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Angular Distributions in Fission Induced by Alpha Particles, Deuterons, and Protons*

C. T. Coffin† and I. Halpern‡
Physics Department, University of Washington, Seattle, Washington

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Protons of 11 Mev, deuterons of energies up to 22 Mev, and alpha particles of energies up to 43 Mev were used to study fission fragment angular distributions in the following targets: Bi^{209}, Ra^{226}, Th^{232}, U^{238}, U^{235}, Np^{237}, and Pu^{239}. All of the measured distributions were qualitatively similar in that more fragments were emitted forward and backward along the beam direction than sideways. The largest ratios of 0° to 90° differential cross sections were slightly greater than 2 and were obtained in the alpha-particle bombardments. The smallest ratios occurred in the proton bombardments. If one decomposes the fissions observed at a given bombarding energy into symmetric and asymmetric mass components, the anisotropy for each component decreases smoothly as the value of Z^2/A of the compound nucleus increases. The asymmetric anisotropies are larger than the symmetric ones. There is no observable effect of the value of the target spin on the observed anisotropies. It is pointed out that some of the observed features of the anisotropies may be accounted for in terms of the fact that some of the fissions occur only after the evaporation of neutrons.

I. INTRODUCTION

ANGULAR distributions of the fragments in fission have been studied with a number of different bombarding particles at many energies.[1–5] Usually the bombarding energy was low enough to insure that the energy and angular momentum brought in by the incident particle were shared by the entire nucleus. In these experiments, the qualitative character of the observed angular distributions seems to be understandable in terms of the conservation of angular momentum. For example, in photoinduced fission, more fragments come off at right angles to the beam than along it[1]; in particle-induced fission, on the other hand, the fragments tend to come off forward and backward along the beam.[6] These observations suggest that the orbital angular momentum between separating fragments is to some degree lined up with the angular momentum contributed by the incident particle. It is not possible to make *quantitative* predictions about the expected degree of lineup without making some specific assumptions about the nuclear structure. Yet any nuclear model in which the orbital angular momentum between fragments is given a reasonable share of the angular momentum contributed by the incident particle would lead to distributions having the qualitative character of those observed. It follows that if measurements of fission angular distributions are to prove useful for examining models of the fission process, it is necessary that both the measurements and the theoretical predictions be as quantitative as possible.

We have measured in some detail angular distributions of fragments in fissions induced in a number of heavy targets by alpha particles. The maximum energy of the alpha particles was 43 Mev and the corresponding maximum angular momentum with which such particles can strike a heavy nucleus is about 21 $\hbar$. Since it is true for most of the targets that were used, that the major fraction of the reaction cross section is the fission cross section, it must certainly be true that the compound nuclei which eventually decay by fission are originally formed in states of rather large angular momentum. It was because of the apparent close connections between angular momentum and fission angular distributions that it was considered desirable to study the distributions induced by alpha particles. Such particles bring into a reaction more angular momentum per unit excitation energy that the lighter projectiles which had been used earlier. Although the main point of this investigation was to learn something of alpha-particle-induced fission, deuteron- and proton-induced fission were studied as well. All three projectiles are readily available at the University of Washington cyclotron.

II. EXPERIMENTAL DETAILS

The fission fragments were observed with the so-called catching technique. A thin target of fissionable material placed at the center of a cylinder was struck by a well-collimated beam from the cyclotron. The beam direction was perpendicular to the cylinder axis. The fragments emitted from the target embedded themselves in foils arranged around the cylinder and the fission activity in the foils was counted after the "exposure" by conventional Geiger counters. During the course of the experiment, a number of slightly different setups were used for the exposures. For example, one

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† Now at Nevis Cyclotron Laboratory, Columbia University, New York, New York.

‡ Now at the CERN Laboratories, Geneva, Switzerland.

[1] E. J. Winhold and I. Halpern, Phys. Rev. **103**, 990 (1956).

[2] Cohen, Jones, McCormick, and Ferrell, Phys. Rev. **94**, 625 (1954); Cohen, Ferrell-Bryan, Coombe, and Hullings, Phys. Rev. **98**, 685 (1955).

[3] Brolley, Dickinson, and Henkel, Phys. Rev. **99**, 159 (1955).

[4] R. L. Henkel and J. E. Brolley, Jr., Phys. Rev. **103**, 1292 (1956).

[5] Lozhkin, Perfilov, and Shamov, J. Exptl. Theoret. Phys. S.S.S.R. **29**, 292 (1955) [translation: Soviet Physics JETP **2**, 116 (1956)].

[6] Exceptions occur at energies very close to the fission threshold. See reference 4 and L. Wilets and D. M. Chase, Phys. Rev. **103**, 1296 (1956).

setup was designed for the precise comparisons of different targets and another was made for the examination of distributions at small angles to the beam. The essential features common to all of the setups are illustrated in Fig. 1.

In a typical run the counting rate of any of the catcher foils was measurable to better than one percent. A considerable amount of time and effort was spent trying to make sure that the observed counting rates actually measured the fission activity per unit solid angle to something approaching this accuracy. In our final arrangement, polyethylene catcher foils were used whose thickness was a few times the maximum range of fission fragments. The back foils (Fig. 1) were introduced mainly to permit the subtraction of activities induced in the catcher foils by neutrons. These back foils generally had negligible activities. To maintain reproducibility to 1%, it was found necessary to cycle the exposed foils from different angles through the set of Geiger counters with a definite pattern in time. This was because the backgrounds and efficiencies differed from one counter to the next and tended to drift too much to allow us to count each foil in a single counter as one sometimes does.

The most serious difficulty in obtaining angular distributions to the desired accuracy was connected with the scattering of fragments in the fission target. The existence of scattering effects was first suspected when it was noticed that observed angular distributions depended to some extent on the orientation of the target foil with respect to the incident beam. Since scattering can be responsible for systematic errors in the measured distribution and for possible large reductions in the angular resolution of the measurement, it was decided to study the scattering in some detail. Direct scattering measurements showed that fission fragments which still possess most of their initial energy do not scatter enough to interfere with the desired accuracy of the results. The annoying dependence of the observed distribution on target orientation apparently came from those fragments that were emitted at large angles to the target foil normal. It was hoped, at first, that such fragments were not being detected in any of the setups. This was because data were not accepted at large angles to the foil normal. More specifically, it was required that for an angle to be acceptable, the maximum path length in the target foil of those fragments emitted at this angle must be less than one third of the minimum fission fragment range. (The usual thickness of fissionable plating on the target foils was about 10% of the mean fragment range.) Unfortunately it turned out that this criterion did not suffice to keep the experiment free from scattering effects. It appears that many of the fragments emitted at angles near 90° to the foil normal are slowed down enough on their long paths in the target so that they scatter very easily through large angles. Some of these fragments were being scattered into angles where "acceptable" catcher foils were located. It was possible to eliminate these slow scattered fission fragments by placing thin covers of Mylar or collodion over the catchers. Figure 2 shows a typical distribution of activity as a function of depth in a catcher foil. These results were obtained with a stack of very thin collodion foils. The very shortest range of fission fragments is about 1.0 mg/cm^2. The small amount of activity appearing at shorter distances is presumably largely due to the slow scattered fragments mentioned above. This spurious "short-range" activity was observed to be somewhat larger at forward angles than at backward angles. This is consistent with the expectation that in addition to fission fragments there would appear in the forward hemisphere some radioactive recoils from nuclear reactions. They would also have very short ranges. All of the data to be described were obtained with 0.8 mg/cm^2 collodion or Mylar covers over the catchers. A check was made to establish that no spurious activities get through such covers by making a run which differed from a normal run only in that the aluminum target foil was not plated with a fissionable material. In this run, the catchers remained inactive.

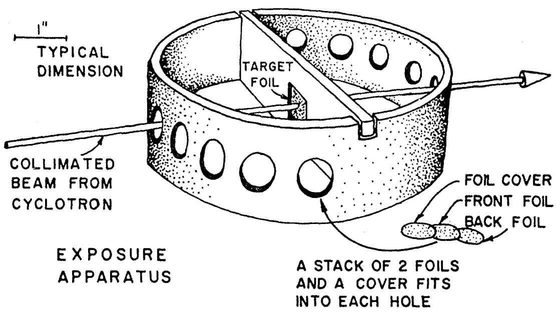

FIG. 1 A typical arrangement for measuring fission fragment angular distributions with the catching technique. The need for back foils and cover foils as well as catcher foils is explained in the text.

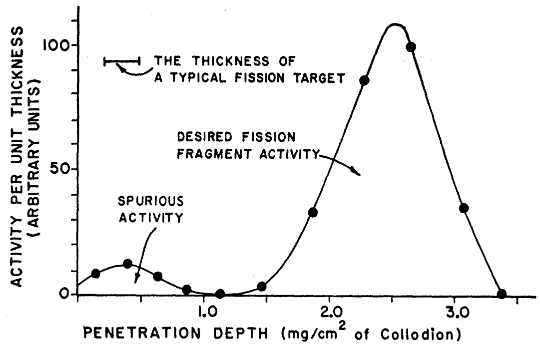

FIG. 2. The distribution in range of fission fragment activities observed at 10° to the beam.

A final check to demonstrate that it was both safe and proper to use the covering foils was made in a special apparatus constructed for the purpose. This apparatus was like that of Fig. 1 except that it was smaller and could be rotated at a uniform rate about the cylinder axis. The rotating apparatus was placed in a strong flux of fast neutrons produced by the cyclotron and the catcher activities were measured after exposure. Because of the rotation, one expects an isotropic activity distribution. The measured distribution proved to be isotropic to within $\frac{1}{2}\%$ at angles within 45° to the target foil normal. In the measurements to be described, data were taken only within such angles. It was, of course, still possible to measure activities at any angle *to the beam* by properly orienting the target foil with respect to the beam.

The measurements to be described consist essentially of three parts: (1) a measurement with good angular resolution of an angular distribution in just one target, (2) a comparison of angular distributions in several targets, and (3) an investigation of the energy dependence of angular distributions.

III. MEASUREMENT OF AN ANGULAR DISTRIBUTION WITH GOOD RESOLUTION

Thorium was chosen as the target for the detailed study of an angular distribution and 43-Mev alpha particles were used as the bombarding particles. The general purpose of the measurement was to see to what extent the large average angular momentum brought in by the alpha particles appeared in the fission fragment distribution.

The following simple classical model is useful for letting one see qualitatively what sort of distribution to expect.[7] We asume that the target nucleus is a sphere and that it is not rotating (that is, that the original angular momentum of the target nucleus is negligible compared to the angular momentum brought in by the alpha particles). The incident alpha particle joins the nucleus and sets it rotating about an axis perpendicular to the plane of its trajectory. The nucleus is assumed to rotate through many revolutions and then to break up like a flywheel in the plane perpendicular to the rotation axis. In this plane the fragments come off at all angles with equal probability, so that $dN/d\theta$ is a constant, where θ is the angle between a fragment direction and the original direction of the incident particle. In three dimensions, one would observe the number of fragments per unit solid angle, $dN/\sin\theta d\theta$, which would consequently be proportional to $(\sin\theta)^{-1}$. This angular distribution peaks very sharply in the forward and backward directions.

Were the major fraction of the "input" angular momentum to feed into the orbital momentum between fragments, one would expect the fragment distribution to resemble that of this very simple classical model. This is more true of the alpha-particle bombardments than of the bombardments with lighter particles. The alpha particles bring in angular momenta with a maximum l value of about 21 which is close (as such considerations go) to the classical maximum l, which is infinity.

The results of a number of measurements are given in Fig. 3. Some of the plotted data actually refer to points taken at angles π-θ instead of θ. After appropriate corrections for the center-of-mass motion of the struck nucleus (see Sec. VII), the backward and forward data overlap reasonably well showing the expected front-to-back symmetry. The dashed curve, which has been drawn in for reference, is the angular distribution, $(\sin\theta)^{-1}$, for the classical or "flywheel" model. It is seen that although the anisotropy in the observed angular distribution is fairly large, the distribution is not nearly so sharp as that of the model.

The difference between the two distributions can be seen in more detail if they are analyzed in terms of Legendre polynomials. Since both distributions are symmetrical about 90°, only P_n's of even n appear in the analyses. The observed distribution is

$$W(\theta)=1+0.37P_2+0.07P_4+0.04P_6+\cdots,$$

where the estimated errors in the coefficients of P_2, P_4, and P_6 all happen to be about ±0.02. The analysis of $(\sin\theta)^{-1}$ gives

$$1+1.25P_2+1.27P_4+1.27P_6+\cdots.$$

It is seen that the higher angular momentum components in the observed distribution drop off rapidly compared to those in $(\sin\theta)^{-1}$.

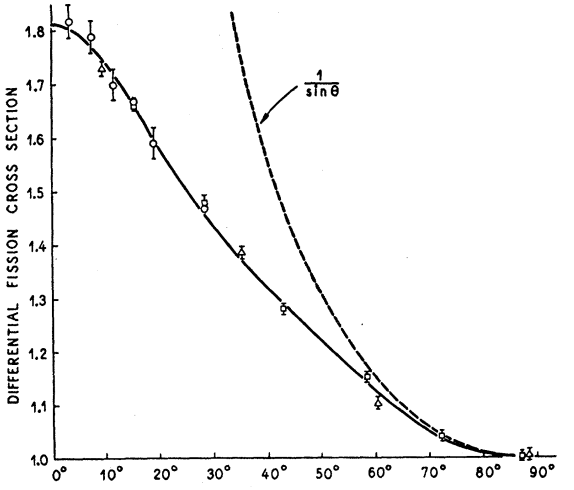

FIG. 3. The angular distribution of fission fragments from Th^{232} bombarded with 43-Mev alpha particles. The different kinds of points refer to slightly different types of experimental setpus. All of the data have been corrected for the center-of-mass motion of the fissioning nucleus. The ordinates were normalized to make the activity at 90° correspond to 1.0.

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[7] A generalization of the classical model is described by A. Bohr, *Proceedings of the International Conference on the Peaceful Uses of Atomic Energy, Geneva, 1955* (United Nations, New York, 1956), Vol. 2.

Although there is some evidence for higher values of n than $n=6$ in the data, the amounts are too small to determine. There is therefore no direct evidence for significant amounts of orbital angular momentum between the fragments greater than $3\hbar$. This number should be compared with $14\hbar$, the average angular momentum of the compound nucleus formed when 43-Mev alpha particles strike thorium nuclei.

Whatever else this difference between "input" and "output" angular momentum may mean, it implies that the average value of the vector sum of spin angular momenta of the fission fragments (and any neutrons emitted before fission) is *at least* $11\hbar$. If the neutrons do not carry away much of the "missing" angular momentum (see Sec. VII), it would suggest that fragments in high-energy fission tend to be formed with moderately large spins. This observation is consistent with the available excitation curves for the formation of high-spin fission fragments.[8]

IV. COMPARISON OF ANGULAR DISTRIBUTIONS IN A NUMBER OF TARGETS

The angular distributions from the following seven target nuclides were compared in an apparatus similar to that in Fig. 1: Pu^{239}, Np^{237}, U^{235}, U^{238}, Th^{232}, Ra^{226}, and Bi^{209}. The distributions were measured with 43-Mev alpha particles for all targets, with 22-Mev deuterons for all but the last target and with 11-Mev protons for all but the last two targets. It was not possible to examine all seven targets with deuterons and protons because the fission cross sections in the lighter targets were too small.

The apparatus used in these "comparison" studies lacked the angular resolution of the apparatus used to obtain the results of the preceding section; catchers were placed at only four angles. It was more appropriate here to analyze the distributions in powers of $\cos^2\theta$ rather than in Legendre polynomials. All but the sharpest distributions were very well reproduced by such an expansion in which only the first three terms (i.e., through $\cos^4\theta$) were included. The required coefficients were determined by a least-squares fit.

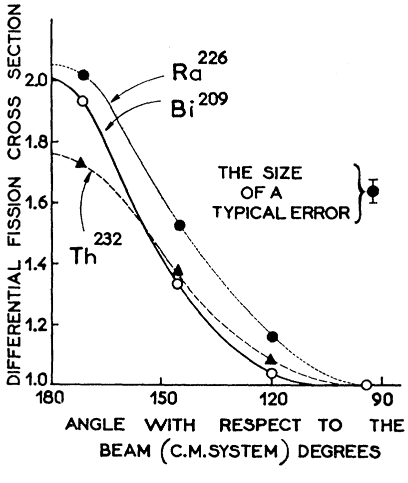

FIG. 4. Angular distributions of fission fragments from three targets bombarded with 43-Mev alpha particles. The difference between the curve for thorium given here and that in Fig. 3 is explained in the text.

TABLE I. Anisotropies for alpha-particle-, deuteron-, and proton-induced fission.

Target nucleus	Projectile 43-Mev alpha particle	 22-Mev deuteron	 10-Mev proton
Pu^{239}	1.37±0.03	1.17±0.04	1.03±0.03
Np^{237}	1.40±0.03	1.19±0.04	1.05±0.03
U^{235}	1.44±0.03	1.21±0.04	1.09±0.03
U^{238}	1.54±0.03	1.25±0.04	1.07±0.03
Th^{232}	1.76±0.03	1.42±0.04	1.12±0.03
Ra^{226}	2.04±0.05	1.28±0.04	
Bi^{209}	2.02±0.07		

A few of the distributions observed with 43-Mev alpha particles are illustrated in Fig. 4. The differences in the shapes of the distributions observed with different targets were generally quite small. It is therefore probably most meaningful as well as most convenient to compare the distributions with respect to their anisotropies alone. By "anisotropy" we mean the ratio of the cross section at 0° or 180° to the beam (corrected for center-of-mass motion) to the cross section at 90°. (This is presumably the ratio of the maximum to the minimum differential cross section.) It was in order to determine the appropriate cross sections at 180° and 90° that the measured distributions were analyzed in powers of $\cos^2\theta$.

The anisotropies computed from the data in this way are given in Table I. The estimated errors are also incuded in the table. They indicate the extreme values the anisotropy can have if the distribution is to be of the assumed form and is to pass within a standard deviation of each data point.

It must be pointed out that the anisotropy determined for 43-Mev alpha particles on thorium by the procedure just described (Fig. 4 or Table I) is about 3% smaller than that implied by the more complete data of Fig. 3. The difference indicates the presence of some relatively high harmonics in (at least) the thorium distribution which cannot be detected without data at rather small angles to the beam.

It is seen from Table I that the alpha particle anisotropies are larger than the deuteron anisotropies which in turn are larger than the proton anisotropies. This feature of the data is consistent with expectations based on the angular momenta of the projectiles.

The alpha particle and deuteron anisotropies are plotted in Fig. 5 as a function of Z^2/A for the compound nucleus formed. As usual, Z is the nuclear charge and A

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[8] H. G. Hicks and R. S. Gilbert, Phys. Rev. 100, 1286 (1955); W. F. Biller, University of California Radiation Laboratory Report UCRL-2067 (unpublished).

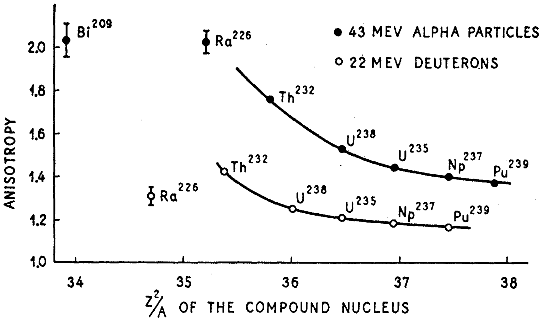

FIG. 5. The observed anisotropies (essentially 0° to 90° ratios of fission fragment activities) plotted as a function of Z^2/A of the compound nucleus. The points are labelled according to the target nucleus. Those estimated probable errors that are not drawn in are about 2% for alpha-particle bombardments and 3% for deuteron bombardments.

is the mass number. It should be admitted that we are aware of no clear *a priori* reason to expect that Z^2/A should be a particularly significant parameter in these experiments. But since it was introduced in the liquid drop model for fission, this parameter has very often been used to characterize fissioning nuclei which are being compared with regard to some feature of the fission process. Generally such features seem to depend in a regular way on Z^2/A, especially if they have to do with fission at low excitation energies.

It is seen in Fig. 5 that except for the radium and bismuth points, the anisotropies vary quite regularly with Z^2/A. Radium presents a strange anomaly. For fission with alpha particles, its anisotropy is larger than that of thorium. For fission with deuterons it is smaller.

This anomaly can be explained along the following lines. The anisotropy is known to be correlated with the asymmetry in the mass distribution, the more asymmetric fragments coming off with greater anisotropies.[2,9] The mass distribution in the deuteron fission of radium[10] has been found to be essentially symmetric. Presumably that in the alpha particle fission of bismuth is also symmetric.[11] It is for this reason that the corresponding anisotropies are low compared to those for the heavier targets with the same projectiles. One can, in fact, decompose the curves for anisotropy *versus* Z^2/A into asymmetric and symmetric components with the curve for each mass component varying monotonically with Z^2/A. The asymmetric curve lies higher. That is, the asymmetric component has the larger anisotropy at all values of Z^2/A.

Unfortunately it is not possible, on the basis of available data to tell precisely how much higher the asymmetric component lies.

Along the preceding lines it is possible to eliminate the problem of the "radium anomaly" by re-expressing it in terms of two other problems. These are the problems of accounting for the mass-angle correlation and for the smooth decrease of the anisotropy (for either mass component) with increasing Z^2/A. Both these questions are considered in Sec. VII.

V. DEPENDENCE OF ANISOTROPY UPON INCIDENT ENERGY

The energy dependence of the fission fragment anisotropies was investigated in only two targets, Th^{232} and Np^{237}. These particular targets were selected from the seven targets available (Sec. IV) because they differ as much as any two of them in properties that might be expected to influence the angular distributions. Th^{232} has an even number of protons, Np^{237} an odd number. The two nuclides are also fairly well separated in Z^2/A and consequently their anisotropies are significantly different. Both targets have large enough fission cross sections to permit angular distribution measurements over a considerable range of incident energy.

Measurements were made with an apparatus like that of Fig. 1 down to energies of about the height of the Coulomb barrier for the incident particles. The beam was degraded by being passed through some copper foils. The results (Fig. 6) for thorium and neutunium were quite similar and so it was considered unnecessary to investigate the other targets. The anisotropies increase very slowly with increasing energy.

With the help of the curves in Fig. 6 and the data of Table I, it is possible to estimate the anisotropy that one would observe in the alpha particle fission of U^{235} at 37 Mev. This estimate is of interest because the same compound nucleus is formed (at the same excitation energy) in the bombardment of Np^{237} with 22-Mev deuterons. The estimated anisotropy in $\alpha+U^{235}$ is 1.38 whereas the corresponding (measured) anisotropy in the

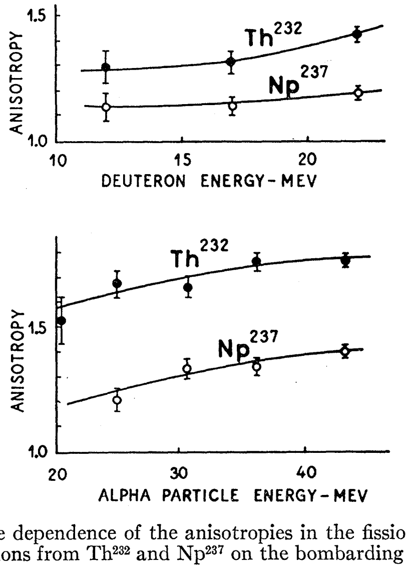

FIG. 6. The dependence of the anisotropies in the fission angular distributions from Th^{232} and Np^{237} on the bombarding energy.

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[9] Fairhall, Halpern, and Winhold, Phys. Rev. **94**, 733 (1954); M. P. Hickenlooper and A. W. Fairhall (unpublished).

[10] R. C. Jensen and A. W. Fairhall (to be published).

[11] Bismuth fission: A. W. Fairhall, Phys. Rev. **102**, 1335 (1956).

$d+\mathrm{Np}^{237}$ bombardment is only 1.19. The average "input" angular momentum in the alpha-particle bombardment happens to be about 1.7 times that in the deuteron bombardment. The simplest conclusion to be drawn from this comparison, and from similar ones that can be made from the data, is that the anisotropy increases with the angular momentum contributed by the projectile.

In pursuing the connection between anisotropy and the "input" angular momentum it is worth contrasting their dependence on the bombarding energy. Consider the alpha-particle anisotropy of Th^{232}, for example. At the left of the curve, near the top of the Coulomb barrier, the mean input angular momentum is some small number, l, times $\hbar$. (On a classical model, both the cross section and the mean angular momentum are zero when the projectile energy is just equal to the barrier height.) At the right of the curve, at 43 Mev, the incident particles strike the nucleus with a maximum value of l of 21 and an average value of 14. Thus, in contrast to the anisotropy, the input angular momentum has a strong energy dependence in the energy range of Fig. 6. A successful theory of the anisotropy will have to account as well for this apparent lack of strong connection between the anisotropy and the angular momentum as for the connections discussed earlier.

VI. ROLE OF THE TARGET SPIN

The fission fragment angular distribution in the low-energy photofission of U^{235} is isotropic whereas it is quite anisotropic in U^{238} and Th^{232}. The isotropy in U^{235} has been blamed on the large ground-state spin of this nuclide.[1,7] It is seen from Fig. 5 that, in contrast to the results in photofission, the anisotropies of the present study seem to depend smoothly on Z^2/A although the nuclei involved have spins that show strong fluctuations between adjacent points. Inasmuch as the relevance of Z^2/A is not too clear as regards the anisotropies, it seems desirable to eliminate it from considerations concerning the target spin. This can be done by comparing the anisotropies induced by maximum-energy deuterons and alpha particles in the same target. The mean angular momentum brought in by the former particles is half that brought in by the latter. In the deuteron bombardment of U^{235}, this input angular momentum is only about twice as large as the target spin, $\frac{7}{2}$.[12] One might therefore expect, in this bombardment, anomalously low anisotropy because of the random orientations of the target nuclei with respect to the beam. That is, one would expect that for a U^{235} target, the deuteron anisotropy would be smaller relative to the alpha-particle anisotropy, than it would for a target of zero spin like U^{238}.

TABLE II. Anisotropy ratios, deuteron to alpha-particle bombardments.[a]

Target nuclide	Target spin I	$I/\bar{l}_d$	A_d/A_α
Ra^{226}	0	0	0.63 ± 0.06
Th^{232}	0	0	0.81 ± 0.04
U^{238}	0	0	0.81 ± 0.04
U^{235}	$\frac{7}{2}$	0.49	0.84 ± 0.04
Np^{237}	$\frac{5}{2}$	0.35	0.85 ± 0.04
Pu^{239}	$\frac{1}{2}$	0.07	0.85 ± 0.04

[a] The symbols used have the following meanings: $\bar{l}_d\hbar=7.1\hbar$ is the average angular momentum brought in to the targets in this table by a 22-Mev deuteron. A_d is the anisotropy observed with 22-Mev deuterons and A_α is that observed with 43-Mev alpha particles.

In Table II, the ratios of deuteron to alpha-particle anisotropies are listed along with target spins for the six targets for which there are data. In interpreting the ratios listed in the table, one should probably overlook the radium entry. As we have seen (Sec. IV), the angular distributions produced by deuterons and alpha particles in radium are not really comparable in the same sense that they are in heavier targets. The remaining entries show a remarkably constant ratio. There is certainly no depression of this ratio for U^{235}.

Taken at face value, this result indicates that the target spin must be playing a very minor role in determining the anisotropy. This same point, which we have made on the basis of the data in Table II, can also be made from considerations of the energy dependence of the anisotropy. It was mentioned above that at the left of the curves in Fig. 6, the input angular momentum becomes very small. In particular, it gets to be as small as the ground state spin[13] of Np^{237}. For reasons similar to those given above, one would expect the anisotropy in Np^{237} relative to that in Th^{232} to be significantly smaller at the left end of the curves than it is at the right end. Although the data here are not so conclusive as that in Table II, it would seem that within the accuracy of the data, once again no effect of the ground-state spin is discernible. A theory of fission anisotropies will have to account for this apparent difference between photofission and particle-induced fission.

VII. IDENTIFYING THE FISSIONING NUCLEUS

In the foregoing description and discussion of results, certain general inferences were drawn without an attempt to identify the nuclei which are actually undergoing fission in each case. It would seem that before a truly quantitative theoretical account of the anisotropies at moderate energies can be give, it is necessary to know how many neutrons are evaporated, on the average, before fission, and to what extent fission occurs after so-called direct interactions rather than after the formation of a compound nucleus.

The foregoing measurements can, in principle, provide

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[12] Hutchison, Llewellyn, Wong, and Dorain, Phys. Rev. **102**, 292 (1956).

[13] Bleaney, Llewellyn, Pryce, and Hall, Phil. Mag. **45**, 992 (1954); F. S. Tomkins, Phys. Rev. **73**, 1214 (1948).

some information on the latter question. If complete amalgamation of the incident particle with the target nucleus takes place in every interaction leading to fission, then for a given bombarding energy, every fissioning nucleus has exactly the same forward momentum. From the knowledge of the average kinetic energy release in fission, one can uniquely determine the ratio of average laboratory differential cross sections at forward angles to the cross sections at corresponding angles in the backward hemisphere. In our considerations of the data, this procedure was reversed, i.e., from the forward-folding of the angular distributions we determined the mean forward momentum of the fissioning nucleus. This was done in three cases involving alpha-particle bombardments. (The forward folding effect is larger for alpha particles than for the lighter projectiles.) Th^{232} and Pu^{239} were bombarded at 43 Mev and Th^{232} was also bombarded at 30 Mev. In all three distributions, the measured mean forward momentum of the fissioning nucleus was about $25\pm12\%$ lower than that expected. The discrepancy is in the right direction to be the result of "direct interactions," i.e., reactions in which the incident particle transfers less than its full momentum to the compound nucleus. It is unlikely, however, that such reactions occur often enough to be responsible for a 25% effect.[14] It is possible that some of the discrepancy is due to counting errors. A 2% error in either the backward (or the forward) counting rates would give rise to a 12% discrepancy in the measured forward momentum of the fissioning nucleus. We may have missed some systematic error responsible for increased rates of 1 or 2% at some angles in the backward direction. At any rate, it seems to be fairly safe, in thinking about these angular distribution measurements, to ignore direct interactions and to assume that at least in the alpha-particle bombardments, all fissioning nuclei are formed originally by the complete absorption of the incident particle.

The question remains—at what excitation energies and in what nuclear species do the fissions take place? That is, how many neutrons are evaporated before fission?

One reason that it is important to try to answer this question is that the observed variation of anisotropy with Z^2/A may be due only to the variation of neutron emission probabilities with Z^2/A. This would come about in the following way. The targets with lower Z^2/A have smaller fissionabilities and therefore the fissions arising from them would tend to occur at lower excitation energies than in the heavier nuclides. That is, more neutrons would be evaporated, on the average, before fission. Now there exists very clear evidence that the anisotropy increases very strongly as the excitation is lowered by neutron evaporation. Henkel and Brolley[4] find that in the fission of Th^{232} with neutrons, the anisotropy increases sharply (from 1.1 to about 2.5) just past the threshold for fission following $Th^{232}(n,n')$. This must mean that the new group of fissions, the $(n,n'f)$ events, are very anisotropic. The fissioning Th^{232} nuclei involved in these events differ from the Th^{233} nuclei involved in the (n,f) events occurring at the same bombarding energy in at least two ways. The Th^{232} nuclei have excitation energies much closer to the fission threshold and their spin distribution is slightly smeared out (because of the neutron evaporation) compared to that of the Th^{233}. Since the latter difference would tend to reduce the anisotropy in the $(n,n'f)$ events, and the observed anisotropy happens on the contrary to be much larger, it is clear that the important effect is connected with the excitation energy. The effect is so strong that it seems almost fair to assume that generally most of the anisotropy is due to those fissions that happen to take place within a few Mev of the fission threshold. In order to estimate whether the observed decrease of anisotropy with increasing Z^2/A is due *entirely* to effects of neutron evaporation, one would need quantitative information on (1) the dependence of the anisotropy on the excitation energy above the fission threshold and (2) the dependence of the fission probability on excitation energy for all of the nuclear species involved. Unfortunately the available data on both these questions are not at present precise enough to permit one to decide whether the entire "anisotropy *versus* Z^2/A" dependence is connected with difference in neutron evaporation probabilities, or whether there must also exist some more intrinsic connection between the anisotropy and Z^2/A. A semiquantitative analysis shows that it is certainly not impossible for the entire effect in, say, the anisotropies in fission induced by alpha particles, to arise from the differences in neutron evaporation probabilities.§

In the same way, it is possible that the observed correlations between mass distributions and angular distributions are not fundamental to the fission process —but arise from fortuitous effects connected with neutron evaporation.[15] Fission taking place at lower excitation energy tends to be asymmetric in its mass distribution. We have seen that it also tends to be more

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[14] Measurements have recently been made of the mean forward momentum of the fragments in alpha-particle fission by a more direct method than that described here. To within a few percent the measured momentum is that expected if the incident alpha particle is completely amalgamated to the target nucleus. [W. J. Nicholson (unpublished)].

§ *Note added in proof.*—A recent paper (Contribution P/1513, Second United Nations International Conference on the Peaceful Uses of Atomic Energy, Geneva, by I. Halpern and V. M. Strutinski) provides a fairly quantitative account of a number of observations discussed in the present paper. Among the observations considered there are the dependences of the anisotropy on Z^2/A, target spin and bombarding energy. A reasonable account is also given of the observed correlation between the mass and angular distributions.

[15] It was pointed out in reference 1 that the correlation between mass and angle observed in photofission may similarly arise from the fact that not all fissions occur at the same excitation energy. In this case it is the use of a continuous bremsstrahlung spectrum that is responsible for the spread in excitation energy at fission.

anisotropic than fission at higher excitation energy. These two effects may be entirely unconnected and yet, in any bombardment, they would be responsible for an observable correlation between mass and angular distributions. The fissions taking place before much neutron emission would be rather symmetric and isotropic; those occurring later would be asymmetric and anisotropic. Here again a semiquantitative analysis shows that it is not impossible that the observed correlations are entirely due to this "coupling" through neutron evaporation.§

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Reactions of Uranium-238 with Carbon Ions*

TORBJØRN SIKKELAND, STANLEY G. THOMPSON, AND ALBERT GHIORSO
Radiation Laboratory, University of California, Berkeley, California

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The excitation functions for some reactions of U^{238} with monoenergetic C^{12} ions have been measured by use of the stacked-foil technique. The $(C,4n)$ and $(C,6n)$ reactions were found to occur through the formation of a compound nucleus followed by neutron evaporation. The results were consistent with calculations made by a modified Jackson-type treatment. Application of the information from the $U^{238}(C,xn)$ reactions to the calculation of cross sections for the $Pu^{242}(C,4n)Fm^{250}$ reaction was found to give agreement with experimental results.

The $(C,\alpha 4n)$ reaction probably proceeds mainly by a stripping mechanism, but there is also an indication of evaporation of alpha particles from a compound system.

INTRODUCTION

MOST of the quantitative information on nuclear reactions in the heavy-element region has been confined to investigations with helium ions or lighter particles because of the difficulties of obtaining intense monoenergetic beams of heavier ions. Heavy ions such as carbon, nitrogen, oxygen, and neon have been accelerated in cyclotrons, but usually with relatively low intensities and with broad energy spectra so that quantitative interpretation of the experimental results is difficult.[1–7] However, more recently, investigations have been made in Russia of the dependences of the spallation cross sections of gold bombarded with monoenergetic nitrogen ions using the 150-cm cyclotron of the ANSSSR.[8] The cross-section curves exhibited sharp maxima consistent with the theory of evaporation processes. Another group at the same location studied the fission cross sections of ytterbium, rhenium, gold, bismuth, U^{235}, and U^{258} as functions of energy,[9] using the monoenergetic nitrogen ions.

The use of a linear accelerator for obtaining beams of monoenergetic heavy ions has many advantages. It is readily adaptable to the acceleration of a wide range of different ions. The linear accelerator can be changed rapidly to accelerate the desired particles, the external beams are well focused and of high intensities, and the particles are of well-defined energies. Such linear accelerators have been constructed at Berkeley[10,11] and at Yale University. These accelerators produce ions with energies of 10 Mev per nucleon.

The heavy-element region is particularly interesting for the study of the reaction mechanisms, since fission competition has a large influence on the spallation cross sections.[12] A knowledge of the excitation functions with

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