NOTAS DE FÍSICA
VOLUME IX
Nº 15

FISSION OF URANIUM, THORIUM AND BISMUTH BY 20 GeV PROTONS

by
G. Cortini, M. Muchnik, G. Potenza, R. Rinzivillo, W. O. Lock
and H. G. de Carvalho

CENTRO BRASILEIRO DE PESQUISAS FÍSICAS
Av. Wenceslau Braz, 71
RIO DE JANEIRO
1962

Notas de Física - Volume IX - Nº 15

FISSION OF URANIUM, THORIUM AND BISMUTH BY 20 GeV PROTONS

G. Cortini, M. Muchnik, G. Potenza, R. Rinzivillo
Istituto Nazionale di Fisica Nucleare
Sottosezione di Napoli
Istituto di Fisica Superiore dell'Università di Napoli

W. O. Lock
C.E.R.N., European Organization for Nuclear Research
Geneva, Switzerland

H. G. de Carvalho *
Centro Brasileiro de Pesquisas Físicas
and Comissão Nacional de Energia Nuclear

(Received August 1, 1962)

SUMMARY. The cross-sections for the proton induced fission of U, Th and Bi have been mensured at 20 and 21.8 GeV. They turn out to be smaller than at 600 MeV by a factor between 3 and 4, while the ratios of the cross-sections of the various elements remain approximately constant in the same energy interval.

---

* On leave of absence at the Istituto Nazionale di Fisica Nucleare - Sottosezione di Napoli when this work was performed.

We report here briefly some results on the fission of U, Th and Bi induced by protons of kinetic energy between 20 and 22 GeV.

The only existing published figure for the fission cross-section above 1 GeV concerns uranium at 9 GeV and is due to Perfilov et al [1]. For the present work we have used nuclear emulsions loaded with Uranium, Thorium and Bismuth.

The fission cross-section, σ_f may be defined as

$$\sigma_f = \frac{n_f}{\phi N} \tag{1}$$

where n_f is the number of fission events per unit volume of emulsion, ϕ the proton flux per unit area, and N the number of fissionable nuclei per unit volume. The fissionability x, is defined as

$$x = \sigma_f/\sigma_t \tag{2}$$

where σ_t is the total inelastic cross-section for the proton-nucleus interaction.

Low sentitivity KO Ilford emulsions ~400 μm thickness, loaded and processed with the techniques developed by us [2], have been exposed at normal incidence on July 7, 1961 to 20 GeV, and on November 1, 1961, to 21.8 GeV proton beams of the C.E.R.N. proton-synchrotron. For the first exposure, the measurement of Φ, was accomplished by means of a single counter telescope and was rather unprecise (~ ± 20%). In the second exposure, we made use of four different electronic monitors whose absolute calibration was repeatedly made by means of sensitive (K5) emulsions, and we obtained a quite precise flux measurement (~ ± 2%). Due to the very low sensitivity obtained by us in K0 emulsions, only tracks of very high ionization were visible; the tracks of protons and of light nuclei ($Z \leqslant 6$) were not recorded.

The majority of recorded events consisted of single, straight tracks, which are due to the two fission fragments moving apart in opposite directions. For these tracks, the range R was measured and an accurate analysis of the range spectrum as well as a comparison between loaded and unloaded emulsions was performed.

Fig. 1 shows a typical range distribution of observed tracks, in U loaded plates (fig. 1a) and in unloaded plates (fig. 1b). The peak in the 20 μm region observed in U-loaded plates is clearly due to U fission. However, the discrimination of these events from the background is not so clear-cut as in other experiments performed at lower energy, as is seen by the comparison with the range distribution observed by us [3] for U-fission produced by 600 MeV protons (fig. 1c).

The single tracks in the intermediate range region (12-17 μm) are due partly to the fragmentation of Ag, Br and U present in emulsion and partly to U fission. Probably the majority are due to fragmentation rather than to fission (see references (4) and (5)). Therefore, we count as fission events only those single tracks with $R \geqslant 17$ μm. To a first approximation the number of fission events with $R < 17$ μm, which we neglect, will be counterbalanced by the fragmentation events which have $R \geqslant 17$ μm and which are wrongly counted as fission events.

A small number of the single tracks are non-collinear, with an angle >10° between the two parts of the track. In previous work [3] we found that the non-collinear events induced by 600 MeV protons in KO emulsion showed a range distribution similar to that of straight tracks, in the loaded as well as in the unloaded plates: the situation was similar to that of fig. 1c. Therefore, the attribution of non-collinear events to the fission of the loading elements was sure; they gave a rather small contribution (7% for U) to the total number of fissions. At 20 GeV the situation is not so simple because the unloaded plates show a number of non-collinear tracks in the range region of the U-fission events. Thus, the number of non-collinear fissions in the loaded plates could be obtained only by subtracting this background, so that the statistical errors were increased. However, this is not a serious shortcoming, since the fraction of non-collinear events is still rather small, and indeed agrees with that observed at 600 MeV (~10%).

The experimental data are summarized in Table I. Is is seen that the second exposure gave more accurate results, mainly because of the improved flux measurements. The results from the two exposures are consistent with one another, as regards the absolute and the relative values of the cross-sections. The errors quoted in columns 7 and 8 of Table I are compounded of the statistical error arising from the number of events found, the error in the amount of loading in each emulsion, the scan-

TABLE I

Loaded Nuclide	Exposure date	Proton energy (GeV)	Emulsion type	Loading density (nuclei/cm^2) x 10^{-18}	Number of observed fission events	Cross sections (barns) (uncorrected)	Mean cross sections (barns) (Uncorrected)	Mean cross sections (barns) (corrected)
U 238	7.7.61	20	KO 1x	6.2	508	0.60 ± 0.15	0.60 ± 0.15	0.37 ± 0.13
	1.11. 61	21.8	KO 2x	10.4	155	0.52 ± 0.05	0.56 ± 0.04	0.35 ± 0.09
			KO 2.5x	11.0	598	0.57 ± 0.03		
			KO 2.5x	11.0	112	0.56 ± 0.06		
Th 232	7.7.61	20	KO 1x	7.0	149	0.26 ± 0.08	0.26 ± 0.08	0.17 ± 0.07
	1.11.61	21.8	KO 2x	9.5	396	0.29 ± 0.02	0.31 ± 0.03	0.20 ± 0.05
			KO 2.5x		350	0.33 ± 0.02		
Bi 209	7.7.61	20	KO 1x	5.3	25	0.07	~ 0.07	~ 0.05
	1.11.61	21.8	KO 2.5x	12.3	60	0.07		

ning efficiency and an estimate for the accuracy of the discrimination criterion ($R \geqslant 17\,\mu m$).

A serious systematic error arises from those fission events which are produced by the secondary particles (both charged and uncharged) which come from interactions produced in the emulsion stack by the primary proton beam. The magnitude of this error is difficult to calculate exactly, but on the basis of the best existing data we estimate it to be of the order of 35%, with an uncertainty of ± 40% *. The corrected cross-sections are given in column 9 of Table I where the error (at least, for the second exposure) is now essentially the uncertainty in the calculation of the number of secondary fissions.

The value given for the Bi fission cross-sections is only an estimate, since the discrimination uncertainty is rather large in the Bi loaded plates due to the smallness of the Bi fission cross-section. Fig.2 shows our results (corrected for secondary effects) and those of other authors (6 to 12) for the absolute fission cross-sections of U, Th and Bi in the energy region up to 22 GeV. The only data above 600 MeV are those of Perfilov et al at 9 GeV and the data of the present paper at 20 and 21.8 GeV.

It is seen that:

---

* This correction may seem surprisingly high, as our emulsion stack was thin (~3 mm, that is ~1% of an interaction mean free path). Its magnitude is due to the high number of secondary particles from the interactions. It is apparent that all the fission measurements at multigeV energies should be analyzed very carefully in this respect.

i) The U and Th fission cross-sections (and probably also that for Bi) seem to be slowly decreasing functions of energy from 0.6 to 22 GeV.

ii) The Th to U fission cross section ratio seems to be nearly constant in the same energy range. The same is probably true for the ratio for Bi to U.

iii) By using the total inelastic cross-sections σ_t found by Cocconi [13] at 25 GeV, the fissionabilities at 21.8 GeV turn out to be for uranium thorium and bismuth respectively: 0.15, 0.09 and ~0.03. At 600 MeV, [3] using for σ_t the values quoted by Metropolis et al [14], the corresponding figures are 0.63, 0.43 and 0.14. It is seen that all three fissionabilities diminish by about the same factor of 4, as the energy rises from 600 MeV to 22 GeV.

It is generally agreed that the fission process is a rather slow one, happening at an advanced stage of the cascade-evaporation process. The general tendency of fissionabilities to decrease with increasing energy is to be expected on these grounds, as the fissioning nucleus is more and more different from the original highly fissionable one. That the relative fission cross-sections for U, Th and Bi are practically independent of energy may indicate that most of the fission events we observe result from disintegrations with a small cascade and thus with a small excitation energy for the evaporation process. The residual nucleus will still have high A and Z, and thus a high fissionability. Further, if only a few particles have been emitted, the fissioning nucleus will still "remember" the identity of the original struck nucleus.

Acknowledgements

We are glad to express our warmest thanks to the C.E.R.N. PS staff for their help throughout the two exposures, and to the experimental groups on whose beams we were able to parasite, especially Dr. L. Hoffman and Dr. D. Evans for the 20 GeV exposure and Dr. E. Dahl-Jensen and Dr. J. Geibel for the monitoring set-up and operation of the 21.8 GeV beam.

* * *

References

1. N. A. PERFILOV, V. P. DAROVSKIKH, G. F. DENISENKO and A. I. OBUKHOV: Zurn. Eksp. Teor. Fiz., 38, 716 (1960). See also N. A. PERFILOV: Zurn. Eksp. Teor. Fiz., 41, 871 (1961).
2. H.G. DE CARVALHO, A.CELANO, M.MUCHNIK, G.POTENZA and R.RINZIVILLO: in preparation.
3. H.G. DE CARVALHO, G. POTENZA, R. RINZIVILLO, E.SASSI and G. VANDERHAEGHE: Nuovo Cimento, 25, 880 (1962).
4. N.A.PERFILOV, O.V.LOZHKIN and V.P.SHAMOV: Usp.Fiz.Nauk, 60, 3 (1960): Sov. Phys. Usp., 3, 1 (1960).
5. J.M.MILLER and J.HUDIS: Ann.Rev.Nucl.Sci., 9, 168 (1959).
6. P.C.STEVENSON, H.G.HICKS, W.NEVIK and D.R.NETHAWAY: Phys. Rev., 111, 886 (1958).
7. C. B. FULMER: Phys. Rev., 116, 418 (1959).
8. A. KJELBERG and A.C.PAPPAS: Nucl. Phys., 1, 322 (1956).
9. G.N.HARDING: A.E.R.E. Report no. 1438 (Harwell, June 1954).
10. J.JUNGERMANN and H.M.STEINER: Phys. Rev. 101, 807 (1956).
11. N.S.IVANOVA: Zurn. Elsp. Teor. Fiz., 31, 413 (1956); Sov. Phys. JETP, 4, 365 (1957).
12. V.P.SHAMOV: Dokl. Akad. Nauk SSSR, 103, 593 (1955).
13. G.F.DENISENKO, N.S.IVANOVA; N.R.NOVIKOVA, N.A.PERFILOV, E.I.PROKOFFIEVA and V.P.SHAMOV: Phys. Rev., 109, 1779 (1958).
14. M.MUCHNIK, R.RINZIVILLO and L. VAN ROSSUM: private communication.
15. G.H.MCCORMICK and B.L.COHEN: Phys. Rev., 96, 722 (1954).
16. A.K.LAVRUKHINA and L.D.KRASAVINA: Journ. Nucl. Energy, 5, 236 (1957).
17. VINOGRADOV et al.: Chem. Sess. of Conf. of the Academy of Sc. of the USSR on the Peac. Uses of Atomic Energy (July 1-5, 1955).
18. V.F.BILLER: UCRL 2067 (1952).
19. L.G.JODRA and N.SUGARMAN: Phys. Rev., 99, 1470 (1955).
20. P.KRUGER and N. SUGARMAN: Phys. Rev., 99, 1459 (1955).
21. G.COCCONI: Proc. Rochester Conf. on High-Energy Phys. (1960), p. 799.
22. N.METROPOLIS, R. BIVINS, M. STORM, A. TURKEVICH, J.M.MILLER and G. FRIEDLANDER: Phys. Rev., 110, 185 (1958).

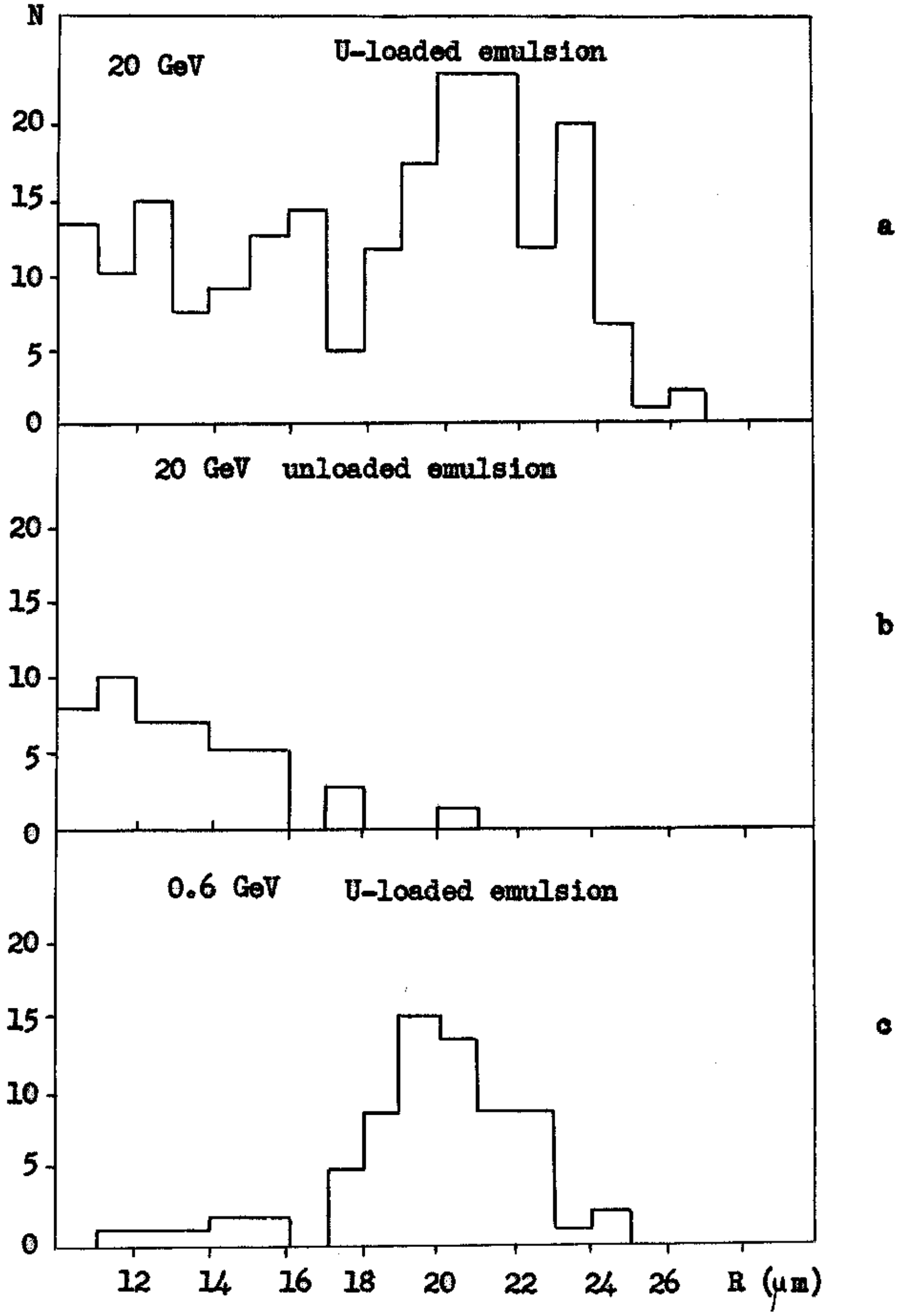

Fig. 1

a) Range distribution of straight tracks with R ⩾10 μm in unloaded KO emulsion exposed to 20 GeV protons, normalized to the same number of Ag nuclei present in the uranium loaded emulsions.

b) Range distribution of straight tracks with R ⩾10 μm in uranium loaded KO emulsion exposed to 20 GeV protons.

c) Range distribution of straight tracks with R ⩾10 μm in uranium loaded emulsions exposed to 600 MeV protons; unnormalized.

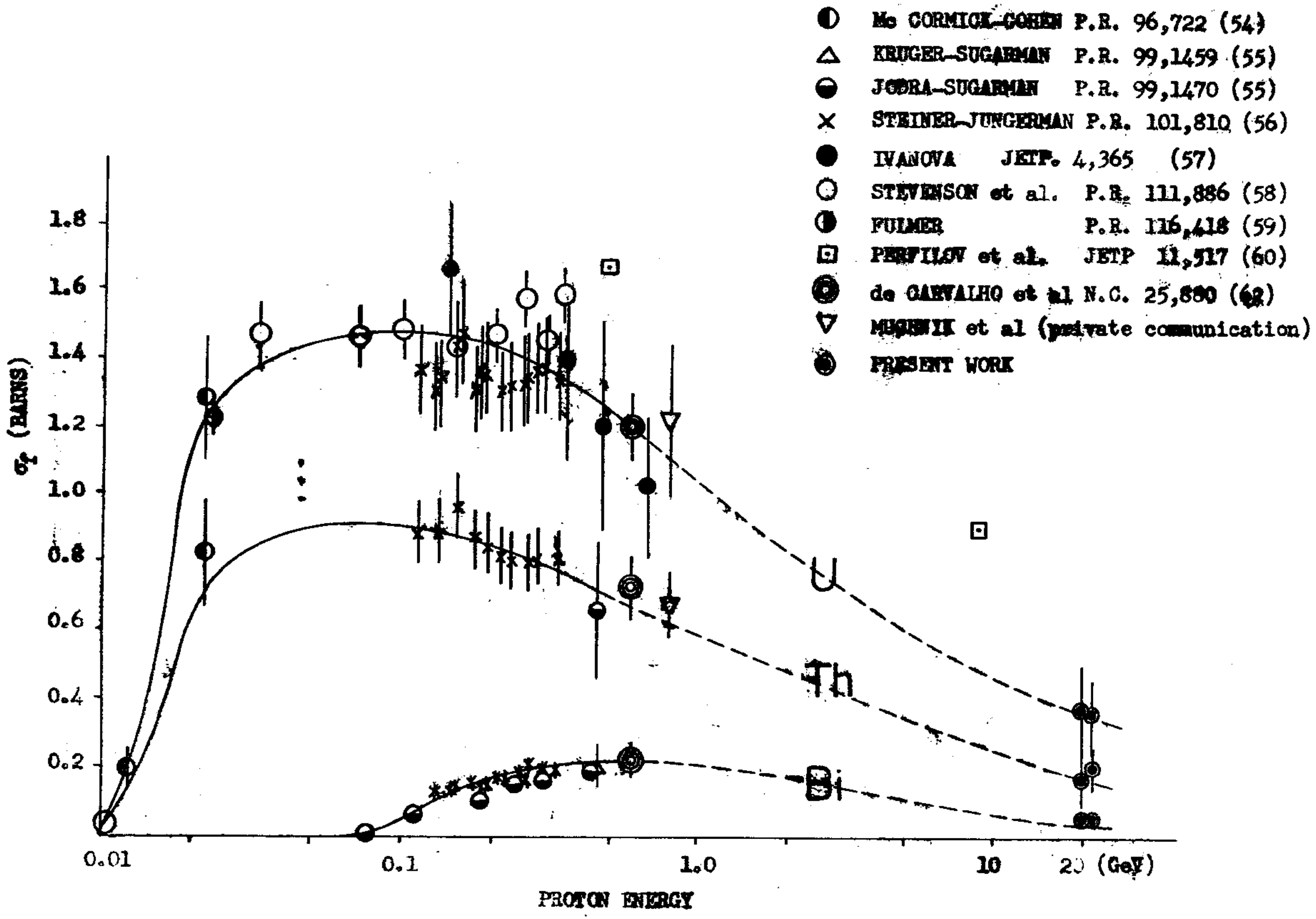

Fig. 2 - Fission cross sections for Uranium, Thorium and Bismuth in the energy range 0.01 - 22 GeV.