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INVESTIGATIONS OF NUCLEI-PRODUCTS FORMATION IN TARGET AND CONSTRUCTION MATERIALS OF ELECTRO-NUCLEAR INSTALLATIONS IRRADIATED BY 1.5 GeV AND 130 MeV PROTONS.

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Different versions of installations for transmutation or incineration of actinides and long-lived fission products are being considered nowadays; the source of neutrons in these installations is supposed to be a nuclon-meson cascade arising under interaction of 0.8 - 1.5 GeV proton beam and the substance of a target. "Heavy" materials: eutectics of lead and bismuth or tangsten, are supposed to be used as targets [1, 2]. In correspondence with this, measurements of the cross sections of spallation of nuclides of these materials under impact of the protons of different energies are going on in ITEP. Nuclides used as construction materials for the accelerator are also being measured. Numerical simulation of experimental results with utilization of the codes HETC, INUCLE, CEM95 capable to calculate the process of nuclon-meson cascade in the investigated targets is being carried out.

The character of description of the reactions of spallation may be presented in the form:

$$ {}^{A_M}_{Z_M}T(p,ypxn){}^{A}_{Z}P \qquad (1), \text{ where} $$

T, P - are chemical synbols of the elements,

$A_M Z_M$ - correspondingly mass number and the charge of a nuclon used as the target;

y, x - number of protons and neutons knocked out of an investigated nuclide;

A, Z - correspondingly mass number and the charge of a nuclide produced as a result of the reaction of spallation

$$(A = A_M + 1 - y - x, Z = Z_M + 1 - y)$$

Methodics of experimental definition of the cross sections of reactions of spallation.

Nuclide ${}^{A}_{Z}P$ produced in the result of interaction of protons and investigated nuclide may be radioactive as well as stable. The cross sections of formation of radioactive products of spallation reactions are being defined in this work. That is why the methodics of experimental definition of the investigated cross sections is constructed on utilization of a relative method with utilization of γ-spectrometry with Ge-Li detectors of high resolution.

Reaction of the type is used as monitor

$${}^{27}_{13}Al(p,3pn){}^{24}_{11}Na \qquad (2)$$

In this case the expression for calculation of reactions cross sections of spallation may be presented in the form:

$$\frac{\sigma(p,ypxn)}{\sigma(p,3pn)} = \frac{S^{AP}}{S^{^{24}Na}} \frac{\lambda^{^{24}Na}}{\lambda^{AP}} \frac{Y^{^{24}Na}}{Y^{AP}} \frac{\varepsilon^{^{24}Na}}{\varepsilon^{AP}} \frac{N^{^{27}Al}}{N^{AMT}} \frac{K_{\mu}^{AMT}}{K_{\mu}^{^{27}Al}} \frac{f(t)^{^{24}Na}}{f(t)^{AP}} \qquad (3),$$

where

$\frac{\sigma(p,ypxn)}{\sigma(p,3pn)}$ — is the ratio of the values of the cross sections of investigated standard reaction;

$\frac{S^{AP}}{S^{^{24}Na}}$ — is the ratio of intensities of γ-irradiation produced in an experimental sample and in the standard one;

$\frac{\lambda^{^{24}Na}}{\lambda^{AP}}$ — is the ratio of decay constants of nuclides produced in an experimental sample and in the standard one;

$\frac{Y^{^{24}Na}}{Y^{^{A}P}}$ — the ratio of absolute quanta outputs of nuclides produced in an experimental sample ind in the standard one;

$\frac{\varepsilon^{^{24}Na}}{\varepsilon^{^{A}P}}$ — the ratio of relative effecincies of spectrometry registration under energies corresponding γ-lines of nuclides produced in an experimental sample and in the standard one;

$\frac{N^{^{27}Al}}{N^{AMT}}$ — ratio of number of nuclei in experimental and standard samples;

$\frac{K_{\mu}^{AMT}}{K_{\mu}^{^{27}Al}}$ — ratio of corrections defining absorption of γ-quanta by the material of an experimental sample and of a standard one;

$\frac{f(t)^{^{24}Na}}{f(t)^{^{A}P}}$ — ratio of time corrections.

The number of nuclei in an experimental sample and in a standard one are found with the aid of a gravimetric method.

The experiments are being carried out at the beam ejected out of the proton synchrotron of ITEP U-10 with the aid of the system of slow ejection (fig. 1).

Under every irradiation cycle a thin experimental sample together with a standard and an aluminium layer between them were installed in perpendicular direction to protons trajectories. Standard sample, in the shape of a thin aluminium foil, was placed in front of an experimental sample. The diameters of the experimental sample, a layer and of standard were strictly identical and equal 10.5 mm.

Measuring installation consists of spectrometric channel containing germanium detector GC2518, a modulus 1510 (analog-digital converter, an amplifier, a set of high voltage), a plate S-100 which jointly with an IBM PC emulates a multichannel analyser. Energy resolution of the installation is 1.8 keV at the line 1332.5 keV of ^{60}Co .

Processing of the measured γ-spectra is being realized with the aid of a set of codes ASPRO realized in an IBM PC [3]. The spectra processed are combined in a single file which is an initial one for the code SIGMA. Using the value of energy of γ-line, calculated value of half-life and nuclear data base GDISP [4], this code automatically identifies produced nuclides and calculates the cross sections.

As it is seen from the formul [1] calculation of a measured cross section is carried out with the aid of relative efficiency of registration of the spectrometer. Procedure of implementation is based upon utilization of γ-sources with rather high number of γ-lines with well studied relative radiation intensities in the spectrum. ^{228}Th, ^{152}Eu, ^{110m}Ag and additionally ^{137}Cs and ^{60}Co were used as such sources. The dependence of relative efficiency of the spectrometer registration in energy range from 36.5 to 2650 keV is presented in the fig. 2.

The value of k_{μ} is found in accordance with papers [5,6].

Results

The results of experimental definition of the reactions of spallation cross sections of ^{209}Bi, ^{208}Pb, ^{207}Pb, ^{206}Pb, ^{65}Cu and ^{63}Cu by 130 MeV and 1.5 GeV protons are presented in this work. The characteristics of experimental samples, their isotopic composition and the modes of irradiation are presented in the tables 1 and 2.

Table 1.

Characteristics and the modes of irradiation of the samples

	Diameter (mm)	Thickness (mm)	Weight (mg)	Integral flux	Protons energy
^{209}Bi (100%)	10.5	0.46	368.05	2.41E+13	1.5 ~~ÃýÂ~~ GeV
	10.5	0.47	372.25	1.12E+13	1.5 ~~ÃýÂ~~ GeV
	10.5	0.68	564.70	1.07E+13	1.5 ~~ÃýÂ~~ GeV
	10.5	0.51	432.35	1.53E+11	130 ~~ÌýÂ~~ MeV
^{208}Pb (97.2%)	10.5	0.13	117.00	1.31E+13	1.5 ~~ÃýÂ~~ GeV
	10.5	0.155	132.87	1.56E+13	1.5 ~~ÃýÂ~~ GeV
	10.5	0.155	125.92	1.47E+11	130 ~~ÌýÂ~~ MeV
^{207}Pb (93.2%)	10.5	0.14	110.00	1.18E+14	1.5 ÃýÂ GeV
	10.5	0.13	106.85	9.08E+12	1.5 ~~ÃýÂ~~ GeV
	10.5	0.17	136.30	1.43E+11	130 ~~ÌýÂ~~ MeV
^{206}Pb	10.5	0.13	116.85	1.64E+13	1.5 ~~ÃýÂ~~ GeV

(92.3%)	10.5	0.13	126.62	1.42E+13	1.5 ~~ÃýÂ~~ GeV
	10.5	0.13	122.77	1.40E+11	130 ~~ÌýÂ~~ MeV

^{63}Cu (99.6%)	10.5	0.63	417.20	1.31E+13	1.5 ~~ÃýÂ~~ GeV
	10.5	0.63	397.05	7.54E+12	1.5 ~~ÃýÂ~~ GeV
	10.5	0.63	425.55	1.43E+11	130 ~~ÌýÂ~~ MeV
^{65}Cu (98.7%)	10.5	0.73	508.10	1.36E+13	1.5 ~~ÃýÂ~~ GeV
	10.5	0.73	527.45	9.58E+12	1.5 ~~ÃýÂ~~ GeV
	10.5	0.73	521.60	1.37E+11	130 ~~ÌýÂ~~ MeV

Table 2.

Isotopic composition of the samples.

^{204}Pb	^{206}Pb	^{207}Pb	^{208}Pb
< 0.01	0.87	1.93	97.2
< 0.01	1.39	93.2	5.41
0.19	92.3	5.1	2.41

^{63}Cu	^{65}Cu
99.6	0.4
1.3	98.7

The spectra of γ-radiation of the reactions products in experimental samples as the results of irradiation by protons are presented in the figures 3, 4 and 5.

The values of the cross sections of monitoring reaction $^{27}Al(p,3pn)^{24}Na$ under energies of protons 1.5 GeV and 130 MeV were calculated from the approximation of the form $\sigma = \sum_{i=0}^{k} a_i * E^i$ (GeV) with coefficients obtained in RI named after V.G. Khlopin.

Values of approximation coefficients are presented in the table 3.

Table 3.

Values of approximation coefficients,

Parameters of ai	Interval of protons energy (GeV)		
	0.100 — 0.350	0.350 — 0.800	0.800 — 2600
	k = 4	k = 5	k = 4
à0	0.16082579E+2	0.91163994E+0	0.10809485E+2
à1	-0.98011691E+2	0.72710174E+2	0.12760849Å+1
à2	0.48105521E+3	-0.22074848E+3	-0.25036816E+1

à3	-0.92886532E+3	0.33836270E+3	0.10439362E+1
à4	0.63086480E+3	-0.25781415E+3	-0.13817290E+0
à5		0.77078179E+2	

The results of calculations of the cross sections of spallation of ^{209}Bi, ^{208}Pb, ^{207}Pb, ^{206}Pb, ^{65}Cu and ^{63}Cu by 130 MeV and 1.5 GeV protons are presented in the tables 2, 3 and 4. Analysis of the errors of the obtained results shows that their values are in the range appr. from 10% to 25%. The main contribution into the calculated error are brought by indefiniteness of the values of nuclear data. Presented experimental results are of preliminary character as the work on measurements and analysis of γ-spectra and on calculation of cross section of spallation is going on now; for isotopes of Cu it is completed to 80% - 85% and for Bi and isotopes of Pb - to 20% - 25%. Besides, it is supposed that experimental samples will be weighted for the second time by more accurate analytical scales.

Jointly with experiments on measuring of cross sections of ^{209}Bi, ^{208}Pb, ^{207}Pb, ^{206}Pb, ^{65}Cu and ^{63}Cu by 130 MeV and 1.5 GeV protons modelling or simulation of these results was being carried out with the aid of cascade-vapourizing (HETC), cascade-vapourizing-fissioning (INUCL) and cascade-exciton (CEM95) codes [7 - 13]. The INUCL and CEM95 codes are made 100000 generations in each calculation, and HETC — 50000 ones.

The experimental results are presented in the tables 4, 5, 6 and 7.
The calculation results are presented in the tables 8, 9, 10,11, 12 and 13.

Table 4.

Experimental values of cross section of spallation of ^{63}Cu and ^{65}Cu under protons energy 1.5 GeV

		^{63}Cu		^{65}Cu	
Nuclide	$T_{½}$ (hour)	σ (mb)	Δσ	σ (mb)	Δσ
^{7}Be EC	1279	6.5	0.8	4.9	0.6
^{24}Na B-	15.02	1.6	0.2	1.7	0.2
^{28}Mg B-	20.91	0.16	0.02	0.2	0.03

^{42}K B-	12.36	2.6	0.3	3.6	0.4
^{43}K B-	22.3	1.0	0.1	1.6	0.2
^{44}Sc EC	3.927	6.2	1.2	4.2	1.0
^{44}Sc IT	58.608	7.5	0.8	5.4	0.6
^{46}Sc B-	2011.4	6.3	0.7	8.0	1.0
^{47}Sc B-	80.28	2.6	0.3	4.0	0.5
^{48}Sc B-	43.7	0.4	0.06	1.0	0.1
^{48}V EC	383.38	9.3	1.0	7.0	0.8
^{48}Cr EC	21.56	0.4	0.04	0.2	0.02
^{51}Cr EC	664.9	30.1	3.2	22.0	2.5
^{52}Mn EC	0.35167	12.1	1.3	1.6	0.2
^{52}Mn EC	134.18	5.8	0.6	4.1	0.5
^{54}Mn EC	7490.9	19.1	2.1	22.9	2.6
^{56}Mn B-	2.5785	2.2	0.3	5.2	0.6
^{59}Fe B-	1067.9	0.6	0.07	4.1	0.5
^{55}Co EC	17.53	1.1	0.2	0.5	0.06
^{56}Co EC	1850.9	5.7	0.6	3.2	0.4
^{57}Co EC	6523.2	33.6	3.5	21.2	2.5
^{58}CoEC	1702	30.0	1.6	25.0	2.8
^{57}Ni B+	35.65	0.8	0.1	0.3	0.03
^{61}Cu EC	3.408	14.5	3.0	4.8	1.0

Table 5.

Experimental values of cross section of spallation of ^{63}Cu and ^{65}Cu under protons energy 130 MeV

		^{63}Cu		^{65}Cu	
Nuclide	$T_{1/2}$ (hour)	σ (mb)	Δσ	σ (mb)	Δσ
^{56}Mn B-	2.5785	1.1	0.2	2.4	0.2
^{57}Co EC	6523.2	71.	9.	34.	4.0
^{58}Co EC	1702	59.	8.	47.	5.0
^{61}Cu EC	3.408	79.	18.	22.	5.0

Table 6.

Experimental values of cross section of spallation of ^{209}Bi, ^{208}Pb, ^{207}Pb and ^{206}Pb under protons energy 1.5 GeV

		^{209}Bi		^{208}Pb		^{207}Pb		^{206}Pb	
Nuclide	$T_{1/2}$ (hour	σ (mb)	Δσ	σ (mb)	Δσ	σ (mb)	Δσ	σ (mb)	Δσ
^{206}Bi EC	149.8	29.	3.						
^{205}Bi EC	367.5	32.	4.						
^{204}Bi EC	11.22	28.	4.	3.3	0.4	3.4	0.7	3.1	0.4
^{203}Bi EC	11.76	21.	3.						
^{204}Pb IT	1.12	5.9	1.3			10.2	1.7	10.2	2.1
^{203}Pb EC	51.873	47.	5.	23.	3.	34.	3.	39.	4.
^{202}Pb IT	3.53	3.2	0.4	5.	1.	5.8	0.7	6.7	1.0
^{201}Pb EC	9.33	39.	5.	18.	2.	24.	3.	29.	3.
^{200}Pb EC	21.5	29.	3.	16.	2.	23.	3.	21.	2.
^{199}Pb EC	1.5	35.	9.	22.	8.	28.	7.	31.	8.
^{202}Tl EC	293.52	6.1	0.7	15.	2.	17.	2.		
^{198}Au B-	64.704	0.4	0.1	2.3	0.2	1.7	0.2		
^{179}Re EC	0.325	22.	3.	35.	7.			47.	9.
^{169}Lu EC	34.06	18.	2.	16.	2.	20.	2.	18.	2.
^{103}Ru B-	942.24	5.	0.6						
^{67}Cu	61.92	5.6	0.7	8.9	1.0	11.	1.	11.	1.

B-									

Table 7.

Experimental values of cross section of spallation of ^{209}Bi, ^{208}Pb, ^{207}Pb and ^{206}Pb under protons energy 130 MeV

		^{209}Bi		^{208}Pb		^{207}Pb		^{206}Pb	
Nuclide	$T_{½}$ (hour)	σ (mb)	Δσ	σ (mb)	Δσ	σ (mb)	Δσ	σ (mb)	Δσ
^{203}Pb EC	51.873	222	26	157	17	168	18	197	26
^{201}Pb EC	9.33	127	15	169	19	193	22	200	28
^{200}Pb EC	21.5	185	24	162	20	173	21	190	15

Table 8.

Calculated values of cross section of spallation of ^{63}Cu and ^{65}Cu under protons energy 1.5 GeV

Nuclide	HETC		CEM95		INUCL	
	^{63}Cu	^{65}Cu	^{63}Cu	^{65}Cu	^{63}Cu	^{65}Cu
^{7}Be				0.01		
^{24}Ne → ^{24}Na			3.3	2.8	4.8	0.4
^{28}Mg			0.02		0.4	0.45
^{42}K		0.02	3.9	5.3	10.1	10.8
^{43}Ar → ^{43}K			0.8	1.3	1.9	2.8
^{44}Sc	20.4	21.9	12.7	11.5	14.2	12.2
^{46}Sc		0.04	11.2	12.7	11.6	13.0
^{47}Ê → ^{47}Ca → ^{47}Sc		0.05	2.1	3.4	2.6	3.8
^{48}Sc			0.6	1.1	3.3	4.5
^{48}Cr → ^{48}V	24.3	24.8	12.0	10.2	17.6	15.0

^{48}Cr			0.1		0.7	0.5
$^{51}Mn \rightarrow {}^{51}Cr$	25.7	24.0	17.9	15.6	18.9	18.3
$^{52}Fe \rightarrow {}^{52}Mn$	27.5	25.0	11.6	8.9	19.7	16.8
^{54}Mn	1.2	1.2	14.6	15.4	17.4	17.5
$^{56}Cr \rightarrow {}^{56}Mn$	0.4	0.7	1.6	3.3	4.6	6.8
^{59}Fe	1.0	2.1	0.8	2.3	0.9	1.9
^{55}Co	0.8	0.6	1.52	0.7	3.6	1.9
$^{56}Ni \rightarrow {}^{56}Co$	40.6	69.3	11.7	7.9	12.9	8.1
$^{57}Ni \rightarrow {}^{57}Co$	38.5	47.6	17.4	13.1	12.8	11.7
^{58}Co	10.5	15.8	20.5	18.1	20.4	17.2
^{57}Ni	2.7	2.7	0.7	0.14	12.8	1.6
^{61}Cu	32.5	14.8	0.06	5.8	15.9	5.0

Table 9.

Calculated values of cross section of spallation of ^{63}Cu and ^{65}Cu under protons energy 130 MeV

Nuclide	HETC		CEM95		INUCL	
	^{63}Cu	^{65}Cu	^{63}Cu	^{65}Cu	^{63}Cu	^{65}Cu
$^{56}Cr \rightarrow {}^{56}Mn$			1.5	2.2	8.9	6.7
$^{57}Ni \rightarrow {}^{57}Co$	71.5	76.4	49.8	23.3	48.8	27.2
^{58}Co	77.1	1.5	62.1	41.9	88.7	76.3
^{61}Cu	79.2	66.3	47.2	25.3	45.7	33.2

Table 10.

Calculated values of cross section of spallation of ^{209}Bi, ^{208}Pb, ^{207}Pb and ^{206}Pb under protons energy 1.5 GeV of CEM95 code

Nuclide	CEM95			
	^{209}Bi	^{208}Pb	^{207}Pb	^{206}Pb
94.5% $^{206}Po \rightarrow {}^{206}Bi$	19.3	1.0	0.6	4.1
99.5% $^{205}Po \rightarrow {}^{205}Bi$	16.8	1.0	0.7	0.6
99.4% $^{204}Po \rightarrow {}^{204}Bi$	14.6	1.2	1.2	0.9
99.9% $^{203}Po \rightarrow {}^{203}Bi$	9.9	1.4	1.0	0.9
^{204}Pb	11.3	15.4	18.3	25.6

$0.008\%\ ^{207}Po \rightarrow\ ^{203}Pb$ $99.9\%\ ^{203}Po \rightarrow\ ^{203}Bi \rightarrow\ ^{203}Pb$	21.6	15.5	17.9	19.7
$5.5\%\ ^{206}Po \rightarrow\ ^{202}Pb$ $98\%\ ^{202}Po \rightarrow\ ^{202}Bi \rightarrow\ ^{202}Pb$	19.1	12.6	13.5	15.2
$5.5\%\ ^{206}Po \rightarrow 9.5\%\ ^{202}Pb \rightarrow\ ^{202}Tl$ $98\%\ ^{202}Po \rightarrow\ ^{202}Bi \rightarrow 9.5\%\ ^{202}Pb \rightarrow\ ^{202}Tl$	4.9	10.4	9.8	11.1
$98.4\%\ ^{201}Po \rightarrow\ ^{201}Bi \rightarrow\ ^{201}Pb$ $0.5\%\ ^{205}Po \rightarrow\ ^{201}Bi \rightarrow\ ^{201}Pb$	17.5	10.5	11.6	13.7
$86\%\ ^{200}Po \rightarrow\ ^{200}Bi \rightarrow\ ^{200}Pb$	15.7	8.1	9.9	11.2
$86\%\ ^{200}Po \rightarrow\ ^{200}Bi \rightarrow\ ^{200}Pb \rightarrow\ ^{200}Tl$	5.8	9.4	8.8	9.0
$88\%\ ^{199}Po \rightarrow\ ^{199}Bi \rightarrow\ ^{199}Pb$	15.0	7.6	8.0	10.9
$88\%\ ^{199}Po \rightarrow\ ^{199}Bi \rightarrow\ ^{199}Pb \rightarrow\ ^{199}Tl$	6.0	9.1	8.8	8.8
$30\%\ ^{198}Po \rightarrow\ ^{198}Bi \rightarrow\ ^{198}Pb$	12.9	6.2	7.5	8.1
^{198}Au	0.6	2.1	1.5	1.1
$^{203}Au \rightarrow\ ^{203}Hg$	0.8	3.3	3.0	2.6
$^{179}Ir \rightarrow\ ^{179}Os \rightarrow\ ^{179}Re$	5.0	5.8	5.2	4.8
$^{169}Re \rightarrow\ ^{169}W \rightarrow\ ^{169}Ta \rightarrow\ ^{169}Hf \rightarrow\ ^{169}Lu$ $^{173}Ir \rightarrow\ ^{169}Lu$	23.1	28.2	30.1	28.9
$^{103}Nb \rightarrow\ ^{103}Mo \rightarrow\ ^{103}Te \rightarrow\ ^{103}Ru$				
$^{67}Ni \rightarrow\ ^{67}Cu$				

Table 11.

Calculated values of cross section of spallation of ^{209}Bi, ^{208}Pb, ^{207}Pb and ^{206}Pb under protons energy 1.5 GeV of HETC code.

Nuclide	HETC			
	^{209}Bi	^{208}Pb	^{207}Pb	^{206}Pb
$94.5\%\ ^{206}Po \rightarrow\ ^{206}Bi$	25.8	5.6	3.9	0.9
$99.5\%\ ^{205}Po \rightarrow\ ^{205}Bi$	22.4	3.8	5.2	4.3
$99.4\%\ ^{204}Po \rightarrow\ ^{204}Bi$	19.8	3.2	4.6	4.9
$99.9\%\ ^{203}Po \rightarrow\ ^{203}Bi$	14.6	17.1	25.5	30.8
^{204}Pb	14.9	3.9	4.5	5.0
$0.008\%\ ^{207}Po \rightarrow\ ^{203}Pb$ $99.9\%\ ^{203}Po \rightarrow\ ^{203}Bi \rightarrow\ ^{203}Pb$	35.9	19.8	24.6	28.8
$5.5\%\ ^{206}Po \rightarrow\ ^{202}Pb$ $98\%\ ^{202}Po \rightarrow\ ^{202}Bi \rightarrow\ ^{202}Pb$	32.4	21.4	21.5	23.9

5.5% $^{206}Po \rightarrow$ 9.5% $^{202}Pb \rightarrow$ ^{202}Tl 98% $^{202}Po \rightarrow$ $^{202}Bi \rightarrow$ 9.5% $^{202}Pb \rightarrow$ ^{202}Tl	6.8	17.7	13.8	13.3
98.4% $^{201}Po \rightarrow$ $^{201}Bi \rightarrow$ ^{201}Pb 0.5% $^{205}Po \rightarrow$ $^{201}Bi \rightarrow$ ^{201}Pb	36.5	16.6	18.4	19.7
86% $^{200}Po \rightarrow$ $^{200}Bi \rightarrow$ ^{200}Pb	34.1	17.0	17.7	17.4
86% $^{200}Po \rightarrow$ $^{200}Bi \rightarrow$ $^{200}Pb \rightarrow$ ^{200}Tl	6.6	17.5	15.9	16.4
88% $^{199}Po \rightarrow$ $^{199}Bi \rightarrow$ ^{199}Pb	40.3	14.3	15.6	17.7
88% $^{199}Po \rightarrow$ $^{199}Bi \rightarrow$ $^{199}Pb \rightarrow$ ^{199}Tl	9.1	21.3	19.9	19.2
30% $^{198}Po \rightarrow$ $^{198}Bi \rightarrow$ ^{198}Pb	40.1	14.4	14.9	16.7
^{198}Au	0.2	0.8	1.0	1.1
$^{203}Au \rightarrow$ ^{203}Hg	0.6	4.4	4.2	3.0
$^{179}Ir \rightarrow$ $^{179}Os \rightarrow$ ^{179}Re		0.1		
$^{169}Re \rightarrow$ $^{169}W \rightarrow$ $^{169}Ta \rightarrow$ $^{169}Hf \rightarrow$ ^{169}Lu $^{173}Ir \rightarrow$ ^{169}Lu	36.9	34.6	34.6	34.5
$^{103}Nb \rightarrow$ $^{103}Mo \rightarrow$ $^{103}Te \rightarrow$ ^{103}Ru				
$^{67}Ni \rightarrow$ ^{67}Cu				

Table 12.

Calculated values of cross section of spallation of ^{209}Bi, ^{208}Pb, ^{207}Pb and ^{206}Pb under protons energy 1.5 GeV of INUCL code

Nuclide	INUCL			
	^{209}Bi	^{208}Pb	^{207}Pb	^{206}Pb
94.5% $^{206}Po \rightarrow$ ^{206}Bi	14.5	0.7	0.2	
99.5% $^{205}Po \rightarrow$ ^{205}Bi	10.1	0.7	0.7	0.2
99.4% $^{204}Po \rightarrow$ ^{204}Bi	6.0	0.8	0.8	0.4
99.9% $^{203}Po \rightarrow$ ^{203}Bi	9.7	10.9	15.3	33.5
^{204}Pb	3.5	0.5	0.9	0.8
0.008% $^{207}Po \rightarrow$ ^{203}Pb 99.9% $^{203}Po \rightarrow$ $^{203}Bi \rightarrow$ ^{203}Pb	.6	7.6	10.0	12.3
5.5% $^{206}Po \rightarrow$ ^{202}Pb 98% $^{202}Po \rightarrow$ $^{202}Bi \rightarrow$ ^{202}Pb	15.2	5.9	8.0	11.4
5.5% $^{206}Po \rightarrow$ 9.5% $^{202}Pb \rightarrow$ ^{202}Tl 98% $^{202}Po \rightarrow$ $^{202}Bi \rightarrow$ 9.5% $^{202}Pb \rightarrow$ ^{202}Tl	2.5	5.3	7.1	7.9
98.4% $^{201}Po \rightarrow$ $^{201}Bi \rightarrow$ ^{201}Pb	7.8	2.4	4.7	7.9

0.5% $^{205}Po \rightarrow {}^{201}Bi \rightarrow {}^{201}Pb$				
86% $^{200}Po \rightarrow {}^{200}Bi \rightarrow {}^{200}Pb$	3.7	1.6	3.5	6.8
86% $^{200}Po \rightarrow {}^{200}Bi \rightarrow {}^{200}Pb \rightarrow {}^{200}Tl$	3.8	3.7	5.3	5.7
88% $^{199}Po \rightarrow {}^{199}Bi \rightarrow {}^{199}Pb$	1.6	0.8	2.0	3.7
88% $^{199}Po \rightarrow {}^{199}Bi \rightarrow {}^{199}Pb \rightarrow {}^{199}Tl$	4.7	3.4	5.2	7.7
30% $^{198}Po \rightarrow {}^{198}Bi \rightarrow {}^{198}Pb$	0.7	0.2	0.8	2.0
^{198}Au	2.2	3.9	2.1	0.8
$^{203}Au \rightarrow {}^{203}Hg$	0.6	2.8	2.5	1.5
$^{179}Ir \rightarrow {}^{179}Os \rightarrow {}^{179}Re$	5.0	5.9	5.2	6.2
$^{169}Re \rightarrow {}^{169}W \rightarrow {}^{169}Ta \rightarrow {}^{169}Hf \rightarrow {}^{169}Lu$ $^{173}Ir \rightarrow {}^{169}Lu$	11.7	14.3	13.2	13.4
$^{103}Nb \rightarrow {}^{103}Mo \rightarrow {}^{103}Te \rightarrow {}^{103}Ru$	4.9	4.3	5.0	4.5
$^{67}Ni \rightarrow {}^{67}Cu$	6.2	5.4	4.6	5.2

Table 13.

Calculated values of cross section of spallation of ^{209}Bi, ^{208}Pb, ^{207}Pb and ^{206}Pb under protons energy 130 MeV of HETC, INUCL, CEM95 codes

Nuclide	HETC			
	^{209}Bi	^{208}Pb	^{207}Pb	^{206}Pb
0.008% $^{207}Po \rightarrow {}^{203}Pb$ 99.9% $^{203}Po \rightarrow {}^{203}Bi \rightarrow {}^{203}Pb$	108.	90.	90.	91.
98.4% $^{201}Po \rightarrow {}^{201}Bi \rightarrow {}^{201}Pb$ 0.5% $^{205}Po \rightarrow {}^{201}Bi \rightarrow {}^{201}Pb$	124.	112.	105.	94.
86% $^{200}Po \rightarrow {}^{200}Bi \rightarrow {}^{200}Pb$	134.	117.	117.	100.
Nuclide	INUCL			
	^{209}Bi	^{208}Pb	^{207}Pb	^{206}Pb
0.008% $^{207}Po \rightarrow {}^{203}Pb$ 99.9% $^{203}Po \rightarrow {}^{203}Bi \rightarrow {}^{203}Pb$	32.	98.	104.	107.
98.4% $^{201}Po \rightarrow {}^{201}Bi \rightarrow {}^{201}Pb$ 0.5% $^{205}Po \rightarrow {}^{201}Bi \rightarrow {}^{201}Pb$	30.	9.1	33.	77.
86% $^{200}Po \rightarrow {}^{200}Bi \rightarrow {}^{200}Pb$	39.	2.3	11.7	47.
Nuclide	CEM95			
	^{209}Bi	^{208}Pb	^{207}Pb	^{206}Pb

0.008% $^{207}Po \rightarrow {}^{203}Pb$ 99.9% $^{203}Po \rightarrow {}^{203}Bi \rightarrow {}^{203}Pb$	170.	149.	136 .	117 .
98.4% $^{201}Po \rightarrow {}^{201}Bi \rightarrow {}^{201}Pb$ 0.5% $^{205}Po \rightarrow {}^{201}Bi \rightarrow {}^{201}Pb$	131.	142.	148 .	134 .
86% $^{200}Po \rightarrow {}^{200}Bi \rightarrow {}^{200}Pb$	89.	133	134 .	139 .

Comparison between experimental and calculated data will be published in the following paper.

R e f e r e n c e s.

1. Bowman C. Accelerator - driven nuclear energy without long - term high - level waste. // Workshop on nuclear transmutation of long - lived nuclear power radiowastes. Obninsk. July 1 - 5 . 1991. p. 127 - 144.
2. Takizuka T., Takada H., Kanno I. Conceptual design of transmutation plant. // Workshop on nuclear transmutation of long - lived nuclear power radiowastes. Obninsk. July 1 - 5 . 1991. p. 79 - 93 .
3. Atrashkevich V.V., Vaivade Ya.K., Kolotov V.P. et al. Khemometrics in activation analysis. Academic chemistry. V.45, iss. 1, 1990, p. 2 - 28.
4. Spanier L.., Ekstrom P " GDISP " vers 1.2 .april. 1990./ Department of nuclear physics. Solvegatan 14. S - 223 62 Lund, Sweden . ~~Áàçà äàííûõ äëÿ~~ The Data Bank for IBM.
5. Zweifel P.F., Arbor A. Neutron Self - Shielding. // Nucleonics. vol. 18. 1960. p 174 - 175.
6. Storm E., Israel Kh. Cross sections of interaction of gamma irradiation. Hand-book. Atomizdat, 1973.
7. Armstrong T.W., Chandler K.C. HETC - A High Energy Transport Code Nucl. Sci. and Eng. n.**49**, p.110, 1972.
8. Chandler K.C., Armstrong T.W. "Operating Instructions for the High-Energy Nucleon-Meson Transport Code HETC" ORNL-4744, 1972.
9. Vorontsov I.A. et al. Measurements of inclusive cross sections of p,p,p,^{2}H, ^{3}H, ^{3}He under the angle 3.5 degrees under interaction with protons of 10.1 GeV/c energy and Be, Al, Cu, Ta and comparison with models of confluence. ITEP preprint, 129-1985.
10. Stepanov N.V. Statistic modelling of fission of excited nuclei. 1. Formation of the model. ITEP preprint, 81-1987.
11. Stepanov N.V. Statistic modelling of fission of excited nuclei. 2. Calculation and comparison with experiment. ITEP preprint, 55-1988.

12. Gudima K.K., Mashnik S.G., Toneev V.D. " Cascade-Exciton Model of Nuclear Reactions ", Nucl. Phys. , vol. A401,№2, 1983, pp 329-361;
13. Mashnik S.G " Cascade-Exciton Model Analysis of Proton-Induced Excitation Functions ", Izv. Akad. Nauk , vol. 60,№1, 1996, pp 73-84.