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The Cross Section for the Fission of Uranium by High-Energy Protons (140 to 660 MEV)

N. S. IVANOVA
Radium Institute, Academy of Sciences, USSR

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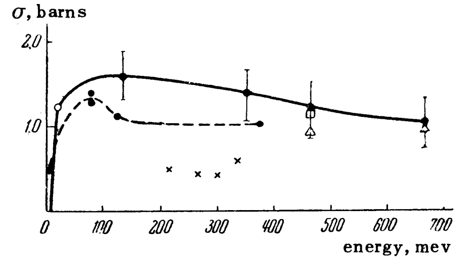
The thick film method was used to measure the fission cross section of U^{238} by protons of energies 140, 350, 460 and 660 mev. The probability that uranium will fission when irradiated by protons of a given energy is also obtained.

THE cross section for uranium fission induced by fast protons has been investigated by several authors[1-6]. Various experimental techniques were used: the ionization chamber[1], radio-chemistry[2,3] and the thick film method[4-6].

The isolated points in the Figure summarize the data available in the literature on the fission cross section by protons of various energies. There are no data on fission by protons at low energies: 22 to 220 mev. In the energy interval 340-380 mev the results obtained by various authors differ widely among one another. Thus, according to Ref. 1, the cross section for uranium fission by protons of energy $E = 340$ mev is 0.6 barns, while according to Ref. 3, the cross section at 380 mev is 2 barns. For energies around 460 mev the fission cross sections obtained in Refs. 4-6 agree within experimental error.

No conclusions about the dependence of the cross section on proton energy can be drawn from the above data.

In the present work thick photographic emulsions were used to obtain the fission cross section over a wide energy interval (140, 350, 460 and 660 mev). Protons of these energies were obtained by using copper and paraffin filters to slow down 660 mev protons from the synchrocyclotron of the Institute for Nuclear Problems of the Academy of Sciences, USSR. Uranium was introduced into the photosensitive layer by washing[7] in an aqueous solution of the salt $NaUO_2(C_2H_3O_2)_3$.



Energy dependence of proton-induced uranium fission. Solid curve — protons; Dotted curve — neutrons, according to Refs. 8 and 9; × — Ref. 1; o — Ref. 2; ▲ — (high) Ref. 3; ◻ — Ref. 4; ● — our results.

The cross section was measured using two types of emulsion: first, relativistic emulsions (NIKFI-R and Ilford G-5), and second, the insensitive, fine-grained emulsion * P-9, having a proton threshold of 25-30 mev. With this emulsion, the incident proton current can be increased by a factor 20-25 over the usable current with the relativistic emulsion which allows a larger number of fissions to be observed.

The current incident on the relativistic emulsions was measured by counting the number of primary proton tracks in the same plate on which the fission events were observed. The current incident on the insensitive P-9 emulsions was measured by counting the protons in a relativistic emulsion exposed (after irradiation of the P-9 emulsion) in the same place as the P-9 was, but for an appropriately shorter time. Exposure times were controlled by an ionization chamber which was placed in the beam directly in front of the emulsions. Having measured the current incident on the sensitive emulsion and knowing how much the current was increased for the insensitive emulsion, the current on the latter could easily be calculated.

In order to calculate the fission cross section it is necessary to know not only the number of fissions per unit volume of emulsion, but also the number of uranium nuclei introduced into the same volume. The latter quantity was measured by a previously described method[7], which was based on the number of α-particles emitted per minute by the uranium in the emulsion. For each bombarding energy, the number of fissions per unit volume of emulsion was measured by scanning the plate under a microscope.

Results of the measurements are shown in the Table.

The solid line in the Figure gives the average

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* The emulsion was prepared in the laboratory of Prof. N. A. Perfilov.

Energy, mev	Emulsion type	Cross section, barns	Probability of fission
140	G-5	1,56±0.4	0.77
	П-9	1.69±0.2	
350	П-9	1,4±0.3	0.86
460*	G-5	1,2±0,3	0,74
660	НИКФИ-R	1,11±0,3	0.65
	НИКФИ-R	0,97±0,25	
	НИКФИ-R	1.01±0,3	

* The fission cross section for 460 mev protons is taken from our previous work (Ref. 5).

cross section so obtained as a function of energy. We see that the uranium fission cross section increases with increasing proton energy, goes through a wide maximum at 50-150 mev and then decreases, going (within the limits of our experiment) to a constant value in the energy range 460-660 mev. In contradiction with the data of Jungerman[1], there seems to be no minimum at 200-350 mev*.

Our curve can be compared with the analogous one for the energy dependence of the cross section for fission by fast neutrons. This curve is also shown in the Figure, the data being taken from Refs. 8 and 9, and lies somewhat below the proton curve. The difference may be due to experimental errors**, but if it really exists, then for fairly low energies, such that the incident nucleon amalgamates with the nucleus, it may be explained by the two different values of Z^2/A obtained for the fissioning nucleus depending on whether a neutron or proton is absorbed by the nucleus.

The probability that fission occurs when a proton of given energy interacts with a uranium nucleus can be obtained from the fission cross section if we assume that the reaction cross section is half the total cross section* . The total cross section has been measured by several authors[10-16] for high-energy neutrons (several values up to 600 mev and one[16] at an energy 1.4 bev). Assuming that the total cross section for fast protons differs little from the corresponding value for neutrons, we obtain the probabilities for fission by protons at our energies as indicated in the last column of the Table.

According to our data, the probability that protons of energy 140-660 mev induce fission is about constant and oscillates around 70-80% of the proton reaction cross section.

In conclusion, the author wishes to thank B. S. Neganov for helping to carry out the work and Prof. N. A. Perfilov for his constant interest.

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* *Note added in proof*: As the present paper was being submitted for publication, there appeared in a new paper (e.g., see Ref. 17) describing measurements on the cross section for U^{238} fission by protons of energies 100-340 mev. The fission cross section obtained agrees well with our data. The authors consider their previous results to have been erroneous.

** The errors for the neutron curve are not known.

* This assumption is justified for a black nucleus. For a semitransparent nucleus the reaction cross section is not quite equal to the elastic cross section, but is close to it.

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Uranium Fission Induced by High-Energy Protons

N. S. IVANOVA AND I. I. P'IANOV
Radium Institute, Academy of Sciences, USSR

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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