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Uranium Fission Induced by High-Energy Protons

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Uranium fission induced by high-energy protons can be accompanied by the emission of charged particles. The latter can arise from a nuclear cascade process or by evaporation from the excited nucleus. We used photographic emulsions to analyze the light charged particles accompanying uranium fission induced by protons of various energies (140 to 660 mev). For incident protons of energies 460 and 660 mev, experimental data on the knock-on particles emitted from the nucleus during a cascade process were compared with the results of a Monte Carlo calculation. Satsifactory agreement was obtained. The average excitation energies of nuclei about to fission upon being bombarded by protons of energy 140, 350, 460 and 660 mev, were also obtained.

THE interaction of high-energy protons with uranium nuclei can be conveniently divided into two stages. In the first stage, the primary proton collides with the nucleons in the nucleus and starts a nuclear cascade process lasting 10^{-21} to 10^{-22} sec. Most of the knock-on nucleons emitted from the nucleus as a result of this process are fast and leave the nucleus in an excited state. In the second stage the residual nucleus de-excites itself by evaporating nucleons. Since Z^2/A is large for uranium, fission can occur in either stage. Fission can compete with nucleon evaporation. During the second stage fission and emission of relatively low-energy nucleons are observed.

Thick, high-sensitivity photographic emulsions can be used to study the emission of charged particles when high-energy protons interact with uranium nuclei. To get the whole picture, the emulsion should be able to detect particles of all energies and masses from those of the fission fragments to those of the primary protons. It is to be noted, however, that if the uranium is introduced into the emulsion as an aqueous solution of uranium salt, then proton-uranium interactions which are unaccompanied by fission cannot be detected (they are hard to separate from reactions with AgBr). However, as is evident from the measured cross sections,[1] such events are relatively rare (~ 20%). Hence a study of those proton interactions which involve fission gives information not only about fission at high energies, but also about the interaction of protons of a definite energy with the heavy nucleus—uranium.

In particular, upon considering all the charged particles accompanying uranium fission, it is interesting to separate out the knock-on particles and to compare experimental data on them with Monte Carlo calculations on the nuclear cascade process initiated by the incident protons of some definite energy.

Our experiments were for protons of energies 140 to 660 mev.

EXPERIMENTAL ARRANGEMENTS

Thick emulsions impregnated with uranium were irradiated by protons of energies 660, 460, 350 and 140 mev, from the synchrocyclotron of the Institute for Nuclear Problems of the Academy of Sciences of the USSR. Protons with energies 350 and 140 mev were obtained by slowing down 660 mev protons in paraffin and copper filters. Uranium was introduced into the photosensitive layer by washing the plates in a 4% aqueous solution of $NaUO_2(C_2H_3O_2)_3$. Several emulsions of different sensitivities were used: a) the relativistic emulsions NIKFI and Ilford G–5 and b) the fine grained emulsion P–9*, with an upper limit on proton sensitivity of 25–30 mev.

Emulsions of the first type allow one to observe all the charged particles accompanying fission. However, since all the primary protons leave tracks one is restricted to low currents, so that one can observe only a few fission events. Thus, when using the relativistic emulsions, the whole photosensitive area yields only about 50 fission events at each energy. This was enough, however, to get a general picture of the proton–uranium interaction at a given energy—in particular, the average number of charged particles per fission, the angular distribution of the fast and slow charged particles relative to the incident protons, etc.

The particle current incident on emulsions of the second type, P–9, could be nade 20–25 times greater than that incident on the relativistic emulsions. A larger number of fission events could then be observed, and such matters as the characteristics of the soft component of the charged particles emitted upon fission, the ranges of fission fragments and the angle between the fragments could be best studied in the insensitive emulsion.

At all energies except 350 mev, our experiments were carried out on both types of emulsion. For 350 mev protons only the P–9 emulsion was used.

ANALYSIS OF THE LIGHT-CHARGED PARTICLES ACCOMPANYING URANIUM FISSION INDUCED BY HIGH-ENERGY PROTONS

We found that uranium fission, as observed on relativistic emulsions, was almost always accompanied by the emission of light-charged particles. From among all the charged particles, we tried to separate out those due to nuclear cascade processes, and to estimate the number due to evaporation. Such a separation can be effected by analyzing the angular and energy distributions of the charged particles emitted upon fission. In particular, we want the average number of low-energy particles (< 25 mev) per fission. This datum can be obtained from the experiments with the fine-grained emulsion P–9.

TABLE I

Energy of incident protons, mev	Relativistic Emulsions: number of fissions	Average number of charged particles per fission	Ration of number of particles emitted forward to those emitted backward	P-9 Emulsions: number of fissions	Average number of charged particles (< 25 mev) per fission	Ratio of number of particles emitted forward to those emitted backward	Average number of charged particles (< 20-25 mev) per fission with isotropic distribution
140	60	0,4	4	376	0,25	2,6	0,14
350				359	0,56	1,6	0,43
460	47	1,65	3,3	260	0,86	1,3	0,66
660	56	3,06	3,1	150	1,05	1,3	0,81

Table I summarizes the data we obtained for protons of various energies incident on both relativistic and P–9 emulsions. At each energy the Table shows the average number of particles per fission and the direction of emission relative to the incident proton. The second, third and fourth columns refer to relativistic emulsions, and hence include particles of all energies. The remaining columns refer to events observed in P–9 emulsions and hence include only charged particles of relatively low energies (< 25–30 mev).

The average number of all charged particles per fission increases as the incident proton energy increases. This is evident both from the third column of Table I and the curves in Fig. 1. In the latter, number of fission events is plotted against number of accompanying charged particles, as observed in relativistic emulsions. The curves show that as the proton energy increases, the relative number of those fission events which do not produce charged particles decreases, and the proba-

*The P–9 emulsions were prepared in the laboratory of N. A. Perfilov.

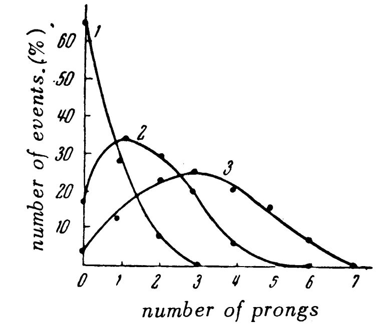

FIG. 1. Distribution functions for number of charged particles accompanying fission. Curve 1—energy of incident protons 140 mev, Curve 2—460 mev, Curve 3—660 mev (relativistic emulsion).

bility of the event being accompanied by an ever-increasing number of charged particles increases.

Most of the charged particles observed in relativistic emulsions are emitted in the forward direction (with reference to the initial proton). This is evident either from the fourth column of Table I, which gives the ratio of the number of charged particles emitted into the forward hemisphere (relative to the incident proton) to the number emitted into the backward hemisphere, and also from the angular distributions shown in Fig. 2 [in these, most of the particles (~ 75%) are emitted with angles smaller than 90°].

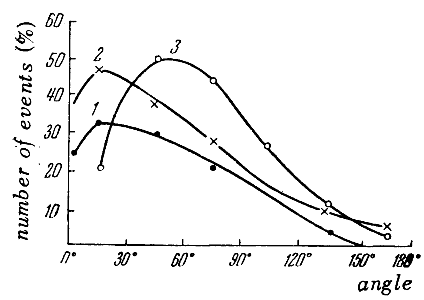

FIG. 2. Angular distribution of light charged particles accompanying fission. Curve 1—energy of incident protons 140 mev, Curve 2—460 mev, Curve 3 — 660 mev (relativistic emulsions).

It is noteworthy that even particles with energy < 25 mev tend to be emitted forward (seventh column of Table I). This is especially noticeable for incident energy 140 mev, where a large fraction of the low-energy charged particles are apparently knock-on particles. This is to be expected, because when the uranium nucleus is, on the average, little excited, few nucleons evaporate off and most of the charged particles accompanying fission are directly knocked out of the nucleus by the incident protons.

As the energy of the incident protons increases, the directional effect in the emission of charged particles (E < 25 mev) decreases (seventh column). This is due to an increase in the number of charged particles emitted isotropically; more particles evaporate as the mean excitation energy decreases.

Viewed in this way, the data in Table I clearly demonstrate the presence of a nuclear cascade process in the interaction of a uranium nucleus with protons of energy more than 140 mev. The data also show how the knock-on particles fit in with all the low-energy particles (E < 25 mev).

In order to separate out completely the knock-on particles from among all the charged particles, we must estimate the number of evaporation particles per fission at various proton energies.

The average number of low-energy (E < 20–25 mev) particles per fission which are emitted isotropically (these are given by the last column in Table I) can be considered to be an upper limit on the mean number of evaporation particles per fission.* A comparison of the average number of charged particles emitted per fission, regardless of energy, with the corresponding number emitted isotropically (E < 25 mev, Fig. 3, curves 1 and 2) then gives the fraction of particles due to a nuclear

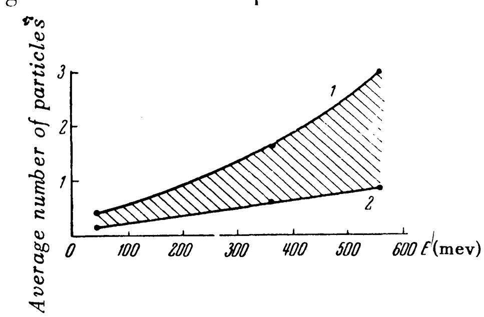

FIG. 3. Dependence of the average number of charged particles per fission on the energy of the incident protons. 1—charged particles of all energies, 2—charged particles with E < 20–25 mev and having an isotropic distribution.

cascade process. The shaded area in Fig. 3 gives the average number of knock-on particles at various proton energies. Clearly, at the energies considered, a large part (~ 70%) of the particles emitted upon fission are knock-on particles.

It is interesting to compare our experimental data on the number of knock-on particles with Monte Carlo type calculations on a nuclear cascade process. We carried out such calculation for the

*This is only an upper limit because it includes knock-on particles scattered through large angles.

interaction of 460 and 660 mev protons with uranium nuclei. The heavy nucleus is considered to be a "Fermi gas"[2] in which the incident proton undergoes successive collisions with the nucleus in the nucleus. The Pauli principle was taken into account—i.e., collisions in which the final state of one of the colliding nucleons had an energy less than the maximum Fermi energy for the type of nucleon in question were forbidden. Calculations were performed by the method described in Ref. 3, with certain simplifications.

In order to carry out the computations, it was necessary to know the probabilities of the various elementary processes which can occur when high energy nucleons (660 mev and less) collide with nucleons in the nucleus. We used the latest experimental data on the total cross section[4] and the differential cross section for elastic scattering of nucleons.[5] However, in calculations on the interaction of 660 mev protons with uranium nuclei we did not take meson formation into account, although in this case it can be important. This is because the experimental data available are insufficient.

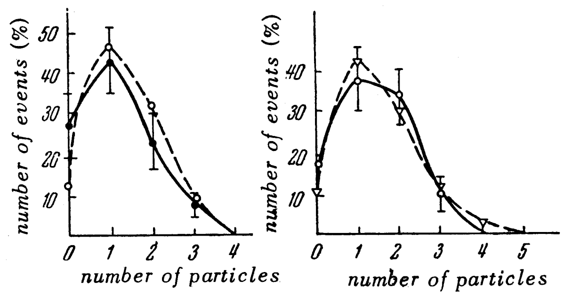

FIG. 4. Distribution functions for the number of charged knock-on particles ($E > 20$ mev). Solid curves—experimental, dotted—calculated. Curve a—incident proton energy 460 mev, curve b—incident proton energy 660 mev.

At each energy of the primary proton, 50 proton—nucleus interactions were computed. This should be enough to show the fundamental character of the process. The results could in some measure be compared with the experimental data.

Of particular interest in a nuclear cascade process is the distribution function for the number of emitted particles. Experimentally, we can obtain this from our experiments with sensitive emulsions, which register particles of all energies. Number of events was plotted as a function of the number of emitted particles with energy > 20 mev and compared with the corresponding distribution obtained by calculation. In Fig. 4, the solid curve is the experimental distribution, while the dotted curve was calculated [a) corresponds to 460 mev and b) to 660 mev]. The two curves agree well at both energies.

The angular distributions of fast charged particles ($E > 20$ mev), as obtained experimentally (relativistic emulsions), and by calculation, could also be compared. This is done in Fig. 5 [a) and b)].

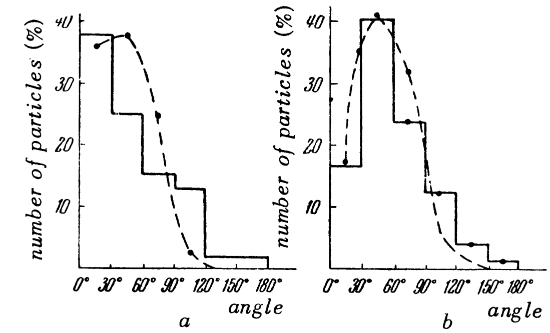

FIG. 5. Histograms for the angular distribution of charged knock-on particles ($E > 20$ mev). Dotted curves are calculated. Angles are measured from the direction of the incident proton. Curve a—incident proton energy 460 mev, curve b—660 mev.

The histograms show the experimental angular distributions for the fast ($E > 20$ mev) charged particles relative to the incident current at 460 and 660 mev. The general shapes of the experimental and calculated curves are the same. Unfortunately, few particles (52) were available in constructing the histogram at $E = 460$ mev, so the statistical errors are large. The histogram for 660 mev protons was constructed from 100 particles, and agrees well with the calculated curve. The fact that slightly more particles were observed at large angles than indicated by the calculations might be due to meson formation, which we did not take into account.

At $E = 460$ mev, there is satisfactory agreement (within experimental error) between the experimental and calculated values for the average number of knock-on particles (with $E > 20$ mev) per fission (Table II). For 660 mev protons the experimental value is somewhat larger than the theoretical. This effect can presumably be accounted for by the meson production our calculations neglected.

TABLE II.

Energy of incident proton (mev)	Averzge number of charged knock-on particles ($E > 20$ mev)	
	Experimental	Calculated
460	1.0 ± 0.2	1.3
660	2.2 ± 0.3	1.6

We consider that the agreement between the experimental data and the results calculated under the stated assumptions is satisfactory.

We present now some further results obtained in the course of the calculations. Figure 6 shows the energy distribution of the knock-on particles, as calculated by us for $E = 660$ mev. There are many particles with energy 20–30 mev. These will be superimposed on the spectrum of the evaporation particles.

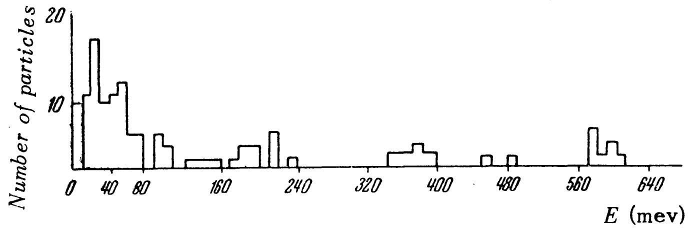

FIG. 6. Energy distribution of charged knock-on particles for incident proton energy 660 mev. Obtained from calculations on a nuclear cascade process in uranium.

AVERAGE EXCITATION ENERGY IN A FISSIONING URANIUM NUCLEUS AND EVAPORATION PARTICLES

Collisions bewween the primary protons and the nucleons in the nucleus knock out particles from the nucleus and leave the residual nucleus in an excited state. The work described in Ref. 6 shows that the mean excitation energy of the fissioning nucleus can be estimated from the angle between the fission fragments. As the nucleus fissions under the influence of a fast particle, the fragments do not go off in opposite directions, but make a certain small angle with this line, the angle depending on the speed of the fissioning nucleus. According to Ref. 6, the average energy of excitation of a nucleus about to fission under the action of protons of various energies is given by the formula

$$E_{\mathrm{exc}} = E_{\mathrm{p}} + m_0c^2 - c\sqrt{m_0^2c^2 + (p_{\mathrm{p}} - m_{\mathrm{n}}v_{\mathrm{n}})^2} - E_{\mathrm{b}}.$$

Here F_{p} , p_{p} and m_0 are the energy (mev) , momentum and mass of the primary proton, c is the velocity of light, m_{n} and v_{n} are the mass and velocity of the fissioning nucleus (the velocity being obtained from the angle between the fragments) and E_{b} is the average binding energy per fission going into the knock-on particles. The latter quantity can be estimated from the average number of protons knocked out, assuming that the relative numbers of knock-on protons and neutrons is the same as in the original nucleus, uranium.

Table III shows the average excitation energies so obtained for various proton energies.

TABLE III.

Energy of incident proton (mev)	140	350	460	660
Average excitation energy (mev)	80±20	140±40	165±45	185±60

The values in Table III for proton energies 460 nnd 660 mev are somewhat larger than those in Ref. 7, but the difference lies within experimental error.

Another quantity of interest in fission is the range distribution of the fragments. As is well known, this changes radically as the energy of the primary, fission-inducing particles increases from thermal energies to 50–60 mev. The change is from the twin-peaked curve characteristic of asymmetric fission to a single-peak curve (symmetric fission). Fig. 7 shows our measurements on the range dis-

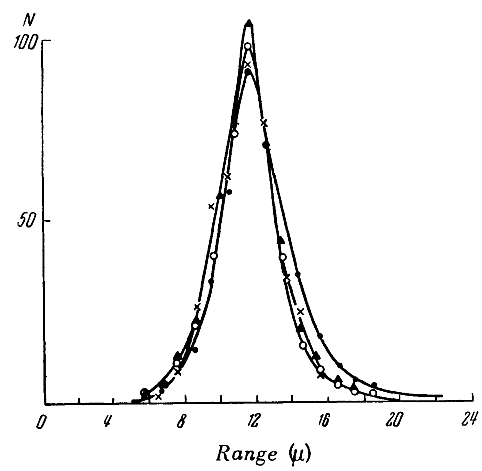

FIG. 7. Range distribution of isolated fission fragments. O—incident proton energy 140 mev, ×—350 mev, Δ—660 mev.

tribution of isolated fragments at the excitation energies presented above. The range distribution is clearly insensitive to changes in the excitation energy from 80 to 180 mev.

The excited nucleus can lose energy by evaporating nucleons (mostly neutrons); since the uranium nucleus has a large Z^2/A (which becomes even larger as neutrons escape), fission competes with evaporation. Inasmuch as up to now there has been no data indicating that fission takes a considerably longer time than neutron evaporation, fission can in general occur in any excited state. Only if neutron evaporation went much faster than fission could the nucleus completely de-excite itself by evaporation before undergoing fission.

The average number of charge particles evaporating from nuclei excited to the energies shown in Table III is given in the eighth column of Table I. It would be natural to compare these data with calculations based on existing theories of evaporation. However, it should be pointed out that even if experimental and calculated values for the average number of charged particles evaporating were to agree, we could not yet conclude, as was done in Ref. 7, that the nucleus de-excites itself completely by evaporation before undergoing fission. Calculations for uranium based on evaporation theory[8] indicate that the average number of charged evaporation particles depends but little on whether the nucleus fissions at about half it original excitation energy or whether it fissions after having completely de-excited itself by evaporation. In the former case, the excited fission fragments have an excess of neutrons and hence emit mostly neutrons, so that the difference in the numbers of charged particles emitted in the two cases will be the number of protons and α-particles which would have evaporated from the nucleus had it gone from half its excitation energy to zero. This number is quite small since, as is well known, most of the charged particles evaporate at the beginning, at the higher excitation energies. For example, according to calculations,[8] a nucleus excited to 150 mev and losing all its excitation energy by evaporation will emit 0.7 charged particles, while if it fissions at half this energy (75 mev) with the excited fission fragments then evaporating off particles, 0.6 charged particles are emitted. The average number of charged particles will be much smaller than in two cases above if the nucleus fissions immediately, before losing any excitation energy at all. This is because the excited fission fragments emit mostly neutrons. Hence, it would be of interest to compare experimental and calculated data on the number of charged evaporation particles for the case of uranium. However, calculations carried out by two different methods—Le Couteur[8] and Hagedorn[9]—give, at the relatively low nuclear temperatures of interest here, quite different values for the average number of charged evaporation particles. It is difficult to know which of the two methods is preferable. On the one hand, for nuclei with mass number 100 and temperatures 2–3 mev the method of Ref. 8 gives too low a value* for the average number of charged particles, so that the same may be expected for uranium. On the other hand, although calculations with the method of Ref. 9 give results in agreement with experiment for AgBr (in the indicated temperature range), the ratio of the probabilities for neutron and proton emission in this method does not depend on excitation energy. This is clearly not realistic, and should lead to too many charged evaporation particles in our temperature range. It is therefore our opinion that in view of the inadequacy of evaporation theory, a comparison of the experimental with the calculated data on the average number of charged evaporation particles would not give a reliable answer to the question of interest.

In conclusion the authors would like to express their gratitude to Prof. N. A. Perfilov for his constant interest in their work.

*According to references[10,11] the average number of charged particles evaporating from AgBr excited by 50 mev is about 2.0. The calculated value from Ref. 8 is 0.4 for the same excitation energy.

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Scattering of π^+-Mesons by Hydrogen. II. Discussion and Interpretation of the Results

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A phase analysis is made of the data obtained on scattering by hydrogen of π^+-mesons of different energies up to 307 mev. The analysis was carried out, using a high-speed electronic computer, on the assumption that the scattering process can be sufficiently accurately described by *S*- and *P*-waves [(*S-P*)-analysis], as well as on the assumption that the scattering process must be described by five parameters [(*S-P-D*)-analysis]. The energy dependence of the various phase shifts obtained for the (*S-P*)- and (*S-P-D*)-analyses are shown in the Figures. It follows from the measurements that the radius of meson-nucleon interaction is about 7×10^{-14} cm.

As is known, Fermi and others[1] analyzed the aggregation of data on scattering of π^+-mesons up to 200 mev on the assumption that only *S*- and *P*-waves are involved in the scattering and therefore the scattering processes are described by six phase shifts. In the case of positive pions and in the absence of *D*-waves the scattering is described by only three phase shifts α_3, α_{31} and α_{33} which determine the corresponding interaction in the *S*-, $P_{1/2}$- and $P_{3/2}$-states with isotopic spin 3/2.

In the present work, which is a continuation of the work described in Ref. 2, the data on scattering of positive pions are analyzed on the assumption that the contribution of *D*-states to the scattering process is neglibly small, i.e., the interaction takes place only in the *S*- and *P*-states [(*S-P*)-analysis] as well as on the assumption that the contribution of the *D*-states cannot be neglected [(*S-P-D*)-analysis]. The latter assumption is quite reasonable for such high energies as 300 mev. Besides, the data of Ref. 2 presented in Table 10 confirm this assumption to a certain extent.

In the case when *S*-, *P*- and *D*-waves contribute to the scattering of π^+-mesons, beside the above-mentioned three phase shifts α_3, α_{31} and α_{33}, the phase shifts corresponding to the *D*-states with total angular momenta 3/2 and 5/2 are different from zero and will be subsequently designated by δ_{33} and δ_{35}.