Fission Product Yields in Helium Ion-Induced Fission of Au^{197}, Pb^{204}, and Pb^{206} Targets*

E. F. NEUZIL† AND A. W. FAIRHALL
Departments of Chemistry and Physics, University of Washington, Seattle, Washington
(Received 5 November 1962)

Mass-yield curves have been measured radiochemically for fission of Au^{197}, Pb^{204}, and Pb^{206} target nuclei bombarded with 41.9-MeV helium ions. Fission is symmetric in all three cases, the data being satisfactorily represented by Gaussian-shaped curves with full widths at half-maximum of 30, 27, and 24 mass units, respectively. The widths at half-maximum, $W_{1/2}$, of a number of cases of fission in the symmetric mode are examined and it is shown that the widths appear to be correlated with the excitation energy $E_{S.P.}$* which the fissioning nucleus possesses at the saddle point. Over the excitation energy interval 10–23 MeV the data follow the empirical expression $W_{1/2}=E_{S.P.}$*$+7$.

I. INTRODUCTION

THERE exists at the present time a very large body of experimental information concerning nuclear fission phenomena of the actinide elements at moderate excitation energies ($E<50$ MeV).[1] Relatively little information is available about the fission behavior of elements lighter than thorium at comparable energies,[2–12] although considerable work is currently in progress on these elements.

The work which has been done on the lighter members of the heavy elements (lead and bismuth) at moderate excitation energies[5–12] indicates that there are differences in the fission behavior of these elements compared with the heaviest elements. Whereas the heaviest elements tend to fission with an asymmetric division in mass, elements in the region of bismuth are observed to fission symmetrically. And while there are very large differences in fissionability between the heaviest elements and bismuth, the fissionability of bismuth increases exponentially with excitation energy[8,9,12] in contrast with the step-wise increase in fissionability with excitation energy of the heaviest elements. At the beginning of this study it was not clear whether the rapid increase in the probability of fission with increasing excitation energy is an intrinsic property of bismuth or whether it reflects a rapid increase in the fissionability of lighter isotopes formed by increasing neutron boil-off from the initial compound nucleus with increasing excitation energy. Studies of the fissionability of separated lead isotopes showed that the former possibility is correct.[7]

It seems appropriate that further studies be carried out on elements lighter than bismuth in order to better characterize their behavior. Hopefully, these studies might furnish new insights into the fission process. The present paper concerns experiments on the distribution in mass of the fission products from fission induced in the target species Au^{197}, Pb^{204}, and Pb^{206} by 41.9-MeV helium ions.

II. EXPERIMENTAL PROCEDURE

Targets of Au^{197}, Pb^{204}, and Pb^{206} were prepared for bombardment in the form of thin foils. Pure gold was readily available in 4 in.×4 in. sheets, ~2.6 mg/cm² thick, as dental gold foil. The gold target consisted of several thicknesses of this foil cut into a strip approximately 1 cm×8 cm. It was bombarded between two pure aluminum foils, each about 3 mg/cm² thick, which served to catch fission fragments escaping from the target foil.

Table I lists the samples of enriched lead isotopes which were available along with their isotopic compositions. The sample of Pb^{204} was first made into an electroplating solution from which targets were prepared by electrodeposition on thin (2.6 mg/cm²) gold foil. The amount of lead in each target was about 1 mg, deposited over approximately 1.5 cm² of gold foil. The amount of gold and lead in the target foil was deter-

TABLE I. Isotopic analyses of enriched lead targets.

Enriched target	% isotopic composition			
	Pb^{204}	Pb^{206}	Pb^{207}	Pb^{208}
Pb^{204}	39.1	30.8	12.5	17.7
Pb^{206}	<0.1	89.5	8.1	2.4
Pb^{207}	0.2	3.5	71.5	25.0
Pb^{208}	0.07	2.0	10.0	88.0

* Supported in part by the U. S. Atomic Energy Commission.
† Present address: Department of Chemistry, Western Washington State College, Bellingham, Washington.
[1] E. K. Hyde, University of California Reports UCRL-9036, −9065, 1960 (unpublished).
[2] R. C. Jensen and A. W. Fairhall, Phys. Rev. **109**, 942 (1958); **116**, 160 (1959).
[3] R. A. Nobles and R. B. Leachman, Nucl. Phys. **5**, 211 (1958).
[4] H. C. Britt, H. E. Wegner, and J. Gursky, Phys. Rev. Letters 8, 98 (1962).
[5] N. Sugarman, Phys. Rev. **79**, 532 (1950).
[6] A. W. Fairhall, Phys. Rev. **102**, 1335 (1956).
[7] A. W. Fairhall, R. C. Jensen, and E. G. Neuzil, in *Proceedings of the Second United Nations International Conference on the Peaceful Uses of Atomic Energy, Geneva, 1958* (United Nations, Geneva, 1958), Vol. 15, p. 452.
[8] E. F. Neuzil, Ph.D. thesis, University of Washington, 1959 (unpublished).
[9] W. J. Nicholson, Jr., Ph.D. thesis, University of Washington, 1960 (unpublished).
[10] T. T. Sugihara, J. Rocsmer, and J. W. Meadows, Jr., Phys. Rev. **121**, 1179 (1961).
[11] R. Vandenbosch and J. R. Huizenga, Phys. Rev. **127**, 212 (1962).
[12] J. R. Huizenga, R. Chaudhry, and R. Vandenbosch, Phys. Rev. **126**, 210 (1962).

mined by weighing before and after the deposition of the lead, and after all excess gold foil had been trimmed away from the lead deposit.

Gold foil was used as the backing material for the Pb^{204} target for several reasons. The small amount of enriched Pb^{204} which was available precluded the radiochemical processing of the target foil itself; one target foil would have to suffice for several experiments. It was, therefore, necessary to catch the fission fragments recoiling from the target foil by bombarding it between aluminum foils and chemically processing only the latter. In order to minimize the loss of the fission fragments which stop in the backing foil, it was important to use something which was thin, heat resistant, and had the lowest stopping power for fission fragments. Thin gold foil seemed to fit these requirements best. Unfortunately, the proportions of gold to Pb^{204} were such that fission of the gold made a significant contribution, of the order of 20%, to the observed fission product yields. We later discovered that the subtractions which were necessary to correct for the fission contributions from gold introduced a greater uncertainty in the fission yields of Pb^{204} than we would have liked.

In order to have some idea of the fraction of the fission fragments which were stopped by this target foil, a Pb^{206} target 2.55 mg/cm^2 thick plated on gold foil was bombarded between two aluminum foils. Each aluminum foil and the target foil was processed separately for Y^{93}. The relative amounts of Y^{93} observed in the front and back catcher foils and in the target foil itself were 9.0, 8.7, and 5.4, respectively. The 23% retention of Y^{93} by the target in this experiment probably is greater than the retention which occurred in the Pb^{204} target foils, because the latter had much thinner (about 0.7 mg/cm^2) deposits of lead than in this experiment. Probably something like a 15% retention of fission products was present in the Pb^{204} targets. The rather low retention of fission fragments is partly the result of the anisotropic emission of the fragments which is predominantly in the forward and backward direction with respect to the helium ion beam and normal to the target foil. Neglecting the fragments retained in the target foil probably has a negligible effect on the results.

The sample of Pb^{206} was a 1-lb brick of radiogenic (uranium) lead. The material contained extremely minute amounts of 19.4-yr Pb^{210} and its daughter products Bi^{210} and Po^{210}. As might be expected from its origin, the sample contained also minute amounts of uranium impurity the fission of which was sufficient to mask any fission which might be induced in the Pb^{206} itself. Consequently, a portion of the sample was purified by zone-refining. The purity of the refined material was checked by bombarding a portion of it with 43-MeV helium ions and isolating Ba^{139} from the bombarded material. The absence of detectable amounts of this uranium fission product proved that the uranium impurity level had been reduced to a negligible value.

The purified material was made into an electroplating solution from which targets were prepared by electrodeposition on 2.6-mg/cm^2 gold foil. Because of the plentiful supply of enriched Pb^{206}, several mg were plated onto each target foil and the entire target with its aluminum catcher foils was processed radiochemically for the fission products. Because of the higher ratio of Pb^{206} to gold in this target compared with the Pb^{204} targets, the contribution of gold fission to the total observed fissions was much smaller.

For bombardment, the target foil with its aluminum catcher foils was clamped to a water-cooled aluminum target plate placed in the external 43-MeV helium-ion beam of the University of Washington 60-in. cyclotron. The aluminum catcher foils and covering foil degraded the beam to an average energy in the target of 41.9 MeV. The beam current incident upon the target plate was measured by a microammeter and current densities as high as 3.5 μA/cm^2 caused no visible damage to the targets.

Following the bombardment, the target sandwich, or the aluminum catcher foils only in the case of Pb^{204}, was analyzed radiochemically for selected fission products. Standard radiochemical procedures were used,[13] modified slightly to allow for the presence of aluminum, gold, or lead in the solution. Hold-back carriers of Hg and Tl were added to minimize possible radioactive contaminants of these elements arising from activation of the gold foil in the targets.

The fission product Y^{93} was isolated in every experiment, serving as an internal standard to which the fission yields of the other fission products were normalized. Each purified element was precipitated in some suitable form, filtered onto a small filter paper, dried, and weighed to determine chemical yield. The samples were then mounted on Scotch tape and covered with thin (2 mg/cm^2) polystyrene foil. Each sample was counted in one of a set of four end-window Geiger-Müller counters with nearly identical shelf assemblies. Slight differences in the detection efficiencies between counters were measured with a Pb^{210} standard source. The decay curves were plotted and analyzed in the usual way, and the half-lives of the component species always agreed closely with the values for known fission product species of the elements being counted. Saturation counting rates for each species were computed from counting rates extrapolated to the end of bombardment. Corrections for absorption of the radiations by air, polystyrene, and counter window; and for scattering by Scotch tape, filter paper, polystyrene, air, and counter housing were made from data of Pappas.[14] Sample absorption and scattering corrections were made according to the curves of Nervik and Stevenson.[15]

[13] *Radiochemical Studies: The Fission Products*, edited by C. D. Coryell and N. Sugarman, National Nuclear Energy Series Div., IV, Vol. 9. (McGraw-Hill Book Company Inc., New York, 1951).
[14] A. C. Pappas, MIT Tech. Rept. No. 63, 1953 (unpublished).
[15] W. E. Nervik and P. C. Stevenson, Nucleonics **10**, No. 3, 18 (1952).

Tabulated[16] energy values for the radiations were used in making counting corrections.

After subtracting the estimated contribution from fission of the gold backing foil, in the case of the lead targets, the yields of each species were calculated relative to an arbitrary 10% yield for Y^{93} and were assumed to represent the total fission yield of that mass number. In the absence of any information on nuclear charge distribution in these elements at these energies, no attempt was made to correct the observed yields for the yields of unobserved species formed closer to the stable isobar of the fission product chain. It is believed that such corrections will be small, probably less than 20%. The resulting data were then plotted vs mass number of each measured fission product. The yields of corresponding complementary fragments were determined in the usual way by assuming a reasonable value of ν, the number of neutrons emitted during the fission raction. The "best" smooth curve was then drawn through the points and the yield values along this curve were summed and renormalized to give a total yield of 200%, as is customary in fission yield curves.

Because the Pb^{204} target is only 39% Pb^{204}, the remaining 61% being heavier lead isotopes, principally Pb^{206}, the question arises about the contributions to the observed yields with the Pb^{204} target from these several isotopes. To give a complete answer to this question it would be necessary to know both the mass distributions of each isotope in the target along with their relative fissionabilities. Fortunately, it turned out that Pb^{204} was considerably more fissionable than Pb^{206}, the principal "impurity" isotope in the target. The fissionabilities and abundances of Pb^{207} and Pb^{208} are sufficiently less than the Pb^{204} in the Pb^{204} target that the observed fission product yields are predominantly from Pb^{204}. This conclusion is based on the following experimental data.

Samples of enriched Pb^{207} and Pb^{208} were available for making targets. However, since the measurement of a fission yield curve is a very time-consuming task, for these heavier lead isotopes it was decided to measure the fission yield of only one fission fragment, namely Y^{93}. The mass yield curve for Bi^{209} bombarded with 22-MeV dueterons, equivalent to Pb^{207} bombarded with approximately 37-MeV helium ions, had previously been shown to be narrow and symmetric. We would, therefore, be reasonably safe in assuming Pb^{207} and Pb^{208} bombarded with 41.9-MeV helium ions would also be narrow and symmetric, and the only question was how much they would contribute to the mass yields in the Pb^{204} target.

Targets of each of the four enriched lead isotopes were bombarded with 41.9-MeV helium ions and the cross-sectional yields for formation of Y^{93} were determined radiochemically. From the knowledge of the isotopic composition of each target (Table I) it was possible to solve four simultaneous equations in four unknowns for the formation cross section of Y^{93} of each of the four lead isotopes separately. These cross sections were determined in this manner to be the following: Pb^{204}, 3.4×10^{-28} cm^2; Pb^{206}, 4.9×10^{-29} cm^2; Pb^{207}, 9.2×10^{-29} cm^2; Pb^{208}, 1.5×10^{-29} cm^2. It should be pointed out that the Q values for the formation of the compound nuclei are different in the four cases. Hence the excitation energies are different, and since fissionability is a function of excitation energy a meaningful intercomparison of the cross sections to determine the relative fissionabilities is not readily made. However, this is a separate problem from the one under consideration here.

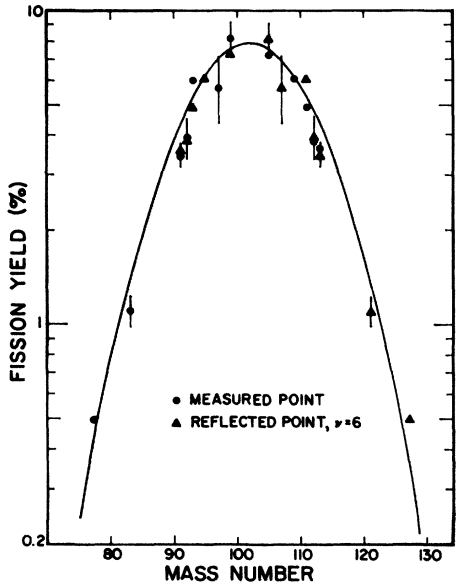

FIG. 1. Mass-yield curve for the fission of Pb^{206} bombarded with 41.9-MeV helium ions. The curve drawn through the data is Gaussian in shape with a full width at half-maximum of 24 mass units.

By multiplying these cross sections by the abundances of the isotopes in the sample of enriched Pb^{204}, given in Table I, it follows that about 82% of the observed Y^{93} from the enriched Pb^{204} target comes from fission of Pb^{204} with the remainder contributed about equally by Pb^{206} and Pb^{207}. We may conclude, therefore, that the fission yields observed for the Pb^{204} target are predominantly those of Pb^{204}.

III. RESULTS AND DISCUSSION

The renormalized fission yields are plotted in Figs. 1–3 for Pb^{206}, Pb^{204}, and Au^{197} targets, respectively. Evidently, fission in these cases is of the symmetric type similar to that of bismuth bombarded with deuterons. However, there is one notable difference between them in regard to the widths of the mass distributions. While the scatter of the points in Figs. 2 and 3 make somewhat

[16] D. Strominger, J. M. Hollander, and G. T. Seaborg, Rev. Mod. Phys. **30**, 585 (1958).

TABLE II. Observed widths of mass distribution curves for a variety of target elements and bombarding particles.

Target	Projectile	C.N.	$E_{C.N.}$*	E_f[a]	$E_{S.P.}$*	$W_{1/2}$	Reference
Au^{197}	25.5-MeV He^3	Tl^{200}	35.9	19.4	16.5	22.9±0.6	b
Au^{197}	42-MeV He^4	Tl^{201}	40.2	19.6	20.6	30	c
$Tl^{203,205}$	25.5-MeV He^3	$Bi^{206,208}$	~35	~21	~14	21.9±0.6	b
Pb^{204}	42-MeV He^4	Po^{208}	35.7	16.7	19.0	27	c
Pb^{206}	25.5-MeV He^3	Po^{209}	32.6	18.2	14.5	20.6±0.6	b
Pb^{206}	42-MeV He^4	Po^{210}	35.7	19	16.7	24	c
Bi^{209}	36-MeV H^1	Po^{210}	41	19	22	18	10
Bi^{209}	22-MeV H^2	Po^{211}	27	17	10	17	6
Bi^{209}	25.5-MeV He^3	At^{212}	30.6	15	15.6	21.3±0.6	b
Bi^{209}	22.1-MeV He^3	At^{212}	27.2	15	12.2	19.8±0.6	b
Bi^{209}	43-MeV He^4	At^{213}	33.2	15.8	17.4	25	11
Ra^{226}	10.5-MeV H^1	Ac^{227}	15.2	5.9	9.6	17	2
Ra^{226}	21.5-MeV H^2	Ac^{228}	29.3	6.2	23.1	30	2
Ra^{226}	14.5-MeV H^2	Ac^{228}	22.3	6.2	16.1	24	2

[a] Computed using Eq. (8) of reference 16.
[b] H. C. Britt, H. E. Wegner, and J. Gursky (unpublished). Private communication from H. C. B. A Gaussian shape is assumed in fitting these mass-distribution curves, obtained by pulse height analysis.
[c] This work.

arbitrary the choice of the best curve to fit the data, nevertheless the mass distributions in these two cases appear to be somewhat wider than in the case of Pb^{206}, Fig. 1. In all three cases the curves, as drawn, are Gaussian in shape. The widths of the curves at half maximum are 24, 27, and 30 mass units for Pb^{206}, Pb^{204}, and Au^{197} targets, respectively. All three are significantly wider than the mass-yield curve for bismuth bombarded with 22-MeV deuterons where a width at half-maximum of 17 mass units was found.

The explanation of the variation in the widths of the mass distribution curves of nuclides which fission in the symmetric mode probably lies in the excitation energy available to the fissioning nucleus. It seems reasonable to suppose that with increasing excitation energy the less-favored, more asymmetric mass splits would become more probable, that is the mass-distribution curve would widen.

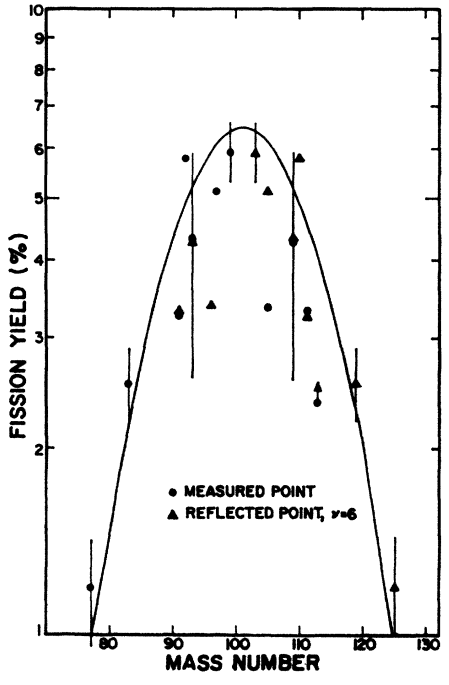

FIG. 2. Mass-yield curve for the fission of Pb^{204} bombarded with 41.9-MeV helium ions. The curve drawn through the data is Gaussian in shape with a full width at half-maximum of 27 mass units.

In support of this hypothesis, we present in Table II an analysis of the widths of a number of mass distribution curves for fission in the symmetric mode. This includes not only the cases of pure symmetric fission, but also those cases involving fission of actinium compound nuclei where both symmetric and asymmetric fission are present as apparently separate fission modes. Here the widths refer only to the symmetric mode. Table II also lists the estimates of the excitation energies of the compound systems at the saddle point. The latter is a quantity which can be calculated from the excitation energy of the compound nucleus and the fission threshold energy. Fission excitation functions have been used to determine a number of fission threshold energies and these have been used by Huizenga, Chaudhry, and Vandenbosch[12] to derive an empirical equation for fission threshold energies which is probably accurate to 1 to 2 MeV.

The data of Table II are plotted in Fig. 4. It is seen that with one exception the data cluster rather closely about a straight line, which suggests a real connection between the widths of the mass distribution and the excitation energy available at the saddle point. Over the excitation energy interval 10 to 23 MeV the widths are represented by the empirical equation

$$W_{1/2}=E_{S.P.}*+7, \quad (1)$$

where $W_{1/2}$ is in mass units and $E_{S.P.}*$ is in MeV.

The exceptional datum which does not appear to follow the trend of the other points is that[10] of 36-MeV proton bombardment of Bi^{209}. For the cases given in Table II it is assumed that fission follows the formation of a compound nucleus. However, in this particular case the excitation energy of the compound system is

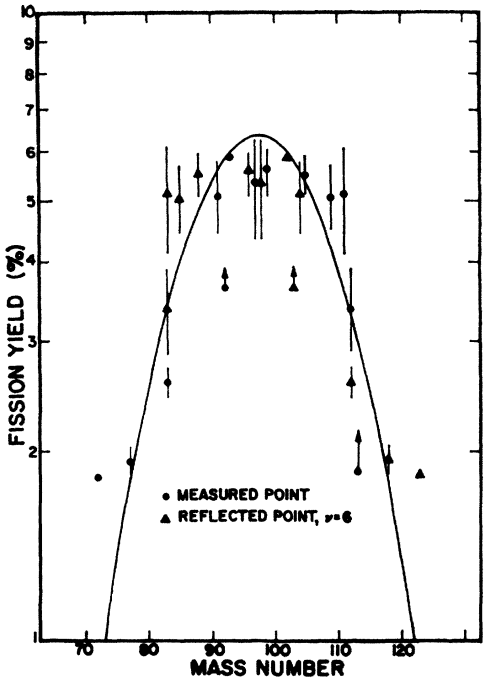

FIG. 3. Mass-yield curve for the fission of Au^{197} with 41.9-MeV helium ions. The curve drawn through the data is Gaussian in shape with a full width at half-maximum of 30 mass units.

41 MeV and a width of 29 mass units would be expected on the basis of the trend exhibited by the other data. The observed width of about 18 mass units is very narrow implying a lower excitation energy of the nucleus which undergoes fission. A possible explanation for the discrepancy may be that most of the observed fission does not follow the formation of a compound nucleus. If indeed most of the initial interactions of the incident 36-MeV protons are direct, such as the (p,n) reaction, the observed result would be consistent with an initial direct interaction in which an 8-MeV neutron is directly ejected and the residual nucleus which is left, and which may subsequently fission, has about 30 MeV of excitation energy.

It would be of interest to find a theoretical explanation for the result expressed by Eq. 1. One of the simplest approaches is to start from the statistical theory of fission[17] where the relative yields of two fission products m and n would be expected to be of the form

$$Y_m/Y_n \sim \exp[\Delta E_{m,n}/T]. \quad (2)$$

Here $\Delta E_{m,n}$ is the difference in the energy release between the two different mass splits, and T is the nuclear temperature.

A Gaussian mass-yield curve, on the other hand, implies that the relative yields are of the form

$$Y_m/Y_n \sim \exp[-f(A_m,A_n)/aW_{1/2}^2], \quad (3)$$

[17] P. Fong, Phys. Rev. **102**, 434 (1956).

where A_m and A_n are the mass numbers of the fission fragments. Comparison of these two expressions leads to the conclusion that $W_{1/2}^2$ should vary with T, and as T is usually taken to be proportional to the square root of the excitation energy, we have the expectation that $W_{1/2}$ should vary as $E^{*1/4}$. This is a very much less steep dependence on excitation energy than the one which is observed, even allowing for the possibility that the relevant excitation energy which determines the mass distribution is not that of the system at the saddle point but rather the excitation energy at the moment of scission. We conclude that this simple statistical model approach does not account for the observed widths of the mass distribution curves.

At the moment the result summarized in Eq. (1) remains an empirical observation for which we have no good theoretical explanation. Perhaps the correlation is just an accident. We have included only those data were formation of a compound nucleus is reasonably certain. We have not included a few results from higher energy bombardments where the fissioning nucleus and its excitation energy is not well known. It would seem to be desirable to obtain more experimental results, particularly in the region below 10 MeV excitation energy. However, in this energy region the results will be difficult to obtain because the cross section for fission of the elements which fission in the symmetric mode fall off very rapidly with decreasing energy. Experi-

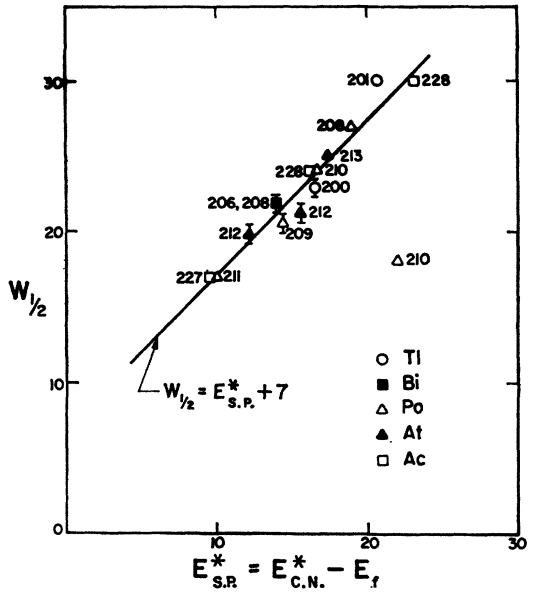

FIG. 4. Observed widths at half-maximum (in mass units) vs excitation energy (in MeV) of the fissioning nucleus at the saddle point. The uncertainties in the measured widths, except where they are shown explicitly, are about 1 mass unit; in the energies, owing to the uncertainties in the fission threshold energy, E_f, 1 to 2 MeV. The numbers refer to the mass number of the nucleus which fissions.

ments in the region of the higher excitation energies will be complicated by the fact that they will involve bombarding particles and energies where compound nucleus formation is in doubt. Furthermore, at the higher excitation energies contributions from second chance fission may become important and the results will therefore become more difficult to unfold. It is perhaps easier to turn attention to other target elements other than those listed in Table II to see if they continue the trend which has been observed so far. Further work along these lines is in progress.

IV. ACKNOWLEDGMENTS

We wish to thank T. D. Morgan and the crew of the cyclotron for assistance with the bombardment. We are indebed to Professor I. Halpern and Professor L. Wilets for helpful discussions.

PHYSICAL REVIEW VOLUME 129, NUMBER 6 15 MARCH 1963

Angular Distribution of Fragments from Fission Induced by Heavy Ions in Gold and Bismuth*

VICTOR E. VIOLA,† JR., T. DARRAH THOMAS,‡ AND GLENN T. SEABORG§
Lawrence Radiation Laboratory, University of California, Berkeley, California
(Received 17 September 1962)

We present the results of measurements of the angular distribution of fission fragments produced by irradiation of Au^{197} and Bi^{209} with various heavy ions. The projectiles, B^{11}, C^{12}, N^{14}, and O^{16}, had energies from a few MeV above the Coulomb barrier to 10.4 MeV per nucleon. The gross features of these results can be explained by use of a model and parameters that have been used by others to account for angular distributions of fission fragments from helium-ion bombardments. In detail, however, these results appear to indicate that the models used to predict the average value of the angular momentum of the compound nucleus give values too low near the Coulomb barrier. Furthermore, at high bombarding energies it is necessary to consider the fact that appreciable direct interaction is taking place.

I. INTRODUCTION

THE development of heavy-ion accelerators at Berkeley and at Yale has made it possible to extend the investigation of nuclear fission reactions to compound nuclei possessing large amounts of excitation energy and total angular momentum. Studies of charged-particle-induced fission at lower energies have established that fission-fragment angular distributions are related to the spin orientation and Z^2/A of the fissioning species.[1–3] Heavy ions have been shown to substantially enhance these effects.[4–6]

Consideration of the energy and spin states of the stably deformed nuclei led Bohr to propose a model that has been successful in explaining the anisotropies observed in low-energy fission.[7] Halpern and Strutinski[8] and, independently, Griffin[9] have extended this theory to describe fission at higher energies. Interpretation of results from both heavy-ion-induced and helium-ion-induced fission studies has shown that the theory provides a reasonable model for the explanation of such reactions.

We have attempted to amplify and extend the results from earlier studies of angular distributions in heavy-ion fission. In particular, we have studied differences in

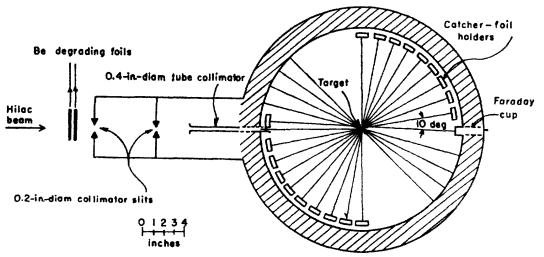

FIG. 1. Diagram of angular-distribution chamber.

* Work done under the auspices of the U. S. Atomic Energy Commission.
† Present address: CERN Laboratories, Geneva, Switzerland.
‡ Present address: Frick Chemical Laboratory, Princeton, New Jersey.
§ Present address: U. S. Atomic Energy Commission, Washington 25, D. C.
[1] I. Halpern and C. T. Coffin, Phys. Rev. **112**, 536 (1958).
[2] R. Vandenbosch, H. Warhanek, and J. R. Huizenga, Phys. Rev. **124**, 846 (1961).
[3] R. Chaudhry, R. Vandenbosch, and J. R. Huizenga, Phys. Rev. **126**, 220 (1962).
[4] *Proceedings of the Second Conference on Reactions Between Complex Nuclei, Gatlinburg, Tennessee*, edited by A. Zucker, E. C. Halbert, and F. T. Howard (John Wiley & Sons, Inc., New York, 1960), pp. 201–235.
[5] G. E. Gordon, A. E. Larsh, T. Sikkeland, and G. T. Seaborg, Phys. Rev. **120**, 1341 (1960).
[6] H. C. Britt and A. R. Quinton, Phys. Rev. **120**, 1768 (1960).
[7] A. Bohr, in *Proceedings of the International Conference on the Peaceful Uses of Atomic Energy, Geneva, 1955* (United Nations, New York, 1956), Vol. 2, p. 151.
[8] I. Halpern and V. Strutinski, in *Proceedings of the Second United Nations International Conference on the Peaceful Uses of Atomic Energy* (United Nations, Geneva, 1958), Vol. 15, p. 408.
[9] J. J. Griffin, Phys. Rev. **116**, 107 (1959).