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Physics-Fission

SOME STUDIES OF THE PRODUCTS OF THE HIGH-ENERGY
FISSION PROCESS*

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ABSTRACT

The energy-dependence of the formation cross section of certain nuclides formed in fission of uranium and thorium has been studied. Excitation functions in the hundred-Mev region are given for Ni^{66} , Zr^{97} , Ag^{111} , Ba^{131} , and Ba^{139} . Protons, deuterons, and alpha particles from the Berkeley 184-inch frequency modulated synchro-cyclotron were used to induce the activities.

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SOME STUDIES OF THE PRODUCTS OF THE HIGH-ENERGY FISSION PROCESS

INTRODUCTION

It has been recognized that fission induced by particles accelerated to high energies differs from low-energy induced fission. Newton⁽¹⁾, in bombarding thorium with 38-Mev helium ions obtained a peak-to-valley ratio of less than two in the fission yield curve, in contrast to a value of 600 for thermal fission of U^{235} ⁽²⁾, and of about 300 obtained by Turkevich for fission of Th^{232} ⁽³⁾ induced by pile neutrons of average energy estimated as 2.7 Mev. It is evident, therefore, that in the range from several Mev to 38 Mev, the nature of the fission process has changed. The first radiochemical investigations of fission induced in the hundred-Mev region were made on bismuth with 190-Mev deuterons by Goeckermann and Perlman⁽⁴⁾. It was found that symmetrical fission was the most probable mode, and that the fission products did not all necessarily contain an excess of neutrons. O'Connor and Seaborg⁽⁵⁾ using 380-Mev helium ions on uranium, and Folger⁽⁶⁾ using 340-Mev protons on uranium, studied the fission product distribution, and reached conclusions similar to those of Goeckermann and Perlman. By counting fission recoils, Jungermann⁽⁷⁾ obtained excitation functions for total fission induced in thorium and uranium with alpha particles, deuterons, and protons from threshold into the hundred-Mev region. He concluded that the total cross sections rise to constant values in this region, being largest for alpha particles, smallest for protons.

In view of the lack of information on the manner in which individual fission reactions change from threshold to the hundred-Mev region, a radiochemical study of the excitation functions for certain chosen fission products was made for uranium and thorium. The reactions were induced with helium ions, deuterons, and protons at energies from 50 Mev to 380, 190, and 340 Mev, respectively. The fission products chosen for study were Ba^{139} , Ba^{131} , Ag^{111} , Zr^{97} , and Ni^{66} . Ba^{139} , Ag^{111} , and Zr^{97} were selected because these nuclides were considered indicative of the "symmetry" of the fission process. Since Ni^{66} was found to occur as a fission product only in hundred-Mev fission^(4,6), the excitation function for this nuclide was established. Ba^{131} was chosen for study because its occurrence in fission⁽⁶⁾ was felt to be associated with an increasing yield of neutron-deficient isotopes as the available excitation energy was increased. In order to investigate further the appearance of neutron-deficient isotopes in high-energy fission, a short study was made on the isotope Ba^{128} as a fission product. The Ba^{131} and Ba^{128} had to be detected through their respective 9.6-day and 3.8-minute cesium daughters because of the preponderance of Ba^{140} in the barium fraction. The necessary genetic relationships were calculated from the decay modes

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EXPERIMENTAL PROCEDURE

Bombardments

Uranium and thorium foils from one to ten mils thick were bombarded for from several minutes to several hours with helium ions, deuterons, or protons in the 184-inch cyclotron at Berkeley.

Proton and deuteron bombardments were always made in the internal circulating beam. Probe position determined the bombarding energy. Due to the likelihood of deuteron contamination of the circulating alpha particle beam, helium-ion bombardments were carried out using the pulse-deflected helium ion beam synchronized with the pulsed-arc source. The stacked-foil technique was used with aluminum absorbers to achieve the various energies needed to establish the excitation function.

All bombardments were monitored with aluminum foils; cross sections for Na^{24} production from aluminum are based upon data of Stevenson and Folger for protons⁽⁸⁾, of Batzel and Crane for deuterons⁽⁹⁾, and of the authors for helium ions⁽¹⁰⁾.

Chemical Procedures

A. Ba^{139} , Ag^{111} and Zr^{97}

The irradiated uranium or thorium target was dissolved in concentrated nitric acid which contained barium, silver and zirconium carriers. A small amount of ammonium fluosilicate was added to facilitate the dissolution. Fuming nitric acid was added, the whole cooled in an ice bath, and the resultant barium nitrate precipitate removed by centrifugation. The supernatant liquid was diluted to about 4N HNO_3 , and the zirconium extracted for 20 minutes into 0.25 M thenoyltrifluoroacetone (TTA) in benzene. The aqueous layer was allowed to stand for three hours from the end of the bombardment (to ensure decay of Pd^{111}), and a small volume of hydrochloric acid added. The resultant precipitate of silver chloride was removed by centrifugation.

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The barium nitrate was dissolved in water, and barium chloride precipitated with 80 per cent HCl - 20 per cent ether reagent after chilling in an ice bath. This step was repeated and the final barium chloride precipitate dissolved in water. This solution was equilibrated with "Dowex 50" ion exchange resin and the barium eluted with 0.5 M ammonium citrate at pH 7.8. This accomplished satisfactory separation from radium isotopes. Sodium chromate was added to the eluate and the barium chromate precipitate washed, mounted on an aluminum plate, weighed and counted.

The benzene solution of zirconium TTA was washed for 10 minutes with 4 N HNO₃, then shaken with freshly prepared five per cent HPO₃ in 8 M HNO₃ and warmed in a water bath. The white precipitate was washed with 4 N HNO₃, with acetone, and then dried in a water bath. The precipitate was transferred to a platinum crucible, ignited to zirconium pyrophosphate, cooled, weighed on an aluminum plate, and counted.

The silver chloride precipitate was washed with nitric acid and with water, and a small quantity of potassium iodide solution added. H₂S was passed through this mixture and the resultant precipitate of silver sulfide was collected, washed, and dissolved in concentrated nitric acid. A small amount of ferric ion was added and the solution made ammoniacal. The ferric hydroxide was centrifuged and discarded. The supernatant was acidified with concentrated HNO₃, and HCl added. The resulting silver chloride was washed twice with water, twice with alcohol, mounted on an aluminum plate, weighed and counted.

B. Ba¹³¹ and Ni⁶⁶

The irradiated uranium and thorium targets were dissolved in concentrated nitric acid which contained barium and nickel carriers. A small amount of ammonium fluosilicate was added to facilitate the dissolution. Barium nitrate was precipitated by the addition of fuming nitric acid and cooling. The supernatant was evaporated to near-dryness, diluted with water, and iron and palladium carriers added. The solution was saturated with ammonia gas in a hot water bath and the precipitate discarded. To the supernatant solution was added a saturated solution of dimethylglyoxime in alcohol. The precipitate was dissolved in concentrated hydrochloric acid, placed on a "Dowex 2" anion exchange column and eluted with concentrated hydrochloric acid. The eluate was brought to 3 N in HCl, and several milligrams of Hg⁺⁺, Cu⁺⁺, Pb⁺⁺ and Ag⁺ added. The solution was saturated with H₂S in a hot water bath, the precipitate centrifuged off and discarded. The supernatant solution was boiled to expel the H₂S, a small amount of ferric nitrate added and the solution made ammoniacal. The ferric hydroxide precipitate was discarded and dimethylglyoxime reagent was added to the supernatant. The precipitate was washed with water and with alcohol, mounted on an aluminum plate, dried, weighed and counted.

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The barium nitrate was dissolved in water, ether-hydrochloric acid reagent added, the whole placed in an ice bath and the white precipitate of barium chloride centrifuged, dissolved, and precipitated with ether-HCl. The final precipitate was dissolved in water and potassium carbonate added. The precipitate of barium carbonate was washed, mounted and weighed. After a period of fourteen days, the precipitate was dissolved in dilute nitric acid, cesium and lanthanum carriers added, and the barium precipitated with ether-HCl reagent. The supernatant was evaporated to dryness and 70 per cent HClO₄ added. The resultant solution was heated to fuming for five minutes and cooled. Sufficient absolute alcohol was added to triple the volume, and the solution cooled in an ice bath. The resultant precipitate of cesium perchlorate was centrifuged and dissolved in HClO₄, and the precipitation procedure repeated. The final precipitate of cesium perchlorate was washed with alcohol, mounted on an aluminum plate, dried, weighed and counted.

Ba¹²⁸

The chemical procedure was similar to that for Ba¹³¹ except that the barium fraction was allowed to stand for half an hour only, and the cesium perchlorate was rapidly dissolved and reprecipitated twice in the presence of barium and lanthanum carriers in water-free fumed perchloric acid solution.

Counting Techniques

All counting of beta radiation was performed with an argon-alcohol-filled Tracerlab type TGC-3A counter, using saturation back-scattering from aluminum. Since all counting rates were relative to an aluminum monitor, the cross sections were independent of counter geometry, and only slightly dependent upon backscattering, self-scattering, and air-window absorption corrections because all radio-isotopes investigated emitted reasonably energetic beta radiations.

In the case of the Cs¹³¹ daughter of Ba¹³¹, the nuclide was detected by counting all the K-X-rays on a sodium iodide scintillation counter of known geometry coupled with a single-channel pulse analyzer. The disintegration rate of the aluminum monitor was in this case determined on a proportional counter of 100 per cent geometry.

Corrections for fission recoil losses were made on all bombardments of one-mil foils. These corrections, determined experimentally for Ag¹¹¹, Ba¹³⁹, and Zr⁹⁷, amounted to from 10 to 18 per cent.

Nuclear absorption corrections were made in the stacked-foil helium ion bombardments. For this purpose the calculated geometrical cross section of 0.64 barns for the aluminum constituting the absorber was used.

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DISCUSSION OF RESULTS

The Fission Model

Before a formal discussion of the excitation functions is attempted, the model described by Goeckermann and Perlman⁽⁴⁾ for the fission of bismuth with 190-Mev deuterons, will be adopted. In this, the various nuclei responsible for high-energy fission are presumed to be formed by evaporation of a large number of nucleons, chiefly neutrons, from the target nuclei. Because of the high state of excitation, the neutron-proton ratio in such a fissionable nucleus is preserved in the fission fragments. It is also assumed that for a given mass chain, a distribution of primary fission products exists, and that this distribution roughly approximates a Gaussian. This assumption is consistent with independent mass yield studies made by Folger⁽⁶⁾ on isobars of masses 83, 111, 140, 156 and 166 in bombardments of uranium with 340-Mev protons, and in thermal fission of U²³⁵ described by Glendenin⁽¹¹⁾.

Energy-Dependence of Cross Sections

It is convenient to represent the situation diagrammatically as in the nuclide chart of Figure 11, in which the number of protons is plotted versus the number of neutrons. The dashed curved line represents the line of stability. Isobaric lines are shown for the nuclides studied, namely masses 66, 97, 111, 128, 131 and 139. It is along these lines that the isobaric distribution is assumed to occur. Four arbitrary lines are drawn through the origin, these being labeled as A, B, C, and D. These lines represent loci of nuclei of equal N-P ratio. More generally, the intersection of one of these lines with an isobaric line should correspond to the isobar of highest yield obtained from a fissioning nucleus with the N-P ratio represented by that line.

The positions of U²³⁸ and Th²³² are also shown. Presumably, in the fission of either of these at or near their thresholds, the primary fission products might be distributed along line A. Actually, it has been shown by Glendenin⁽¹¹⁾ that this is not strictly true for thermal fission of U²³⁵, but for purposes of the present discussion the assumption is satisfactory. Obviously, all the products of such low energy fission are arrayed to the right of the stability line, hence are beta-emitters. In this type of fission, one radio-nuclide of conveniently measurable half-life almost always represents the total chain yield.

We now suppose, in a purely arbitrary manner, that the excitation energy imparted to the target nucleus is such that a large number of nucleons is evaporated prior to fission, and that the resultant prefissioning nucleus has an N-P ratio given by the line B. The fission products are thus assumed to be distributed about this line. It is noteworthy that the isobaric line 139 intersects line B at barium, whereas the intersection of the isobaric line 97 is still about one unit removed from zirconium. For

the isobaric line 111, silver lies about two units from the intersection. This might be interpreted as meaning that a sizeable fraction of the yield of mass 139 will have $Z > 56$ and that the yield as measured by Ba^{139} will not represent the mass yield; those of higher Z will be missed. Ag^{111} , however, should still represent the chain yield for mass 111, while the case for Zr^{97} is intermediate between these two. It would, furthermore, appear that at an energy represented by the line B, Ba^{131} should not appear among the isobars of mass 131 because of the presence of a stable nuclide at $Z = 54$. The situation should be even more accentuated in the case of Ba^{128} . In short, these neutron-deficient nuclides should have high thresholds. The experimental data may now be examined in the light of this over-simplified discussion.

Reference to Figures 5 and 6 show that, for either U^{238} or Th^{232} targets, the Ba^{139} cross sections decrease above about 100 Mev. Zr^{97} excitation functions exhibit maxima at about 180 Mev while for Ag^{111} the peak cross section occurs at about 220 Mev. The same trend was observed in all charged-particle bombardments for both uranium and thorium. The behavior of these excitation functions seems to be consistent with the simple treatment discussed above, for Ba^{139} should be the first of the nuclides studied which should fail to represent total mass yield with increasing bombardment energy. One may suppose that beyond the maximum cross section for any of these three beta-emitters, increasing amounts of isobars of higher Z are being formed. As will be shown below by analogy, this is apparently the case.

Figures 7 and 8 show the complete excitation functions for formation of Ba^{131} from U^{238} and Th^{232} . The very high threshold of between 50 and 100 Mev contrasts with those for the beta-emitting fission products described above. Again, this high threshold was predictable on the basis of the excitation necessary to achieve the required N-P ratio of the fissioning nucleus.

The simplified picture presented above would seem to lead to the conclusion that yields for the beta-emitting fission products should not only approach maxima, but that they should also become negligible at higher energies. That this is not the case may be explained by the fact that, on the average, only a fraction of the energy of a high-energy particle will be transferred to the target nucleus (12). Hence, fission by nuclei corresponding to various degrees of nuclear evaporation will occur. It must be expected, therefore, that the formation cross section for a given fission product is merely the average value of cross sections due to a continuous spectrum of excitation energies. Thus, even at 400 Mev, yields of Ba^{139} , though decreasing, are still appreciable. Furthermore, the value of 7 mb found for Ba^{131} from U^{238} bombarded with 340-Mev protons is of the same order of magnitude as that found by Folger (6) for Ta^{131} . While it is true that the excitation curve for Ba^{131} cross section may be rising rapidly and that for Ta^{131} probably decreasing (similar to Ba^{139}), nevertheless, the spread of four units in atomic number indicates that even at 340 Mev, the

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type of fission characterized by neutron-rich fission products and associated with relatively low-energy fission, is still appreciable.

Referring to Figure 11, one would expect Ba¹²⁸ to have a lower formation cross section than Ba¹³¹ in the region of line C. The cross section for formation of Ba¹²⁸ from U²³⁸ bombarded with 340-Mev protons was found to be about 0.2 mb, as compared to a value about 7 mb for Ba¹³¹.

Figures 9 and 10 give the complete excitation functions for formation of Ni⁶⁶. The rather high threshold of about 50 Mev is consistent with the fact that nuclides of such low mass have not been detected in thermal or in relatively low-energy fission. The presence of both Ni⁶⁶ and Ag¹¹¹ in good yield in high-energy fission indicates that the strong tendency in threshold fission for a particular asymmetric mode is absent in high-energy fission. For this reason, the beta-emitting nuclides such as Ni⁶⁶ and Ag¹¹¹ might be considered as "high-energy" fission products.

The Fissioning Nucleus

It is of some interest to speculate as to the N-P ratio of the fissioning nuclei. Obviously, no single nucleus can be said to be responsible for all the fissions occurring at a given energy. Nevertheless, the shapes of the excitation functions enable one to postulate, for some given energy, the approximate N-P ratio of the hypothetical fissioning nucleus.

The very low yield of Ba¹²⁸ and the increasing yield of Ba¹³¹ in 340-Mev proton bombardments of uranium would indicate that the maximum of the isobar distribution would lie to the right of line D - perhaps at line C. On the other hand, the decrease in yield of Ag¹¹¹ above 220-Mev bombardment energy shows that isobars of $Z > 47$ are being formed at this energy; at 340 Mev it is likely that the peak of the mass 111 isobar distribution curve would lie on the neutron-deficient side of line B. This would still leave the majority of the mass 111 yield to show up at Ag¹¹¹ as is actually the case. In agreement with this is the fact that although Ag¹¹¹ and Ba¹³¹ have nearly the same N-P ratio, the Ba¹³¹ yield is rising rapidly while that for Ag¹¹¹ shows only a slight decrease. Thus, the maximum of the isobar distribution for mass 131 must lie on the neutron-rich side of the line D. The approximate locus of the maxima of the isobar distribution curves for 340 Mev is, therefore, taken as line C. At $Z = 92$, a fissionable precursor lying along line C would correspond to $N = 128$, or to mass 220. This would imply a reaction such as $U^{238}(p, p18n)U^{220}$ or $U^{238}(\alpha, \alpha 18n)U^{220}$. Since it is doubtful that the evaporation of neutrons would occur to the exclusion of protons, such reactions as $U^{238}(p, 3p21n)Th^{215}$, $(p, 4p22n)Ac^{213}$ or $(p, 5p24n)Ra^{210}$ - all of which lie about line C - might be postulated as leading to the observed distribution of fission products. Although this represents a very large number of nucleons to be evaporated, evidence of another nature indicates that this may be the case. Douthett(13), in a radiochemical study of the ranges of fission recoils of uranium in aluminum, found that the ranges of Sr⁸⁹, Ag¹¹¹, and Ba¹⁴⁰ were actually smaller in

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335-Mev proton-induced fission than in 18-Mev deuteron-induced fission. This phenomenon was explained by considering that the complementary fragments of these fission recoils were actually smaller in the high- than in the low-energy fission. Through conservation of momentum he calculated that in order to account for the difference in ranges in the two cases, it was necessary to assume that the complement, in the case of Sr^{89} , must have been lighter in the high-energy case than in the low-energy case by about 26 mass units.

Symmetry of Fission in Uranium and Thorium

It has already been pointed out that the character of the fission process changes with increasing energy of bombardment. As yet no attempt has been made to compare the characteristics of high-energy fission in uranium with that in thorium. A convenient way to examine this effect is to express the yields of Ba^{139} and Zr^{97} in per cent of the yield of Ag^{111} at a particular energy. This has been done by taking cross section values from the smooth curves of Figures 1 - 6. The values thus calculated are shown in Table I for uranium and for thorium, for all three bombarding particles.

TABLE I
Per cent Yields of Ba^{139} and Zr^{97} Relative to
 Ag^{111} for Uranium and Thorium

Mev	ALPHAS				PROTONS				DEUTERONS			
	U		Th		U		Th		U		Th	
	Zr ⁹⁷	Ba ¹³⁹	Zr ⁹⁷	Ba ¹³⁹	Zr ⁹⁷	Ba ¹³⁹	Zr ⁹⁷	Ba ¹³⁹	Zr ⁹⁷	Ba ¹³⁹	Zr ⁹⁷	Ba ¹³⁹
50					132	74	110	79	120	100	85	67
100	96	68	69	31	120	58	85	43	95	69	76	43
150	89	59	65	26	114	51	80	35	91	59	75	36
200	84	53	63	23	107	47	77	31	89	51	73	27
250	80	48	61	20	104	44	71	27				
300	76	45	58	18	95	42	65	22				
340	74	43	55	16	87	41	60	20				

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It is noteworthy that at higher energies the relative yields of Zr^{97} and Ba^{139} become progressively smaller, barium being the smallest and exhibiting the greatest proportionate decrease. The explanation for this behavior was given previously in the discussion of the positions of these nuclides relative to a line of constant N-P ratio.

It might also be pointed out that the values in Table I are, invariably, highest for protons and lowest for alpha particles. This phenomenon will be discussed later.

It is significant that the values in Table I are always lower for thorium than for uranium. In short, thorium always exhibits a more "symmetrical" type of fission than does uranium. This can be understood in the following manner: the fission products Ba^{139} and Zr^{97} are characteristic products of comparatively low excitation energy. At least part, therefore, of these two products will come about as a result of collisions involving transfer of only a small fraction of the kinetic energy of the high-energy particle. It is known (14) that the fission cross section of thorium at or near the threshold is considerably smaller than that of uranium at the same energy. Hence, those products arising from fission at low excitation should have smaller cross sections in the case of thorium than in the case of uranium. Such nuclides are Zr^{97} and Ba^{139} . That this discrepancy in the cross section for formation from uranium and from thorium does not hold at high excitation energies is suggested by the fact that nuclides such as Ni^{66} (cf Figures 9 and 10) and Ag^{111} which are formed in greatly increased yield only in high-energy fission have nearly identical cross sections in thorium and in uranium. The same is nearly true of Ba^{131} (cf Figures 7 and 8); the slight difference could be experimental variation.

While it is true that the smaller mass of the Th^{232} nucleus might account for minor differences in the type of fission mass yield obtained as compared to uranium, nevertheless, reference to Figure 11 shows that both Th^{232} and U^{238} have nearly identical N-P ratios; fission products of a given N-P ratio should, therefore, exhibit a similar energy dependence in thorium and uranium. Inspection of Figures 1 - 10 confirms this.

Although the present work does not include sufficient data to permit estimation of the total fission cross section, nevertheless of the five nuclides studied, it seems logical to conclude that the total fission cross section for U^{238} would be somewhat larger than that for Th^{232} . This would be in keeping with the work of Jungeman (7). He found values of 1.3 and 1.1 barns, for the fission cross sections of U^{238} , and Th^{232} , respectively, when bombarded with 190-Kev deuterons.

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Comparison of Alpha-Particle-, Deuteron-, and Proton-Induced Fission

Several significant features can be noted in the excitation functions (Figures 1 - 10) for the three different bombarding particles. Without exception, proton-induced fission cross sections are smallest, while the alpha-induced values are, with one exception, largest. This exception is unquestionably due to experimental error. Deuteron-induced cross sections are, of course, intermediate. This phenomenon may be understood in terms of the velocity of the bombarding particle. A proton possesses a velocity twice that of an alpha particle of the same kinetic energy. It would, therefore, be more likely to cause "knock-on" type reactions than an alpha-particle of the same energy, while the alpha-particle, because of its smaller velocity, would be more prone to distributing its energy to a nucleus. This would lead to excitation and, finally, fission. The role of deuterons, of intermediate mass, is obvious. While the qualitative agreement with experiment is satisfactory, no data at present are available to confirm the implication that protons should exhibit higher "knock-on" cross sections. It is of interest to note that the total fission cross sections found by Jungerman⁽⁷⁾ are also largest for alpha-particles and lowest for protons, for both uranium and thorium.

In Figure 12 are plotted the cross sections versus the mass numbers for uranium and thorium bombarded with alpha-particles, protons and deuterons. An important feature of these "profiles" (which may also be seen from the data in Table I) is that alpha-particle-induced fission in every case accentuates the yield of Ag^{111} relative to Ba^{139} and Zr^{97} , as compared to deuterons or protons of the same energy. As was seen previously, a large relative yield of Ag^{111} is associated with a highly excited precursor; conversely, large relative yields of Zr^{97} and Ba^{139} indicate relatively low-energy fission. It is significant, therefore, that the profiles in uranium and thorium for 150-Mev alpha-particles are reasonably similar to those for 300-Mev protons. This is shown also in Table II, in which the value for Ag^{111} is taken as unity. The data were taken from the smooth curves of Figures 1-10.

TABLE II

The Ratios $\text{Zr}^{97}:\text{Ag}^{111}:\text{Ba}^{139}$ for U^{238} and Th^{232}

	Th	U
150 Mev α	0.66:1.00:0.30	0.89:1.00:0.59
300 Mev p	0.65:1.00:0.22	0.93:1.00:0.42

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The ratios show that 150-Mev alpha-particles, due to their lower speed, induce roughly the same excitation in uranium and thorium as do protons of 300-Mev energy.

Fission Yields

For many purposes the fission yield, defined as the ratio of the activation cross section for a particular fission product to the total fission cross section, is a more convenient quantity than the cross section, since the fission yield eliminates the energy-dependence of the fission cross section. The only available data for total fission excitation functions are those of Jungerman⁽⁷⁾. Although these data could have been used to calculate fission yields for the fission products studied in this treatment, it was felt that uncertainties inherent in the two investigations would give values for fission yields of such uncertainty that they would have been of little use in interpretation. However, the usefulness of the concept of fission yield is evident, and when further data on the total fission cross sections for uranium and thorium become available, these quantities will be calculated.

Acknowledgments

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FIGURE 1 Zr^{97} PRODUCED IN THE FISSION OF U^{238}

FIGURE 2 Zr^{97} PRODUCED IN THE FISSION OF Th^{232}

FIGURE 3 Ag^{111} PRODUCED IN THE FISSION OF U^{235}

FIGURE 4 A_9^{111} PRODUCED IN THE FISSION OF Th^{232}

FIGURE 5 Ba^{130} PRODUCED IN THE FISSION OF U^{235}

FIGURE 6 Ba^{139} PRODUCED IN THE FISSION OF Th^{232}

FIGURE 7 Ba¹³¹ PRODUCED IN THE FISSION OF U²³⁸

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FIGURE 8 Ba^{131} PRODUCED IN THE FISSION OF Th^{232}

FIGURE 9 Ni^{60} PRODUCED IN THE FISSION OF U^{235}

FIGURE 10 N^{14} PRODUCED IN THE FISSION OF Th^{232}

FIGURE 11 RELATIONSHIPS AMONG FISSION PRODUCT NUCLIDES
ON THE NUCLIDIC CHART

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FIGURE 12 MASS-YIELD PROFILES FOR URANIUM AND THORIUM BOMBARDED WITH HIGH-ENERGY PARTICLES

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