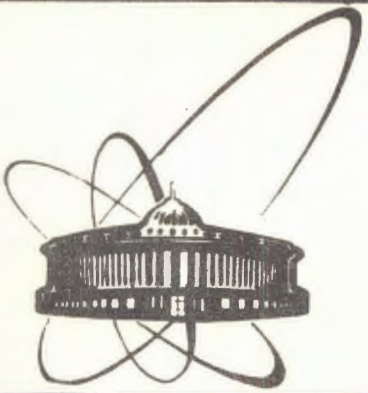

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INVESTIGATION OF ALUMINIUM, TITANIUM AND IRON STRUCTURAL MATERIALS ACTIVATION BY 1.0-1.3 GeV PROTONS

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Introduction

To solve the problems connected with radiation shielding of accelerator structures, evaluation of radiation conditions on the board of spacecrafts, determination of induced background in detectors,etc.,data on activation of aluminium,titanium, iron and other structural materials by protons with energies of several dosens of MeV up to hundreds of GeV are needed. Partial information is available, for example, in /1-3/ where the yeild of a set of nuclides in thin targets irradiated by protons in the energy range up to several hundreds of megaelectronvolts is investigated. Ref. /4/ deals with the results of investigation of proton interactions at T=1Gev[1)] with heavy targets whose dimensions are about the ionization path length of incoming particles in a target material. However, the data known from current literature are related to a narrow set of materials and to a rather limited energy range which is insufficient to solve the problems mentioned above. Moreover, it seems doubtful to get a detailed data bank sufficient for any problem appearing in practice.

Having these circumstances in mind, it seems preferable to create a flexible mathematical model, representing necessary characteristics of radiation passing through heterogeneous material samples consisting of complex chemical composition which is able to calculate the chains of radioactive transformations of excited nuclei produced in the matter, specifically, γ-ray spectra of induced radioactivity. Since such models are usually based on definite roughness in their representation of physical processes and contain sets of phenomenological parameters and correction

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1) Here and further T means kinetic energy of incident protons in laboratory system.

coefficients, their development has to be carried out in parallel with correcting experimental measurements, revealing necessary improvements of the model and helping to estimate soberly the precision of results obtained.

The main goal of our investigation is to obtain the data, concerning γ-emitters produced in frequently used structural materials based on Al, Ti and Fe by protons with energy T about 1GeV and their comparison with the results of calculations according to a developed mathematical model.

Measurement procedure and results

Al, Ti,Fe targets formed as a parallelepiped 6x6 cm in its base and from 1 to 13 cm in height, were irradiated by proton beams with energies T=1.0 and 1.3 GeV on the ITEP accelerator. The target was composed of separate plates of 1 to 10 mm thick, which allowed to study the distribution of nuclear reaction products along the target depth.

Incident particle beam intensity reached about 10^6 protons/pulse, their fluence totalled up to $1.2\text{-}2.0\times10^{10}$ over the exposure time. Employment of such relatively low intensity is motivated by three advantages. First, using such beams it is possible to achieve high precision beam monitoring which results in sufficiently high error estimation accuracy in theoretical calculations and their comparison with the results of measurements. Secondly, low level of induced activity in the target enables to minimize the cooling time from the end of the irradiation process to the moment of the beginning of counting procedure which permits to watch the short-lived emitters in the experiment. Finally, the fluence of protons which hit the target during the exposure time appears to be close to that of primary cosmic protons effecting the structural materials of spacecrafts, situated over the boundaries of the earth atmosphere for several years which permits to use the data derived to evaluate the level of induced γ-activity in Al, Ti and Fe irradiated in conditions of prolonged cosmic flights.

Proton beam monitoring has been carried out using a plastic scintillator in optical contact with photoelectronic miltiplier through the light conductor. Cross-section of the scintillator is

precisely equal to the dimensions of the irradiated target which appears to permit one with high accuracy to record the protons, hitting the target, and to make the high precision beam control during the experiment unnecessary.

γ-spectrum measurements of irradiated targets have been carried out in succession which permits the identification of radionuclides produced in the target over their halfdecay periods. Each sample has been exposed for 8 - 10 times. Minimal cooling time reached 3-5 min, maximal - up to 2 days at exposure time from 5 min to 2 hours. Such time table ensured the registration of γ-radiation of radionuclides with halfdecay periods ranging from several minutes to several days.

Semiconductor Ge(Li) detector with effective volume of 80 cm^3 served as a γ-radiation detector. Spectrometer was calibrated both over the radiation energy and the absolute photoregistration efficiency with the help of the standard spectrometric γ-ray source and ^{226}Ra source.

The yeilds of radionuclides in aluminium, titanium and iron targets with respective thicknesses of 13.5, 4.54 and 7.87 g/cm^2 measured at T=1.1GeV are presented in Table 1. Distribution of ^{24}Na nuclei along the aluminium target depth is shown in fig.1.

Apparatus spectra of γ-radiation from activated targets are demonstrated in figs.2 and 3. The most intensive identified emitters are marked with arrows.

Table 1

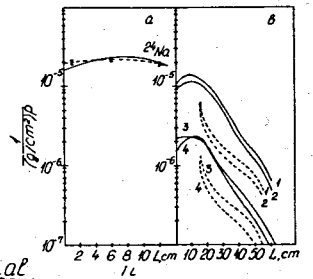
Radionuclide yeilds (in units of $10^{-4}(g/cm^2)^{-1}$ per one incident proton). Statistical errors of calculated data are presented.

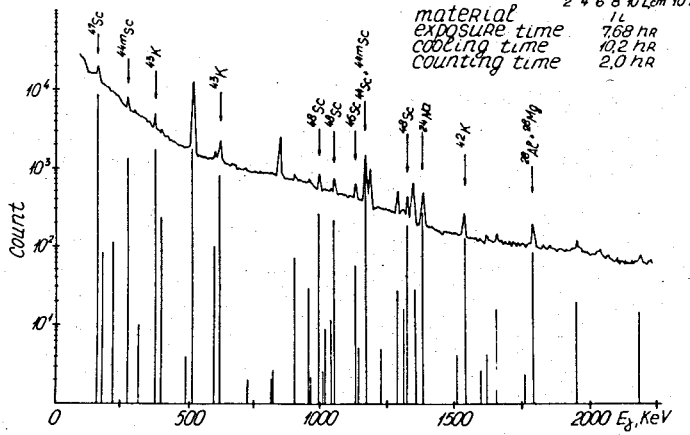
Target	Nuclide	Experiment	Calculations
1	2	3	4
Al	^{27}Mg	0.98 ± 0.19	1.21 ± 0.18
"	^{24}Na	2.53 ± 0.18	2.59 ± 0.31
Ti	^{48}Sc	0.42 ± 0.12	0.36 ± 0.10
"	^{48}V	0.17 ± 0.03	0.14 ± 0.04

Table 1(continued)

1	2	3	4
...	^{47}Sc	4.02 ± 0.32	4.18 ± 0.39
...	^{46}Sc	2.23 ± 0.67	1.78 ± 0.24
...	^{45}K	0.068 ± 0.024	0.053 ± 0.02
...	^{44}Sc	1.28 ± 0.15	1.04 ± 0.21
...	^{44m}Sc	0.75 ± 0.10	0.68 ± 0.14
...	^{43}K	0.43 ± 0.05	0.51 ± 0.12
...	^{43}Sc	0.44 ± 0.04	0.38 ± 0.09
...	^{42}K	1.12 ± 0.22	0.82 ± 0.17
...	^{41}Ar	0.20 ± 0.03	0.25 ± 0.09
...	^{39}Cl	0.12 ± 0.03	0.16 ± 0.05
...	^{38}S	0.10 ± 0.03	0.07 ± 0.02
...	^{38}Cl	0.23 ± 0.07	0.27 ± 0.09
...	^{34m}Cl	0.18 ± 0.05	0.19 ± 0.06
...	^{29}Al	0.22 ± 0.07	0.16 ± 0.05
...	^{28}Mg	0.087 ± 0.026	0.08 ± 0.02
...	^{28}Al	0.58 ± 0.16	0.61 ± 0.14
...	^{27}Mg	0.94 ± 0.32	0.76 ± 0.17
...	^{24}Na	0.38 ± 0.05	0.33 ± 0.12
Fe	^{56}Mg	0.56 ± 0.03	0.49 ± 0.11
...	^{53}Fe	0.80 ± 0.17	0.72 ± 0.14
...	^{53m}Fe	0.61 ± 0.18	0.68 ± 0.12
...	^{52}Mn	1.04 ± 0.19	0.79 ± 0.15
...	^{52m}Mn	0.88 ± 0.08	0.58 ± 0.11
...	^{49}Cr	0.41 ± 0.11	0.46 ± 0.12
...	^{48}Sc	0.11 ± 0.03	0.12 ± 0.04
...	^{48}Cr	0.12 ± 0.03	0.12 ± 0.04
...	^{48}V	0.64 ± 0.15	0.54 ± 0.11
...	^{47}Sc	0.66 ± 0.13	0.58 ± 0.13
...	^{44}Sc	0.83 ± 0.12	0.64 ± 0.10
...	^{44m}Sc	0.78 ± 0.10	0.58 ± 0.09
...	^{43}K	0.27 ± 0.05	0.32 ± 0.10
...	^{42}K	0.48 ± 0.07	0.69 ± 0.14
...	^{41}Ar	0.15 ± 0.02	0.12 ± 0.03
...	^{38}S	0.068 ± 0.018	0.072 ± 0.03
...	^{38}Cl	0.05 ± 0.02	0.058 ± 0.02
...	^{24}Na	0.11 ± 0.02	0.086 ± 0.03

Fig.1. Distribution of radionuclides along the target depth. Dashed lines - measurement results, solid lines - calculations. a) ^{24}Na in aluminium target, T=1.3 GeV. b) 1 - ^{54}Mn, 2 - ^{51}Cr, 3 - ^{56}Mn, 4 - ^{52}Mn. T=1.0 GeV. Experimental data are taken from /4/.





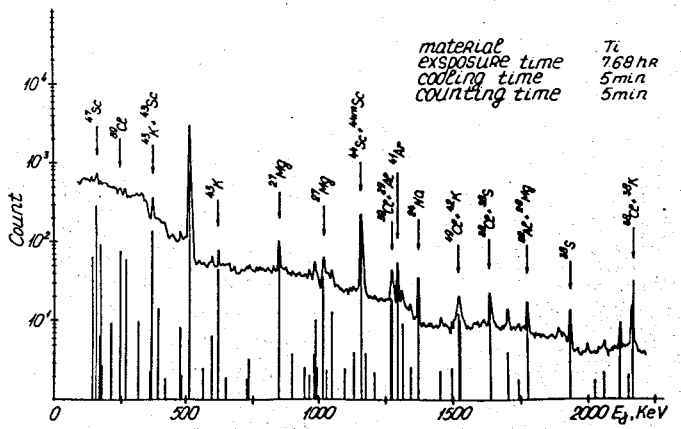


Fig.2. γ-radiation spectrum from titanium target. T=1.1GeV. Exposure time 7.68 hours. Upper part relies to the cooling time of 10.2 hours, the counting time of 2 hours; lower part relate to a case when both are equal to 5 minutes.

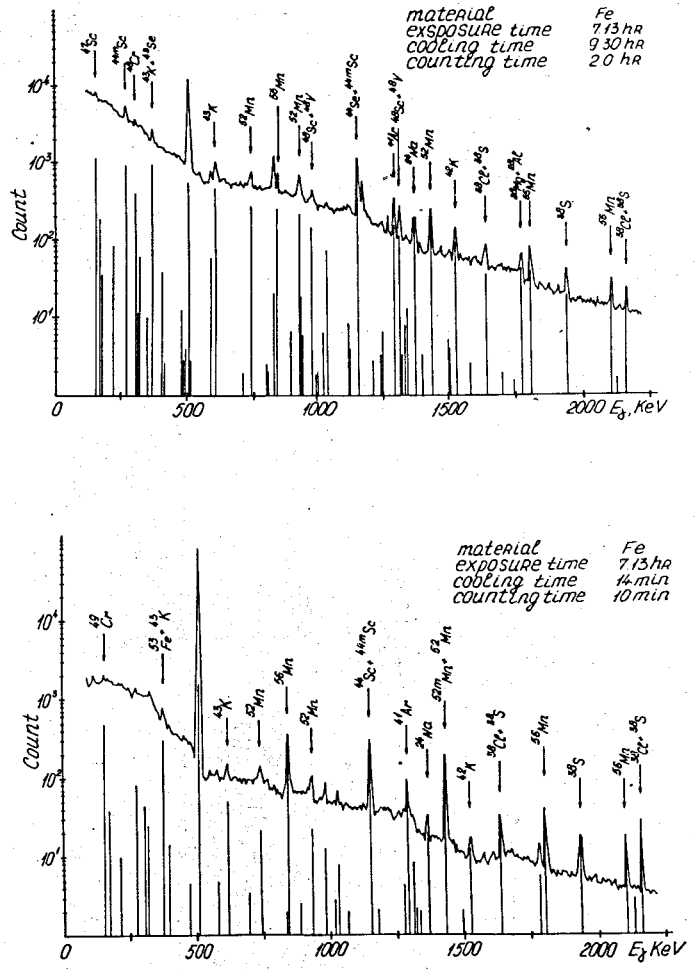


Fig.3. γ-radiation spectra from iron target. T=1.1 GeV. Exposure time - 7.13 hours. Upper part relates to the cooling time value of 9.3 hours, the counting time - 2 hours; lower part - to the cooling time is 14 minutes, counting time - 10 minutes.

Calculation method and procedure

Passing through the target material, primary proton causes an hadronic cascade, which results in production of excited nuclei - products of spallation and splitting reactions - in the target material. They loose their excitation energy in "evaporation cascade" and by subsequent emission of γ-quanta during their transition from low excited aftercascade states to the ground unexcited states. Radionuclides produced as a result of α, $\beta^{\pm}$ - decays and electron absorption reactions undergo a series of radioactive transformations accompanied by γ-quanta emission as well.

While simulating such complicated processes, it is important to take into account all features of the experiment, specifically,characteristics of spectrometric installation.

The most adequate approach to solve the problem under discussion is based on the Monte-Carlo method. In order to simulate hadronic cascade in the target material we invoked the program complex "CASCADE" /7/. The data on the rates of nuclear interactions products generation and their distribution over the target volume are used to calculate the photopeak areas of model spectra with computer program "SPECTR" /8/ which is provided with information on the dependence of the apparatus spectrum channel number and absolute registration photoefficiency on the energy of γ-radiation and on other features of spectrometric installation. /9/. Simulation of apparatus spectrum is carried out taking into consideration the target geometry in the experiment, absorption and scattering of γ-quanta inside the target, the duration of irradiation, cooling and exposure time of the samples /10/ are also considered.

Discussion

It is clear from Table 1 that the average values of theoretical and measured yeilds of radionuclides are rather close to each other. The same could be said about their distribution along the target depth. The measured and theoretical values for a relatively small Al target used in our experiment and for a considerably thicker Fe target from /4/ are compared in fig.1. (Similar results are obtained in /11/ at T=1 and 3 GeV).

Distributions possess an evident maximum at a depth of 10-15 cm, which corresponds to the uppermost intensity of cascade shower and after that point they display a smooth decrease along the target depth, where the measured and calculated results are in good agreement (up to a constant coefficient). The lack of data on yeild distributions along the target depth for full target cross-section in /4/ prohibited to compare quantitatively the simulation and experimental results, however, as a whole the model provides a satisfactory description of the distributions of activation products.

In most cases the average measured and theoretical yeild values differ not more than 20 - 30 % that is the values which could be compared with experimental errors and statistical errors of the calculated data. The agreement may be somewhat improved by means of increased statistics of Monte-Carlo calculations, and more careful consideration of proton beam fluctuations in accelerator as well as other intricate peculiarities of the experiment, however, essential growth of accuracy requires more detailed calculation procedures concerning the inelastic hadron-nucleus interaction description. Generally accepted intranuclear cascade model including evaporation from residual nuclei which demonstrates a good representation of average values behaviour is not enough to achieve this goal.

The photopeaks of calculated γ-radiation spectra are shown in figs.2 and 3 with the segments of straight line which height is equal to the area of a respective theoretical photopeak, and their position on energy scale corresponds to the energies of γ-quanta.More detailed data including the half decay periods of radionuclides and energies of γ-quanta emitted by them which have been used to identify a nuclide are presented in Table 2. In the

Table 2

Counts in full absorption peaks of apparatus and model γ-radiation spectra from activated targets. Statistical errors of calculated data are presented.

Target	Nuclide	Halfdecay period	Energy of γ-quanta KeV	Quantum yeild,%	Counts exper	Counts calc
1	2	3	4	5	6	7
Al	^{24}Na	15.02 hr	1368.5	100.0	1156±63	1145±136
...	^{24}Na	15.02 hr	2753.9	99.9	500±40	553±66
...	^{27}Mg	9.46 min	843.7	71.8	96±17	123±18
...	^{27}Mg	9.46 min	1014.4	28.2	51±17	60±9
Ti	^{24}Na	15.02 hr	1368.5	100.0	641±70	533±158
			2753.9	99.9	311±30	249±75
...	^{27}Mg	9.46 min	1014.4	28.2	48±19	38±8
...	^{28}Al	2.24 min	1779.0	100.0	136±43	131±31
...	^{28}Mg	20.93 hr	1778.8	100.0		
...	^{29}Al	6.52 min	1273.3	90.6	26±9	21±7
...	^{34m}Cl	32.06 min	2127.3	43.2	22±8	24±8
...	^{38}S	2.84 hr	1941.9	84.0	88±27	60±18
...	^{38}S	2.84 hr	1642.4	40.4	66±21	81±25
...	^{38}Cl	37.24 min	1642.4	31.6		
...	^{39}Cl	55.6 min	250.2	46.3	183±51	252±78
...	^{41}Ar	1.83 hr	1293.7	99.1	220±20	290±93
Ti	^{42}K	12.36 hr	1524.6	18.3	293±58	197±41
...	^{43}K	22.3 hr	372.8	87.9	2790±210	2440±634
...	^{43}Sc	3.89 hr	372.8	22.5		
...	^{43}K	22.3 hr	617.5	78.3	847±76	1035±243
...	^{44m}Sc	2.44 days	271.2	77.8	1714±256	1552±308
...	^{44}Sc	3.93 hr	1157.0	99.9	2976±312	2367±348
...	^{44m}Sc	2.44 days		100.0		

Table 2(continued)

1	2	3	4	5	6	7
...	^{44}Sc	3.93 hr	1157.0	99.9	264±30	183±37
...	^{45}K	17.8 min	174.3	75.3	215±94	160±54
...	^{46}Sc	83.8 days	889.2	100.0	104±32	80±11
...	^{47}Sc	3.34 days	159.4	68.0	9510±410	9934±894
...	^{48}Sc	1.82 days	1037.5	97.5	319±91	275±74
...	^{48}Sc	1.82 days	983.5	100.0	343±63	313±83
...	^{48}V	15.97 days				
	^{24}Na	15.02 hr	1368.5	100.0	201±41	156±50
...	^{24}Na	15.02 hr	2753.9	99.9	95±24	72±23
...	^{38}S	2.84 hr	1941.9	84.0	60±16	65±24
...	^{38}S	2.84 hr	1642.4	40.4	69±25	78±26
...	^{38}Cl	37.24 min	1642.4	31.6		
...	^{41}Ar	1.83 hr	1293.7	99.1	181±30	148±46
...	^{42}K	12.36 hr	1524.6	18.3	107±19	130±25
...	^{43}K	22.3 hr	372.8	87.9	798±140	931±267
...	^{44m}Sc	2.44 days	271.2	77.8	1792±228	1320±201
...	^{44}Sc	3.93 hr	1157.0	99.9	1623±66	1232±184
...	^{44m}Sc	2.44 days	1157.0	100.0		
...	^{47}Sc	3.34 days	159.4	68.0	1187±238	1076±237
...	^{48}Sc	1.82 days	1037.5	97.5	73±23	83±27
	^{48}Sc	1.82 days	983.5	100.0	179±47	151±30
...	^{48}V	15.97 days				
...	^{48}Cr	22.96 hr	308.3	99.0	417±120	399±129
...	^{49}Cr	42.1 min	152.9	30.9	374±120	414±94
...	^{52m}Mn	21.1 min	1434.1	98.3	319±25	209±40
...	^{52}Mn	5.59 days	744.2 935.5	90.0 94.5	328±64 336±60	250±48 264±50
...	^{53m}Fe	2.58 min	1011.5	84.8	35±13	37±6
...	^{27}Mg	9.4 min	1014.4	28.2		
...	^{53}Fe	8.51 min	377.9	40.0	291±72	263±30
...	^{56}Mn	2.58 hr	846.8	98.9	1218±67	1040±239

cases when energy sensitivity of the spectrometer could not allow one to split closely located peaks of two different nuclides or when γ-quanta are emitted by nuclides with equal energies (as a rule they are the nuclei related to the same isobaric chains of radioactive transformations /12/) the data for unresolved (total) peaks are shown in the Tables. Respective nuclides are marked with brackets.

As in Table 1 and in fig.1a, presented above, the discrepansies of theoretical and experimental data as a rule do not exceed 20-30%. Twofold discrepansies take place on several occasions. The model based on the cascade-evaporation mechanism of nuclear interactions could be used with the same accuracy in evaluation and predictions of γ-radiation from materials irradiated by hadron fluxes with energies up to T about 10 GeV. In the region of higher energies the cascade model which includes the quark-gluon string mechanism /13,14/ should be employed.

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