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# Asymmetry of Fragment Ranges in the Fission of Heavy Nuclei by Ultrafast Particles

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From the data of a study of fission of U, Bi and W by 660 mev protons, carried out in fine-grained nuclear P-9 emulsions, we have constructed the distribution of the ratio of fragment ranges for various excitation energies of the fissioning nucleus. We find that with increasing excitation energy the fraction of strongly asymmetric fissions increases; this increase is significantly greater for Bi than for U. For excitation energies $\gtrsim$ 400 mev, the character of fission is the same for U, Bi and W. The region of excitation energy in which fission is most symmetric is estimated to be 60-100 mev for uranium, and $\sim$ 100 mev for Bi.

## INTRODUCTION

THE distribution of fragment masses from the fission of heavy nuclei by slow neutrons is a double-peaked curve, indicating the asymmetric character of the fission. With increasing energy of the particles producing the fission, the mass distribution becomes more symmetric, so that for 90 mev neutrons the spectrum of fragment masses has one sharp maximum.

Thus, in this region of excitation energy of the U nucleus, the role of the symmetric form of fission increases with increasing excitation. The change in the character of fission for still greater excitation energies is extremely interesting and is of importance for clarifying the mechanism of nuclear fission at high excitation energies.

Unfortunately, radiochemical methods can be applied to this problem only in the range of energy of the incident particle for which the fissioning nucleus is completely black, since only then can we identify the excitation energy of the nucleus with the energy of the particle. In the high energy range a given energy of the incident particle will give a whole spectrum of nuclei at various excitation energies, and only an insignificant number of nuclei will have excitation energies equal to the kinetic energy of the particle. In applying radiochemical methods to study the fission products, we can only get some average excitation energy, which depends slightly on the particle energy in the region where the nucleus is transparent, so that it is difficult to detect any change in the character of fission which may exist.

An attempt has been made in the present work to determine the character of fission of heavy nuclei as a function of excitation energy for high excitation ( > 100 mev).

## EXPERIMENTAL DATA

As a first attempt to solve the problem, we have used the method of thick-layered emulsions. Type P- 9 nuclear plates, loaded with uranium, bismuth and wolfram by soaking in appropriate aqueous solutions, were irradiated with a 660 mev proton beam. The developed plates were searched under a microscope to study cases of fission of these nuclei. The fission of heavy nuclei by protons of a given energy is frequently accompanied by the emission of several charged particles; as shown in reference 1, the emergence of a certain number of charged particles corresponds to a definite average angle between the fragment directions, and consequently to a definite excitation energy of the nucleus. Therefore, if we classify cases of fission according to the number $n$ of charged particles emitted during fission, we automatically select fissioning nuclei with a given excitation energy.

Figure 1 shows the distribution in range in emulsion of individual fragments from the fission of U, as a function of the excitation energy of the fissioning nucleus ( $\sim$ 200 fragments were measured in each group). Distributions are shown for $E_{exc} \approx 60$, 240 and 540 mev together with the range distribution for thermal fission of U, for comparison.

From consideration of Fig. 1, we can arrive at the following conclusions:

1. The most probable range of the fragments decreases with increasing excitation energy; this is apparently related to the decrease in kinetic energy of the fragments because of the lowering of the $Z$ of the nucleus before fission.

2. Unlike the fission by slow neutrons, the range distribution of the fragments shows a single well-defined maximum, but the half-width of the distribution curve increases substantially as we go

[1] V. P. Shamov, Otch. RIAN (Report of Radium Inst., Acad. Sci., USSR) 1954

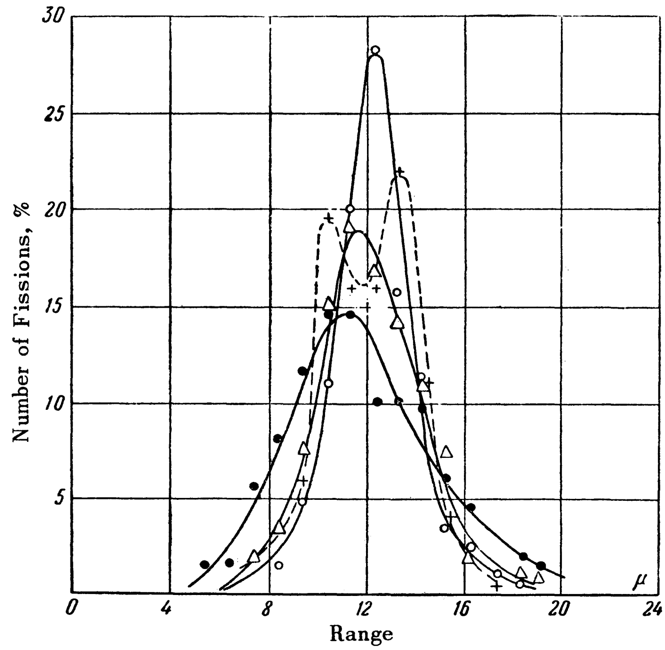


FIG. 1. Range distribution of individual fragments from uranium fission: + – fission of $U^{235}$ by thermal neutrons, O – fission of uranium for $E_{exc} \approx 60$ mev, Δ – fission of uranium for $E_{exc} \approx 240$ mev, ● – fission of uranium for $E_{exc} \approx 540$ mev.

to high excitation energies.

Since this increase in half-width of the fragment range distribution suggests an increase in the fraction of asymmetric fissions with increasing excitation energy, we have studied the distribution of the ratio of the ranges of the two fragments for various excitation energies in U, Bi and W. The Table and Figs. 2 and 3 show the results of measurements of the ratio $l_l/l_h$ ($l_h$, $l_l$ are the ranges of the heavy and light fragments, respectively) for various excitation energies of U and Bi, as well as for the fission of W.

The Table also gives the distribution of the ratio of fragment ranges for fission of $U^{235}$ by slow

| Ratio of Ranges | Fraction of fissions with given $l_l/l_h$, in % | | | | | | | |
|---|---|---|---|---|---|---|---|---|
| | U | | | Bi | | | W | $U^{235}$ |
| | $n=0$, $E_{exc} \approx 60$ mev | $n=2$, $E_{exc} \approx 240$ mev | $n \geqslant 3$, $E_{exc} \approx 380$ mev | $n=0;1$, $E_{exc} \approx 150$ mev | $n=2$, $E_{exc} \approx 240$ mev | $n \geqslant 3$, $E_{exc} \approx 380$ mev | $n \geqslant 1$, $E_{exc} \approx 400$ mev | Thermal Neutrons |
| 1.0—1.15 | 46 | 32 | 28.5 | 54.5 | 38.3 | 29.8 | 32 | 28 |
| 1.15—1.30 | 32 | 27.2 | 25.6 | 23.6 | 28.0 | 17.3 | 21 | 45.5 |
| 1.30—1.45 | 8 | 19.4 | 18.6 | 8.2 | 14.7 | 22.0 | 15 | 17.3 |
| 1.45—1.60 | 10 | 10.7 | 8.4 | 7.25 | 7.35 | 11.5 | 13 | 4 |
| 1.60—1.75 | 2 | 5.8 | 6.4 | 2.70 | 7.35 | 9.6 | 4 | 4 |
| 1.75—1.90 | 3 | 1.0 | 2.8 | 3.60 | 2.94 | 1.92 | 4 | 1.34 |
| 1.90—2.05 | — | 1.0 | 4.6 | — | 1.47 | 0.96 | 2 | — |
| 2.05—2.20 | — | 2.0 | 1.46 | — | — | 2.88 | 2 | — |
| 2.20—2.35 | — | — | 0.3 | — | — | 1.92 | 3 | — |
| 2.35—2.50 | — | 1.0 | 1.27 | — | — | 1.96 | 2 | — |
| 2.50—2.65 | — | — | 0.99 | — | — | — | 1 | — |
| 2.65—2.80 | — | — | 0.67 | — | — | 0.96 | — | — |
| 2.80—2.95 | — | — | 0.16 | — | — | — | — | — |

neutrons, observed in the same type of emulsion.

## DISCUSSION OF EXPERIMENTAL DATA

From the Table and Figs. which have been presented, we can draw some very important conclusions if we are convinced that the features of the distributions of ranges and range ratios observed in the experiment are related to the mass distribution of the fragments. A basis for such a conclusion is that fact that for fission of U by thermal neutrons the range distribution of the fragments mimics the mass distribution of the fragments, so that asymmetry of fission with respect to fragment ranges can signify only an asymmetry of fission with respect to fragment masses. Moreover, in all cases the spectrum of fragment ranges has a less marked dependence, so that we may hope that the changes observed in the spectra of fragment ranges occur even more markedly in the spectra of fragment masses*.

The dependence of $l_l/l_h$ shown in Figs. 2 and 3 is very interesting. From analysis of these data we can draw the conclusion that with increasing excitation energy (i.e., energy transferred to the nucleus by the 660 mev proton) the fraction of strongly asymmetric fissions increases for both U and Bi. This applies to excitations > 60 mev for uranium, and > 150 mev for bismuth. If we draw the same distributions for fixed excitation energy and for the various nuclei (Figs. 4, 5, 6) we can reach the following conclusions:

1. For not too high excitation energy ($\sim$ 100 mev), the fraction of symmetric fissions is greater for bismuth than for uranium.
2. As the excitation energy is increased, the character of fission undergoes a more marked change in bismuth than in uranium.
3. For excitation energies $\sim$ 400 mev, the character of fission is the same for all the nuclei, U, Bi and W.

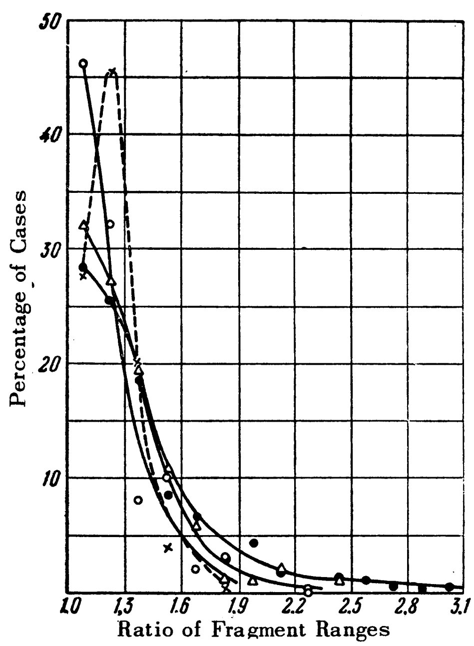


FIG. 2. Distribution of the ratio $l_l/l_h$ of ranges of fragments from fission of U for various excitation energies: O – $E_{exc} \approx 60$ mev, $\Delta$ – $E_{exc} \approx 240$ mev, ● – $E_{exc} \approx 380$ mev, × – fission by thermal neutrons.

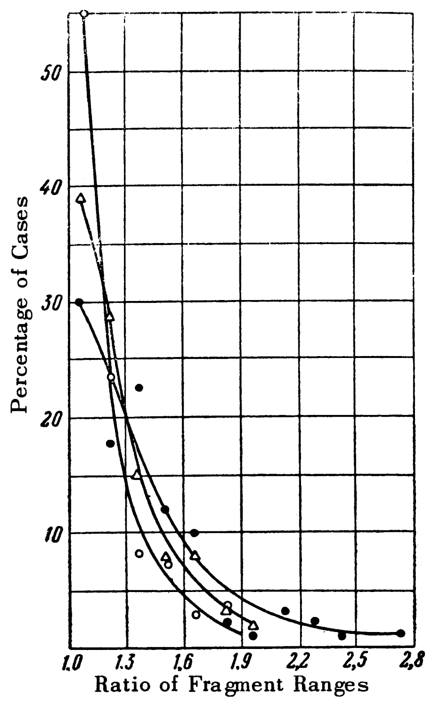


FIG. 3. Distribution of ratio $l_l/l_h$ of ranges of fragments from fission of Bi for various excitation energies: O – $E_{exc} \approx 150$ mev, $\Delta$ – $E_{exc} \approx 240$ mev, ● – $E_{exc} \approx 380$ mev.

In order to convince ourselves that the observed asymmetry in fragment ranges was not caused by the

* Similar conclusions can be drawn from reference 2, where it was shown that in 96% of the cases of uranium fission, longer range was associated with smaller mass.

[2] R. Mathieu and P. Demers, Canad. J. Phys. 31, 97 (1953)

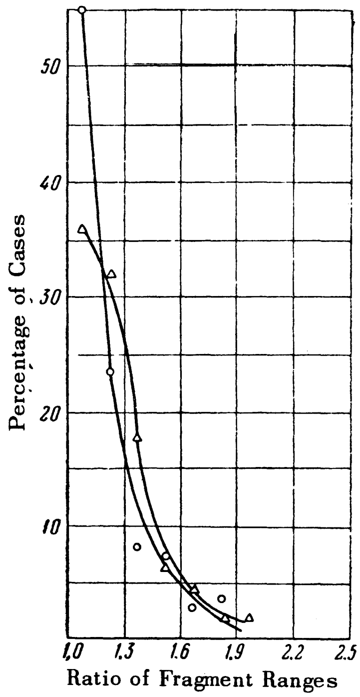


FIG. 4. Distribution of ratio of fragment ranges for fission of U and Bi, for initial excitation energy ≈ 150 mev: O – Bi. Δ – U.

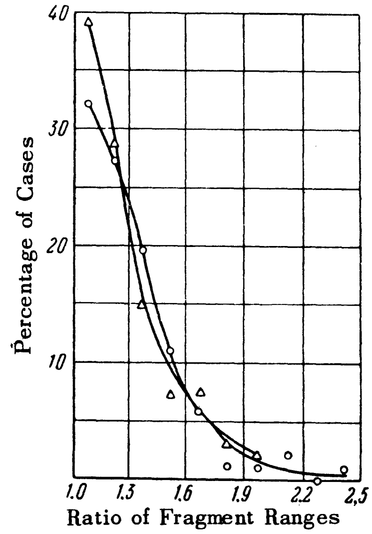


FIG. 5. Distribution of ratio of fragment ranges for fission of U and Bi, for initial excitation energy ≈ 240 mev: O – U, Δ – Bi.

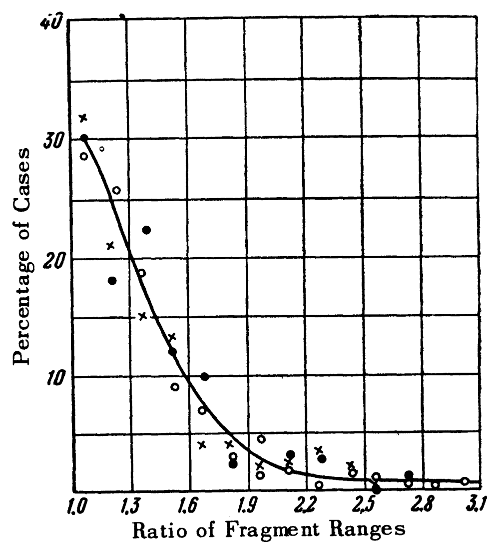


FIG. 6. Distribution of the ratio of fragment ranges from the fission of U, Bi and W for excitation energy ≈ 400 mev: O – U, ● – Bi, × – W.

translational velocity of the fissioning nucleus, we calculated the resulting asymmetry for maximum velocity of the uranium nucleus (excitation energy $\approx$ 600 mev), assuming that the fission is symmetric. It turned out that the maximum possible asymmetry in this case was $l_I/l_{II} = 1.13$, which could by no means account for the distribution of $l_l/l_h$. In addition, if there were actually an effect of the translational velocity on the asymmetry in fragment ranges, then it would be difficult to explain the large effect of the velocity on the range distribution of fragments from uranium fission and the small effect on the range distribution from the lighter Bi nucleus, whose velocity is larger for equal excitation energy.

These remarks lead to the conclusion that at high excitation energy an asymmetric form of nuclear fission begins to play an important role. This increase in the role of strongly asymmetric fissions with excitation energy can be expressed very roughly in terms of the variation of the ratio of fissions with $l_l/l_h \geq 1.45$ to fissions with $l_l/l_h \leq 1.15$ (cf Fig. 7). From the graph we can make a crude estimate of the range of excitation energy in which the fission of U and Bi is most symmetric. We may expect that this region will occur in the range 60-100 mev for uranium, and close to the threshold for emissive fission, i.e., $\sim$ 100 mev for bismuth.

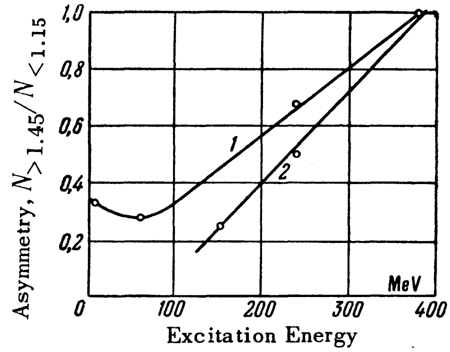


FIG. 7. Dependence of asymmetry of fission of U and Bi on excitation energy: *1.* U, *2.* Bi.

In conclusion we should point out that none of the existing hypotheses for explaining the character of nuclear fission fits the present case. In addition, one is obliged to assume that the character of fission is determined, not by the excitation energy remaining in the nucleus at the moment of fission after the emission of particles, but rather by the initial energy of excitation of the nucleus as a result of its interaction with the proton. This makes it necessary to study these questions further.

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