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V.S.Barashenkov, V.M.Pankov[1], A.N.Sosnin,
P.I.Taranenko[2], S.N.Fedotov[2], Yu.G.Shkurkin[1]

INVESTIGATION OF TUNGSTEN AND LEAD STRUCTURAL MATERIALS ACTIVATION BY 1.0-1.1 GeV PROTONS

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[1]Institute for Cosmic Research, Moscow, USSR
[2]Moscow Engineering and Physics Institute, Moscow, USSR

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INTRODUCTION

The present work is indeed a continuation of our previous publication[1], where the abilities of the computer program complex "CASCADE" in the field of simulation of γ-activity, induced in irradiated material by high energy protons, have been considered and the results of comparison of calculated and experimental data for alluminium, titanium and iron structural materials are illustrated. The main interest is fixed on characteristics of γ-activity of heavy structural materials, such as tungsten and lead widely used in radiation shielding, different collimators, masks and coding appertures manufacturing.

Our objective is to further illustrate the abilities of the program complex on the example of simulation of induced γ-activity in materials with large atomic mass A and atomic charge Z under the irradiation by protons with energies 1.0-1.1 GeV. To examine the adequacy of the model to experiment and to evaluate its accuracy, calculated results are compared with spectrometric data and yields of products of nuclear interactions, obatined on the proton accelerator (Institute of Theoretical and Experimental Physics, Moscow).

The data on activation of collimating materials by high energy protons are of great practical importance. In part such data can be found in current piblications - see, e.g.[2-4], where yields of a set of nuclides in massive lead targets under irradiation by protons at energies of 0.5-0.1 GeV were investigated. Unfortunately, these data are evidently insufficient to solve diverse problems arising in everyday practice. To receive additional data on the yields of products of nuclear reactions in lead and tungsten under proton irradiation at energy 1.1 GeV is an extra aim of the present work.

MEASUREMENT METHOD AND RESULTS

Tungsten and lead targets formed as a parallelepiped 6x6 cm in its base and 1.2 and 3 cm correspondingly in height were irradiated by a proton beam at energy of 1.1 GeV on the ITEP accelerator. The targets are composed of separate plates

Table 1

Yields of radionuclides (in units of 10^{-5} $(g/cm^2)^{-1}$ per one incident proton). Statistical errors of calculated data are presented

Target	Nuclide	Experiment	Calculations
1	2	3	4
W	^{150}Tb	2.06±0.48	2.91±0.9
	^{151}Tb	3.04±0.67	3.78±1.04
	^{152}Dy	3.89±1.35	5.82±1.30
	^{152}Tb	2.64±0.39	1.74±0.64
	^{155}Dy	2.72±0.24	3.86±1.03
	^{157}Dy	1.24±0.12	1.16±0.37
	^{158}Er	3.12±1.27	5.53±1.21
	^{158}Ho	1.42±0.58	2.32±0.82
	^{159}Er	4.27±1.73	6.40±1.36
	^{160}Er	3.56±1.47	4.94±1.19
	^{161}Er	2.22±0.14	2.04±0.77
	^{161}Tm	3.73±1.52	2.92±0.92
	^{163}Tm	1.91±0.61	1.45±0.59
	^{165}Tm	0.40±0.21	0.58±0.36
	^{166}Yb	2.24±0.70	3.78±0.95
	^{166}Tm	0.76±0.24	1.16±0.38
	^{169}Hf	5.84±2.34	7.27±1.48
	^{169}Lu	6.08±1.41	5.23±1.23
	^{170}Hf	6.59±1.98	9.31±1.64
	^{171}Hf	5.86±1.72	7.85±1.51
	^{172}Ta	6.59±2.03	5.82±1.29
	^{173}Hf	4.87±0.85	4.65±1.16
	^{174}Ta	5.09±1.03	6.11±1.33
	^{175}Ta	12.62±3.34	11.04±1.79
	^{176}Ta	7.61±0.52	6.40±1.32
	^{177}W	15.34±3.88	14.83±2.07
	^{178}Ta	4.65±0.89	5.82±1.30
	^{181}Re	3.08±1.31	4.07±1.09
	^{184}Ta	1.76±0.62	2.04±0.77
	^{187}W	8.54±3.04	9.89±1.69
Pb	^{206}Bi	4.59±1.55	5.30±1.11
	^{204}Bi	4.51±0.88	3.61±0.86
	^{204}Pb	17.60±1.04	20.95±2.24

Table 1 (continue)

1	2	3	4
Pb	^{203}Pb	10.23±1.72	13.24±1.25
	^{202}Bi	2.96±0.69	2.65±0.33
	^{202m}Pb	6.36±1.22	7.70±1.0
	^{201}Pb	5.59±0.67	7.22±0.92
	^{200}Bi	3.60±1.39	2.89±0.73
	^{200}Tl	5.28±0.57	5.06±0.86
	^{199}Pb	5.96±1.85	4.21±0.70
	^{199}Tl	5.31±1.25	6.26±1.22
	^{198}Tl	2.79±0.32	3.98±0.69
	^{198m}Tl	2.41±0.60	3.98±0.69
	^{196}Tl	4.55±0.47	4.09±0.71
	^{195}Tl	7.10±2.1	4.21±0.70
	^{194m}Tl	2.52±1.14	3.7±0.68
	^{193}Tl	3.75±1.19	4.33±0.80
	^{193}Hg	1.33±0.71	2.41±0.54
	^{192}Tl	2.61±0.87	3.85±0.68
	^{192}Au	0.96±0.30	1.94±0.69
	^{191}Au	0.77±0.17	1.09±0.33
	^{191}Pt	2.03±0.67	1.20±0.43
	^{190}Au	0.90±0.28	1.44±0.44
	^{186}Ir	0.22±0.09	0.40±0.13
	^{185}Ir	1.21±0.44	0.97±0.38
	^{184}Ir	0.54±0.17	0.82±0.25
	^{182m}Re	0.51±0.12	0.40±0.15
	^{181}Os	0.84±0.20	1.08±0.39
	^{181}Re	0.99±0.19	1.44±0.32
	^{177}W	2.13±0.67	1.46±0.49
	^{176}Ta	0.87±0.16	0.72±0.23
	^{174}Ta	1.21±0.30	1.45±0.53
	^{171}Hf	3.50±1.35	4.09±0.97
	^{170}Hf	2.30±0.90	3.14±0.83
	^{169}Lu	0.31±0.06	0.36±0.19
	^{166}Yb	1.93±0.53	2.19±0.91
	^{166}Tm	0.16±0.04	0.18±0.09
	^{161}Er	0.78±0.19	0.93±0.37
	^{160}Er	2.16±0.52	1.82±0.83

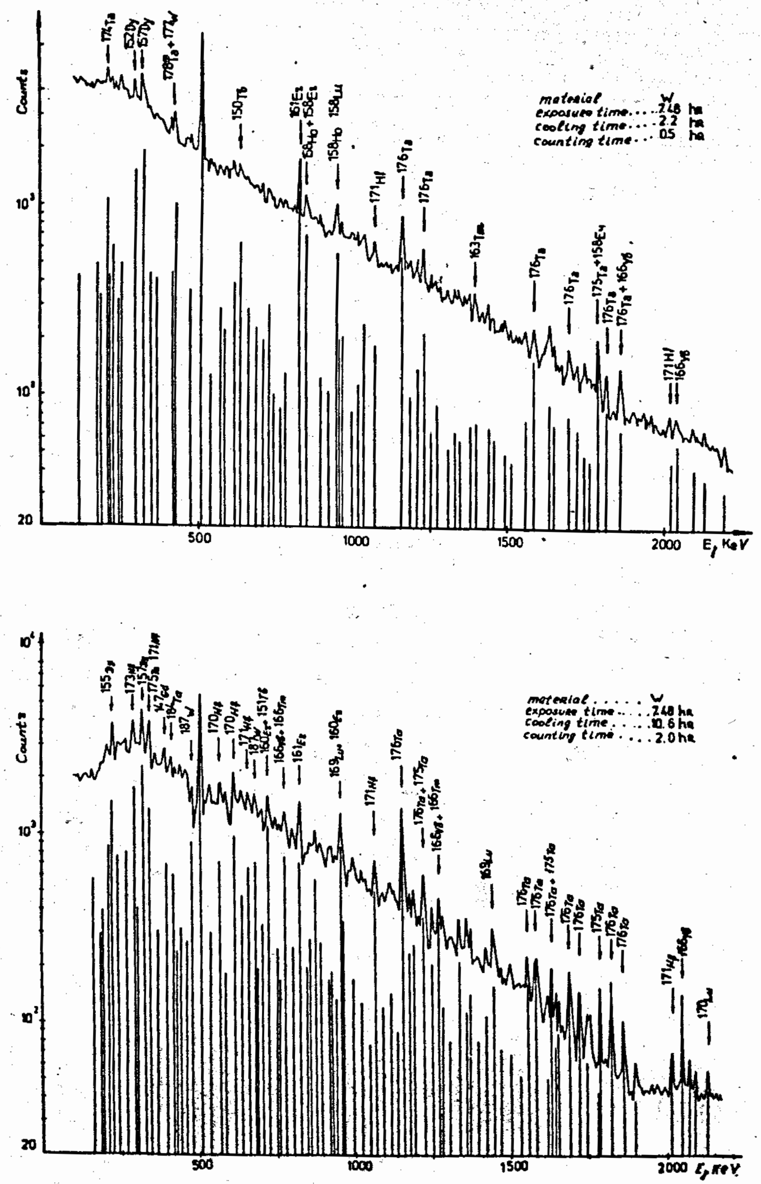

Fig. 1. γ -radiation spectrum from tungsten target. Proton energy-1.1 GeV. Exposure time-7.48 hr. The upper drawing - cooling time is 2.2 hr, counting time - 30 min; the lower drawing - cooling time is 10.6 hr, counting time - 2.0 hr.

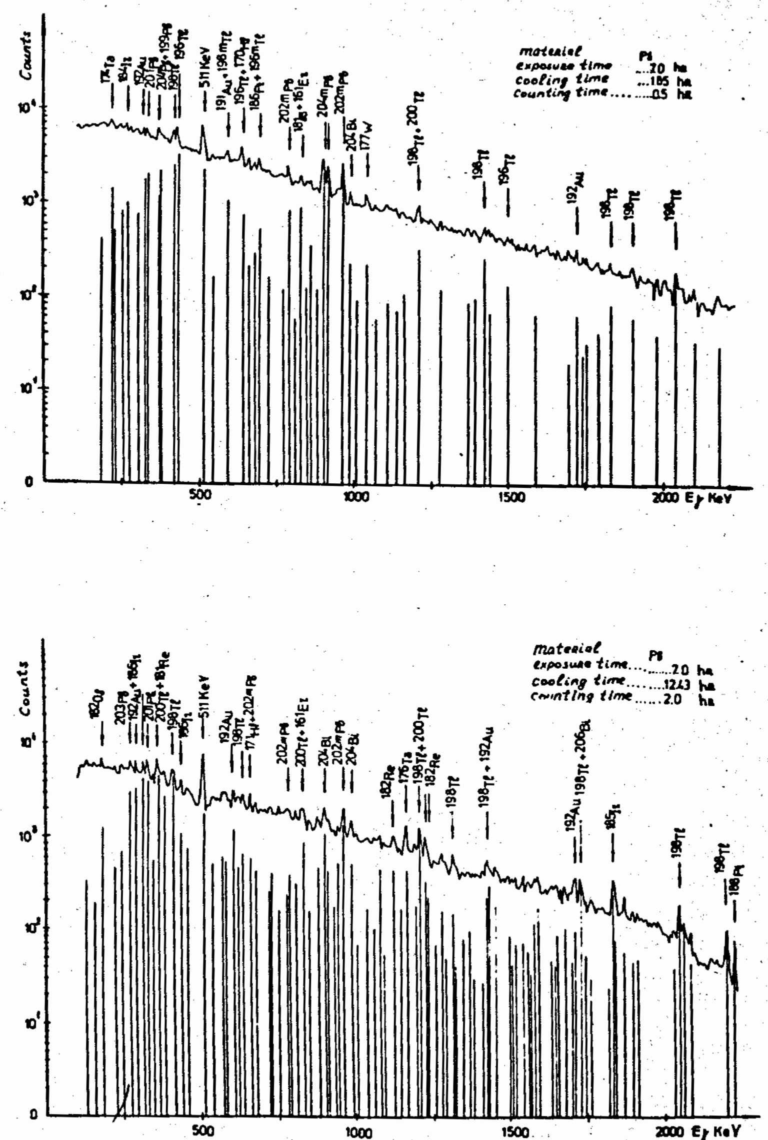

Fig. 2. γ -radiation spectrum from lead target. Proton energy-1.1 GeV. Exposure time-7.0 hr.The upper drawing - cooling time is 1.85 hr, counting time - 30 min; the lower drawing - cooling time is 12.43 hr, counting time - 2.0 hr.

1 to 5 mm thick. The intensity of the beam of bombarding particles was about 10^6 protons/pulse, their integral flux over the exposure time reached up to 2×10^{10}.

Monitoring of the beam and direction of induced γ-activity have been carried out in the same way as in/1/.

The yields of radionucleides in tungsten and lead targets 22.73 g/cm² and 34.02 g/cm² thick measured at energy of bombarding protons of 1.1 GeV are presented in table 1. The yields of activation products in a lead target are in good agreement with the data from/3,4/ for inset target, placed on the axis of massive lead targets at a depth of 50-60 mm from its front plates, bombarded by 1.0 and 1.1 GeV protons.

It is necessary to mention that out of 30 γ-emitters identified in tungsten target, 8 have a half decay time which is less than one hour, the most short living one (^{169}Hf) has a half decay time $T_{1/2}$ = 3.25 min.

Apparatus spectra of γ-radiation from activated targets are presented on figs.1, 2. The most intensive identified emitters are marked with arrows.

DISCUSSION

The procedure of calculation of activation γ-activity characteristics is covered in/1/, where further references can be found.

The average data for theoretically and experimentally defined yields of radionuclides in lead and tungsten are presented in Table 1. It is clear that these values are in good agreement. The same could be said about the data from Table 2, where the data on experimentally determined yields of nuclear reactions products for a massive lead target from ref./3/ and the results of our calculations for energy of bombarding protons are presented.

While testing the internuclear cascade model in the matter, main interest is the distribution of products of nuclear reactions along the depth of massive targets, dimensions of which are comparable to ionization path of bombarding particles. Distributions of measured yields of several nuclides from/3/ along the depth of the cylindrical lead target calculated by means of interpolation of the data over the target radius are shown in fig. 3. The results of our calculations using the "CASCADE" complex are also presented there with dashed lines. For the most part these distributions possess a stressed maximum on a depth of 5-12 cm, which corresponds to the utmost intensity of cascade particles shower, and

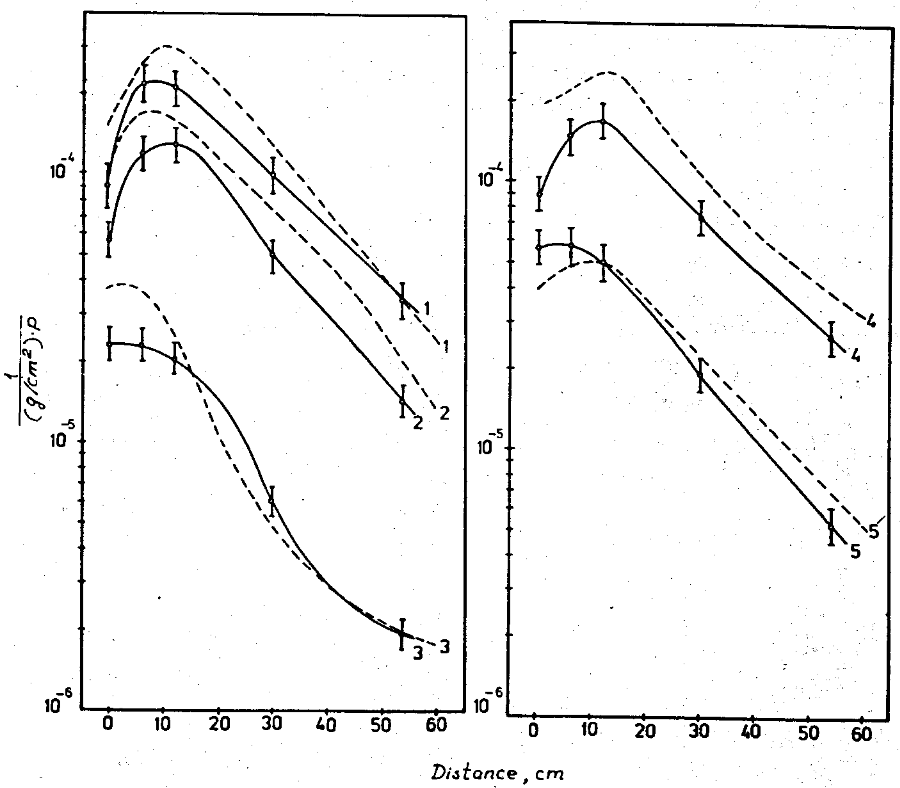

Fig. 3. Nuclide yields distribution along the lead target depth. Incident protons with energies 1.0 GeV. Solid lines - results of the measurements from/3/, dashed lines - our calculations. 1 - ^{201}Pb, 2 - ^{202m}Pb, 3 - ^{193m}Hg, 4 - ^{199}Tl, 5 - ^{192}Hg.

a subsequent smooth decrease along the increasing depth. Taking account of experimental errors and statistical errors of calculations (20-40%) both theoretical and experimental data present good consent.

As follows from the analysis of the data presented in Table 1 the average values of experimental and calculated yields differ no more than by 25-35%, that is by the value, comparable to statistical errors of measured and calculated data. The agreement can be even somewhat improved by the increase in statistics of Monte-Carlo calculations up to 10^6-10^7 events, more careful consideration of time-dependent fluctuations of incident proton beam, employment of more precise nuclear constants, making use of other specifics of the experiment.

Table 2

Yields of radionuclides (in units of 10^{-2} reactions/proton) from a lead target 200 mm in diameter and 600 mm in length. Experimental data from /3/ with errors 20-40% and our calculation results are presented. Incident proton energy 1.0 GeV

Nuclide	Half-decay period	Yield from /3/	Our results
^{206}Bi	6.24 days	0.64	1.04±0.16
^{204}Bi	11.22 hr	0.69	0.89±0.14
^{203}Bi	11.76 hr	0.79	0.71±0.13
^{202m}Pb	3.53 hr	4.0	5.6±0.4
^{201}Pb	9.33 hr	7.66	9.32±0.65
^{199}Tl	7.42 hr	5.88	4.22±0.32
^{198}Tl	5.3 hr	5.9	4.92±0.35
^{195m}Hg	41.6 hr	0.46	0.40±0.10
^{193m}Hg	11.8 hr	0.67	0.84±0.14
^{192}Hg	4.9 hr	1.71	1.94±0.21
^{196}Au	6.18 days	0.16	0.19±0.06
^{194}Au	39.5 hr	0.32	0.35±0.09
^{191}Pt	2.90 days	2.4	3.59±0.29
^{189}Pt	10.89 hr	3.58	2.95±0.26
^{186}Ir	15.8 hr	0.52	1.14±0.17
^{185}Os	93.6 days	1.45	1.93±0.22
^{183}Os	13.0 hr	0.74	0.96±0.15
^{175}Hf	70.0 days	0.77	0.84±0.14
^{173}Hf	23.9 days	0.74	1.06±0.16
^{171}Lu	8.22 days	0.53	0.77±0.13

Photopeaks of the calculated spectrum of γ-radiation from activated samples are shown in figs.1 and 2 with the segments of straight lines with a height equal to the area of the corresponding calculated photopeak, and their position on the energy scale corresponds to the γ-quanta energies. More detailed data together with half decay periods of radioemitters and energies of emitted γ-quanta used for nuclide identification are listed in Table 3. In cases when the energy resolvation of the spectrometer appeared to be unsufficient to separate closely positioned peaks of two different nuclides

Table 3

Number of counts in the peaks of full absorption of apparatus and model spectra of γ-radiation from activated target. Statistical errors of calculated data are shown

Target	Nuclide	Half-decay period	γ-quanta energy, keV	Yield of γ-quanta,%	Counts exper	Counts calc
1	2	3	4	5	6	7
W	^{150}Tb	3.55 hr	638.0	72.3	571±132	811±251
	^{151}Tb	17.6 hr	479.0	16.0	691±152	983±252
	^{187}W	23.9 hr	479.5	25.3		
	^{152}Dy	2.38 hr	256.9	97.5	371±129	639±149
	^{152}Tb	17.5 hr	344.3	57.0	1524±220	976±367
	^{155}Dy	10.0 hr	226.9	68.8	1064±244	1572±421
	^{157}Dy	8.1 hr	326.2	93,2	2548±246	2380±524
	^{158}Er	2.25 hr	218.2	43.0	376±154	670±158
	^{158}Ho	11.3 min		43.0		
	^{159}Er	36 min	649.3	25.0	178±72	280±59
	^{160}Er	28.6 hr	879.1	23.0	179±74	254±62
	^{160}Er	28.6 hr	961.9	21.0	763±110	1260±397
	^{169}Lu	34.06hr	960.6	20.3		
	^{161}Er	3.24 hr	826.5	61.5	1843±114	1690±638
	^{161}Tm	38 min	1648.1	19.5	72±31	51±17
	^{163}Tm	1.81 hr	1434.3	7.6	106±34	75±30
	^{165}Tm	30.06hr	242.9	35.5	296±160	454±214
	^{165}Tm	30.06hr	297.4	13.8	1705±264	2062±516
	^{173}Hf	23.9 hr	297.0	33.8		
	^{166}Yb	2.36 days	1273.4	20.1	163±51	294±74
	^{166}Tm	7.71 hr		17.4		
	^{169}Hf	3.25 min	492.9	88.9	143±71	178±36
	^{169}Lu	34.06 hr	1449.7	9.4	177±41	152±36
	^{168}Hf	25.9 min	896.0	21.0	182±68	132±32
	^{168m}Lu	6.7 min		16.0		
	^{162}Tm	21.7 min	899.9	5.6		
	^{170}Hf	16.0 hr	572.9	18.5	527±158	761±155
	^{171}Hf	12.1 hr	662.0	14.8	496±146	685±131
	^{172}Ta	36.8 min	214.1	51.8	350±108	309±59
	^{174}Ta	62.6 min	206.5	57.0	1147±231	1445±303
	^{175}Ta	10.5 hr	1793.1	4.4	142±41	124±20
	^{176}Ta	8.08 hr	1159.3	23.8	1427±83	1195±255

Table 3 (continue)

1	2	3	4	5	6	7
W	^{177}W	2.25 hr	1036.4	10.2	372±94	357±50
	{ ^{178m}Ta	2.45 hr	426.4	96.9	843±162	1159±209
	^{177}W	2.25 hr	427.0	13.1		
	^{181}Re	20.0 hr	365.5	56.4	427±183	582±155
	^{184}Ta	8.55 hr	414.0	73.9	483±172	577±162
	^{187}W	23.9 hr	685.8	31.6	535±140	703±120
Pb	{ ^{160}Er	28.6 hr	728.1	36.0	485±117	409±123
	^{160m}Ho	5.02 hr		30.0		
	{ ^{166}Yb	2.36 days	1273.4	20.1	208±57	236±75
	^{166}Tm	7.7 hr		17.4		
	{ ^{169}Lu	34.06 hr	960.6	20.3	997±135	1108±149
	^{202m}Pb	3.53 hr	960.7	91.4		
	^{170}Hf	16.0 hr	620.7	22.9	187±73	255±67
	^{171}Hf	12.1 hr	1071.4	11.9	202±78	236±56
	^{174}Ta	62.6 min	206.5	57.0	1112±272	1333±532
	^{176}Ta	8.08 hr	1159.3	23.8	561±101	468±149
	^{177}W	2.25 hr	1036.4	10.2	278±87	191±64
	{ ^{161}Er	3.24 hr	826.5	61.5	944±140	1119±310
	^{181}Os	1.75 hr	827.0	20.8		
	{ ^{181}Re	20.0 hr	365.5	56.4	2238±254	3054±549
	^{200}Tl	26.1 hr	367.9	87.2		
	^{182m}Re	12.7 hr	1121.4	31.9	466±104	372±142
	^{184}Ir	3.02 hr	264.0	67.5	1128±291	1697±527
	^{185}Ir	14.0 hr	1828.8	9.8	183±66	152±60
	^{186}Ir	15.8 hr	434.8	33.8	543±212	999±340
	^{190}Au	42.8 min	295.8	72.5	513±161	817±248
	^{191}Au	3.18 hr	586.4	16.0	783±168	1107±332
	^{191}Pt	2.90 days	538.9	13.7	348±115	206±74
	^{192}Au	5.03 hr	316.5	78.3	1654±488	3344±1180
	{ ^{192}Tl	9.4 min	422.8	81.0	541±131	807±101
	^{202m}Pb	3.53 hr	422.1	85.5		
	^{193}Hg	3.80 hr	861.1	13.0	166±91	301±67
	^{193}Tl	21.6 min	1044.7	28.0	149±76	172±29
	^{194m}Tl	32.8 min	749.0	77.0	137±62	201±37
	^{195}Tl	1.16 hr	1363.9	9.07	172±51	102±17

Table 3 (continue)

1	2	3	4	5	6	7
	^{196}Tl	1.84 hr	425.7	83.7	2072±205	1863±318
	^{198}Tl	5.3 hr	411.8	81.8	2291±252	3270±568
	{ ^{198m}Tl	1.87 hr	587.2	51.0	902±162	1206±256
	^{191}Au	3.18 hr	586.4	16.0		
	^{199}Pb	90 min	1135.0	11.5	264±82	186±31
	^{199}Tl	7.42 hr	455.5	12.3	561±132	661±129
	^{200}Bi	36.4 min	1026.5	100.0	188±72	151±38
	^{200}Tl	26.1 hr	1205.7	29.9	624±65	598±102
	^{201}Pb	9.33 hr	331.2	78.7	1844±220	2383±305
	^{202m}Pb	3.53 hr	787.0	49.7	869±146	1050±131
	{ ^{202}Bi	1.72 hr	657.5	60.6	846±146	774±97
	^{202m}Pb	3.53 hr	657.5	32.3		
	^{203}Pb	2.16 days	279.2	80.1	1494±219	1931±183
	^{204}Bi	11.22 hr	984.0	58.0	619±117	494±118
	^{204m}Pb	67.2 min	899.2	99.2	3454±151	4102±439
	^{206}Bi	6.24 days	803.1	98.9	248±84	287±60

or when γ-quanta are emitted by nuclides with similar energy (as a rule, they related to the same isobaric chain of radioactive transformations[7]), the data for unresoled (summarized) peaks are shown in the Table. The corresponding nucleides in the Table are marked with figure brackets.

As with the data from Tables 1 and 2 and fig.3 discussed above the discrepancy between theoretical and experimental data as a rule does not exceed 25-35%. However, in about 10% of all cases it reaches 60-80%. Possessing such an accuracy, the model, based on the cascade-evaporation mechanism of nuclear interactions, could be used to evaluate and to forcast γ-radiation from materials activated by hadrons with energies up to 10-20 GeV. Substantial increase in accuracy requires more detailed simulation of inelastic hadron-nucleus interactions. The adopted internuclear cascade model with the evaporation from residual nucleus, which reproduces accurately the behaviour of average values, is already insufficient to achieve this goal. In the energy range exceeding 10 GeV, cascade models with quark-gluon strings[1] should be used to describe nuclear interactions.

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