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HIGH-ENERGY-PROTON FISSION CROSS-SECTIONS OF U, Th AND Bi *

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At the end of 1960, measurements obtained from the ciclotron proton energy range [1, 2], that is up to 600 MeV, gave reason for belief that the fission cross-section for heavy nuclei was totally independent of energy from 100 MeV up. However, measurement made by de Carvalho et al. [3], in 1961 using the CERN PS. machine, have shown that the uranium fission cross-section induced by 20 GeV protons is only about one half of the cross-section in the above mentioned plateau region of 100 MeV up to 1000 MeV. This strong decrease in cross-section has been confirmed by other measurements in the energy range from 1 GeV up to 30 GeV [4, 7]. Three important problems remain to be solved: the first is the exact pattern of the fission

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cross-section in this region of decrease (in particular there is a special interest in pin-pointing at what energy such a decrease in the cross-section begins); the second is to know what happens at energies larger than 30 GeV; finally is the knowledge of the mechanism responsible for such a fission cross-section decrease.

Since nuclear emulsion is the detector and the target simultaneously, it allows 100% detection efficiency. Using a special development process, it is possible to eliminate the undesired strong background of less ionizing particles, such as low energy ions with $A < 30$. This enables us to discriminate very accurately between fission fragments and highly ionizing fragments from reactions induced by incident protons on the emulsion heavy elements, i.e. Br and Ag. In order that nuclear emulsion should work both as a detector and uniform target, the target element must have been uniformly incorporated into the nuclear emulsion (KO Ilford) which emulsion is also of uniform thickness. Nuclear emulsion pellicles $\sim$0.20 mm thick were carefully weighed and cut into rectangles of 4 cm x 5 cm. From the results of all measurements and from the homogeneous distribution of the target element in nuclear emulsion, it was possible to determine the number of target nuclei per cm^2 of emulsion. Unloaded nuclear emulsion pellicles were added to the stacks for identification of the fission fragments and the highly ionizing ions arising from high energy proton interaction with Br and Ag and for the subsequent correction of this background effect.

The stacks were bombarded at 12.3 GeV in the Argonne Z.G.S. external proton beam. The total number of protons to which each stack was exposed was estimated by means of the production of Na^{24} in aluminum monitor foils. The results were calculated with $\sigma_{Al}(Na^{24}) = 8.6$ mb, as given by J. B. Cumming [7]. The error limits of calibration were about ± 3%. Cumming [7] gives 6.5% as the error limit for the cross-section. A radioautograph taken during a calibration run helped to locate the region where the proton beam was impinging on the emulsion. About 90% of the incident protons were in an area of 2 cm x 1.5 cm. The proton intensities were about 0.3 to 2×10^{10} protons/cm^2. To reduce the effect of secondary particles inducing fission, the emulsion pellicles were made as thin as possible. Hudis and Katcoff [6] studied the secondary particle effect on target stack thickness and have shown that within experimental error, for their thick witness targets, it was negligible. The total thickness of the stacks in the present experiment (0.6 g/cm^2) is no greater than of those used in Katcoff's work [6].

Irradiated emulsion pellicles were submitted to a special development process [9] in order to make the tracks of the charged particles visible. In this work a development method was used and adjusted so as to secure a good discrimination between the fission fragments tracks and those arising from any other reaction process, as well as to eliminate the background of less ionizing particle owing to the storage time of the alpha radiative elements. This development method consists essentially in making the induction time for development of less ionizing particle tracks so long (compared to the time sufficient for developing fission fragment tracks) that the discrimination is perfect for confirming the absence of a less ionizing particle back ground of Z < 10.

After the developing process, the tracks of all events were measured in two pellicles, one of unloaded emulsion and the other of emulsion loaded with uranium developed under the same conditions in a region of emulsion enclosing the area reached by the incident flux. The same was done with thorium and bismuth. From microscope measurement data, the true ranges were obtained by means of a computer program. The events were clearly distributed into two distinct parts, one arising from proton-induced reactions in the elements of the emulsion (Br and Ag), and the other from the fission events contribution of uranium. Discrimination between the two above mentioned types of range distribution makes it possible to determine the number of fission events in the loaded emulsion. The range distribution of background tracks arising from Ag and Br fission and heavy recoil nuclei, induced in the unloaded emulsion developed simultaneously with the target pellicles, was carefully obtained. It shows a strong peak in the region of short range tracks and becomes very handy for the background substraction. Once the shape of the curve of such a distribution is well known, the background can be subtracted from the track distribution obtained in each target pellicle. With the true number of fission events in all target pellicles, the fission cross-sections of uranium, thorium and bismuth were obtained. The results are listed in Table I.

In 1968, Matusevitch et al.[5] measured fission cross-sections of uranium and bismuth with glass techniques at energies from 0.66 GeV up to 9.0 GeV. Their results for uranium were very low and those for bismuth very high, when compared with those in this paper. Hudis and Katcoff [6] and Brandt et al. [7], using mica as detectors, arrived at different results for the cross-sections of these same elements. Hudis and Katcoff's measurements [6] are in good agreement with present results, while those of Brandt et al. [7] are considerably higher. The results of the present experiment show that for uranium, thorium and bismuth, the fission cross-sections at 12.3 GeV all decrease by a factor of about 2, when compared to their maximum values (fig. 1).

A semi-empirical interpretation of the mechanism of fission process from 100 MeV up to ultra high energies is obtained by means following reasoning. From the results of Metropolis et al. [10, 11] using the Monte Carlo calculations on intranuclear cascade initiated by high energy protons in the fast stage of nuclear reaction, it is possible to determine an average mass number of the residual nucleus and its excitation energy for each incident proton energy. Supposing such a residual nucleus to be representative of the distribution of product cascade nuclei and considering that the nuclear excitation energy is dissipated by successive boiling off of nucleons, it is possible, for the first evaporation step, to calculate the relative probability of the proton to neutron emission p_p/p_n as a function of the proton energy, using the ordinary probability expression of nucleon evaporation in Weisskopf's statistical model [12] and the formula given by Lang and le Couteur [13] for level densities of the excited nucleus (fig. 2). Observing the trend, for uranium, of the relative probability of proton to neutron evaporation with the proton fission cross-section, the following conclusions resulted:

i) For energies where the relative probability p_p/p_n is very low, the fission cross-sections present their maximum value in a plateau region. This can be explained by the fact that at this energy range the energy excitation of the main fraction of residual cascade nuclei is not high enough for a dominant charged particle evaporation, owing to hindering of the Coulomb barrier effect, and so the large sequence of emitted neutrons always leads to a fissionability parameter Z^2/A, large enough so as to favor the fission process during the deexcitation process and thus resulting in the fission of a large fraction of the number of residual nuclei produced by the initial cascade.

ii) The rising point of relative probability p_p/p_n in the neighbourhood of 1 GeV, coincides with the energy where the fission cross-sections decrease abruptly. Here, the increase in the number of emitted cascade particles leads to a large variety of residual nuclei further away from the target nucleus, with a wide spectrum of excitation energies in such way that for the most highly excited residual nuclei the Coulomb barrier does not forbid evaporation of charged particles (specially protons). On the other hand, for high excitation energy, in the sequence of the initial stages of evaporation, the relative probability p_p/p_n is practically constant. In this case, at the beginning of the evaporation process, the fissionability parameter Z^2/A decreases strongly, owing to two effects: one caused by the large number of charged particles emitted in the cascade process, and the second owing to charged particles emitted in the evaporation process. However, after the evaporation of a large number of nucleons, the excitation energy of the residual nucleus gradually becomes so low that Coulomb barrier effect begins to hinder the charged particle emission. In this stage of evaporation, in most cases, the excitation energy is not high enough for the emission of the necessary number of neutrons for making a residual nucleus with Z^2/A favorable to fission to take place. Since the probability of this occurence increases as the excitation energy of the residual nuclei increases and this last parameter is a rising function of the incident energy proton, a consequent decrease in the fission cross-sections should be expected at the energy range mentioned above.

iii) At energies higher than 10 GeV, the fission cross-sections tend to an asymptotical value, owing to the fact that in the wide spectrum of excitation energies of the wide mass spectrum of residual nuclei, there are some of the nuclei with energies below the shielding Coulomb barrier effect for charged particle evaporation. Thus, there always exists a reasonable fraction of the total residual nuclei undergoing fission from the same dominant mechanism responsible for energy fission below 1 GeV. For uranium the asymptotical trend begins to be clearly observable at 12 GeV. This was the main reason for choosing 12 GeV energy for the present work and it is worthwhile pointing out the importance of measuring fission cross-sections at energies near to 300 GeV (presently available) for confirmation of this prevision.

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TABLE I

Target, scanning and fission cross-sections **data for** 12.3 GeV incident protons. The errors indicated are only the statistical ones.

Target	Number of target nuclei /cm^2	Total number of fission events	Cross-sections (mb)
U	4.1×10^{18}	3.45×10^4	794 ± 80
Th	3.9	2.47	597 ± 60
Bi	5.4	0.65	114 ± 12

FIGURE CAPTIONS

Fig. 1 - General behaviour of fission cross-sections of U, Th and Bi as a function of incident proton energy, 100 MeV up to ultrahigh energy. Filled circles ●, present work; diamond ◆, ref. 3; empty circles ○, ref. 6; filled squares ■, ref. 14; empty squares □, ref. 1.

Fig. 2 - General behaviour, for uranium, of relative probability of proton to neutron evaporation as a function of incident proton energy. Observing the trend, for uranium, of the relative probability of proton to neutron evaporation with the proton fission cross-section, the following conclusions resulted:

i) For energies where the relative probability p_p/p_n is very low, the fission cross-sections present their maximum value in a plateau region.

ii) The rising point of relative probability p_p/p_n in the neighbourhood of 1 GeV, coincides with the energy where the fission cross-sections decrease abruptly.

iii) At energies higher than 10 GeV, where the relative probability p_p/p_n tends to be constant, the fission cross-sections tend to an asymptotical value.

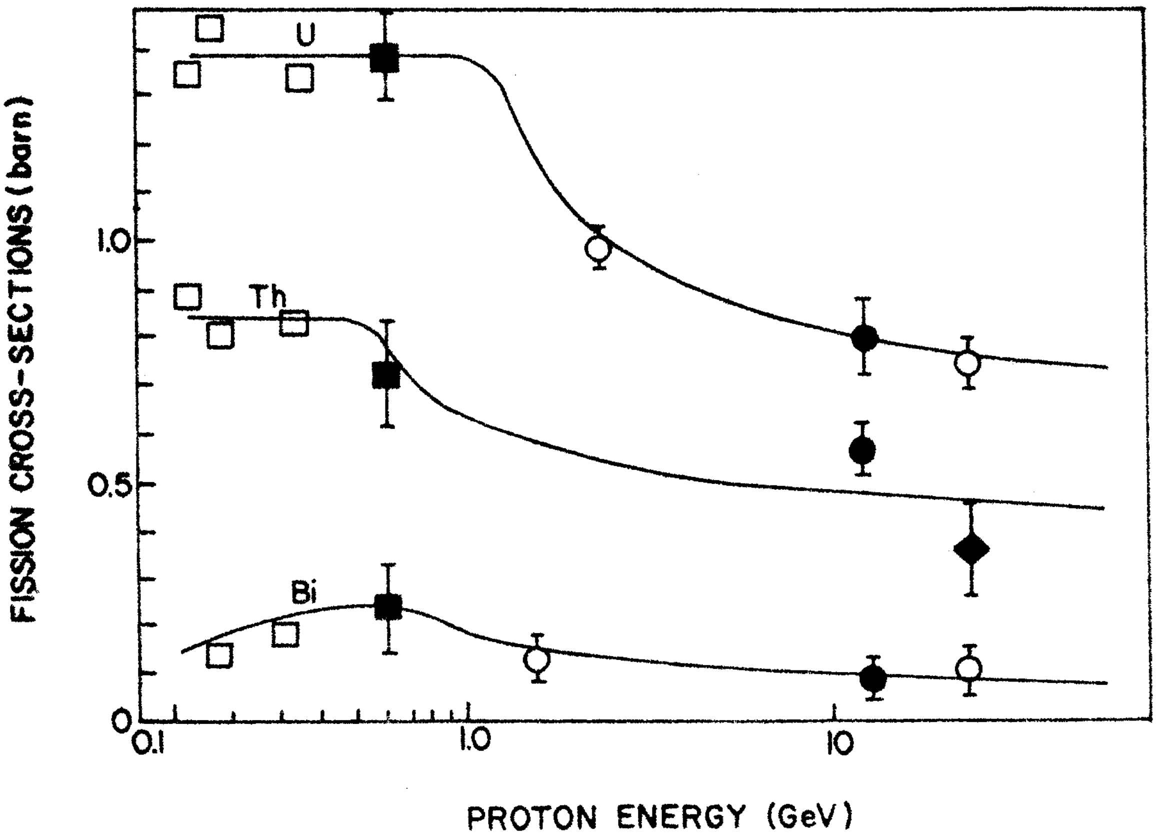
FISSION CROSS-SECTIONS (barn)
PROTON ENERGY (GeV)
0
0.5
1.0
0.1
1.0
10
U
Th
Bi

Fig. 1

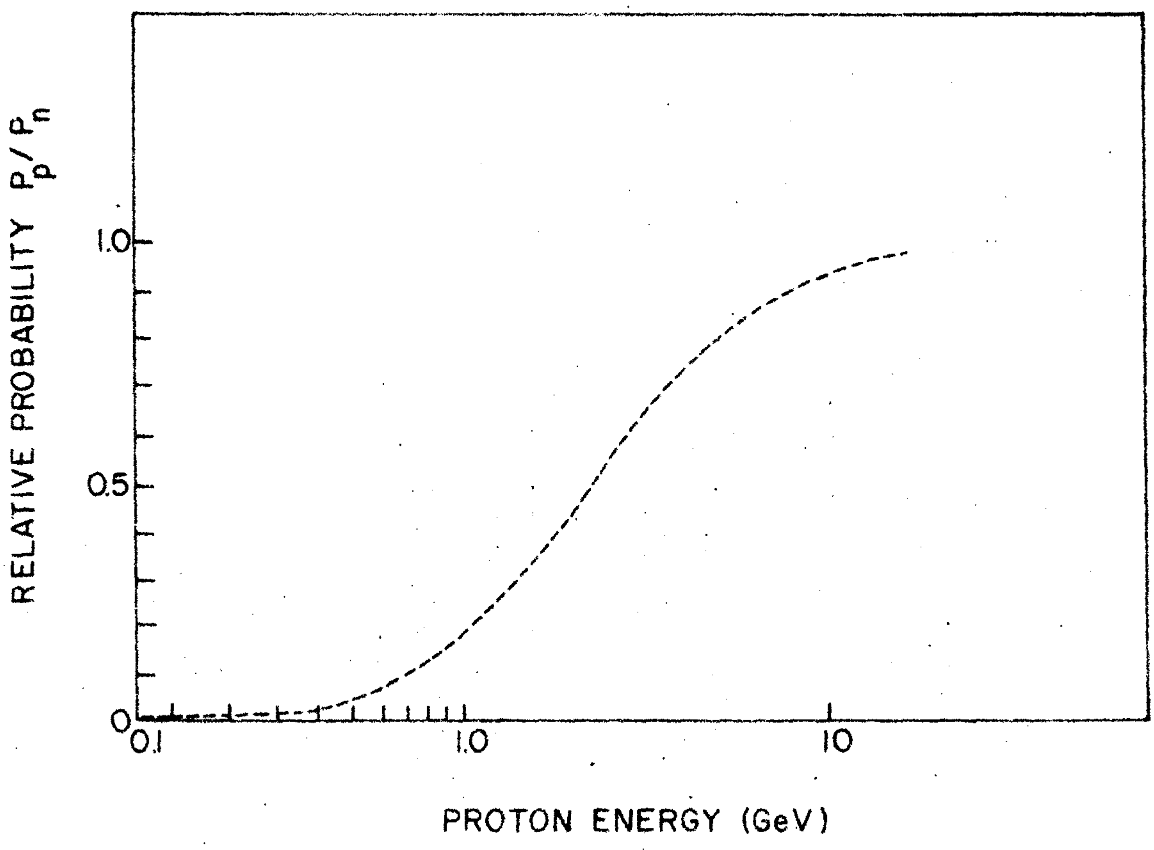

Fig. 2

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