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STUDY OF NUCLEAR FRAGMENT EMISSION FROM TARGETS BOMBARDED BY INTERMEDIATE-ENERGY PROTONS

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A nuclear fragment registration by 6-μm lavsan film detectors was studied in experiments with 0.2–4 GeV proton beam. The targets from Be to Pb were used in these measurements. Only the nuclear fragments with large local energy deposition and $Z > 5$ produced in reactions of spallation, fragmentation and fission were detected. A dependence of number of the registered secondary nuclei on energy of incident protons and mass number of target nuclei is discussed.

Изучена регистрация ядерных фрагментов детекторами на основе лавсановой пленки толщиной 6 мкм в экспериментах на пучке протонов с энергиями 0,2–4 ГэВ. В измерениях использовались мишени от Be до Pb. Детектировались только ядерные фрагменты с $Z > 5$, образующиеся в реакциях расщепления, фрагментации и деления и производящие высокое локальное энерговыделение. Обсуждается зависимость числа зарегистрированных вторичных ядер от энергии падающих протонов и массового числа ядра мишени.

INTRODUCTION

Originally the purpose of the undertaken research on a proton beam of JINR's Synchrophasotron was to study background effects because of a registration of fast secondary nuclei by solid-state nuclear track detectors (SSNTD). Such nuclei are produced in materials surrounding the detectors as a result of spallation, fragmentation and fission processes in $p-A$ interactions. In our experiments we used thin lavsan film for the nuclear fragment detection. Such research was important for successful application of the method advanced for low-energy region [1] in measurements of yields and cross sections of fission reactions with high-energy protons [2, 3]. Other important result of this research became an extension of the method of threshold detectors up to hundred MeV range [4–6].

In numerous measurements with protons in an energy interval of 0.2–4 GeV and targets from Be up to Pb, the big experimental material was saved up. In this paper we present and discuss the results on a dependence of yield of registered nuclear fragments on energy of protons, mass number of target nuclei and a direction of fragment emission.

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1. THE METHOD

In our experiments a wide set of targets Be, Al, PVC (polyvinylchloride), Ti, Cu, Cd, Ta and Pb were irradiated by intermediate-energy protons. The targets were made as disks 19 mm in diameter and 0.2–0.4 mm in thickness that considerably exceeded a path length of the secondary nuclei in the target material. The fast secondary nuclei leaving targets were registered by SSNTDs on a basis of 6-μm lavsan film (polyethylene terephtalate, PETP) settled down close to targets.

After irradiation the SSNTDs were etched for 60 min in alkaline solution KOH at a temperature of $(60 \pm 0.1)\,^{\circ}$C, and then a number of tracks was defined on a surface of diameter 14.15 mm with the help of the automatic spark counter of tracks [7]. The emitted secondary nucleus is registered if the following conditions are realized:

1) the density of ionization dE/dx in the lavsan film of the detector is larger than the threshold value $dE/dx_{\rm th}$, which is a function of angle between a fragment trajectory and a normal to the SSNTD surface;

2) the projection of a nucleus path in the lavsan film on a normal to the detector surface is more than 5 μm (taking into account the detector thickness and etching process).

The for lavsan film has $dE/dx_{\rm th} \sim 600$ keV/μm. The density of energy deposition strongly depends on energy and especially on the effective charge of a nuclear fragment. Taking into account both conditions mentioned above only the nuclei with energies between ~ 0.4 and several MeV/nucleon have the best characteristics for registration by the lavsan detectors. A minimum energy deposition registered is about 3 MeV. A threshold value of fragment charge is $Z_{\rm th} \sim 5$ [8], which that is also confirmed by results of our measurements. The fragment with definite E and Z can be detected by the method if the angle between a fragment trajectory and detector surface $\theta > \theta_c$, where θ_c is the critical angle and its value depends on dE/dx. For fission fragments having almost optimum characteristics for registration by lavsan detectors the critical angle is 29°. The yield, mass, charge, energy and angular distributions of secondary nuclei depend on mass number of target nuclei, physical process and energy of protons. Thus, the fragments produced in different processes and different combinations of target mass number and proton energy have different registration characteristics and, as a result, an efficiency of registration. Also a consequence of it is a dependence of the methodical error of track number determination on mass number of target nuclei. This error reduces with increasing A. The average methodical errors obtained over the energy region of incident protons 200–2200 MeV for targets Al, Ti, Cu, Cd, Ta and Pb are 33, 27, 24, 15, 13 and 11%, respectively.

The method used in our research did not allow us to obtain the absolute yield of nuclear fragments from the target surface. But it helped us as to study some important dependences of nuclear fragment emission as to get clear understanding of events with large local energy deposition in materials at irradiation with intermediate-energy protons.

2. MEASUREMENTS

In irradiations three types of assemblies with targets (T), SSNTDs (D) and disks from polyethylene (P) were used. The assemblies consisted of the following sections:

1. T-D-T; 2. P-D-T-D-P; 3. P-10D-T-10D-P.

In the single assembly three identical sections were used for reduction of statistical and methodical errors.

The reaction $^{27}Al(p,X)^{24}Na$ was applied for monitoring of the beam of protons. For this purpose two aluminium disks of thickness 3 mm and diameter 14.15 mm (equal to the diameter of SSNTD surface used for track counting) were located at both ends of the assemblies. The monitor reaction cross section was taken from work [9] which is in a good agreement with results of recent measurements [10, 11]. An error of determination of proton flux was 20%.

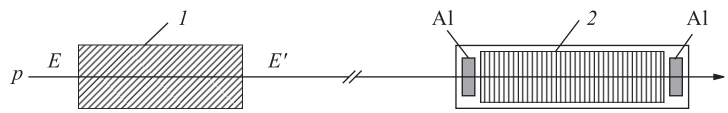

Fig. 1. Geometry of the experiment: *1* — brass moderator; *2* — experimental assembly consisting of targets, SSNTDs and polyethylene disks (screens); Al — aluminium disks for beam monitoring

A geometry of the experiment is shown in Fig. 1. Irradiations were carried out in a focus of the beam. Focusing of the beam on the center of the experimental assembly was performed with the help of two multiwire proportional chambers. The typical size of the beam spot was ~ 15 mm in the vertical and horizontal directions. The beam directly fell on the assembly for protons with $E \geqslant 600$ MeV, while for a case of lower energies a moderation of protons with energy 600 MeV in brass cylinders was used. The brass moderators were located at a distance of 20 cm in front of the irradiated assemblies.

Table 1. **The irradiations executed with proton beam**

No.	E, MeV	Length of moderator, mm	E', MeV	Flux of protons, $\cdot 10^9$	Assembly
1	600	223	200	4.20	1
2	600	178	300	3.71	1
3	600	125	400	3.69	1
4	600	65	500	2.10	1
5	600		600	5.68	1
6	800		800	7.53	1
7	1000		1000	8.34	1, 2, 3
8	2200		2200	4.54	1, 2
9	3170		3650	5.17	1, 2
10	3650		3650	5.17	1, 2, 3

Note. E — energy of beam protons; E' — energy of protons falling on the assembly.

Changes of beam characteristics (composition and energy distribution) after a passage of protons through the moderator were not taken into account at a stage of analysis of the data. A list of the executed irradiations is given in Table 1. In the same table some important characteristics of the experiments (energies of protons in front and behind of the moderators, lengths of the brass moderators and proton fluxes) are presented.

3. RESULTS OF MEASUREMENTS

Performing data analysis, it is necessary to mean a different character of physical processes leading to an appearance of the nuclear fragments at interaction of intermediate-energy protons with light-mass (Al, Cl, Ti), medium-mass (Cu, Cd) and heavy-mass (Ta, Pb) nuclei. Dominating processes of disintegration of target nuclei at intermediate energies are reactions of spallation, fragmentation and fission. The basic processes bringing the greatest contribution to indications of SSNTDs for the specified groups of target nuclei in three different regions of proton energies are shown in Table 2 [12]. Disintegration of light-mass nuclei in spallation and fragmentation reactions approximately equally effectively occurs in all these energy regions, while for medium-mass nuclei these processes begin to give an appreciable yield of fast nuclear fragments registered by SSNTDs only at $E > 500$ MeV. For heavy-mass nuclei for all proton energies the fission reaction plays a main role due to a high value of the fission cross section and optimal registration characteristics of fission fragments.

Table 2. **The basic processes leading to disintegration of target nuclei by protons with formation of nuclear fragments registered by lavsan SSNTDs**

Target	Energy of protons, GeV		
	0.1–0.5	0.5–1	>1
Small A (Al, Ti)	Spallation, fragmentation	Spallation, fragmentation	Spallation, fragmentation
Middle A (Cu, Cd)	No	Spallation, fragmentation	Spallation, fragmentation
Large A (Ta, Pb)	Fission	Fission	Fission, spallation, fragmentation

Study of yield of registered secondary nuclei in front N_F and back N_B hemispheres concerning a direction of the proton beam was carried out in detail at $E = 1.0$ and 3.65 GeV. Results of the measurements with 1.0-GeV protons are shown in Fig. 2. For targets where the dominating processes are reactions of spallation and fragmentation, the emission of secondary nuclear fragments has sharply forward angular distribution with a ratio $N_F/N_B > 8$. For targets Ti, Cu and Cd the measured distributions are in good agreement. However, for heavy nuclei, where reaction of fission brings large contribution to indications of detectors, the values $N = N_F + N_B$ and N_F/N_B considerably differ from those obtained for nuclei with small and middle mass numbers. For Ta and Pb the values of the ratio N_F/N_B are equal to 2.1 and 1.5, respectively. The measurements with 3.65-GeV protons were carried out for limited set of targets PVC, Cu and Pb. The obtained results are shown in Fig. 3.

With a rise in energy the values N_F, N_B and N increase for all the targets at simultaneous reduction of the ratio N_F/N_B for targets PVC and Cu (area of small and middle mass numbers).

A comparison of numbers of counts in lavsan detectors for the assembly of type 3 showed that:

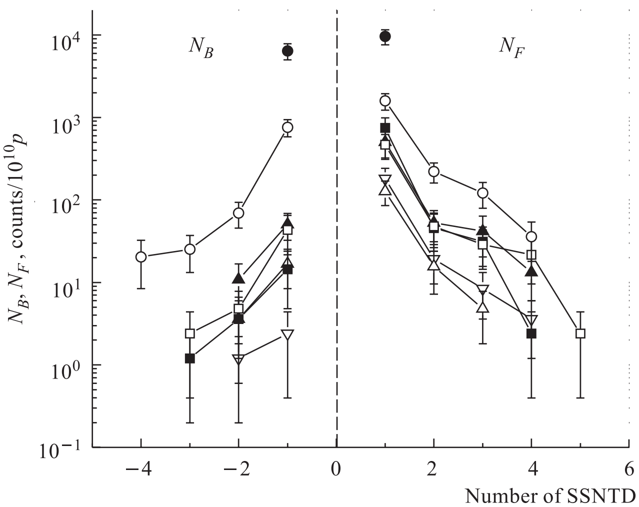

Fig. 2. The registered numbers of counts in front and back hemispheres for 1-GeV protons and the assembly with sections P-10D-T-10D-P. On the horizontal axis the zero corresponds to a position of the target, and numbers specify a number of SSNTD counted from the target. The symbols denote experimental data: ▽ — Al; △ — PVC; ▲ — Ti; ■ — Cu; □ — Cd; ○ — Ta; ● — Pb; the curves — result of fitting

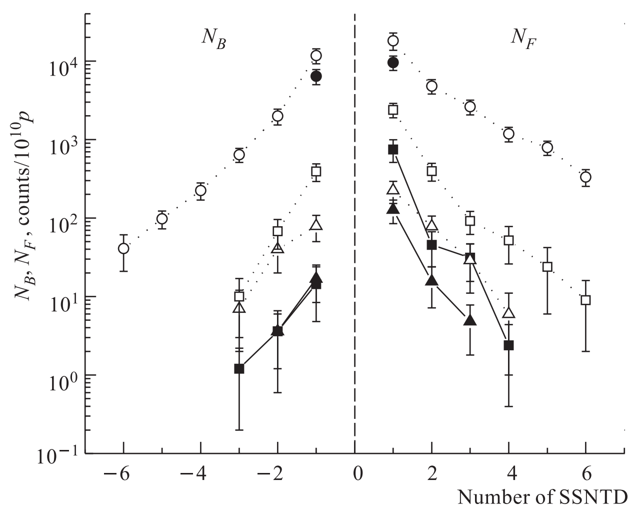

Fig. 3. The same as in Fig. 2 but for two proton energies of 1.0 GeV (solid symbols and curves) and 3.65 GeV (open symbols and dotted curves): ▲, △ — PVC; ■, □ — Cu; ●, ○ — Pb

1) the number of counts quickly decreases with increasing SSNTD number (distance from the target or with growth of the path length of fragments in lavsan);

2) the yield of registered nuclear fragments and their path lengths increase with rise of proton energy;

3) large difference in numbers of the registered tracks is observed for the first and second detectors (a factor of ~ 10 at $E = 1.0$ GeV), and it means that the main fraction of nuclei emitted from the target has a rather low energy and path length not exceeding 1 mg/cm^2.

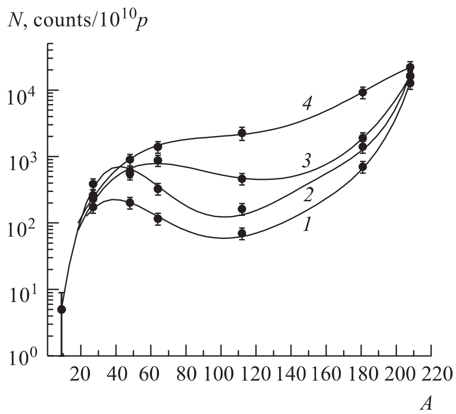

Fig. 4. A-dependence of the number of counts for the assembly T-D-T and four energies of incident protons 0.3 (*1*), 0.6 (*2*), 1.0 (*3*) and 2.2 GeV (*4*). The points — experimental results; the curves — result of fitting

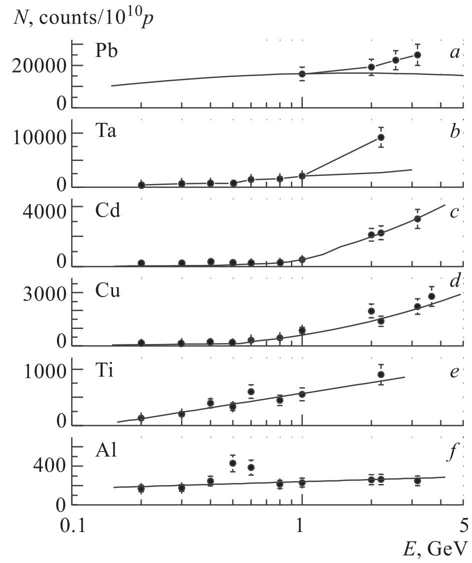

Fig. 5. Energy dependence of the yield of nuclear fragments registered by the PETP detectors in the assemblies T-D-T for various targets. The points — experimental data; the curves — result of fitting

A dependence of number of the registered fragments $N = N_F + N_B$ on mass number of target nuclei A is shown for the assembly T-D-T for several energies of protons in Fig. 4. For light-mass nuclei a weak dependence of the value N on proton energy is observed, while for medium-mass nuclei (Cu, Cd) there is very strong such dependence. In the region lower than 500 MeV the light-mass targets give the greater number of tracks in the lavsan detectors than the medium-mass targets. However, at further rising of proton energy the yield of registered secondary nuclei from Cu and Cd targets begins to grow fast and at $E > 1$ GeV the number of tracks from these targets exceeds the same value for light-mass targets. Thus, the sharp threshold character for the dependence $N(E)$ is observed in the range of medium-mass targets. Coming to the range of heavy nuclei the fission reaction begins to play an increasing role. It gives both a strong rise of the value N and its weak dependence on proton energy in the studied region.

Energy dependences of number of registered tracks in the assembly T-D-T with various targets are shown in Fig. 5. As a whole, for aluminium target a slow rise of number of counts with proton energy is observed (the enhanced yield around 500 MeV is not understood). The dependence $N(E)$ gradually gets a threshold character with increasing mass number of target nuclei. One can see a sharp slope in the case of Cu and Cd targets. For the heavy targets (Ta and Pb) contributions from two components are well seen. Here the process of fission is responsible for rather big contribution which is smoothly varying with proton energy (corresponding curves in the figure are obtained using estimated fission cross sections [13] normalized to the results of our measurements in the energy region $E \leqslant 1$ GeV). The second component observed at proton energy higher than 1 GeV is the fast increasing contribution from the spallation and fragmentation processes.

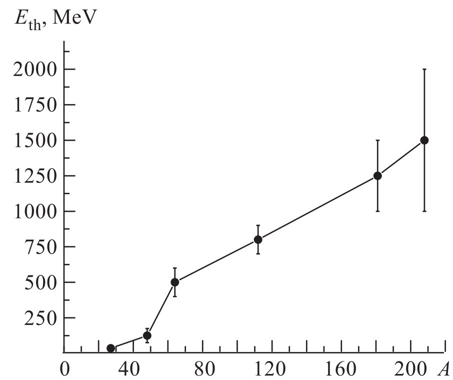

Fig. 6. A-dependence of threshold energy $E_{\rm th}$ of effective formation of detected nuclear fragments in the spallation and fragmentation processes. The curve is a result of fitting

The experimental data allowed us to perform a rough estimation of the proton energy range $E > E_{\rm th}$, where the contribution from the spallation and fragmentation reactions occurs. The threshold energy values $E_{\rm th}$ for the used method of registration are shown in Fig. 6 as a function of mass number A, and $E_{\rm th}$ is seen to grow with increasing A.

4. DISCUSSION OF THE RESULTS

The characteristics of residual nucleus, fragments and fission fragments formed in interactions of intermediate-energy protons with nuclei were studied in a great number of experimental and theoretical works. Last decade a systematical investigation of secondary nuclei production was carried out in an energy interval of protons 200–2600 MeV for a large set of target nuclei from C up to Au within the framework of the international cooperation [10, 11]. During the same period the theoretical model of the statistical multifragmentation of nuclei explaining a mechanism of fragment formation and their characteristics was developed [14].

An analysis of results on double differential cross sections of various fragment production by protons showed that for light-mass nuclei their formation begins at rather low energies. In reaction p–Al at 180 MeV the effective production of various secondary nuclei was observed [15]. All of them were emitted in a forward hemisphere, and the sharpest angular distribution was obtained for the fragments with $A \sim 27/2$ (a half of mass number of the target nucleus). For the same reaction but at considerably higher energies of protons 2.1 and 4.9 GeV, it was shown that the output of fragments with $Z > 5$ ($A > 10$) also strongly depends on an emission angle in the laboratory frame and mainly concentrates in a range of small angles around a direction of incident protons [16]. Irrespective of proton energy the maximum of fragment energy spectrum falls at energy range of hundred keV per nucleon. Such nuclei have small path length in a substance and, in our case, they can be registered only from very thin surface layer of a target. All this is in a good agreement with the results obtained in our measurements for aluminium target and explains low and poor dependence of registered fragment yield on proton energy and great value of the ratio N_F/N_B as well.

Similarly to our results, for target nuclei in the range of middle and large mass numbers a strong dependence of yield of fragments with $Z > 5$ ($A > 10$) on proton energy is observed. A maximum of the energy spectrum of fragments increases up to several MeV per nucleon with mass number of target nucleus [17]. The last fact promotes more effective emission and registration of nuclear fragments from a thick target. However, for the secondary light-mass nuclei formed in the fragmentation of heavy nuclei the ratio N_F/N_B is equal to ~ 2. It is much less than the value obtained in our measurements with Ti, Cu and Cd targets and 1-GeV protons. It proves that in the studied energy region the main contribution to counting rate is given by the fast residues produced in the central collisions of protons with target nuclei. In such collisions a large momentum is transferred to nuclear residues, and it explains why their emission is mainly observed in the forward direction. As was shown in our data analysis, a distinction between numbers of the secondary nuclei detected in forward and back hemispheres decreases with proton energy up to 3.65 GeV. Apparently, this testifies that relative contribution of light-mass fragments increases as a result of sharp growth of fragmentation cross section with proton energy between 1 and 3.65 GeV.

For heavy fissile nuclei with $A \sim 200$ and energy range higher than 1 GeV, the fission cross section weakly depends on proton energy. At the same time, the cross section of secondary nuclei formation with a momentum high enough for registration by the method used in this work fast grows. For tantalum target the contributions to registered number of counts from fission fragments and from secondary nuclei formed in the other processes become equal at a proton energy of ~ 2 GeV, and for lead it occurs at approximately twice greater energy.

CONCLUSION

The study of emission of energetic nuclear fragments producing an energy deposition larger than 3 MeV on a length of 5-μm in lavsan detectors showed that the results of measurements considerably depend on mass number of target nuclei and energy of protons. The greatest yield of such fragments is observed for heavy targets with $A > 180$ where the fission reaction is dominating process. In a range of small and middle A the nuclear fragments are mainly registered in the forward direction with negligible yield in back hemisphere. An effective threshold on energy of protons for production of the residues and fragments in spallation and fragmentation reactions increases from tens of MeV to several GeV with proton energy. The strongest energy dependence of the fragment yield occurs in a range of middle mass numbers. It has a sharp threshold character with a value of threshold energy between 0.5 and 1 GeV which rises with mass number of target nucleus.

The obtained results can find an application in various areas, such as a design of detector systems, dosimetry and monitoring of neutron/hadron fields, study of destruction of materials in radiation fields on accelerators and radiation effects in space, production of isotopes and secondary nuclear beams. An essential reduction of background effects caused by nuclear fragments can be achieved by a choice of materials and their arrangement.

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