (0.50)	5.56 (0.58)	5.00 (0.51)	4.75 (0.45)	4.22 (0.39)	3.51 (0.34)
^{83}Rb	c	86.2 day	–	2.45 (0.23)	7.16 (0.71)	31.5 (3.0)	41.8 (3.8)	54.9 (5.8)	54.0 (5.6)	44.7 (4.5)	39.1 (3.7)	33.4 (3.3)	26.1 (2.7)
^{82m}Rb	i(m)	6.472 h	–	–	3.39 (0.35)	7.51 (0.66)	11.4 (1.0)	17.6 (1.8)	18.8 (1.9)	16.2 (1.5)	14.1 (1.2)	12.3 (1.1)	9.82 (0.94)
^{81}Rb	c	4.576 h	–	0.69 (0.18)	3.4 (1.3)	11.5 (1.3)	22.3 (2.0)	36.9 (3.7)	39.1 (3.9)	32.5 (3.3)	27.6 (2.5)	24.0 (2.3)	18.4 (1.9)
^{79}Rb	c	22.9 min	–	–	–	1.46 (0.18)	3.89 (0.36)	8.15 (0.86)	10.1 (1.1)	8.9 (1.0)	8.20 (0.76)	6.33 (0.74)	5.02 (0.59)
^{79}Kr	c	35.04 h	–	–	–	4.56 (0.96)	11.9 (1.1)	25.3 (2.6)	31.8 (3.3)	27.0 (2.7)	25.2 (2.3)	22.0 (2.1)	16.9 (1.7)
^{77}Kr	c	74.4 min	–	–	–	0.313 (0.047)	3.07 (0.31)	8.96 (0.91)	12.2 (1.3)	12.1 (1.1)	11.2 (1.0)	8.81 (0.79)	6.65 (0.62)
^{76}Kr	c	14.8 h	–	–	–	0.06 (0.61)	0.71 (0.12)	2.07 (0.31)	1.59 (0.36)	3.45 (0.48	3.55 (0.46)	2.89 (0.31)	2.22 (0.23)
^{82}Br	i($m+g$)	35.30 h	–	–	0.70 (0.18)	0.43 (0.22)	0.42 (0.41)	0.60 (0.19)	0.8 (1.2)	0.48 (0.55)	0.35 (0.33)	0.35 (0.11)	0.14 (0.35)
^{77}Br	i($m+g$)	57.036 h	–	–	–	–	–	–	–	6.2 (8.6)	12.8 (7.2)	9.7 (4.6)	10.4 (3.2)
^{77}Br	c	57.036 h	–	–	–	0.610 (0.094)	6.52 (0.55)	18.1 (1.8)	26.8 (2.7)	25.9 (2.4)	23.8 (2.2)	20.5 (1.9)	15.7 (1.5)
^{76}Br	i($m+g$)	16.2 h	–	–	–	0.5 (1.1)	3.17 (0.38)	10.9 (1.4)	17.0 (2.0)	17.1 (2.0)	16.3 (1.6)	13.8 (1.3)	10.50 (1.00)
^{76}Br	c	16.2 h	–	–	–	0.59 (0.43)	3.95 (0.57)	13.4 (1.8)	21.3 (2.3)	20.1 (2.1)	19.9 (2.0)	16.8 (1.7)	12.5 (1.3)
^{75}Br	c	96.7 min	–	–	–	0.59 (0.40)	1.9 (1.1)	8.1 (3.4)	11.4 (2.9)	13.8 (3.2)	12.8 (2.8)	10.7 (2.4)	8.0 (1.8)
^{74m}Br	i(m)	46 min	–	–	–	–	1.48 (0.62)	2.11 (0.92)	3.62 (0.69)	3.74 (0.67)	3.72 (0.53)	3.51 (0.53)	2.18 (0.74)
^{74}Br	c	25.4 min	–	–	–	–	–	2.40 (0.99)	1.4 (1.1)	4.7 (2.2)	4.9 (2.6)	3.1 (1.7)	2.0 (1.9)
^{75}Se	c	119.779 day	–	–	–	0.416 (0.045)	4.03 (0.42)	15.5 (1.7)	27.3 (3.1)	29.2 (3.3)	28.5 (2.9)	24.9 (2.6)	19.1 (2.1)

Table 3. (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
^{73m}Se	c	39.8 min	–	–	–	–	–	3.7 (1.2)	7.4 (1.5)	6.8 (1.4)	5.4 (1.7)	6.06 (0.90)	4.53 (0.81)
^{73}Se	i$(m+g)$	7.15 h	–	–	–	–	–	2.39 (0.68)	5.37 (0.89)	7.35 (0.96)	9.3 (1.2)	7.12 (0.76)	5.52 (0.65)
^{73}Se	c	7.15 h	–	–	–	–	0.989 (0.092)	5.10 (0.51)	10.7 (1.1)	12.3 (1.2)	13.2 (1.2)	11.5 (1.1)	8.85 (0.84)
^{72}Se	c	8.40 day	–	–	–	–	0.242 (0.023)	1.91 (0.19)	4.35 (0.42)	5.36 (0.53)	6.05 (0.54)	5.30 (0.49)	4.02 (0.38)
^{74}As	i	17.77 day	–	–	–	0.048 (0.012)	0.427 (0.041)	2.11 (0.61)	4.1 (1.0)	4.60 (0.87)	5.10 (0.92)	4.71 (0.87)	3.66 (0.64)
^{72}As	i	26.0 h	–	–	–	–	1.94 (0.18)	5.91 (0.74)	13.1 (1.5)	13.9 (1.4)	16.2 (1.6)	15.8 (1.6)	11.7 (1.3)
^{72}As	c	26.0 h	–	–	–	–	2.27 (0.45)	8.0 (1.0)	17.9 (2.0)	19.9 (1.9)	22.5 (2.2)	21.4 (2.1)	15.7 (1.7)
^{71}As	c	65.28 h	–	–	–	–	0.548 (0.089)	4.10 (0.46)	9.9 (1.1)	12.9 (1.2)	15.2 (1.4)	13.9 (1.4)	10.6 (1.1)
^{70}As	c*	52.6 min	–	–	–	–	–	1.22 (0.22)	3.84 (0.43)	4.69 (0.51)	6.26 (0.65)	5.99 (0.63)	4.27 (0.47)
^{69}Ge	c	39.05 h	–	–	–	–	0.141 (0.022)	2.22 (0.36)	6.70 (0.99)	9.0 (1.3)	11.9 (1.3)	11.1 (1.4)	9.3 (1.0)
^{67}Ge	c	18.9 min	–	–	–	–	–	–	0.85 (0.11)	1.47 (0.17)	1.93 (0.25)	2.07 (0.25)	1.66 (0.20)
^{67}Ga	c	3.2612 day	–	–	–	–	0.11 (0.11)	1.71 (0.18)	6.65 (0.67)	10.5 (1.1)	15.6 (1.4)	15.5 (1.4)	12.5 (1.2)
^{66}Ga	c*	9.49 h	–	–	–	–	–	0.93 (0.24)	3.53 (0.76)	5.50 (0.64)	8.76 (0.91)	9.08 (0.85)	7.12 (0.84)
^{65}Ga	c	15.2 min	–	–	–	–	–	–	0.74 (0.26)	1.62 (0.43)	2.49 (0.65)	2.58 (0.52)	2.28 (0.54)
^{65}Zn	c	244.26 day	–	–	–	–	0.100 (0.018)	1.23 (0.13)	5.36 (0.52)	9.45 (0.88)	15.6 (1.4)	16.3 (1.5)	13.7 (1.3)
^{62}Zn	c	9.186 h	–	–	–	–	–	–	–	–	0.30 (0.13)	0.83 (0.22)	0.71 (0.14)
^{67}Cu	c	61.83 h	–	–	–	–	–	–	–	–	–	–	0.30 (0.17)
^{61}Cu	c	3.333 h	–	–	–	–	–	0.49 (0.42)	–	2.26 (0.54)	2.31 (0.57)	3.37 (0.86)	3.43 (0.56)
^{60}Cu	c	23.7 min	–	–	–	–	–	–	–	0.43 (0.17)	0.77 (0.14)	0.86 (0.11)	0.69 (0.14)
^{57}Ni	c	35.60 h	–	–	–	–	–	–	–	–	0.118 (0.015)	0.182 (0.019)	0.177 (0.020)
^{62m}Co	i(m)	13.91 min	–	–	–	–	–	–	–	–	0.31 (0.21)	0.198 (0.086)	0.262 (0.053)
^{60}Co	i$(m+g)$	5.2714 yr	–	–	–	–	–	–	–	0.69 (0.20)	2.56 (0.33)	3.10 (0.40)	2.97 (0.36)
^{58}Co	i$(m+g)$	70.86 day	–	–	–	–	–	0.128 (0.014)	1.12 (0.11)	2.75 (0.25)	6.89 (0.59)	8.85 (0.80)	8.79 (0.85)
^{57}Co	c	271.74 day	–	–	–	–	–	–	0.704 (0.086)	1.94 (0.18)	5.34 (0.54)	7.20 (0.70)	7.38 (0.71)
^{56}Co	c	77.233 day	–	–	–	–	–	–	0.21 (0.11)	0.55 (0.12)	1.47 (0.17)	2.07 (0.21)	2.20 (0.24)
^{55}Co	c	17.53 h	–	–	–	–	–	–	–	–	–	0.284 (0.076)	0.55 (0.37)
^{59}Fe	c	44.472 day	–	–	–	–	–	–	0.114 (0.020)	0.233 (0.028)	0.551 (0.054)	0.723 (0.069)	0.717 (0.082)

Table 3. (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
^{53}Fe	c*	8.51 min	–	–	–	–	–	–	–	–	–	0.21 (0.12)	0.47 (0.21)
^{56}Mn	c	2.5789 h	–	–	–	–	–	–	–	0.327 (0.059)	1.00 (0.14)	1.31 (0.19)	1.41 (0.14)
^{54}Mn	i	312.11 day	–	–	–	–	–	–	0.41 (0.13)	1.23 (0.17)	3.96 (0.35)	5.96 (0.54)	6.91 (0.65)
^{52m}Mn	c	21.1 min	–	–	–	–	–	–	–	0.229 (0.096)	0.191 (0.067)	0.446 (0.076)	0.494 (0.082)
^{52}Mn	c	5.591 day	–	–	–	–	–	–	0.114 (0.012)	0.356 (0.100)	1.29 (0.11)	2.07 (0.19)	2.61 (0.25)
^{51}Cr	c	27.7025 day	–	–	–	–	–	–	–	0.88 (0.10)	3.48 (0.31)	5.91 (0.55)	7.42 (0.70)
^{49}Cr	c	42.3 min	–	–	–	–	–	–	–	–	–	0.472 (0.082)	0.761 (0.084)
^{48}Cr	c	21.56 h	–	–	–	–	–	–	–	–	–	0.066 (0.066)	0.085 (0.013)
^{48}V	c	15.9735 day	–	–	–	–	–	–	0.090 (0.009)	0.309 (0.050)	1.28 (0.11)	2.28 (0.21)	3.36 (0.31)
^{48}Sc	i	43.67 h	–	–	–	–	–	–	–	0.048 (0.025)	0.174 (0.029)	0.282 (0.034)	0.474 (0.063)
^{47}Sc	i	3.3492 day	–	–	–	–	–	–	–	–	0.553 (0.049)	0.98 (0.10)	1.50 (0.14)
^{47}Sc	c	3.3492 day	–	–	–	–	–	–	0.058 (0.008)	0.167 (0.018)	0.567 (0.050)	1.010 (0.100)	1.57 (0.15)
^{46}Sc	i$(m+g)$	83.79 day	–	–	–	–	–	–	0.093 (0.011)	0.33 (0.10)	1.09 (0.12)	1.99 (0.19)	3.10 (0.31)
^{44m}Sc	i(m)	58.61 h	–	–	–	–	–	–	0.147 (0.025)	0.27 (0.12)	0.72 (0.36)	1.26 (0.13)	2.10 (0.20)
^{44}Sc	i	3.97 h	–	–	–	–	–	–	–	–	–	0.709 (0.072)	1.30 (0.12)
^{44}Sc	i$(m+g)$	3.97 h	–	–	–	–	–	–	–	0.118 (0.044)	0.362 (0.039)	1.89 (0.17)	3.31 (0.31)
^{43}Sc	c	3.891 h	–	–	–	–	–	–	–	–	0.60 (0.13)	0.76 (0.15)	1.01 (0.13)
^{47}Ca	c	4.536 day	–	–	–	–	–	–	–	–	0.022 (0.008)	0.044 (0.020)	0.063 (0.008)
^{43}K	c	22.3 h	–	–	–	–	–	–	–	–	0.278 (0.032)	0.526 (0.059)	0.774 (0.078)
^{42}K	i	12.360 h	–	–	–	–	–	–	–	–	–	0.97 (0.13)	1.66 (0.17)
^{41}Ar	c	109.34 min	–	–	–	–	–	–	–	–	–	0.294 (0.037)	0.488 (0.059)
^{39}Cl	c	55.6 min	–	–	–	–	–	–	–	–	–	0.215 (0.071)	0.286 (0.047)
^{38}Cl	c	37.24 min	–	–	–	–	–	–	–	–	0.302 (0.073)	0.521 (0.077)	0.866 (0.098)
^{29}Al	c	6.56 min	–	–	–	–	–	–	–	–	–	0.393 (0.079)	1.49 (0.21)
^{28}Mg	c	20.915 h	–	–	–	–	–	–	–	–	–	0.180 (0.065)	0.365 (0.050)
^{27}Mg	c	9.458 min	–	–	–	–	–	–	–	–	–	0.286 (0.100)	0.61 (0.10)
^{24}Na	c	14.9590 h	–	–	–	–	–	–	0.144 (0.033)	0.179 (0.027)	0.560 (0.051)	0.992 (0.092)	2.07 (0.20)
^{22}Na	c	2.6019 yr	–	–	–	–	–	–	–	–	0.324 (0.050)	0.364 (0.076)	0.963 (0.097)
^{7}Be	i	53.29 day	–	–	–	–	0.430 (0.043)	0.84 (0.16)	1.41 (0.15)	2.13 (0.22)	4.06 (0.36)	5.73 (0.53)	8.31 (0.78)

Table 4. Standard deviations $\langle F \rangle$ for $^{\rm nat}$Nb and ^{93}Ni

Model	Sample	Proton energy, MeV										
		40	70	100	150	250	400	600	800	1200	1600	2600
BERTINI	Ni	3.36	2.65	3.48	2.53	1.95	1.71	2.86	2.29	2.90	2.25	2.24
	Nb	2.28	2.42	1.68	3.47	2.58	2.17	3.06	1.66	1.78	2.24	2.05
ISABEL	Ni	5.45	3.64	4.14	2.70	2.21	2.19	3.62	4.15	2.90	2.25	2.24
	Nb	3.00	2.78	1.80	3.62	2.76	2.64	4.65	3.77	1.78	2.24	2.05
CEM03.02	Ni	2.26	2.56	2.37	1.63	1.75	1.67	1.69	1.70	1.89	1.86	2.40
	Nb	3.36	2.59	2.08	2.84	2.26	1.94	2.09	1.94	2.67	2.30	1.92
INCL4.2	Ni	2.01	2.08	1.97	2.52	3.44	4.11	2.28	3.41	3.01	3.48	2.92
	Nb	2.94	2.02	2.12	3.99	3.27	3.26	3.31	4.90	4.63	4.40	3.19
INCL4.5	Ni	2.66	1.62	1.59	1.46	1.90	1.57	1.56	1.59	1.54	1.64	1.85
	Nb	13.78	2.05	3.45	1.98	1.55	1.65	1.63	1.56	1.59	1.55	1.58
PHITS	Ni	3.68	2.95	4.11	3.16	2.45	2.05	2.12	1.96	1.67	1.74	1.76
	Nb	3.38	3.12	2.76	4.35	3.21	2.29	2.37	1.74	2.61	2.01	1.66
CASCADE07	Ni	5.19	3.45	3.47	3.20	2.75	2.77	2.65	2.60	4.37	4.13	3.83
	Nb	9.97	4.73	4.33	3.37	2.65	2.61	2.87	2.37	2.73	3.69	3.01

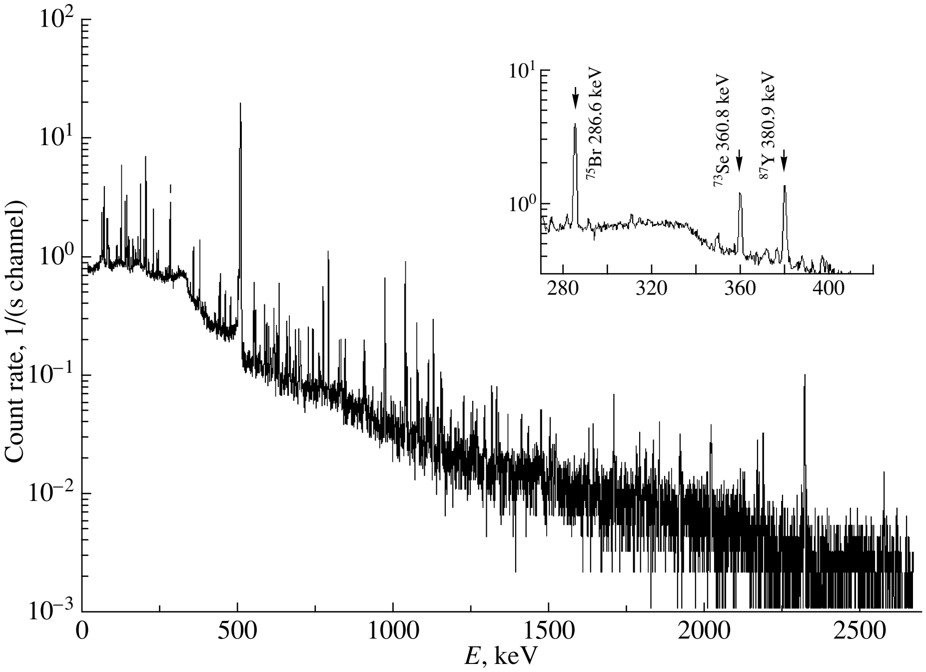

Fig. 1. Example of the γ spectrum of ^{93}Nb no. 05 for $E_p = 2.6$ GeV 1.61 h after irradiation; the measurement duration was 900 s.

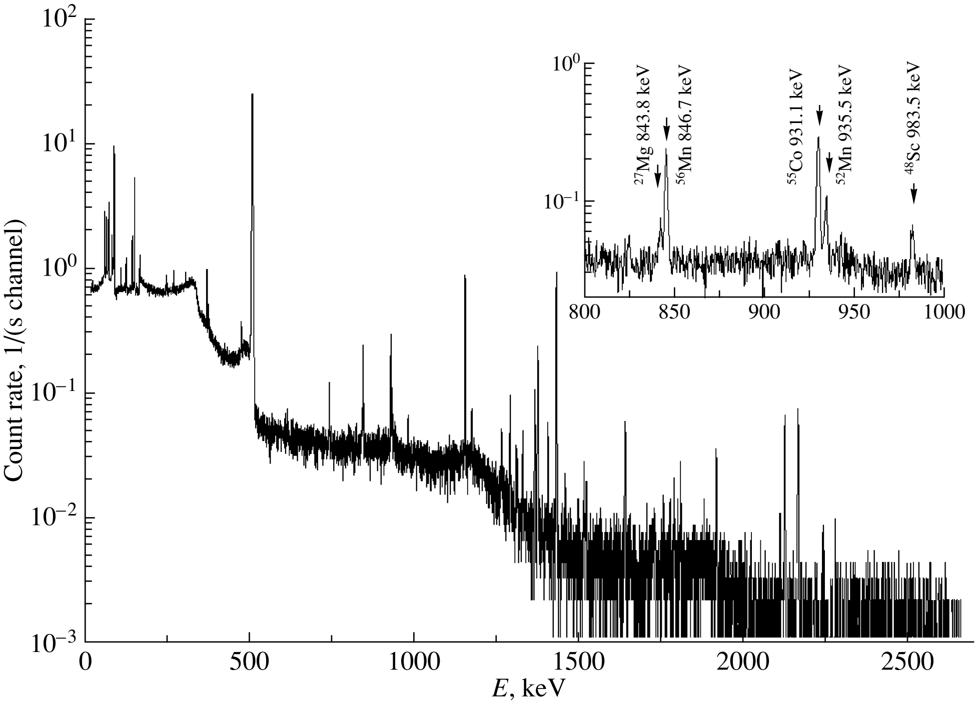

Fig. 2. Example of the γ spectrum of $^{\rm nat}$Ni no. 05 for $E_p = 2.6$ GeV 1.47 h after irradiation; the measurement duration was 900 s.

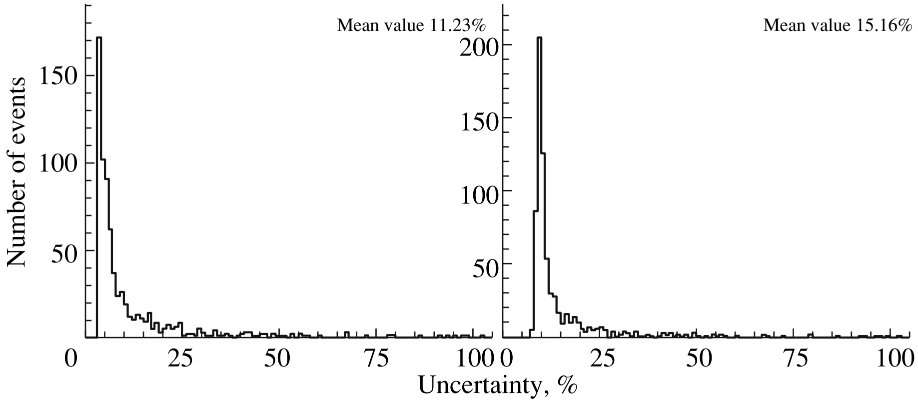

Fig. 3. Distribution of the uncertainties in reaction rates and cross sections for ^{93}Nb.

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 [4].

RESULTS AND THEORETICAL PREDICTIONS

The cross sections for radioactive-nuclide production in the ^{93}Nb(p,x)- and $^{\rm nat}$Ni(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 $\sigma^{\rm ind}(i)$ and $\sigma^{\rm cum}(c)$ for radioactive-nuclide production in $^{\rm nat}$Ni and ^{93}Nb irradiated by protons are 388 ($i = 85, i(m+g) = 42, i(m) = 31$, and $c + c^* = 230$) and 724 ($i = 58, i(m+g) = 85, i(m) = 106$, and $c + c^* = 475$), respectively. Using these data, we obtained 108 and 47 excitation functions for ^{93}Nb and $^{\rm nat}$Ni, respectively; among them, 24 and 9 excitation functions, respectively, were measured for the first time.

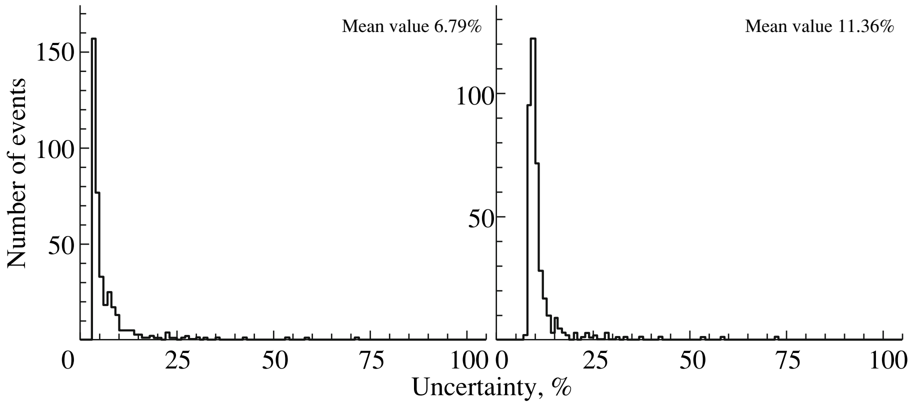

Fig. 4. As in Fig. 3, but for ^{nat}Ni.

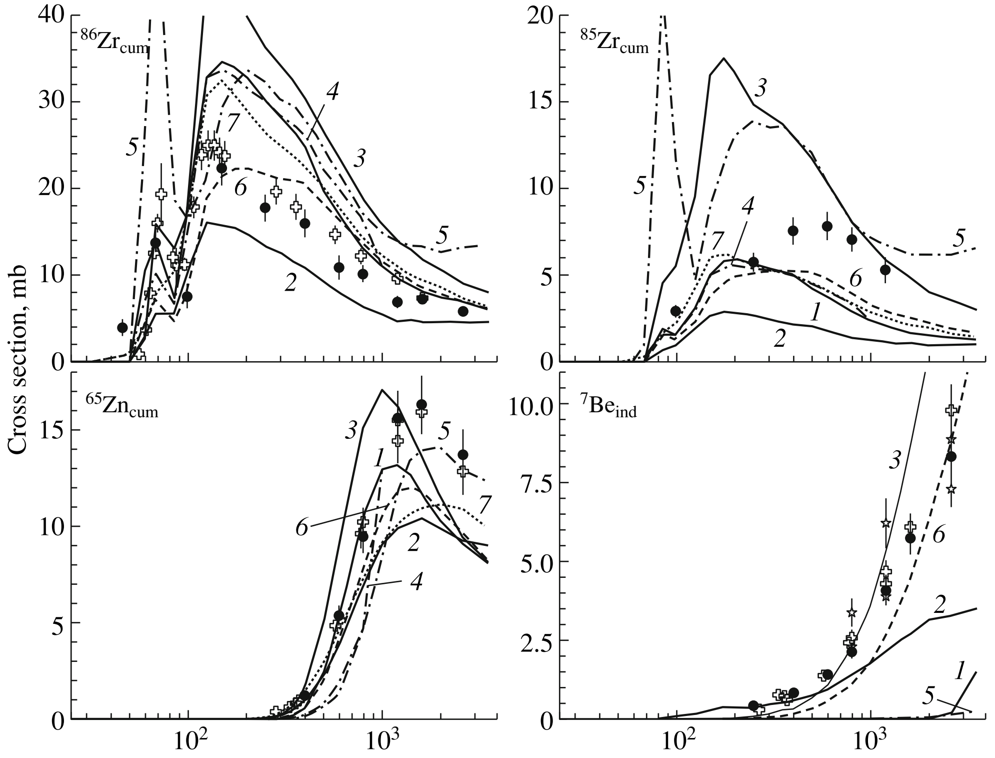

Fig. 5. Calculated and experimental cross sections for the ^{nat}Ni(p, x) reactions. The experimental data were taken from (●) our present study, (✣) [14], and (☆) [15]. Lines *1*, *2*, *3*, *4*, *5*, *6*, and *7* represent the BERTINI, INCL4.5, CEM03.02, ISABEL, INCL4.2, PHITS, and CASCADE07 calculations,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

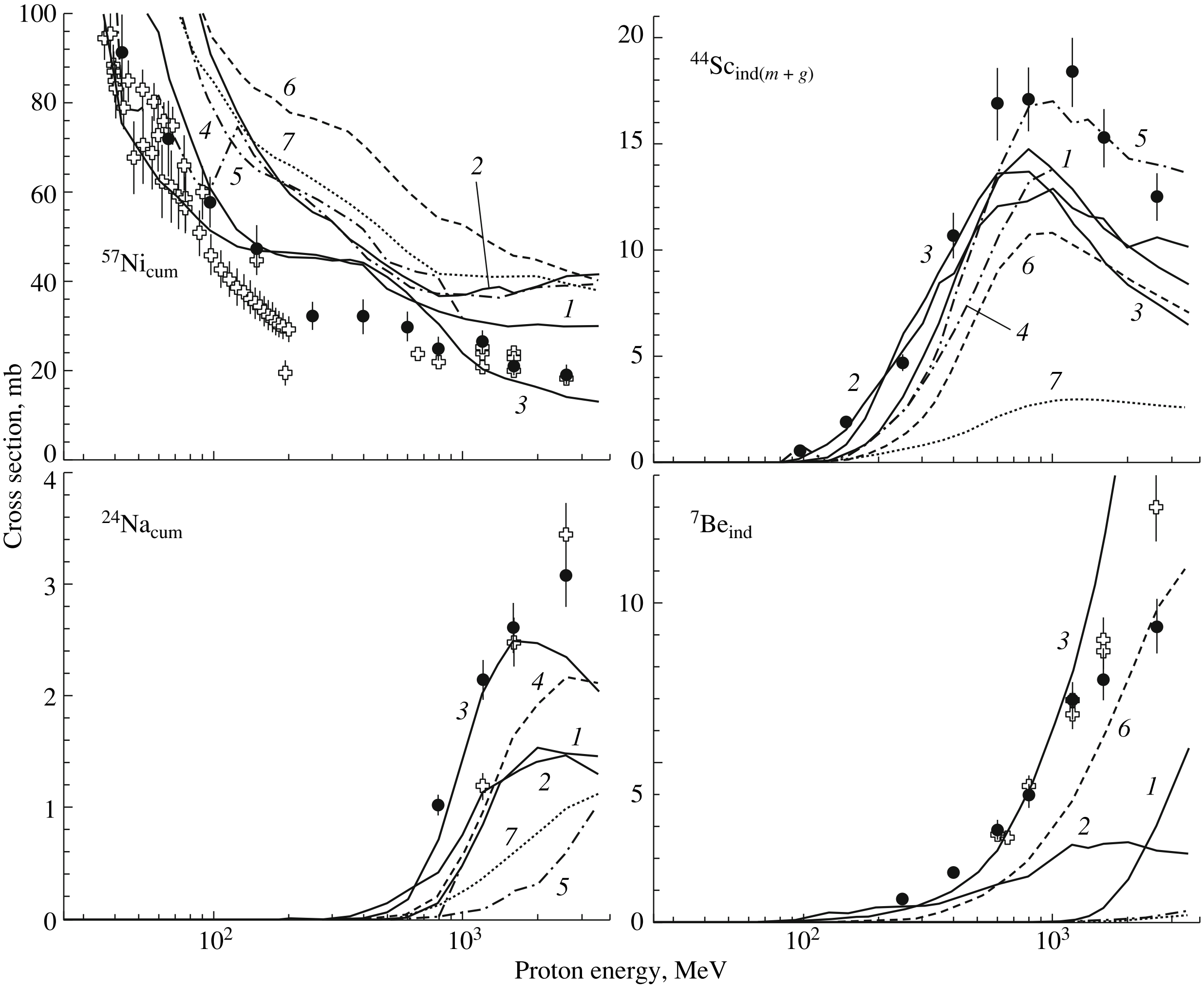

Fig. 6. As in Fig. 5, but for ^{93}Ni(p, x). The experimental data were taken from (●) our present study, (✢) [14, 16–18].

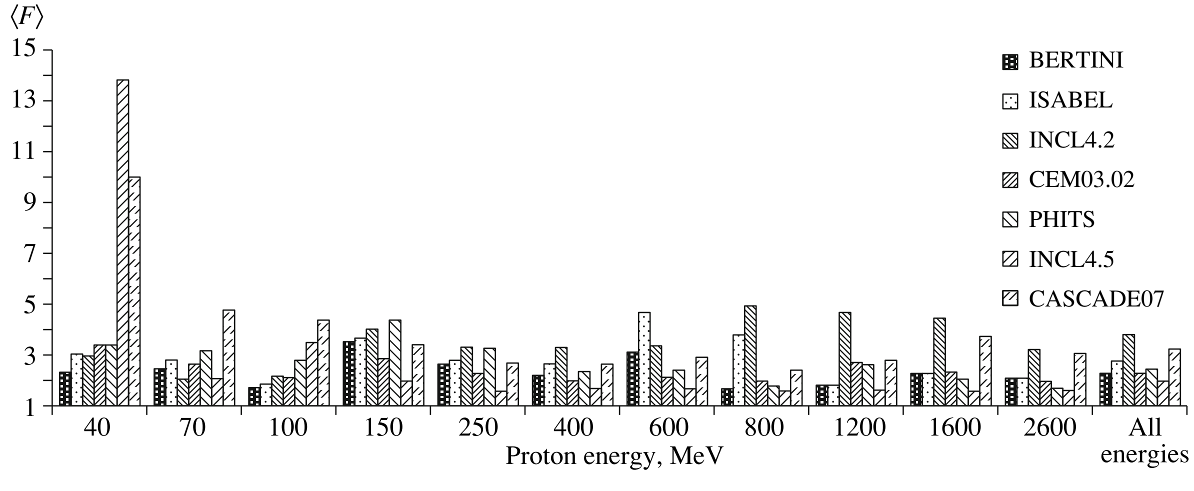

Fig. 7. Deviation coefficients ⟨F⟩ for ^{93}Nb characterizing the predictive powers of the codes.

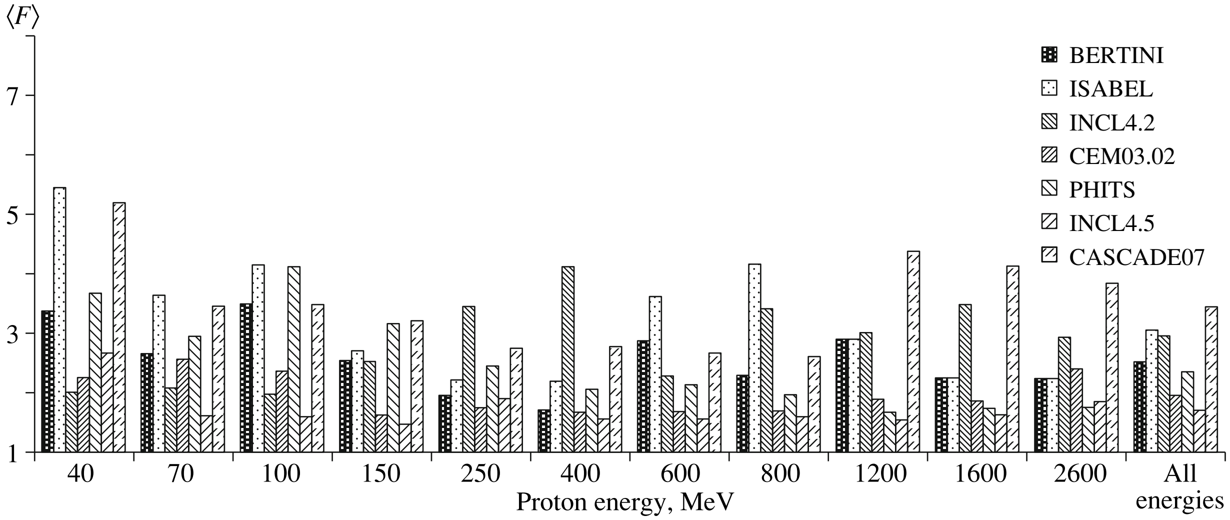

Fig. 8. As in Fig. 7, but for ^{nat}Ni(p, x).

The average accuracy of the determination of the cross sections for radioactive-nuclide production in ^{93}Nb and ^{nat}Ni is 15.2 and 11.4%, respectively. The distributions of the uncertainties of the reaction rates and cross sections are presented in Figs. 3 and 4.

The resulting excitation functions were compared with the respective functions calculated using the BERTINI, ISABEL, CEM03.02, INCL4.2, INCL4.5, CASCADE07, and PHITS codes [5–11]. The formulas for a convolution of the calculated independent yields into cumulative ones were given in [12, 13]. Examples of the calculated and experimental excitation functions are shown in Figs. 5 and 6.

The predictive powers of the codes can be estimated in terms of the deviation coefficients $\langle F\rangle$ defined as [3, 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.

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

CONCLUSIONS

The $\langle F\rangle$ deviation coefficients being considered range from 1.2 to 13.8 for various models. These values correspond to the deviation of the calculations from the experimental data from 20 to 1280%. 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 corresponding designs of electronuclear facilities and spallation neutron sources.

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