EMISSION OF LIGHT CHARGED PARTICLES FROM FRAGMENTS PRODUCED ON FISSION OF URANIUM NUCLEI BY 153 MEV PROTONS AND 1700 MEV NEGATIVE PIONS

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Abstract

We studied the mechanism underlying the emission of light charged particles (LCP) with Z = 1, 2 from fragments produced in fission of uranium nuclei by 153 MeV protons and 1700 MeV negative pions. It was found that LCP accompanying the fission by pions are emitted from non-accelerated fragments immediately after the fission, whereas in the case of 153 MeV protons, the LCP are emitted from the accelerated heavy fragments. The number of LCP emitted in the course of pion-induced fission is 0.7 per fission event, which exceeds by a factor of 30 the corresponding number for 153 MeV protons.

The study of heavy nuclei at high excitation energies was pioneered by I.M. Frank and his coworkers. They performed experiments involving the fission of uranium nuclei by slow pions, fast neutrons, and gamma radiation with energies as high as 250 MeV. These experiments gave new data on the fission process at high excitation energies [1]. In the recent years, these investigations were continued for finding out new information on the mechanisms of interaction of high-energy adrons with heavy nuclei and on the properties of fission fragments (for nuclei far from beta-stability regions) [2-4].

The nuclear fission by high-energy particles is accompanied by emission of charged particles with Z = 1 or 2. These particles leave nuclei before the fission (at the cascade-evaporation stage of the interaction process), during the fission, and after it. The studies concerning emission of such particles can provide deeper insight into the fission mechanism and the properties of excited fragments.

In the experiments on fission of uranium nuclei by slow negative pions and by 153 MeV protons, we were first to observe the emission of low-energy charged particles (E_p < 15 MeV) mostly from the heavy fragments. The emission probability increases with the fission asymmetry [2-4].

It makes sense to reveal the mechanism and energy dependence of the charged particle emission from the fragments arising on fission of uranium nuclei by high-energy particles such as 1700 MeV negative pions.

The main emphasis was made on angular distributions of charged particles (Z = 1 or 2) with respect to the propagation direction of heavy fragments and of primary pion beam, as well as on the energy distributions for these particles [5]. These experimental data were compared to the similar evidence obtained earlier through the studies of light charged particles (LCP) emitted from the fragments of uranium fission by 153 MeV protons [3, 4].

Experiment.

Carrier-free low-sensitivity nuclear emulsions about 300 [mu]m thick were used in the experiments. The emulsions detecting protons with energy Ep < 15 MeV were loaded by uranium and exposed to 1700 MeV negative pion beam in the Institute of Experimental and Theoretical Physics, Moscow. The pion flux incident normal to the emulsion plane was 2.10^{7} cm^{-2}. The processing techniques for emulsions and the methods of their microscopy were reported earlier [3, 4, 6].

We analyzed 2280 fissions of ^{238}U nuclei into two fragments. Among them, 1265 fission events were accompanied by the LCP emission. The number of LCP per fission event ranged from one to ten. The total number of detected LCP was 2210. For tracks with $\varphi_0 < 45°$ (φ_0 is the angle between tracks and the emulsion plane), we measured the ranges for light fragments (R_l), heavy fragments (R_h), and LCP. We also measured the angles between the tracks and the primary pion beam, the angles between the tracks themselves, as well as the ionization produced by LCP (the density of grains within the tracks).

To determine the masses and energies of LCP, we analyzed the tracks of particles stopped in the emulsion and corresponding to $\varphi_0 < 45^{\circ}$. The measured ranges and ionizations allowed us to determine masses and energies of the particles using the calibration curves [6].

For LCP that were not stopped in the emulsion, the ionization measurements allowed us only to discriminate between particles with $Z = 1$ and 2. The tracks of these particles were used only to obtain various angular distributions.

All measured results were recorded by a computer-aided data acquisition system. A straightforward computer routine provided an opportunity to calculate true ranges and energies of LCP, the ranges of fragments, and all angles under study. These data stored in the direct access files were analyzed using program packages allowing us to construct various angular and energy distributions taking into account several additional parameters.

We present here the measured angular and energy distributions for LCP. In fission of uranium nuclei by pions most of the detected LCP were emitted before the fission or from the fission fragments. The contribution of the particles emitted during the fission is negligibly small (about 1% of the total number). This is also true in reference to a small number of observed slow pions and kaons. The employed low-sensitivity emulsions were efficient for detecting protons with energies up to 10 MeV. Therefore, the vast majority of detected LCP are related to the evaporation from fission fragments or from the residual nuclei.

About 50% of the fission events induced by pions are not accompanied by the LCP emission. For other fission events, the number m of LCP emitted during the fission of uranium nuclei by pions ranged from one to ten. In experiments involving the fission of uranium nuclei by 153 MeV protons, where the emulsions of the same sensitivity were used, we had m = 1. The emulsion processing technique and the microscopy methods of scanning the emulsions were the same in the experiments with uranium fission both by protons and pions.

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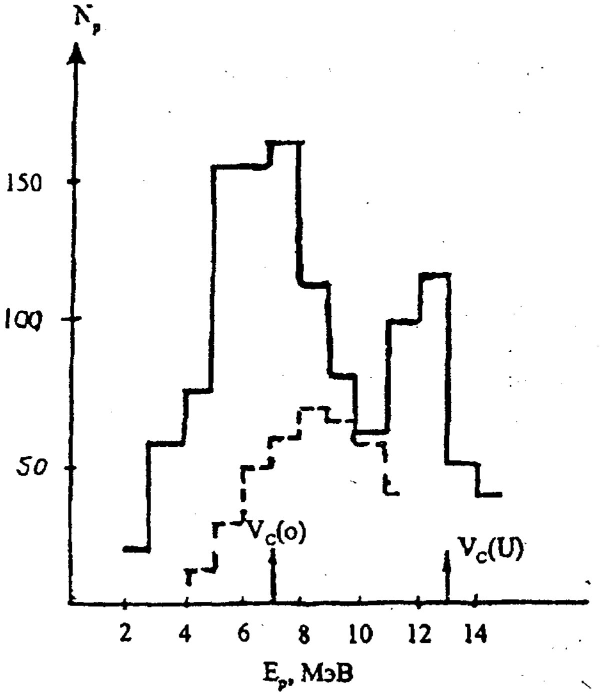
Energy distributions of protons.

The energy distributions of protons accompanying the fission of uranium nuclei by 1700 MeV pions is shown in Fig. 1 (solid histogram). The heights of Coulomb barriers for the emission of protons from uranium nuclei (V_C = 13 MeV) and from fission fragments (V_C = 7 MeV) are indicated by arrows.



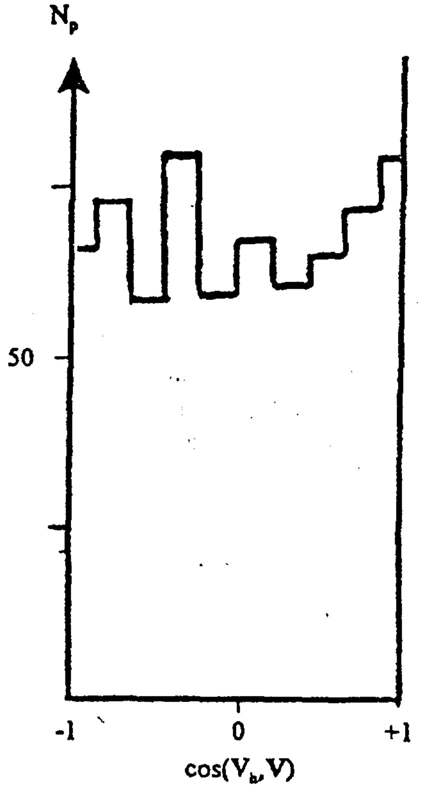


Fig. 1. Proton energy distribution for fission by pions (solid line) and by 153 MeV protons (dashed line).

Fig. 2. Angular distribution of protons (V) with energies less than 10 MeV with respect to the motion direction of heavy fragments (V_h) for fission by pions.

The experimental data for protons emitted from uranium nuclei at rest before their fission result in the energy distribution peaked at 13-15 MeV, whereas for nuclei at rest with $Z = 45$ (corresponding to fission fragments), the peak in the proton spectrum falls within the 6-7 MeV range. [2-4, 7]. In our experiment, we were able to detect efficiently protons with energies below 10 MeV, therefore the energy distribution (Fig. 1) was significantly distorted for energies exceeding 10 MeV.

Thus, it is natural to separate the energy distribution shown in Fig. 1 (solid histogram) into two portions corresponding to protons with energies below 10 MeV emitted from fission fragments and to protons emitted with energies higher than 10 MeV from residual compound nuclei. Protons emitted from fragments comprise 70% of their total number. This fraction is nearly the same both for fission events accompanied by the emission of a small ($m = 3$ or less) or large number of particles. The similar results were obtained for other LCP with $Z = 1, 2$. It is also noteworthy that the energy distributions for protons emitted in the direction of motion of fragments was the same for light and heavy fragments. This result demonstrates that the most part of protons is emitted from the non-accelerated fragments. The dashed line in Fig. 1 illustrates the energy distribution for protons emitted from accelerated heavy fragments of uranium nuclei fission by 153 MeV protons [4]. We can see that the peak in this distribution is shifted by about 2 MeV toward higher energies.

Angular distributions of light charged particles.

The angular distribution (with respect of the direction of motion of heavy fragments) for protons with energies below 10 MeV emitted from the fission fragments is shown in Fig. 2 for the case of fission by pions. The abscissa is $\cos(V_h, V)$, where V_h and V are velocities of heavy fragments and LCP. The ordinate is the number of LCP. The angular distribution of LCP is isotropic, and the ratio of protons emitted at angles larger and smaller than 90^o with respect to the direction of motion for heavy fragments is 1.0 ± 0.1.

The angular distributions for all LCP (V) accompanying the fission by pions with respect to the motion direction of heavy fragments (V_h) are presented in Fig. 3 (solid histograms) at different values of fission asymmetry $M_h/M_l \sim R_l/R_h$, where M_h and M_l are masses of heavy and light fission fragments, respectively: for symmetric fission events $M_h/M_l < 1.3$ (Fig. 3a), for asymmetric fission events $M_h/M_l < 1.3$ (Fig. 3b) , and for all M_h/M_l values (Fig. 3c). Almost all distributions are isotropic, just as in Fig. 2. More than 60% of LCP are emitted from fission fragments. For comparison, the angular distributions for all LCP accompanying the fission of uranium nuclei by 153 MeV protons [3, 4] are shown in the figures by dashed lines. In the latter case, we observe the prevailing LCP emission along the direction of motion of heavy fission fragments, though the percentage of LCP emitted from the fragments is by about a factor of two lower than for the pion-induced fission. Such an angular distribution is related to the LCP emission from accelerated distorted heavy fission fragments [3, 4]. For the pion-induced fission, the isotropic angular distribution of LCP emitted by fragments of uranium nuclei can be explained, if we assume that LCP are emitted from non-accelerated and apparently undistorted fragments immediately after the fission event.

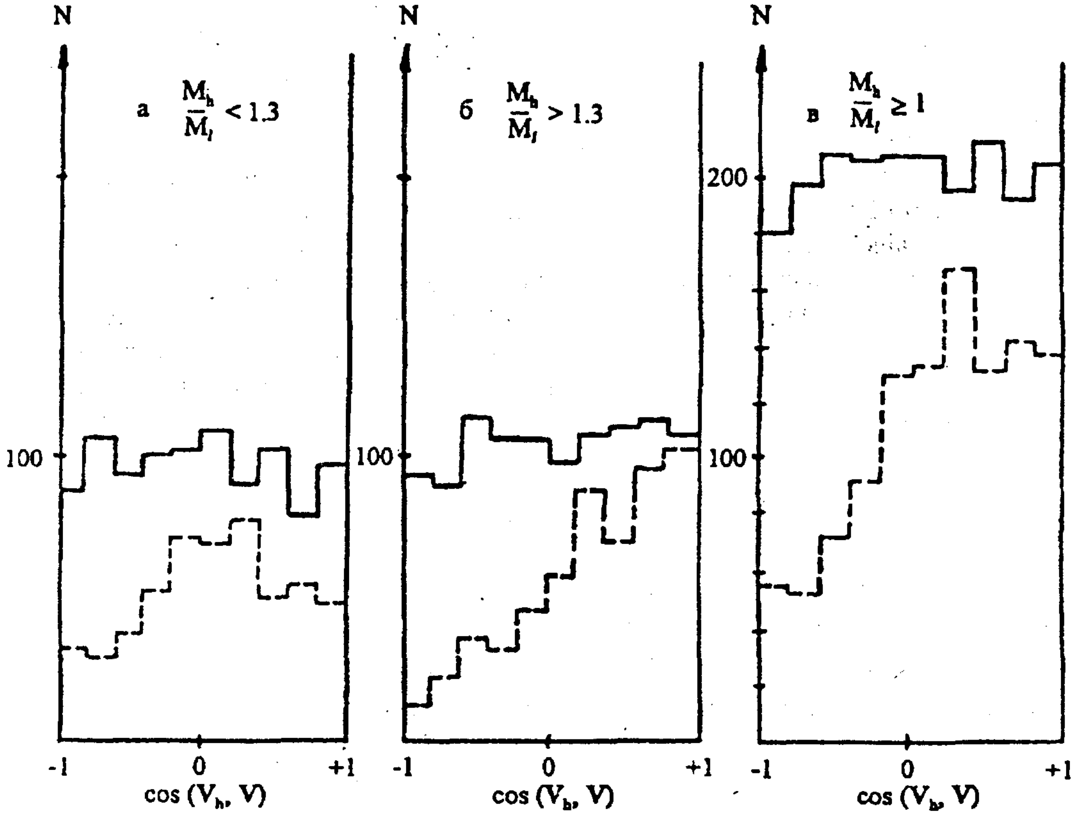


Fig. 3. Angular distribution of LCP (V) with respect to the motion direction of heavy fragments (V_h) for different values of the fission asymmetry M_h/M_l: (a) for $M_h/M_l < 1.3$, (b) $M_h/M_l > 1.3$, and (c) for all values of M_h/M_l. The histograms are plotted for fission by 1700 MeV pions (solid line) and by 153 MeV protons (dashed line).

This conclusion appears to be very important since in all previous experiments LCP and neutrons were emitted from accelerated fission fragments [3, 4, 8, 9, 11].

Now, let us analyze the angular distribution of LCP with respect to the direction of primary proton and pion beams. For pion-induced fission, the distribution turned out to be nearly isotropic. The ratio of LCP numbers corresponding to the emission at angles larger and smaller than 90° is equal to 1.1 ± 0.1. Thus, the detected LCP are emitted mainly from the fission fragments and from residual nuclei at the evaporation stage of the collision. On the fission of uranium nuclei by 153 MeV protons, the ratio of LCP this case, the most part of LCP is emitted along the proton beam before the fission, as the result of direct and semidirect reactions.

The number of LCP emitted from fission fragments.

The data concerning the number of LCP emitted from fission fragments at different values of multiplicity m are presented in Table 1 for fission of uranium nuclei by 1700 MeV pions.

Table 1

The number of LCP emitted from the pion-induced fragments.

Multiplicity LCP - m	Number of fissions	Number of LCP emitted from fission fragments Total	Per fission event
$0 \leq m \leq 10$	1575	1093	0,70 ± 0,03
$1 \leq m \leq 3$	690	635	0,90 ± 0,04
$m \geq 4$	182	458	2,5 ± 0,2

The table demonstrates that the number per fission event of LCP emitted from fragments is close to unity. This number increases with multiplicity, and for $m \geq 4$, each fission event is accompanied by the emission of more than two LCP, i. e., LCP are emitted from each fission fragment.

On fission of uranium nuclei by 153 MeV protons the number of LCP emitted from fragments is less by about a factor of 30 and is equal to $2.4.10^{-2}$ per fission event [3, 4].

Discussion.

In this paper, we compare the mechanisms of LCP emission from fragments produced on fission of uranium nuclei by 153 MeV protons and 1700 MeV pions. Let us discuss in brief the process of interaction between hadrons and uranium nuclei.

It is well known that this interaction involves the cascade process as an initial stage. After that, we have the emission of particles (before attaining the equilibrium), which terminates by the formation of a thermalized nucleus. Then, the particle evaporation process comes into play. This process can compete with the fission of nuclei. Finally, the produced fission fragments emit neutrons and LCP. Neutrons are emitted from the accelerated fragments on fission induced both by low- and high-energy particles [8-10]. The LCP emission from the accelerated fragments was observed earlier only on fission by particles with energies up to 150 MeV [2-4, 10]. In this work, we were first to observe the LCP emission from non-accelerated fragments produced on the fission by high-energy particles (E_π = 1700 MeV). In contrast to neutrons, LCP are emitted from non-accelerated fragments immediately after the fission.

According to [9], during the interaction of uranium nucleus with slow antiprotons, the nucleus emits more than 20 nucleons before the fission. As a result, the nucleus undergoing fission is characterized by $A < 220$ and $Z < 90$, and its excitation energy is about 90 MeV.

On fission of uranium nuclei by 1700 MeV pions, the number of nucleons emitted before the fission is even more. The excitation energy of residual nuclei, nuclei under fission, and fission fragments should be higher than on fission induced by slow antiprotons. In the latter case, the energy introduced to a nucleus does not exceed 800 MeV.

A nucleus emit a large number of neutrons before the fission, therefore the produced fission fragments have a large excess of protons. This fact in combination of the high excitation energy of fragments can cause the LCP emission from non-accelerated fragments immediately after the fission during a time interval shorter than that needed for the fragment acceleration ($< 10^{-20}$ s). This process is followed by the emission of neutrons, but these neutrons are emitted already from the accelerated fragments.

Such a mechanism of the LCP emission from the pion-induced fission fragments allows us to explain the obtained isotropic angular distribution of LCP, presented in Figs 2 and 3 (solid histograms). If the LCP were emitted only from the accelerated heavy fragments, then their angular distribution should be similar to that obtained for the fission of uranium nuclei by 153 MeV protons (see the dashed histogram in Fig. 3). If the LCP were emitted with the equal probabilities both from accelerated light and heavy fragments, then their angular distribution should have the parabolic shapes with the peaks at $\cos(V_h V) = \pm 1$.

The LCP are emitted from the whole bulk of the nucleus, therefore they cannot be focused by the Coulomb fields of the fragments in the direction normal to the axis of fragment emission cone. The focusing takes place only for LCP emitted from the neck of the nucleus undergoing the fission, but the number of such particles is quite small.

There is an additional argument in favor of the LCP emission from the non-accelerated fragments in the course of pion-induced fission. It turns out that the peak in the energy distribution of protons (Fig. 1) is shifted by 2-3 MeV to the left with respect to the peak in the proton spectrum corresponding to the proton emission from accelerated fragments produced on fission of uranium nuclei by 153 MeV protons [4].

Thus, in the spontaneous fission and the fission induced by thermal neutrons, LCP are predominantly emitted from the accelerated light fission fragments and their yield is about 10^{-5} per fission event [10]. On fission by slow pions and 153 MeV protons, LCP are mainly emitted from the accelerated distorted heavy fission fragments, and their yield is about 2.10^{-7} per fission event [2-4]. Finally, the fission by 1700 MeV pions is accompanied by the LCP emission from the non-accelerated fragments immediately after the moment of nucleus rupture into two fragments. In this case, the LCP yield is about 0.7 per fission event.

We see that the characteristic parameters of the fission fragments such as excitation energy, composition (the number of protons and neutrons), deformation, etc.

vary significantly with the increase in excitation energy of residual nuclei and nuclei undergoing fission.

The mechanism of LCP emission from fragments produced on fission of uranium nuclei by pions differ dramatically from the neutron emission mechanism. On fission of nuclei by high-energy particles [9, 11], the number of neutrons emitted from accelerated fragments, remains constant, when the excitation energy varies within 200 - 600 MeV range.

In contrast to neutrons, the number of LCP emitted from the non-accelerated pion-induced fission fragments (see Table 1) increases by about a factor of three with multiplicity m, i. e., with the excitation energy of residual nuclei, and LCP are emitted from non-accelerated fragments immediately after the fission of nuclei.

It is rather surprising that the number of neutrons emitted by fission fragments remains constant. Probably, the cause is that the neutron emission precedes the LCP emission, and only after the LCP neutrons are emitted from accelerated fragments having nearly the same residual excitation energy. This experimental evidence calls for the theoretical analysis, since it characterizes the intrinsic properties of the excited fragments (of nuclei far from [beta]-stability regions).

In our experiments on the pion-induced fission of uranium nuclei, we also found that the number of LCP emitted before the fission of uranium nuclei increases with the multiplicity m, i. e., with the excitation energy of residual nuclei, by a factor equal to that characterizing the growth in the number of LCP emitted from the fission fragments.

The similar relationship between the number of particles emitted before the fission and the number of LCP emitted from the fission fragments was observed in experiments on the fission of heavy nuclei by ions with energies ranging from 100 to 200 MeV. It was found that the excitation energy of a nucleus undergoing the fission increases with the number of LCP emitted from the fission fragments [12]. Our estimates and the data reported in [9] suggest that this energy can be as high as 100 MeV and even higher.

Let us make a concluding remark. On fission of nuclei by high-energy particles, LCP are emitted from the non-accelerated fragments, therefore it is possible that a certain number of neutrons can also be emitted from the non-accelerated fragments, although it is usually assumed that neutrons are emitted only from the accelerated fragments [8, 9, 11]. These neutrons can be considered as emitted before the fission. This can modify the temporal characteristic of the fission process related to the number of neutrons emitted before the fission, as well as the number of neutrons emitted from the fission fragments, and hence the excitation energy of the nucleus undergoing the fission.

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