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Fission of Uranium by Slow π^- Mesons, Fast Neutrons and γ-Rays of Energies Up to 250 mev

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The fission of uranium by slow π^- mesons, fast neutrons and high energy γ-rays has been studied by use of thick photographic plates. It has been found that there is a high probability that the uranium nucleus will undergo fission when it captures a π^- meson. This probability is close to 0.5. At high energies of excitation, fission is often accompanied by the emission of charged particles--protons and α-particles. We have determined the energy distribution and angular distribution of these particles. The mechanism of the fission of uranium at high excitation energies is discussed on the basis of these observations.

IT is known that slow negative π^- mesons, just like slow neutrons, are easily captured by nuclei. It is natural to expect that such mesons should induce the fission of uranium and other heavy elements with high probability. However, since the energy liberated upon capture of a meson is many times larger than upon capture of a slow neutron (6-8 mev) the interaction leading to fission might have quite different characteristics. In part, it might be expected that it would, at least in some respects, be comparable to fission induced by particles of high energies (fast neutrons, etc.).

In order to establish and study the fission of uranium by π^- mesons, the technique of thick-layered photographic plates in which uranyl acetate had been introduced was used. The very first experiments, carried out at the start of 1950, showed that the fission of uranium took place with π^- mesons and established some characteristics of this process. This phenomenon was then studied in more detail during 1950*.

A characteristic of fission induced by slow mesons is the presence, in considerable probability, of protons of energies above 10 mev accompanying fission (of the order of once in every 6-7 fissions).

The fission of uranium by π^- mesons was established and studied independently in the work of Ivanova and Perfilov[4] with results in agreement with ours.

The fission of uranium by π^- mesons has also been the subject of work by Al-Salam[5] and John and Fry[6]. Among twenty-two cases of fission, Al-Salam observed three cases of the emission of fast particles. The author merely states that these particles might be α-particles or protons. In the work of John and Fry, there was observed one such case which the authors regard as an exchange proton, even though its energy is about 7 mev.

Earlier, using various methods, the fission of uranium by neutrons and γ-rays of energies up to 100 mev had been extensively studied. It was established that in addition to fission into two fragments, there occurs fission into three particles in 1-2% of the events. In thermal neutron induced fission, the third particle is an α-particle appearing in two groups of ranges: short range α-particles in a yield of $\sim$ 1% and long range α-particles with a yield of $\sim$ 0.3%[7]. When fission is induced by neutrons of up to 10 mev the yield of long range particles is somewhat smaller[8]. Fast protons have not been observed previously*.

Thus the frequent presence of fast protons as third particles characterizes the fission of uranium with slow π^- mesons and distinguishes it from

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* Preliminary results were communicated by us in the report for April 1950[1]. The complete results were presented in our reports for June 1950 and March 1951[2].

[1] G. E. Belovitskii, L. V. Soukhov, T. A. Romanova and I. M. Frank, Report Phys. Inst., Acad. Sci. USSR, April 1950.

[2] G. E. Belovitskii, L. V. Soukhov, T. A. Romanova and I. M. Frank, Report Phys. Inst., Acad. Sci. USSR, June 1950 and March 1951.

[4] N. S. Ivanova and N. A. Perfilov, J. Exper. Theoret. Phys. USSR **28**, 732 (1955).

* In the work of Hill[9] of the fission of U^{235} by slow neutrons, there has been observed the emission of protons of low energies. However, the yield of these is insignificantly 0.02%.

[5] S. G. Al-Salam, Phys. Rev. **84**, 254 (1951).

[6] W. John and W. T. Fry, Phys. Rev. **91**, 1234 (1953).

[7] Tsien San-Tsiang et al, J. Phys. et Radium **8**, 165 200 (1947).

[8] E. W. Titterton, Phys. Rev. **83**, 673 (1953).

[9] D. L. Hill, Phys. Rev. **87**, 1049 (1952).

earlier examples of fission. It is natural to assume that this characteristic is connected with the large energy of excitation produced in the nucleus by capture of π^- mesons. In order to investigate this hypothesis further, there were carried out in 1951-1952 experiments on the fission of uranium by neutrons having energy of 460 mev and by γ-rays up to 250 mev. (At that time there were no data on the cross section for fission by photons of energy above 100 mev.)*

The results of these studies agree with each other and make possible some conclusions about the characteristics of fission of very highly excited nuclei. The results of our work[1,2,10,11] during 1950-1952 are presented in this article. A short summary has been published already as a letter[12].

1. EXPERIMENTAL PART

In this work we used photographic plates having an emulsion thickness of $100\,\mu$. The plates were sensitive to protons of energy up to 30 mev. In order to increase the efficiency of observing fission events a technique was worked out for introducing uranium salts into the emulsion in large amounts, evenly distributed throughout. To do this the plates were first kept in water at 25° C for 30 min and then in a 2.5-10% solution of uranyl nitrate for 30 min at the same temperature. Experiments showed that the preliminary soaking in water increased the amount of uranium absorbed by the emulsion by a factor of 4 and at the same time induced an even distribution throughout the thickness of the plate. After treatment, the plates were dried in an air stream for 30 min. They were then irradiated and immediately developed. It was established that extensive washing of the plates before development did not wash out the uranium significantly. The presence of uranium in the emulsion not only decreases the sensitivity of the photographic plates and speeds up the disappearance of latent images produced by charged particles but increases the difficulty of subsequent development as a result of contraction and lowering of the pH of the emulsion.

For these reasons the presence of large amounts of uranium necessitated a new method of development. A two solution method was used. The plates were first treated in base (a 3% solution of Na_2CO_3) and then were developed in the following solution: para-amino-phenol--4 gm, anhydrous sulphite--50 gm, H_2O--to make 1000 cm^3.

The preliminary treatment with base corrects the pH of the uranium containing emulsion and accelerates its expansion. This makes it easier for the developer to penetrate into the depths of the emulsion. The result is a more even development, since the depletion of the developer as a result of penetration into the interior of the emulsion is compensated by the higher local concentration of base.

In the final experiments the following development procedure was used:

1) Treatment in base: 30 min at 18° C;
2) Treatment in the developer: 30 min at 18° C;
3) Stop-bath: 15 min (a 2% solution of acetic acid) at 15° C;
4) Distilled water washing: 15 min;
5) Fixing: 1½-2 hrs;
6) Final washing: 1½-2 hrs;
7) Drying.

The search for mesons stopping in emulsion and for fission fragments was carried out with a binocular microscope, objective of 60 × (P· A = 1.0), ocular of 7 × and magnification of 1.5 × (total magnification 630 ×). The measurement of the range of the fragments and the grain counting was made with an objective of 90 × (P· A = 1.3) and with an ocular of 15 ×, giving an overall magnification of about 2000 ×.

The irradiations of the photographic plates with slow π^- mesons and with neutrons of maximum energy equal to 180 and 460 mev were carried out at the synchrocyclotron of the Institute for Nuclear Problems of the Academy of Sciences.

The slow π^- mesons were produced in a lead target 2 mm thick by 560 mev α-particles. They were deflected by the magnetic field of the cyclotron, passed through absorbers which slowed them down and impinged on the photographic plates. These were introduced into the vacuum chamber of the cyclotron in a sealed casette on a special probe. The irradiation time was 5-15 min.

The neutrons used for these experiments were produced either in a bombardment of Cu with 560 mev α- particles or by a bombardment of Be with 180 mev and 460 mev protons.

As was shown in the work of Djelepov and

* The results of these studies were given in our report for Dec. 1952[10]. This work also used photographic techniques. These are described in the report for June 1952[11].

[10] G. E. Belovitskii, L. V. Soukhov and I. M. Frank, Report Phys. Inst., Acad. Sci. USSR, Dec. 1952.

[11] T. A. Romanov, and G. E. Belovitskii, Report Phys. Inst., Acad. Sci. USSR, June 1951.

[12] G. E. Belovitskii, T. A. Romanov, L. V. Soukhov and I. M. Frank, J. Exper. Theoret. Phys. USSR 28, 729 (1955); Soviet Phys. 1, 581 (1955).

Kazarinov[13], the bombardment of targets with monoergic protons produces neutrons with a distribution in energies. The maximum in the spectrum of neutrons is at a lower energy than the energy of the original particles. For protons of 180 mev this maximum lies 20-30 mev lower; for 460 mev protons it lies 80-100 mev lower. Thus the most probable neutron energies in the two cases are 150 and aprproximately 380 mev. A more complete description of the energy spectrum of the neutrons (for energies less than 100 mev) has been given[14], where it is shown that more than 50% of the neutrons have energies less than 100 mev, being formed by evaporation processes from excited Be and Cu nulcei. In the rest of this paper such neutrons with a broad energy spectrum will be called 150 mev neutrons and 380 mev neutrons.

For comparison, we also investigated the fission of uranium with 14 mev neutrons. These experiments were carried out at a high voltage set. In most cases the photographic plates were oriented horizontally relative to the neutron beam. In the irradiations with fast neutrons the photographic plates were protected from slow neutrons by cadmium sheets 1 mm thick.

The irradiations with γ-rays were carried out at maximum γ-ray energies of 30, 80 and 250 mev. In most cases the plates were oriented perpendicular to the γ-ray beam. These irradiations were carried out with the synchrotron of the Lebedev Institute of Physics of the Academy of Sciences.

2. THE INTERACTION OF π^- MESONS WITH URANIUM NUCLEI

Of the more than 3000 π^- mesons ending in the emulsion there were 96 observed cases of π^- mesons producing fission in uranium. For comparison, among 634 π^- mesons ending in emulsions that had not been impregnated with uranyl acetate there was not found a single case of uranium fission. Among the 96 fissions, 81 had only 2 fragments; a third particle was emitted in the other 15 cases.

In the fission of uranium by π^- mesons into two fragments the two particles, as a rule, go off in opposite directions. Figure 1 shows microphotographs of typical fission events induced in uranium by π^- mesons (microphotographs *1-4*). The presence of the π^- meson track usually makes it possible to determine the point where the fission occurred and thus to determine the separate ranges of the two fragments. These fragment ranges were measured with an accuracy no better than 5%.

In Fig. 2 are presented the distribution in total ranges of the two fragments (only including those cases where a recoil nucleus with a range greater than 1-2 was not observed) for 45 cases of π^- meson induced fission of uranium; in Fig. 3 are shown the distributions of ranges of the light and heavy fragments. For comparison in Fig. 2 there is shown the distribution of total ranges of both fragments from 243 cases of uranium fission induced by the neutron background. The larger scatter in the ranges of fragments in the case of meson fission as compared to neutron fission is probably connected with the lower accuracy of measurement, since in the case of neutron fission only those cases were picked which lay in the plane of the emulsion. For comparison there is also presented in Fig. 3 the distribution in ranges of the light and heavy fragments from the thermal neutron fission of U^{235}. This was taken from a report in 1949 by Bøggild[15]. The ranges in air were converted into ranges in emulsion using a relative stopping power factor of 1680.

It is seen from Figs. 2 and 3 that there is no significant change in the ranges of fragments of fission induced by π^- mesons from those arising from neutron fission. It is also seen that π^- meson induced fission proceeds in a more symmetrical fashion than does neutron induced fission.

Among the 96 cases of fission induced by π^- mesons we saw 15 cases accompanied by a third charged particle. Microphotographs of such instances are presented in Fig. 4 (*5-8*). In such fissions the fragment ranges stay the same as in fissions not accompanied by a third particle.

These cases have the following characteristics:

In one case the fission is accompanied by the emission of a long range α-particle. Its full range in emulsion is equal to 105 μ, leading to an energy of 14 mev. The angles between it and the heavy and light fragments are 98 and 82°, respectively.

In one case there was emitted a highly ionizing particle with a range of only 2.5 μ. If it is assumed that this is an α-particle, its energy is equal to 0.8 mev. This particle was likewise emitted at an angle of 90° with respect to both fragments. In 13

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[13] V. P. Djelepov and Y. M. Kazarinov, Dokl. Akad. Nauk SSSR **99**, 939 (1954).

[14] J. Cassels et al, Phil. Mag. **42**, 215 (1951).

[15] J. K. Boggild et al, Phys. Rev. **76**, 988 (1949).

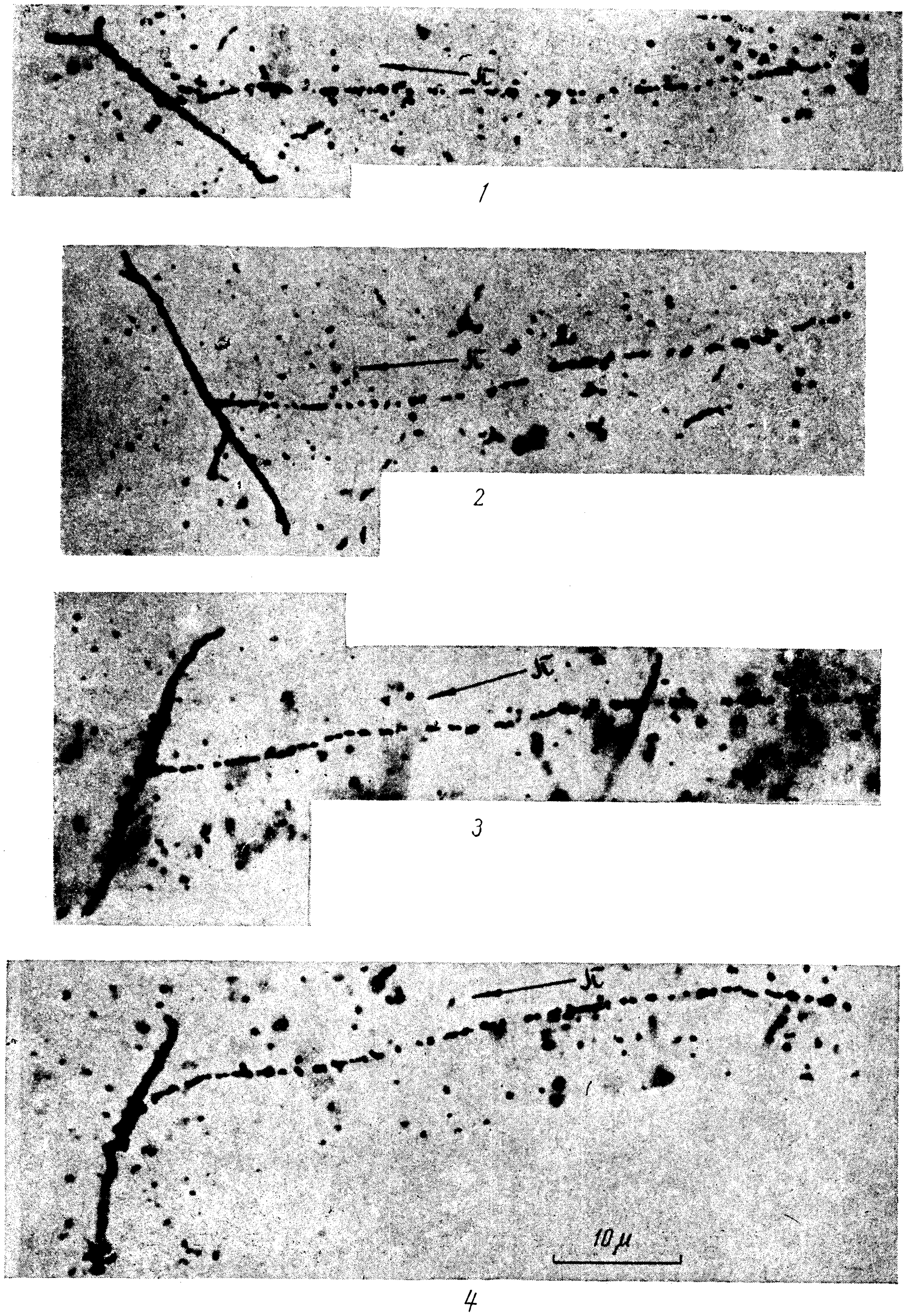

FIG. 1. The Fission of uranium by π^- mesons into two fragments; microphotographs *1-4*.

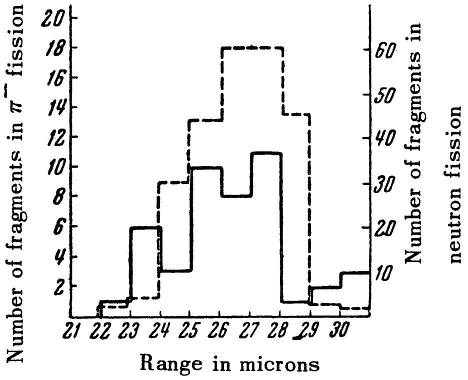

FIG. 2. The distribution in total ranges of the fragments from uranium fission induced by π^- mesons and by neutrons; solid line--fragments from π^- mesons fission; dashed line--fragments from slow neutron fission.

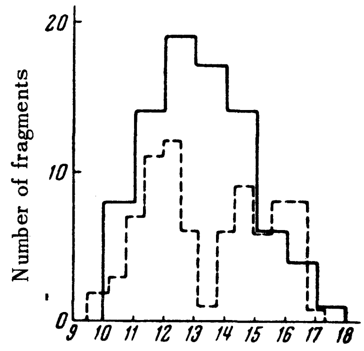

FIG. 3. The distribution in ranges of the light and heavy fragments in the π^- fission and slow neutron fission of uranium; solid line--fragments in π^- fission; dashed line--fragments from slow neutron fission.

cases of fission the third particle emitted is singly charged. Since none of these stopped in the emulsion, a definite mass assignment could not be made. However, since these particles are singly charged, as was established from the observed ionization (grain density along the track), it is natural to assume that most of these are protons. However, it cannot be excluded that among them were some deuterons or tritons. Using the curve of grain density as a function of range of π^- mesons, it was possible to calculate the ranges of these particles from their measured grain densities and from this their energies on the assumption that the particles were protons. This range spectrum is pictured in Fig. 5. (If it is assumed that the particles emitted are α-particles, then their energy must be 16 times the energy of protons producing a track with the same grain density. This would lead to energies in the range 170-450 mev, which are impossible from conservation of energy considerations.)

In view of the possible large fluctuations in grain density, this evaluation of the energy of the particles has an accuracy only to within 20%.

The small number of cases studied makes it impossible to make definite statements about the angular distribution of these particles relative to the direction of motion of the fission fragments. In the observed cases, considering equal solid angles, there were emitted 5 particles between 0 and 48°, 3 particles between 48 and 70° and 5 particles between 70 and 90°. On the basis of these numbers it can be said that there is no strong preference for angles close to 90° such as is observed in the case of α-particles emitted in neutron induced fission.

3. THE PROBABILITY OF URANIUM FISSION BY π^- MESONS

In order to determine the probability of fission of uranium by mesons it is necessary to compare the number of expected captures of π^- mesons by uranium nuclei with the number of observed cases of fission.

The number of uranium nuclei that were incorporated into the emulsion was determined by counting α-particles from the natural radioactivity of uranium. In this measurement a correction was made for the α-particles that left the emulsion. In addition, proper account was taken of the fact that the emulsion is not sensitive all of the time (equal to 3 hours) between the start of the soaking in uranyl acetate until the final state of development.

The amount of uranium in the emulsion turned out to be 0.106 gm/cm^3 of dry emulsion (0.028×10^{22} nuclei/cm^3) and was established with 10% accuracy. From this data and from the atomic constitution of the emulsion it was found that 11% of the π^- mesons stopping in the gelatine would be captured by a uranium nucleus.

The calculation was made under the following assumptions:

1) The emulsion is a heterogeneous mixture--a suspension of AgBr crystals in gelatine.

2) The uranium is completely adsorbed on the gelatine;

3) The fraction of π^- mesons stopping in the

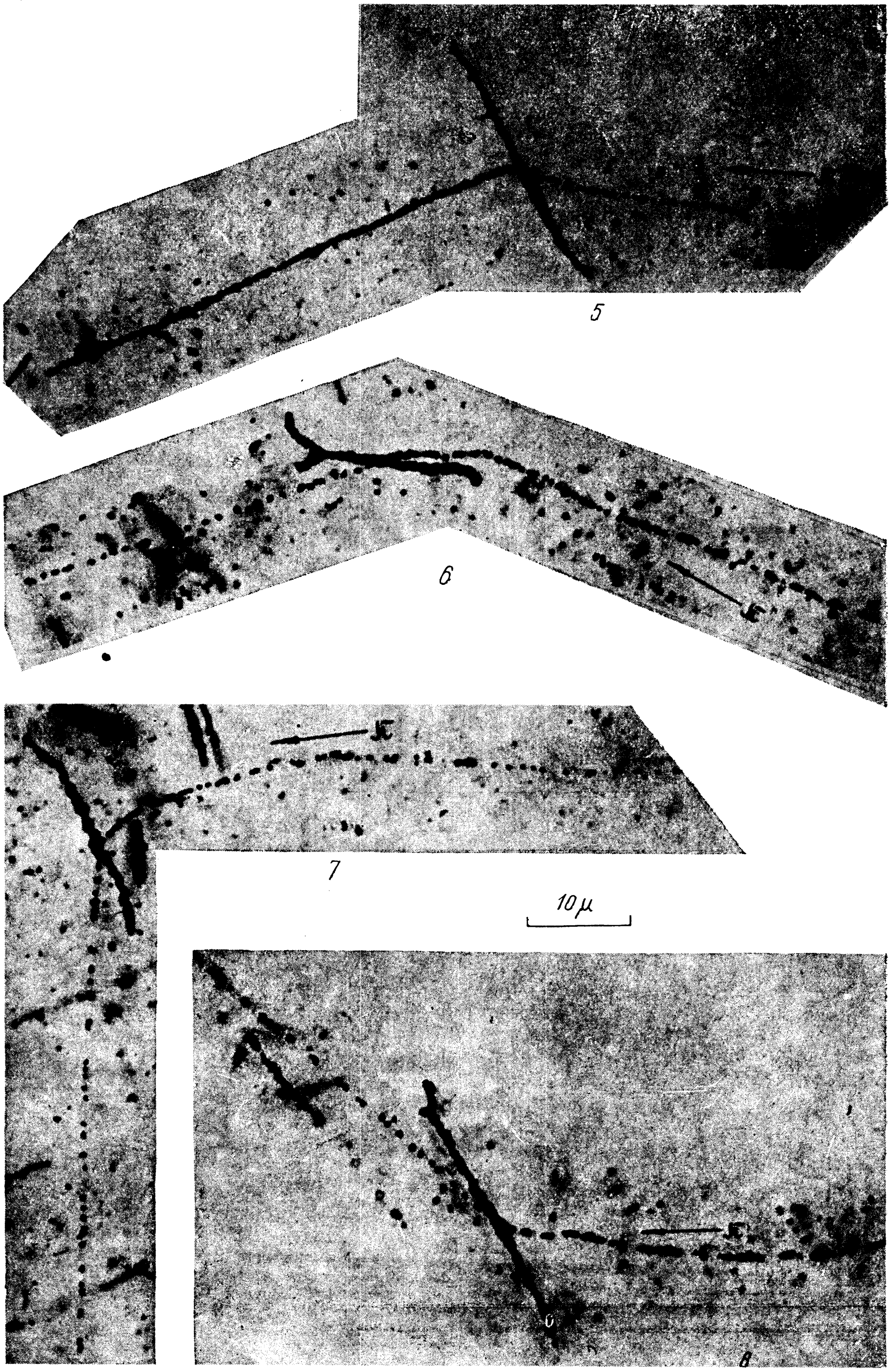

FIG. 4. The fission of uranium by π^- mesons into two fragments accompanied by fast charged particles; microphotograph *5*--a 14 mev α-particle is emitted; microphotograph *6*-- an ~ 12 mev proton is emitted; microphotograph *7*-- an ~ 18 mev proton is emitted; and microphotograph *8*-- a 20 mev proton is emitted.

AgBr and in the gelatine is proportional to the stopping powers of these substances[16];

4) The probability of capture of a π^- meson that stops in the gelatine by the different elements present (C, N, O, U) is proportional to the nuclear charge Z.

This same method for calculating the probability of capture of mesons by uranium was used by John and Fry[6].

Systematic scanning found 1983 π^- mesons stopping in the emulsion. Of these, 72 π^- mesons produced uranium fission (the μ^- contamination in the π^- meson beam was 5%). If one assumes that the efficiency of observing the stopped mesons is about 0.7, then 5.7 percent of the π^- mesons produce fission. This leads to a probability of 0.5 that a π^- meson that has been captured by a uranium nucleus will produce fission.

If the assumptions used in the calculation of the probability of a uranium nucleus capturing a meson are correct, then 50% of the time that a π^- meson is captured by such a nucleus it induces fission. The probabilities of fission found by other workers[4-6] in the same way lie in the regions 0.2-0.4. Since the accuracy of these measurements is not large it is not possible to say that they disagree significantly from each other. If, in contrast to the assumptions made above, the emulsion is regarded as a homogeneous medium and it is assumed that the π^- mesons are captured by the component nuclei with a probability proportional to their charge, then the probability that the π^- meson will produce fission after being captured by a uranium nucleus comes out close to unity.

In view of the inaccuracy of the measurements and the ambiguity of the calculation of the capture probability of mesons by uranium, it is necessary to conclude merely that a significant fraction of the π^- mesons captured by uranium induce fission. It should be mentioned that in this work it was not found possible to establish definitely other types of uranium fission into two or more fragments under the influence of π^- mesons. This was due to the fact that in all this work only those cases of fission were selected in which the two fragments were directed in opposite or almost opposite directions (in the range $\pm 10°$). Other possible types of fission were hard to identify since control plates, not loaded with uranyl acetate, showed similarly appearing cases. Microphotographs of several of the more certain cases of fission of uranium by π^- mesons into 3 or 4 fragments are presented in Fig. 6 (*9-11*). In microphotographs *9* and *10* the tracks have been produced by multiply charged particles. One of the tracks in the microphotograph *10* might be a recoil nucleus. In order to satisfy conservation of momentum it is necessary to assume the emission of several neutrons.

In addition to fission into 3 or 4 fragments there are possible spallation processes involving the emission of 2-3 multiply charged particles, leaving at angles much smaller than 180°, and charged particles with $Z \leq 2$. A microphotograph of such a case is presented in Fig. 6 (*11*).

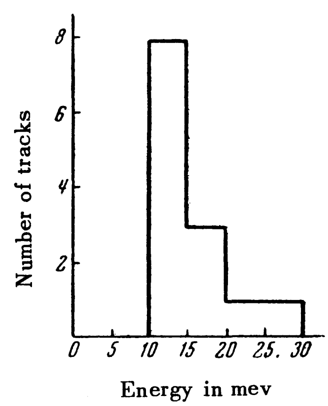

FIG. 5. The energy spectrum of protons accompanying uranium fission induced by π^- mesons.

4. THE FISSION OF URANIUM BY FAST NEUTRONS

There were found 309 fission events in the plates irradiated in the 380 mev neutron beam. In 67 of these the fission was accompanied by the emission of one or more long range charged particles. Twenty-one out of these 67 cases involved the emission of two extra particles; four of them had three; and in two instances there were four extra particles*. Thus with neutrons of this energy the probability of such complex fission events is 1:5.

In photographs irradiated by 150 mev neutrons there were found 389 uranium fission events. Of these 25 were accompanied by a third long range particle. Here the probability of such processes is 1:16.

In the case of photographic plates irradiated with 14 mev neutrons there were found 1917 fission events. Among these there was not a single case of a fission accompanied by a long range alpha

[16] A. Bonettie and G. Tomasini, Nuovo Cim. 8, 693 (1951).

* In Fig. 7 are shown microphotographs of such fission events (microphotographs *12-18*).

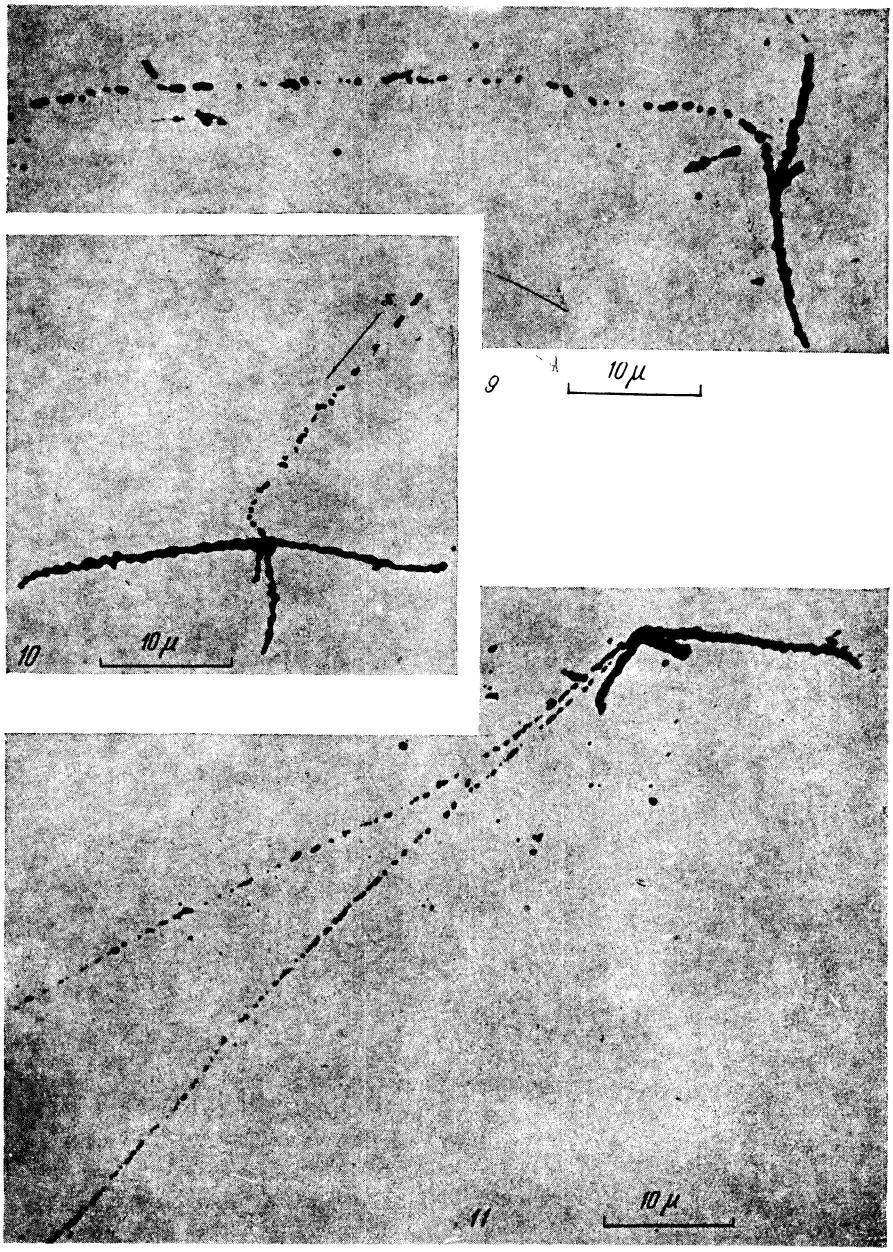

FIG. 6. Probable cases of uranium fission induced by π^- mesons. Microphotograph *9*--fission into three fragments; microphotograph *10*--fission into three or four fragments; microphotograph *11*--division into three fragments accompanied by the emission of a fast charged particle.

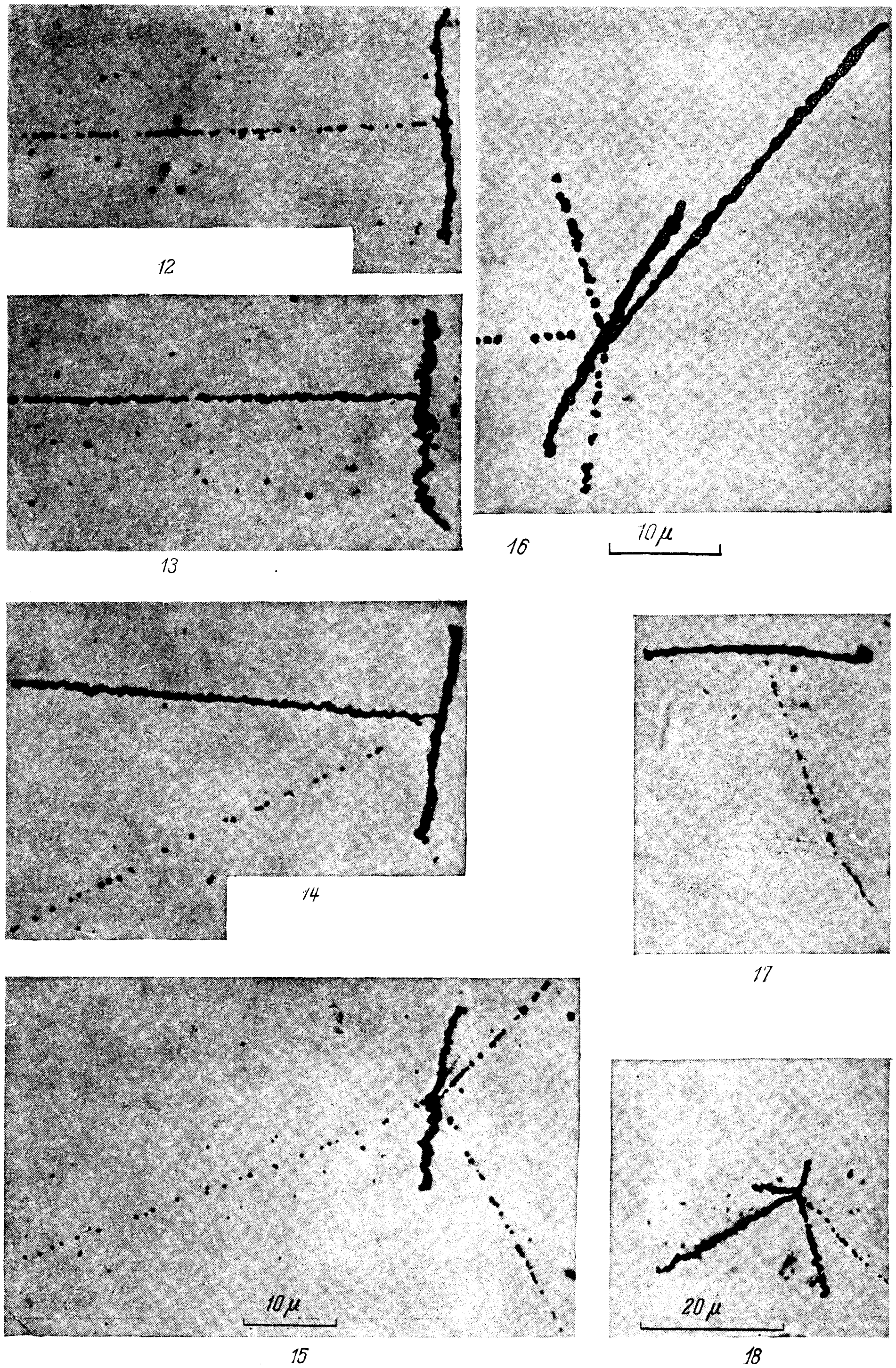

FIG. 7. Cases of the fission of uranium by 150 and 380 mev neutrons accompanied by the emission of fast charged particles. Microphotograph *12* --a 14 mev proton is emitted; microphotograph *13* -- an 18 mev α-particle is emitted; microphotograph *14* --two particles, 16 mev α-particle and a 23 mev proton, are emitted; microphotograph *15* -- three particles, 23, 23 and 14.5 mev protons, are emitted; microphotograph *16* -- four particles, 7, 15 and 30 mev protons, and an ~ 14 mev α-particle, are emitted; microphotograph *17* -- a 1.7 mev proton is emitted; microphotograph *18* -- a probable case of fission into four fragments accompanied by the emission of a fast charged particle.

particle. Thus the production of long range protons and alpha particles in the case of 14 mev neutron fission must be a very rare event.

A comparison of the results of these experiments with neutrons of three different energies clearly shows that the probability of the uranium fission being accompanied by a third long range particle rises with the energy of the incoming neutron and that such fission events are definitely caused by high energy neutrons.

In cases where it was possible we measured the total ranges and the separate ranges of the light and heavy fragments of the fission accompanied by a long range particle. The site of the fission event was assumed to be the point of emission of the fast particle accompanying the fission. The average total range turned out to be the same as the range of fragments from fission caused by low energy neutrons.

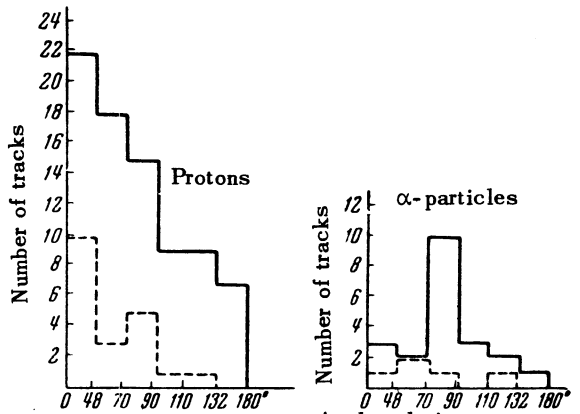

FIG. 8. The angular distribution of protons and alpha particles accompanying uranium fission relative to the original direction of the incident 150 and 380 mev neutron beams (the data have been referred to equal solid angles); solid lines—380 mev neutron data; dashed lines—150 mev neutron data.

The nature and energy of the long range particles was established using grain counting and gap counting[17]. Figures 8 and 9 show the angular distribution of these particles relative to the direction of the incident neutrons and relative to the plane perpendicular to the fission fragment direction. The data are presented in equal solid angles. It is seen from Fig. 8 that most of the protons come off at angles less that 90° relative to the neutron direction. It is seen from Fig. 9 that the protons are emitted essentially isotropically relative to the fission fragment direc-

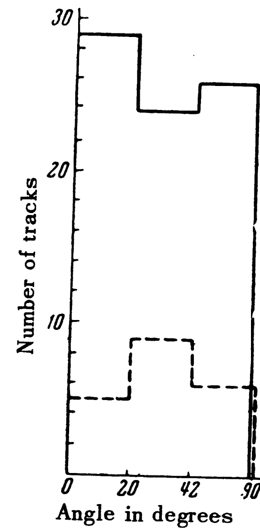

FIG. 9. Distribution of angles (relative to a plane normal to the fission fragment direction) of protons accompanying the 150 and 380 mev neutron fission of uranium (the data have been referred to equal solid angles); solid lines—380 mev neutron data; dashed lines--150 mev neutron data.

tions.

In contrast, α-particles apparently have a strong angular preference. Thus out of a total of 27 α-particles, 16 had angles less than 20° relative to a plane normal to the fission fragment trajectories (see below, Fig. 14).

The energy of the singly charged particles, on the assumption that they are all protons (it is

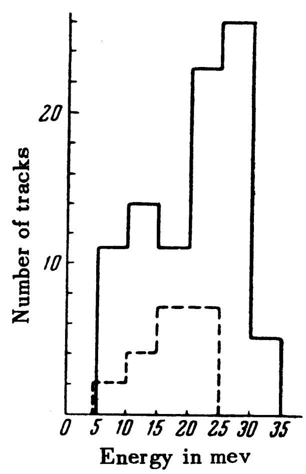

FIG. 10. Energy spectrum of the protons accompanying the fission of uranium by 150 and 380 mev neutrons; solid lines--380 mev neutron data; dashed lines—150 mev neutron data.

[17] P. E. Hodgson, Phil. Mag. 41, 725 (1951).

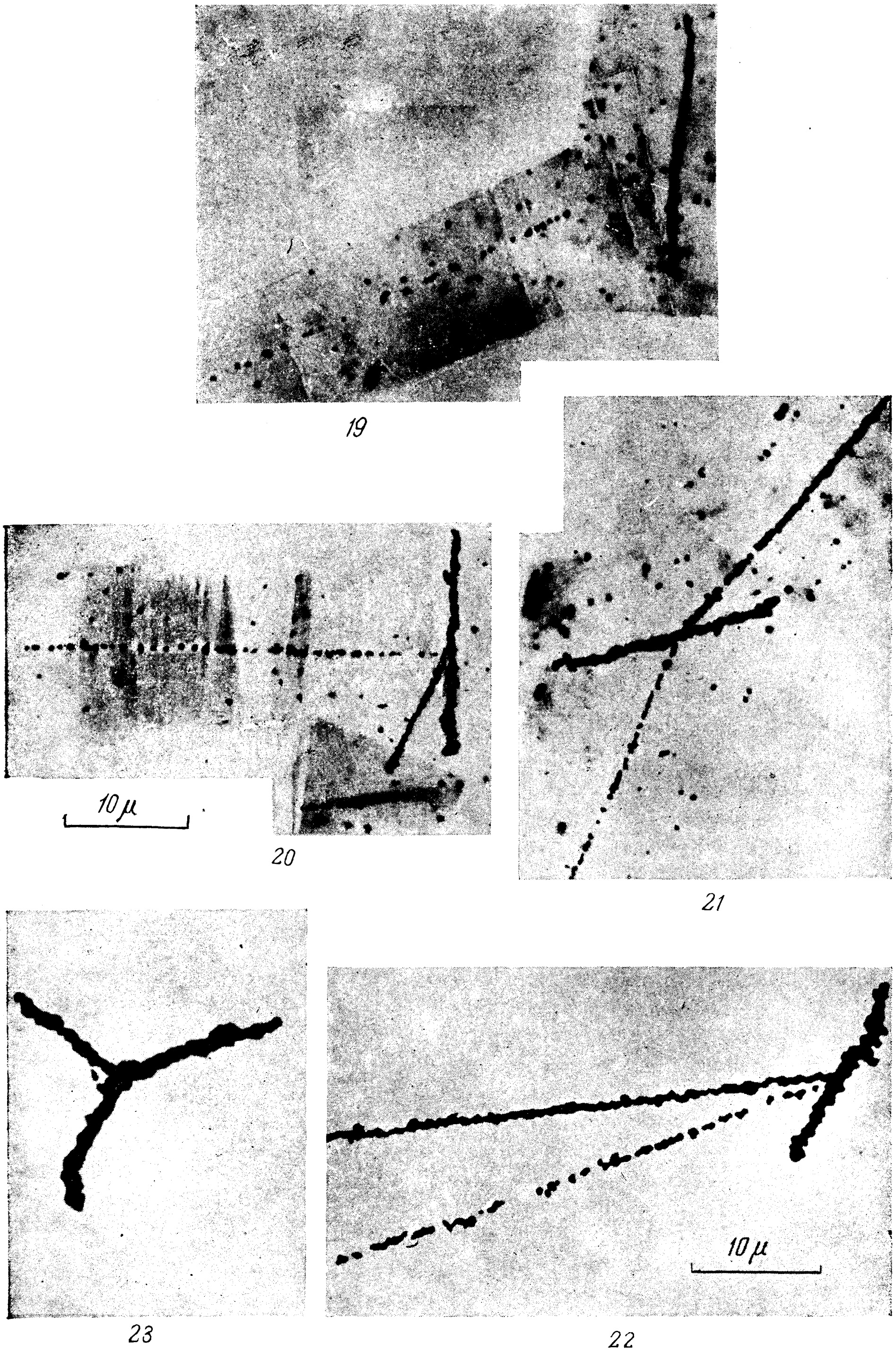

FIG. 11. Cases of uranium fission (induced by γ-rays having energies up to 250 mev) accompanied by the emission of fast charged particles: microphotograph *19* -- a 9.5 mev proton is emitted; microphotograph *20* -- a 13 mev proton and a 35 mev α-particle are emitted; microphotograph *21* -- a 9.7 mev proton and a 24 mev α-particle are emitted; microphotograph *22* -- a 10 mev proton and a 36 mev α-particle are emitted; microphotograph *23* -- a probable fission event into three fragments.

possible that some of these particles are deuterons or tritons), lies mainly in the energy range 10-30 mev (Fig. 10). The energy range of the α-particles lies in the range 14-25 mev. Actually, the range of the protons accompanying the fast neutron fission of uranium might extend to values even higher than 30 mev but because of the limited sensitivity of the photographic plates to such protons these would not be observed. For some of the protons the energy turned out to be lower than the potential barrier of uranium (about 10 mev).

Since the majority of these particles did not stop in the emulsion, it is possible that some of the protons included in Fig. 10 in the energy interval 5-10 mev came to be there because of inaccuracies in the energy determination. However, the emission of such particles is confirmed by other experiments carried out with photographic plates of lower sensitivity (registering protons of energies up to 10-15 mev).

In such photographic plates irradiated with 140 mev neutrons there were found 3293 cases of fission, among which were 33 involving the emission of a long range charged particle. A considerable number of these particles stopped in the emulsion. A majority of them turned out to be protons having an energy of less than 10 mev. In particular, there was observed a proton with an energy as low as 1.7 mev*. The angular distribution of these particles relative to the fragments turned out to be close to isotropic.

5. THE INTERACTION OF HIGH ENERGY γ-RAYS WITH URANIUM NUCLEI

A total of 2066 fission events were found in the photographic plates irradiated with γ-rays of 250 mev maximum energy. Forty-five of these involved the emission of long range charged particles. Thirty-seven were cases of emission of only one; in eight, two charged particles were emitted**. Thus, the probability of such processes is at least one in 46. It was established in control experiments that fission produced by background particles (secondary neutrons) contributed less that 0.2 percent to the observed result. These control experiments were performed by irradiating plates outside the γ-ray beam.

In photographic plates irradiated with γ-rays of 80 mev maximum energy there were found 614

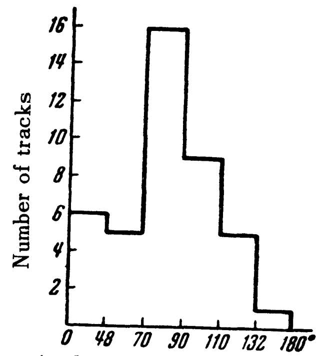

FIG. 12. The angular distribution of the protons accompanying uranium fission relative to the incident 250 mev maximum energy γ-ray beam direction. (The data have been referred to equal solid angles.)

fission events, 3 of them being accompanied by the emission of a third long range particle. Thus the probability of the emission of such a particle here is of the order of one in 200. In experiments with γ-rays of up to 30 mev there were found 717 fission events. In one of these there was a long range α-particle.

Thus the emission of a singly charged particle was not observed. Apparently, at energies of excitation of about 20 mev, close to that produced in the interaction of 14 mev neutrons with uranium, the emission of charged particles has a very low probability.

In those of the 45 fission events accompanied by charged particles we measured where it was possible the total range of both fragments and the ranges of the light and heavy fragments separately. The total range turned out to be the same as in fission produced by low energy neutrons. The majority of the emitted particles accompanying uranium fission were singly charged. Figure 12 shows the angular distribution of these particles relative to the γ-ray beam. The results are presented in equal solid angles. The figure indicates the characteristic maximum at angles close to 90°.

Figure 13 shows the distribution of angles between the singly charged particle and the plane normal to the motion of the fragments. It is seen that this distribution is close to isotropic. On the other hand, α-particles show an asymmetric angular distribution: of eleven cases, six show an angle less than 20° relative to the plane normal to the fragment direction (Fig. 14). Figure 15 shows the energy spectrum of the

* A microphotograph of this case is shown in Fig. 7. Microphotograph *17*.

** Microphotographs and microdrawings of such fission events are presented in Fig. 11, microphotographs *19-22*.

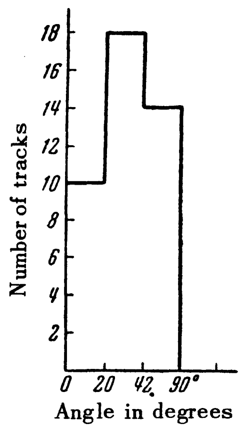

FIG. 13. The distribution of angles (relative to the plane perpendicular to the fragment directions) of the protons emitted in the fission of uranium by γ-rays having energies up to 250 mev. (The data have been referred to equal solid angles.)

singly charged particles. This spectrum (assuming all the particles are protons) extends from 6 to 25 mev. The α-particle spectrum extends from 18 to 35 mev.

These results on the fission of uranium by high energy γ-rays makes it possible to conclude that the effective cross section for uranium fission with γ-rays higher in energy that 100 mev is not negligible, as it appears to be in the energy

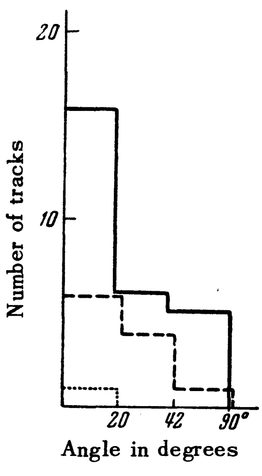

FIG. 14. The distribution of angles (relative to the plane normal to the fragment direction) of the α-particles emitted in the fission of uranium by slow π^- mesons, fast neutrons and γ-rays having energies up to 250 mev; solid line -- α-particles from neutron fission; dashed line -- α-particles from γ-ray fission; dotted line-- α-particle from π^- fission.

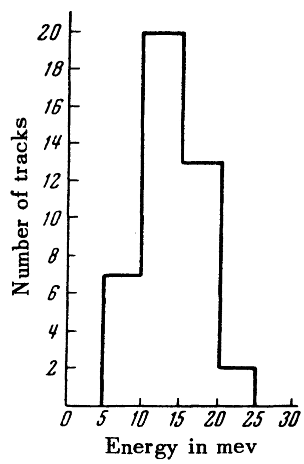

FIG. 15. Energy spectrum of the protons emitted in the fission of uranium by γ-rays of 250 mev maximum energy.

interval 30-100 mev[18]. It is obvious that the significant increase in the fraction of fissions accompanied by a third particle when the γ-ray spectrum is extended to 250 mev indicates that the γ-rays above 100 mev are contributing appreciably to the events being studied. Similar results were obtained by Bannik and Ivanov[19].

The formation of stars when γ-rays of energy higher than 80 mev impinge on the nuclei of emulsion has been studied by Wexler, Pissarev and Lebedev[20] and likewise by Kikuchi[21]. There it has been shown that the cross section for star formation of the nuclei in photographic emulsions increases 3-4 fold in the γ-ray energy interval 80-250 mev. This is in excellent qualitative agreement with our results on the increase in fission events accompanied by long range particles (produced by high energy γ-rays). This would be hard to explain without assuming that the fission cross section rises in this energy interval. Our result has also been confirmed by the recently published work in which the cross section for uranium fission by γ-rays has been determined as a function of energy from 125 to 300 mev[22].

[18] G. C. Baldwin and G. S. Kleiber, Phys. Rev. 71, 3 (1947).

[19] B. P. Bannik and Y. C. Ivanov, Report Phys. Inst., Acad. Sci. USSR, 1953.

[20] V. I. Veksler, C. V. Lebedev and V. E. Pissarev, Report Phys. Inst., Acad. Sci. USSR, 1952.

[21] S. Kikuchi, Phys. Rev. 81, 1061 (1951).

[22] J. Gindler and K. B. Duffield, Phys. Rev. 94, 759 (1954).

6. DISCUSSION OF RESULTS

It is seen from Fig. 2 that the ranges of the fission fragments in the case of π^- fission have the same magnitudes as the ranges of fission fragments produced by moderate energy neutrons. The average total ranges of the fragments in π^- meson fission and in neutron induced fission are 26 and 27 microns, respectively, and thus the same within experimental error. A similar result was obtained from measurements on the total ranges of fragments from fast neutron (150 and 380 mev) fission, and in fission produced by γ-rays of energies up to 250 mev. This result is in good agreement with the recently published data on the ranges of fission fragments produced by the interaction of 335 mev protons with uranium [23]

The distribution and ranges of light and heavy fragments in π^- induced fission when compared with that from slow neutron fission (Fig. 3) indicates that π^- induced fission is more symmetrical. The same result was found for fission induced by fast neutrons and by high energy γ-rays, and agrees with recently published data in the literature[24,25].

If it is assumed that in π^- induced uranium fission the nucleus divides in the usual way into two equal fragments, then the total kinetic energy available for the fragments should be equal to about 160 mev. If to this is added a significant part of the energy available upon capture of a π^- meson, for example, 50 to 100 mev, then the total kinetic energy of the fragments would be 200 to 250 mev. This would produce fragments with ranges of 30 and 33 microns. The observed range (Fig. 2) as a rule did not exceed 29 microns, and ranges greater than 31 microns have not been observed at all. Such long ranges must have a low abundance.

From this we conclude that the energy brought into the uranium nucleus by the π^- meson is not transformed into kinetic energies of fission fragments, but produces other processes*.

Since this originally available energy is used only in small portion for the emission of charged particles, it is natural to assume that the main part is carried off by neutrons. This energy can be transferred to separate nucleons ejected instantaneously from the nucleus, but might also be used to excite the nucleus as a whole. It is known[26] that the average energy of excitation of AgBr nuclei when they capture π^- mesons is approximately 100 mev. The excitation energy remaining in the uranium nucleus could be of the same magnitude. Evaporation theory, developed in published work[27], should be applicable at such energies of excitation of the uranium nucleus.

On the basis of this work, we found that the uranium nucleus, after capturing a π^- meson, can evaporate, on the average, about 10 neutrons before it undergoes fission. These neutrons should have average kinetic energies of 2-3 mev. Approximately the same number of neutrons should be emitted from similarly excited uranium nuclei when they are irradiated with fast neutrons and high energy gamma rays. A similar conclusion was reached by Gol'danskii, Taroumov and Pen'kin[28], and from work on the average number of neutrons emitted by a lead nucleus upon capture by a slow π^- meson[29]. There is somewhat greater interest in the mechanism of the emission of the long range charged particles accompanying fission. The energy spectrum of these particles and their angular distribution is significant in this regard. The energy spectra of the fast, singly charged particles accompanying the fission of uranium by π^- mesons, fast neutrons and high energy γ-rays, are presented in Figs. 5, 10 and 15. Because of the limited sensitivity of photographic plates for high energy protons, these spectra are presented only for energies less than 30 mev and thus represent significantly distorted versions of the true energy spectra of these particles*.

The observed difference in shape of the spectra of protons produced by π^- mesons and γ-rays

* This same conclusion was deduced earlier for fission produced by fast neutrons[3].

[3] J. Jungerman and S. Wright, Phys. Rev. 76, 1112 (1949).

[23] E. Douthett and D. Templeton, Phys. Rev. 94, 128 (1954).

[24] M. Lindner and R. Osborne, Phys. Rev. 94, 1323 (1954).

[25] R. Schmitt and N. Sugarman, Phys. Rev. 95, 1260 (1954).

* From published work by G. Bernardini[30] in which the energy spectra of protons emitted in the interaction of 400 mev protons with the nuclei of photographic emulsions has been determined, it follows that the particles we did not observe (having energies greater than 30 mev) represent 50% of all particles.

[26] M. G. K. Menon et al, Phil. Mag. 41, 583 (1950).

[27] K. J. La Couteur, Proc. Phys. Soc. (London) 63A, 259 (1950).

[28] V. I. Gol'danskii, E. Z. Taroumov and V. C. Pen'kin, Dokl. Akad. Nauk SSSR 101, 1027 (1955).

[29] V. Cocconi-Tongiorgi and D. Edwards, Phys. Rev. 88, 145 (1952).

[30] G. Bernardini et al, Phys. Rev. 85, 826 (1952); 88, 1017 (1952).

from that produced by fast neutrons does not appear significant in view of the small number of events observed. At the same time this difference may be connected with a difference in the type of interaction. When π^- mesons or gamma quanta are absorbed the interaction is with at least two nucleons; a fast neutron on the other hand can interact with a single nucleon in a nucleus. The secondary nucleons produced will have various energies and thus affect the shape of the energy spectrum. It has already been pointed out that these spectra have a small number of particles having energies less than 10 mev. It is hard to say what fraction of all protons have such energies. Using the data of Bernardini[30] to get the fraction of particles that we did not observe, leads to a value of 5% of all protons with energies less than 10 mev. It is still not clear what the mechanism can be for producing such particles with energies less than the coulomb barrier. It is possible that the uranium nucleus, having emitted 10 neutrons, is so proton rich that the proton binding energy is decreased enough to increase the probability of its emission. It can also be assumed that some of these particles are emitted not from the uranium nucleus but from excited fission fragments which have a smaller coulomb barrier.

The α-particles accompanying fission show the characteristic asymmetry in relation to the direction of motion of the fragments. The majority of them are given off in directions close to 90° relative to the fission fragment direction. This conclusion is supported by Fig. 14, in which are presented data on the angular distribution of α-particles emitted in the π^- fission of uranium, fast neutron fission and fission by gamma rays having energies up to 250 mev. It is well known that the α-particles accompanying fission induced by low energy neutrons come out at angles less than 30° relative to the plane normal to the fission fragment motion[7,31]. This angular distribution is determined by the α-particles being emitted in the actual fission process. Since they are affected by the coulomb fields of both fragments they must move in a direction close to 90° relative to the fragment direction. It is reasonable to assume that a considerable fraction of the α-particles that we observed are likewise emitted during the actual fission process.

The angular distribution of fast protons relative to the fission fragment direction is close to isotropic in the fission of uranium by mesons, fast neutrons (Fig. 9) and γ-rays (Fig. 13). From this it appears that the majority of the protons are not emitted in the fission act. The angular distribution of these particles relative to the neutron beam direction (Fig. 8) shows a well-defined preference for the beam direction. Out of 99 particles observed in fission induced by neutrons having energies up to 150 and 380 mev, 75 make an angle less than 90° relative to the incident beam direction and only 27 come out at angles greater than 90°.

When fission is induced by the photons of high energy, the accompanying singly charged particles show a characteristic preference for angles close to 90° relative to the incident beam direction. Such an angular distribution points to the majority of these particles being emitted before the fission act. If these particles were emitted by the uranium nucleus as part of the evaporation process, their angular distribution might be expected to be close to isotropic. Their observed anisotropy indicates that a significant fraction of them are recoil nucleons produced either as a result of the first interaction, or as a result of the development of the nuclear cascade produced by the incident neutron or γ-quantum inside the nucleus. Since it is hard to imagine that in π^- induced fission there should exist a different mechanism of production of charged particles, we believe that this process also occurs in the meson situation.

It follows from the experiments with fast neutrons and γ-rays that the probability of emission of charged particles and their number per fission event increases as the energy brought into the nucleus is increased. In this connection it should be kept in mind that this experiment did not detect the emission of protons having energies greater than 30 mev, nor did it detect fast neutrons which may have accompanied fission. Moreover, the incident neutrons contained more than 50% of neutrons having energies significantly smaller than 100 mev. These, although effective in producing fission, are relatively ineffective as regards the process being investigated. For these reasons the true probability for the emission of fast particles increases with energy at a faster rate than we have observed. Taking into account these factors we conclude that practically every case of fission of uranium induced by 300 mev neutrons has associated with it an emitted fast nucleon.

In conclusion it should be pointed out again that in these investigations of the fission of

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[31] L. Marshall, Phys. Rev. 75, 1339 (1949).

uranium by π^- mesons, fast neutrons and high energy γ-quanta there were selected only fission events in which the fragments came out in opposite or almost opposite directions. We thus do not exclude the possibility that other types of fission, into 2-3, or more fragments, might occur in the interaction of π^- mesons with uranium nuclei. These experiments were not designed to characterize such events. For example, in Fig. 7 there is presented a microphotograph (*18*) of a possible fission of uranium into 4 fragments and accompanied by the emission of a fast charged particle. This was produced by neutrons having an energy of up to 150 mev. In Fig. 11 (*23*) there is presented a probable uranium fission event produced by γ-rays of up to 250 mev energy. This fission is into 3 heavy fragments.

CONCLUSIONS

1. It has been established that different types of particles--slow π^- mesons, high energy γ-rays and fast neutrons--effectively induced fission in the uranium nucleus. The data on the fission of uranium by π^- mesons indicate that, in a significant number of cases (approximately 50%), a meson captured by the uranium nucleus will induce it to undergo fission.

The experiments indicate that photons having energy greater than 100 mev have a significant probability of inducing uranium fission.

2. The ranges of the fragments from uranium fission induced in different ways (π^- mesons, 150-380 mev neutrons, γ-rays with energy up to 250 mev) have the same magnitudes as the ranges of the fragments in the slow neutron fission of uranium. From this it follows that the energy brought in by these different particles is not transformed into kinetic energy of the fragments but is used in other processes. The distribution in fission product ranges indicates that the fission of uranium at high energies of excitation is more symmetrical than is the slow neutron fission of this nucleus.

3. The fission of uranium by slow negative π^- mesons, 150-380 mev neutrons and γ-rays having energies up to 250 mev, is accompanied by the emission of singly charged particles, probably protons. Most of these particles have energies greater than 10 mev and are emitted either as a result of a direct collision or as a result of the cascade process started by the incident particle in the uranium nucleus. Besides the protons there are emitted long range α-particles which, in contrast to the protons, are frequently produced in the act of fission. The frequency of emission of the protons and α-particles increases as the energy of excitation of the uranium nucleus is increased. At energies of excitation of 100-200 mev, star formation preceding fission is observed.

4. The fission of uranium at high energies of excitation is quite frequently accompanied by the emission of fast protons and α-particles. However, the charged particles carry off only an insignificant fraction of the energy brought in by the incident particle. The main part of this energy brought into the nucleus by π^- mesons, fast neutrons and high energy γ-rays must be used up in the emission of neutrons of various energies. A large fraction of the neutrons must be emitted before fission.

In conclusion, we consider it a pleasant duty to express gratitude to M. G. Meshcheriakov, V. P. Djelepov and E. P. Grigoriev for help in carrying out the experiments with the π^- mesons and fast neutrons; to V. I .Veksler and Y. C. Ivanov for help in the experiments with high energy γ-rays; and likewise to A. N. Kouznetsov, Y. N. Lizounov and I. L. Nesmelov who carried out the main labor of the plate scanning.

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