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Fission Excitation Functions for Charged Particles

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Absolute fission excitation functions have been measured with an ionization chamber to detect the pulse of a recoiling single fragment. In the experiment performed, the 60-in. Crocker cyclotron deuterons and alpha-particles were used with Th^{232}, U^{235}, and U^{238} targets. Thresholds of these reactions were also observed. The maximum alpha-particle energy used was 33.5 Mev and the maximum deuteron energy was 17.5 Mev. Beam current was integrated with a Faraday cup and an ionization chamber.

The 184-in. synchrocyclotron was used to extend the fission excitation functions to alpha-particle energies of 390 Mev and deuteron energies of 193 Mev. Bi^{209} and Au^{197} targets were also added. Preliminary results with protons of 340 Mev maximum energy are also reported.

The results of the experiments are summarized in Figs. 3 to 17 inclusive.

I. INTRODUCTION

THE production of fission by means of bombardment with charged particles has been observed by various investigators.[1–5] All of the investigations have utilized the beta-activity of the fission fragments as the indicator of the number of fissions. In particular, in the excitation function measurements of S. C. Wright and the author[5] it was necessary to make an assumption concerning the beta-activity of the fission fragments in order to obtain an absolute cross-section scale. The assumption was made that the beta-activity of the complex of fission fragments was the same, for a given time after a short bombardment, for fission produced by charged particles or by thermal neutrons.

In recognition of the possibly unwarranted assumptions made in the above work concerning the beta-activity of the fragments from the charged particle fission, it was decided to repeat the experiment by a more direct method. This method consisted in counting the pulses of ionization produced by the fission fragments in an ionization chamber. The detection of a fission pulse in the presence of the ionization produced by the beam itself is made possible by use of a cancellation principle due to Baldwin and Klaiber,[6] and independently suggested by C. Wiegand. This principle was used to measure fission excitation functions on the 60-in. Crocker cyclotron and the 184-in. synchrocyclotron.

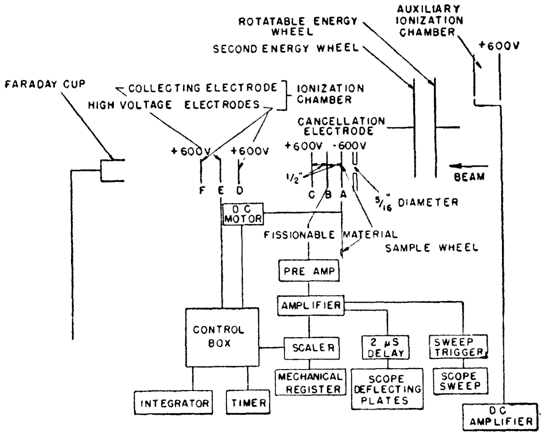

FIG. 1. Experimental arrangement.

II. 60-IN. CYCLOTRON EXPERIMENTS

A. Apparatus

(*1*) *Beam Collimation and Energy Reducing Equipment*

Figure 1 shows a schematic drawing of the experimental arrangement.

The beam collimation was similar to that of Kelly and Segrè[7] except that the exit slit of the collimator was widened to $\frac{1}{4}$ in. The beam emerging from the defining slit was found to be quite homogeneous in energy by Kelly and Segrè because the fringing field of the cyclotron magnet causes the collimating tube to act as a velocity selector. The energy of this homogeneous beam could be varied by means of aluminum foils placed in the two wheels shown in Fig. 1. The arrangement was similar to that described by Kelly[8] except that a window of 0.001 in. dural was substituted for the Faraday cup. One of the wheels could be rotated while the cyclotron was in operation. This wheel had aluminum foils ranging in thickness from 1.5 mg/cm² to 30 mg/cm² and one slot had 339 mg/cm² of aluminum, which was greater than the range of either the deuteron or the alpha-particle beams. The second wheel was provided with aluminum foils whose thickness increased about 30 mg/cm² from slot to slot. In this way it was possible to vary the energy of the beam particles over the entire energy range of the excitation function in steps corresponding to the energy loss in 1.5 mg/cm² of aluminum.

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[1] D. H. T. Gant, Nature **144**, 707 (1939).

[2] I. C. Jacobsen and N. O. Lassen, Phys. Rev. **58**, 867 (1940).

[3] G. Dessauer and E. M. Haffner, Phys. Rev. **59**, 840 (1941).

[4] E. Fermi and E. Segrè, Phys. Rev. **59**, 680 (1941).

[5] J. Jungerman and S. C. Wright, Phys. Rev. **74**, 150 (1948).

[6] G. C. Baldwin and G. S. Klaiber, Phys. Rev. **71**, 3 (1947).

[7] E. L. Kelly and E. Segrè, Phys. Rev. **75**, 999 (1949).

[8] E. L. Kelly, Phys. Rev. **75**, 1006 (1949).

(2) *Fission Ionization Chamber and Beam Current Collecting Equipment*

After leaving the wheels the beam passed through a 0.001 in. dural window, then through about 1 cm of air, and then entered the fission chamber through another 0.001 in. dural window. The beam encountered the fissionable material after passing through 3.4 cm of argon and another 0.001 in. of aluminum upon which the fissionable material was deposited. Any of six different samples could be selected while the cyclotron was in operation by means of a remote-controlled sample changer.

Each sample was provided with a mask which covered all but a circular area of $\frac{3}{8}$ in. diameter. Before striking the sample the beam was collimated by passing through a hole $\frac{5}{16}$ in. in diameter in aluminum of 0.0625 in. thickness. The hole was accurately positioned with respect to the sample mask. It was thus assured that all of the beam particles passing through the ionization chamber had actually traversed the fissionable substance.

The distance from the sample wheel to plate B was $\frac{1}{2}$ in. This was equal to the range of the fission fragments at the pressures used (about 150 cm Hg). Plate B was connected to the grid of the first tube of the preamplifier. It was constructed of aluminum leaf (0.17 mg/cm^2) which was held in position by a brass ring. Plate C was constructed similarly and served as a cancellation electrode. It was placed such that plate B was equidistant from A and C. The potentials were as indicated on Fig. 1.

Plates D, E, and F constituted an ionization chamber used to measure the beam current. The center collecting electrode, E, was surrounded by plates at high potential (600 v) so that the charges would not be collected that were not formed in the region between the ionization chamber plates.

After traversing the ion chamber, the beam passed through a 0.001 in. dural window. It then passed through 2 cm of air and entered a Faraday cup through a similar window. Being near the cyclotron, the apparatus was operated in a magnetic field of 2000 gauss; in this magnetic field the geometry of the cup was such that secondary electrons ejected from the cup by the beam would have to exceed 4 Mev in order to escape striking the entrance walls of the cup.

(3) *Electronics*

A block diagram of the electronic arrangement is also shown in Fig. 1. The pulses from the fission ionization chamber were preamplified before the signal was sent through the thrity feet of cable that was necessary to reach the amplifier outside the cyclotron shielding. The preamplifier was equipped with magnetic shields around each tube so that the effect of the magnetic field on the tube gain would be minimized. The preamplifier was so oriented that the path of the electrons in the tubes was parallel to the magnetic lines of force. A test showed that the electron collection in the fission ionization chamber was unaffected by the magnetic field.

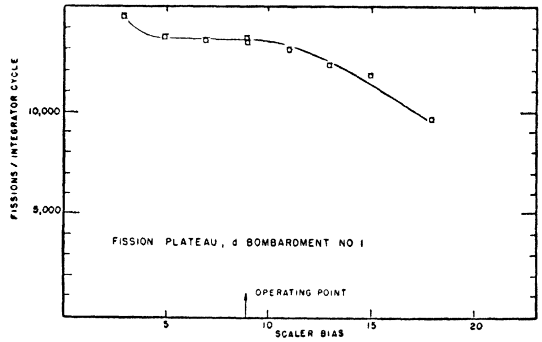

FIG. 2. A typical fission count *versus* discriminator bias curve.

The output of the amplifier was connected to a scale of 64 and mechanical register. By using an oscilloscope with 5 microsecond sweep speed the form of the ionization pulse was observed. A delay in the arrival of the pulse on the deflection plates provided time for the sweep to start. The shape of a typical fission pulse can be obtained by observing the pulse form when fission is induced by slow neutrons.

The pulses recorded as fissions in this experiment were observed to have the same form and magnitude as the slow neutron fission pulses. (Slow neutrons were generated with paraffin and a Ra-Be source.) The amplifier RC was adjusted so that the pulse decayed to $1/e$ in 5 microseconds.

(4) *Beam Current Integrator*

The beam current was integrated by measuring the voltage attained by a known capacitor. The capacitor could be charged directly by the beam current caught in the Faraday cup, or it could be charged with the beam current magnified by the order of ten thousand times by measuring the charge collected by the ionization chamber. Polystyrene coaxial cables conducted the currents to the voltage measuring equipment. The voltage measurement was done electronically using a circuit of Vance.[9] The circuit is characterized by a high input resistance and therefore makes it possible to measure the voltage of the condenser without changing the value of the voltage. This instrument was calibrated using a potentiometer. It was found that no appreciable change in calibration occurred during the course of the experiment.

For the integration of the current from the ionization chamber a capacity of about 10 μf was needed. The condensers made by the John Fast Company of Chicago with a polystyrene dielectric were found to be satisfactory.

Since "fast" condensers of greater than 0.1 μf were not available, the range of the instrument was extended

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[9] A. W. Vance, Rev. Sci. Inst. 7, 489 (1936).

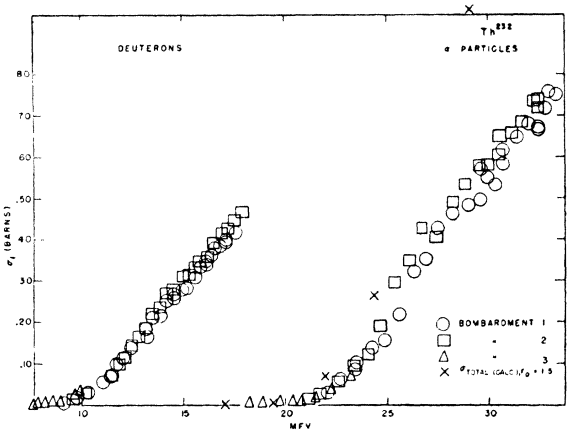

FIG. 3. Fission excitation functions for Th^{232}.

by using a potential dividing arrangement of these capacitors. All capacity elements were measured with a capacity bridge which was in turn calibrated with a standard capacitor.

A control box contained a master gang switch which simultaneously actuated a sweep-second timer, the scaling circuit, and the current integrator. It had two "on" positions; one position allowed voltage on the ionization chamber to be measured by the integrator, while the other connected the Faraday cup to the integrator.

(5) *Targets*

The samples of fissionable material were prepared as described in reference 5. The amount of fissionable material was determined by alpha-counting and weighing. The alpha-counting was done with the ionization chamber and the electronic equipment used for the experiment. In addition the samples were removed and counted in the laboratory alpha-counter. The thicknesses agreed within experimental error (three percent).

The homogeneity of the Th^{232} and U^{238} samples was tested by alpha-counting portions of the large foil from which the bombarded sample was cut. These portions were of the same area as the sample and the alpha-activities differed by a maximum of three percent from the mean. In the case of U^{235} the inhomogeneity would be expected to be greater since it was made in 21 coats and bakings whereas the other samples were made in 130. The thickness of the targets were as follows: U^{238}, 0.85_0 mg/cm^2; Th^{232}, 0.68_3 mg/cm^2; and U^{235}, 0.19_2 mg/cm^2. The U^{235} sample contained greater than 95 percent U^{235}. Since the ranges of fission fragments and alpha-particles are of the same order of magnitude the determination of sample thickness by alpha-count cancels to some degree the error made in the fission count due to the finite thickness of the sample. The error in the fission cross section is estimated to be less than 10 percent from this source.

B. Method

(1) *Excitation Functions*

In the excitation function measurements, operation was as follows: a value of the beam energy was selected by rotating the wheel containing the fine steps of aluminum thickness to the appropriate position. A target was selected with the sample changer. Then the master switch was turned to the ionization chamber position. When the integrator showed that the capacity had reached the appropriate potential, the master switch was returned to the "off" position and the number of fissions and the time was recorded. At full beam energy this process would take about two minutes and several thousand fissions would be obtained. The target was then changed and the process repeated. After all three targets had been bombarded, the energy was again changed by a small amount. In this manner three excitation functions were obtained simultaneously.

At the beginning of each bombardment the number of fissions per unit beam current *versus* the discriminator setting of the scaler was measured. After a certain value of the bias is reached, practically all the fissions are counted and therefore one obtains a fission plateau. Figure 2 shows a typical fission count *versus* discriminator bias curve. At very low values of the bias setting a point is reached where the pulses due to the beam ionization are counted and the plateau ends. In order to minimize the number of spurious counts from the uncanceled beam ionization, the operating point was chosen near the end of the plateau on the high bias side. Fallacious counts could also arise from sparking of the deflector or of the high voltage on the dees of the cyclotron. These were of greater height than the fission pulses and hence could not be removed by discrimination. It was therefore necessary to have the cyclotron in a very steady condition if reliable results were to be obtained. This was found to be the case if the cyclotron had been running previously for several days so that it was well baked in.

One of the samples consisted of an aluminum blank of the same thickness (0.001 in.) as that upon which the fissionable materials were deposited. By selecting this sample while the cyclotron continued to operate at the same level, it was possible to discover how many spurious counts were being recorded as fissions for a given discriminator setting. If operating conditions of the cyclotron were satisfactory, it was always possible to reduce the number of spurious counts from the aluminum blank target to zero.

A second condition on the method of operating the cyclotron was that it produce as few neutrons as possible. To minimize the effect of the neutrons the sample area was made as nearly the same as the beam area as was practicable, and the entire fission ionization chamber was covered with $\frac{1}{32}$ in. of cadmium. An upper limit for the neutron fission background could be obtained for any fissionable sample selected by rotating the energy wheel to the slot which had sufficient aluminum thickness to stop the cyclotron beam. The background obtained by counting the number of neutron fissions for the same time as the charged particle bombardment. The auxiliary ionization chamber, discussed below, monitored the cyclotron radiation level during the measurement.

It was found that the lowest neutron background was reached when the arc current and voltage of the cyclotron were as low as possible. This is reasonable since then the amount of beam that is circulating between (and some of it striking) the dees is as small as possible. In practice the auxiliary ionization chamber shown in Fig. 1 was found useful for estimating the neutron background. It was merely a large (108 in.^{3}) air-filled chamber with 600 v positive potential and a collecting electrode. It was placed near the target chamber of the cyclotron. The collected current was delivered to a direct current amplifier which read 10^{-9} amp. full scale. It was discovered that there was a definite positive correlation between the neutron background and the reading of the d.c. amplifier. This is plausible since it means that the general density of radiation in the target area increased when the neutron density increased. In this manner a continuous check on the quality of the beam was obtained. When optimum conditions were reached the current from this ionization chamber was of the order of 10^{-11} amp. The neutron background was especially important in the case of U^{235}. In this case, although it was only about one percent at the full beam energy, it became the limiting factor at threshold energies.

(2) *Measurement of the Average Energy Required to Form an Ion Pair*

In each excitation function bombardment, data were also taken to find the number of ion pairs produced by one of the beam particles in passing through the ionization chamber. This was done by turning the master switch to the Faraday cup position so that the integrator measured the voltage on the Faraday cup. In the meantime the ionization chamber was charging its circuit. After the Faraday cup had reached an appropriate potential, the energy wheel was turned so as to stop the beam. After grounding the Faraday cup and integrator, the master switch was turned to the ionization chamber position and the potential of its condenser was determined. Photographs of the beam were taken at the entrance to the Faraday cup to check the alignment of the apparatus. The multiplication (number of ions produced by one beam particle) produced in the ionization chamber is then:

$$M=C_{I.C.}V_{I.C.}v/C_{F.C.}V_{F.C.}, \tag{1}$$

where v is the number of electronic charges of the beam particle C and V refer to the capacities and voltages of the Faraday cup and ionization chamber circuits. If the energy lost by one of the beam particles in the ionization chamber is known, the average number of electron volts, w, necessary to form an ion pair in argon can be determined for the energy region involved

$$w=\Delta E/M. \tag{2}$$

ΔE is the energy loss in the ionization chamber in electron volts and M is the quantity referred to above. In this experiment ΔE was calculated from the usual expression for the rate of energy loss by ionization:

$$dE/dx=(4\pi Nz^2Ze^4/mv^2)[\ln(2mv^2/I(1-\beta^2))-\beta^2]. \tag{3}$$

This calculation was made by Aron *et al.*,[10] who used the value 11.5Z for I. This value was determined by Wilson[11] for protons of 4 Mev. The number of argon atoms per cm^3, N, can be determined from the gas laws if the pressure and temperature of the gas are known. The temperature was measured for each bombardment and the pressure was measured on a mechanical pressure gauge which in turn was calibrated against a mercury column.

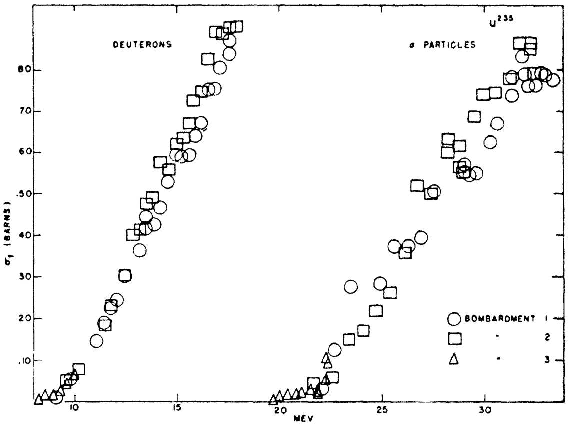

FIG. 4. Fission excitation functions of U^{235}.

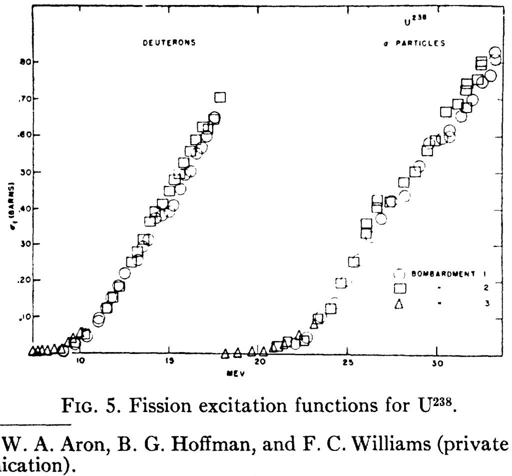

FIG. 5. Fission excitation functions for U^{238}.

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[10] W. A. Aron, B. G. Hoffman, and F. C. Williams (private communication).

[11] R. R. Wilson, Phys. Rev. **60**, 749 (1941).

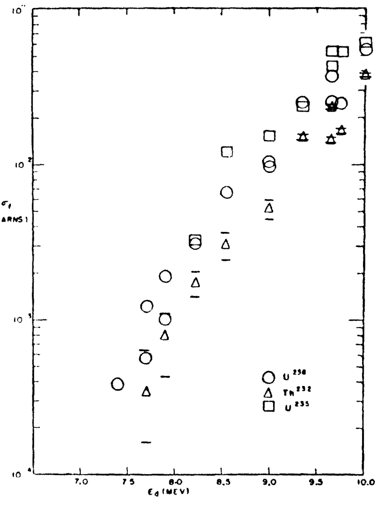

FIG. 6. Fission excitation functions for threshold energies of deuterons.

(3) *Beam Energy Determination*

In each bombardment the energy of the beam particles was determined. This was done by measuring the current collected by the ionization chamber as a function of the amount of aluminum placed in the beam by rotating the energy wheels. When the mean range was determined, the beam energy was obtained from the range-energy relation calculated from the expression for dE/dx given above.

C. Results

(1) *Excitation Functions*

Figures 3 to 5 show the excitation functions for the three substances investigated. In the case of deuterons the number of fissions observed for a point at full beam energy was about 13,000 for U^{238}, 7500 for Th^{232}, and 4300 for U^{235}. In the case of alpha-particle bombardment the corresponding number of fissions was 7300 for U^{238}, 5400 for Th^{232}, and 1800 in the case of U^{235}. The value of the beam energy differed as much as 2.5 percent from run to run. Since the fission cross section rises rapidly with energy, this difference is important if agreement is to be obtained between different bombardments. Besides changing the abscissa of the excitation function plot, an error in the energy also changes the ordinate such that if the energy is assumed to be higher than the correct value, the ordinate is lower and vice versa. This effect arises from the fact that the number of beam particles depends inversely on the energy loss in the ionization chamber.

In the case of the deuteron bombardments the neutron fission background was found to be about two counts for U^{238}, zero for Th^{232}, and about 20 for U^{235}. These background figures are given relative to the number of beam particles giving the number of charged particle fissions quoted above for full energy. For the alpha-particle bombardments the neutron fission background was about one count for U^{238}, zero for Th^{232}, and about 15 in the case of U^{235}. For the latter substance it was necessary to find the neutron background for each point since the numbers given could vary considerably at different times during a bombardment. The sensitivity of the neutron background to beam conditions is illustrated by the fact that during one of the alpha-particle bombardments a change of filament in the ion source raised the neutron background by a factor of four above the figures given.

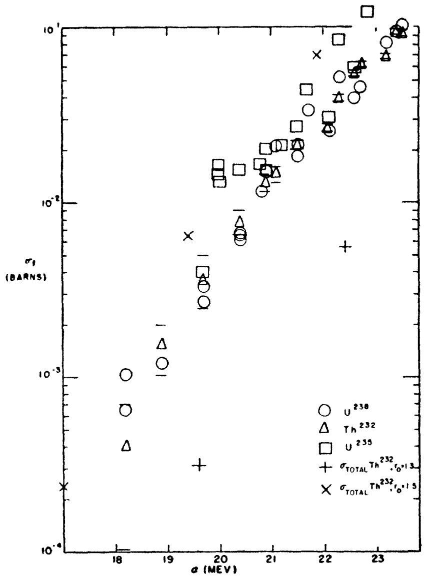

FIG. 7. Fission excitation functions for threshold energies of α-particles.

Figures 6 and 7 show the fission excitation functions near the threshold in greater detail. A logarithmic ordinate was used since in this energy region the cross section is limited by penetration of the Coulomb potential barrier. The results shown include the ends of bombardments 1 and 2 as well as the special threshold bombardment, 3. The lowest points on these curves represent the observation of less than 10 fissions and are therefore unreliable. In the case of U^{235} the excitation function was not carried below the energy at which the neutron background became one-half of the total

TABLE I. Experimental values for w.

Particle	Energy (Mev)	w (ev)
d	16.9	27.1
d	17.0	28.4
d	17.0	29.7
d	16.0	33.2
d	9.6	31.8
α	30.1	31.6
α	28.8	28.7
α	30.4	30.5
α	29.6	31.0
α	22.4	31.4

fission count. Probable errors are shown on the Th^{232} points, which are the most reliable because of low neutron fission background.

(*2*) *Value of w*

The value of *w*, the average number of electron volts necessary to form an ion pair, was determined in several preliminary bombardments as well as bombardments that proved unsatisfactory for the determination of the fission excitation functions. The results are tabulated in Table I. Each value given represents the average of several observations for the given bombardment. The results for lower energy seem to show that the value of *w* is constant over the energy range of the experiment within the experimental error.

The average value of *w* for deuterons of about 17 Mev is then 29.6 ev, and for alpha-particles of about 30 Mev it is 30.5 ev. These values were used to find the multiplication factor, *M*, introduced by the ionization chamber when the computation of the fission cross sections was made. The results reported here for *w* in argon are higher than those given by other investigators. Nicodemus[12] gives 26.9 for 17.4-Mev electrons[12a] and Stetter[13] reports 28.4 ev for the alpha-particles of polonium. Fano[14] has given an approximate calculation of *w* which makes it plausible that *w* should be fairly insensitive to the energy or type of projectile. Recently experiments of Jesse *et al.*[15] have shown *w* to be constant for α-particles in the range one to nine Mev. If this constancy prevails at higher energies, then Stetter's value for *w* would give more accurate values for the fission cross sections.

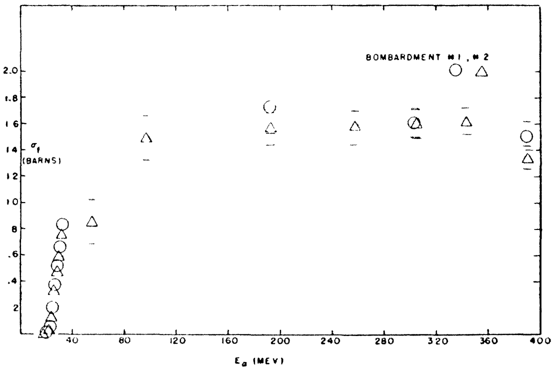

FIG. 8. Fission excitation function for U^{238} bombarded with alpha-particles.

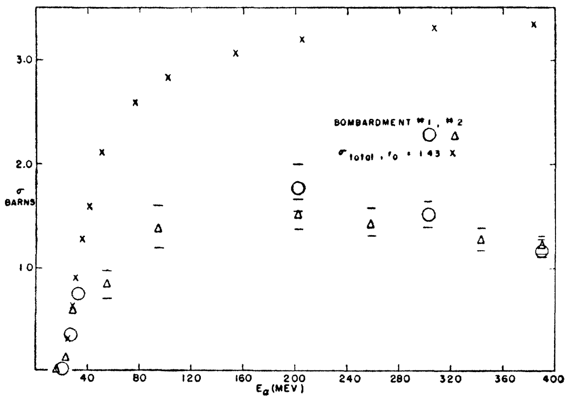

FIG. 9. Fission excitation function for Th^{232} bombarded with alpha-particles.

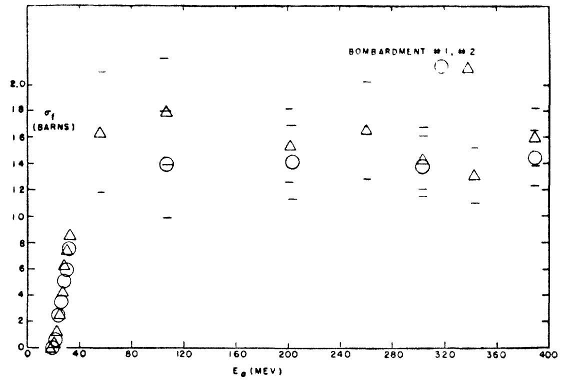

FIG. 10. Fission excitation function for U^{235} bombarded with alpha-particles.

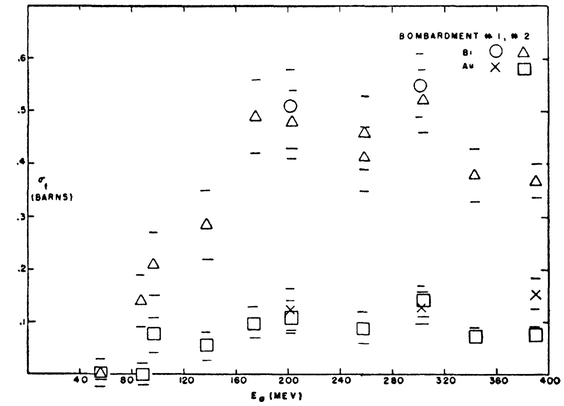

FIG. 11. Fission excitation functions for Bi^{209} and Au^{197} bombarded with alpha-particles.

D. Discussion

(*1*) *Comparison with Beta-Activity Experiment*

Comparison of the present results with those found in the previous experiment[5] indicates that the assumption made concerning the beta-activity of the complex of fission fragments is incorrect by a factor of about 1.5 to 1.7. In each case the charged particle fission seems to give more beta-activity in the fragments for the times after bombardment investigated. Newton[16] has investigated the fission yield *versus* mass spectrum for fission induced in throium by alpha-particles. He finds

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[12] D. B. Nicodemus, thesis, Stanford University (1946).

[12a] Quoted from Rossi and Staub, *Ionization Chambers* (McGraw-Hill Book Company, Inc., New York, 1949), p. 227.

[13] G. Stetter, Zeits. f. Physik **120**, 643 (1943).

[14] U. Fano, Phys. Rev. **70**, 44 (1946).

[15] Jesse, Forstat and Sadauskis, Phys. Rev. **77**, 782 (1950).

[16] A. S. Newton, Phys. Rev. **75**, 17 (1949).

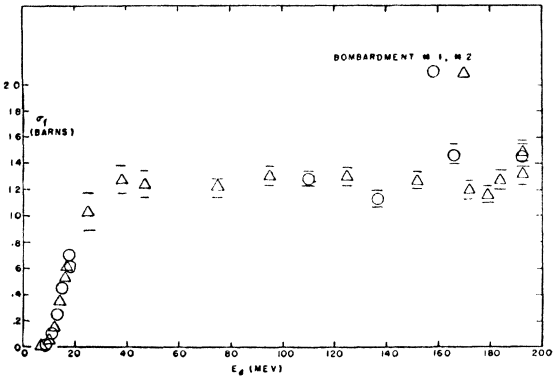

FIG. 12. Fission excitation function for U^{238} bombarded with deuterons.

that the usual dip in the distribution found with low energy projectiles (neutrons) has risen from 1/600 to 1/2 of the peaks of the distribution. The corresponding new beta-activities appearing in the fission fragments might well account for the apparent increase in beta-activity per fission. Newton finds the value 0.6 barn for the fission cross section at 27.5 Mev. This is lower than the results of the present experiment. Part of the discrepancy may be found in the fact that he assumes the incident alpha-particle energy to be 39 Mev, whereas measurements made with the collimated beam by Jungerman and Wright,[5] by Kelly and Segrè,[7] and in in the present experiment, indicate that the maximum alpha-particle energy available was more nearly 37.5 Mev. This would also account for the discrepancy in the fission threshold reported by Newton. He finds 23 to 24 Mev for the threshold, whereas the results of the beta-activity experiment and the present one indicate a value of around 21 Mev.

(2) *Comparison of Fission Cross Sections and Calculated Total Reaction Cross Sections*

Weisskopf[17] has calculated the total reaction cross section for alpha-particles on a thorium target. He assumes 1.48×10^{-13} cm for the radius of the alpha-particle so that the interaction radius between the alpha-particle and the target nucleus has the form $R=(r_0A^{\frac{1}{3}}+1.48)\times 10^{-13}$, where A is the mass number of the target nucleus. Weisskopf gives points for $r_0=1.3$ and $r_0=1.5$. These points are plotted on the threshold excitation function for alpha-particles. It is seen that $r_0=1.3$ is excluded since it gives a fission cross section greater than the reaction cross section.

By continuing the total reaction cross-section curve above the threshold an estimate of the competition existing with fission can be obtained. This is shown for the choice $r_0=1.5$ on the *Th* (α, fission) excitation function. Since all target nuclei will have about the same total reaction cross section for a given projectile and projectile energy, the conclusion is reached that competition is greatest in the case of thorium, and least for U^{235}.

III. 184-IN. SYNCHROCYCLOTRON EXPERIMENT

A. Apparatus and Method

The fission chamber and samples used were the same as those used for the 60-in. cyclotron experiment. The sample areas were increased to $\frac{1}{2}$ in. diameter and the beam was again collimated to $\frac{5}{16}$ in. Collimation was done after the absorber used to reduce the beam energy so that beam particles scattered in the absorber at large angles would not be able to traverse the fission chamber. However, it was not practicable to have a collimator for each sample as in the 60-in. cyclotron experiment. The major collimation was done 12 in. from the fission chamber so that neutrons and other background generated by the beam arresting process would not be formed in the immediate vicinity of the fission chamber. The Faraday cup was altered for the new beam energies by making the collector a solid copper cylinder 3 in. in diameter and $4\frac{1}{2}$ in. in length. This geometry is sufficient to trap the proton beam (340 Mev) according to the data of V. Petersen.[17a] Secondary particles were trapped with a hollow two inch copper cylinder $1\frac{1}{8}$ in. in diameter and $\frac{1}{8}$ in. thick, which was attached to the beam end of the large cylinder. Since the beam intensities were much smaller than the 60-in. cyclotron beam, it was necessary to reduce the capacity of the Faraday cup circuit. This was done by placing the voltage measuring equipment for the Faraday cup in the target area. A meter giving the voltage on the cup was then brought outside the shielding. An identical circuit also simultaneously gave the voltage on the ionization chamber. A small air-cooled oil diffusion pump maintained the Faraday cup at high vacuum (less than 5×10^{-4} mm Hg).

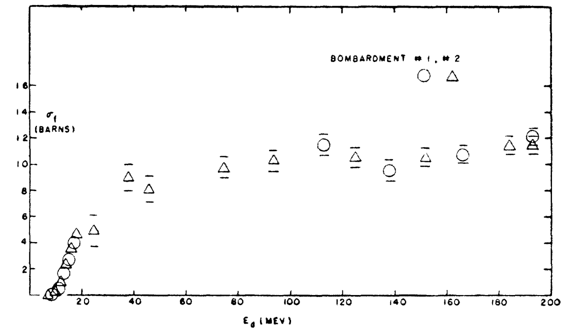

FIG. 13. Fission excitation function for Th^{232} bombarded with deuterons.

The external beam of the 184-in. cyclotron is pulsed so that all beam particles in a given pulse arrive within the resolving time of the apparatus. This circumstance makes the counting of fission pulses more difficult than

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[17] V. P. Weisskopf, MDDC-1175 (1947), Lecture Series in Nuclear Physics.

[17a] V. Petersen (private communication).

in the relatively continuous beam of the 60-in. cyclotron, even though the energy loss by ionization of the beam particle in the fission chamber has decreased due to the high energies involved. Thus it is essential that the cancellation be as complete as possible. A suggestion of O. Chamberlain made it possible to vary the cancellation electrically. This was done by connecting a variable capacity in series with each of the plates A and C shown in Fig. 1. The value of one of these variable capacities could be changed during bombardment by rotating it with an electric motor. Thus while the cyclotron beam was kept constant, the amount of uncanceled beam pulse could be observed in the oscilloscope and minimized with the electric motor.

It was found possible to operate with no spurious beam pulses counting as fissions, provided the beam strength was such that, for example, about 150 fissions per minute were observed with deuterons of 190 Mev incident on the U^{238} sample. If the beam strength were proper, reasonable fission plateaus were again obtained. As in the 60-in. cyclotron experiment the pulse form was observed during operation as a check that the pulses observed were really fissions.

It was also possible to get an estimate of the background fission rate by inserting an absorber into the beam whose thickness was greater than the beam range. This could be done by remote control so that the cyclotron beam was not changed. Twelve different absorbers could be placed in the beam by this remote control device. Aluminum absorbers were used for alpha-particles and deuterons, and copper absorbers were used for protons. This allowed various energies to be selected without shutting off the cyclotron and also provided a method of beam range determination. It was necessary to measure the beam range in each bombardment in order to determine accurately the residual range of the beam in the region where the high energy curves join the curves obtained at the 60-in. cyclotron in the case of alpha-particle and deuteron bombardments.

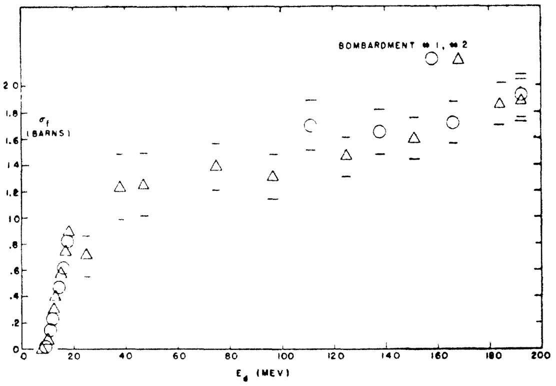

FIG. 14. Fission excitation function for U^{235} bombarded with deuterons.

B. Results

(1) Excitation Functions

Figures 8 to 15 inclusive show the excitation functions observed for alpha-particle and deuteron bombardments. The probable errors in the deuteron bombardments are in general less than for alpha-particles because the energy loss in the fission chamber by a beam particle is less for the former and also because the maximum intensity of the alpha-particle beam was much less than the deuteron beam. The alpha-particle beam was always used at full intensity. The points shown without probable error are from the 60-in. cyclotron experiment. The probable errors of the points that have zero cross section are computed on the assumption of one observed fission. The neutron fission background was about two percent of the charged beam fission rate when deuterons were used on a target of U^{238}. In the case of alpha-particles this background was less than one percent.

Figures 16 and 17 show the present status of the proton excitation functions. These data are quite preliminary since only one bombardment has been made. The low value of the cross section observed as compared with the results of the alpha-particle and deuteron bombardments is rather surprising. Because of this, a check on the equipment was made by changing the cyclotron beam to alpha-particles at the end of a proton bombardment. The alpha-particle cross sections so obtained for U238 and U235 checked within statistics with previous bombardments. The neutron fission background was about two percent for U^{238} for the proton case.

(2) Faraday Cup Measurements

In the case of deuterons the dE/dx curve as calculated from formula (3) was verified within ten percent in the range from 38 Mev to 192 Mev. The best fit was obtained for $w=29.5$ ev/ion pair. In the case of alpha-particles, the measurements were more difficult due to the smaller beam strength, but verification was

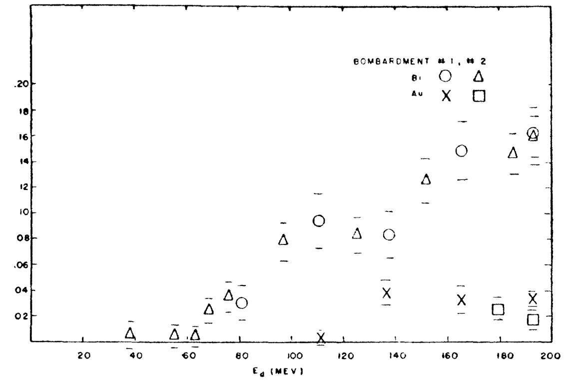

FIG. 15. Fission excitation functions for Bi^{209} and Au^{197} bombarded with deuterons. The ordinate scale should read σ_f (barns).

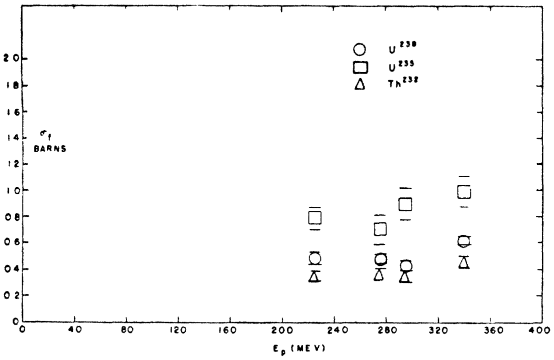

Fig. 16. Fission excitation functions for U^{238}, U^{235}, and Th^{232} bombarded by protons.

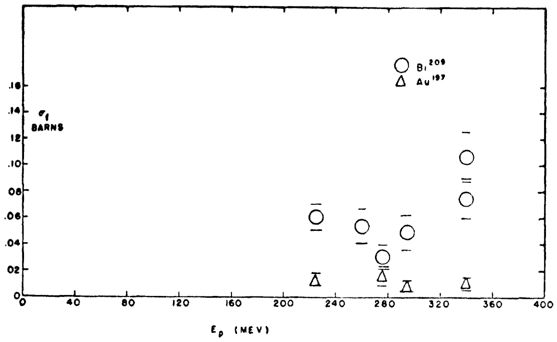

Fig. 17. Fission excitation functions for Bi^{209} and Au^{197} bombarded by protons.

again obtained to about twenty percent in the range 100 Mev to 390 Mev using 30 ev/ion pair. In the case of the proton bombardments, agreement to about twenty percent was obtained in the energy region above 200 Mev with 30 ev/ion pair.

C. Discussion

The fission cross section for full deuteron energy was investigated by Goeckermann and Perlman[18] using chemical techniques. They found a value of 0.2 barn, which is in agreement with the present experiment within the experimental errors. O'Connor and Seaborg[19] have investigated the spallation products and fission products of U^{238} bombarded by 390-Mev alpha-particles. They estimate the value of the fission cross section to be about two barns. This is seen to be somewhat higher than the results of the present experiment.

It is interesting to compare the calculated reaction cross section and the observed fission cross section in the high energy region. For the case of alpha-particles on a thorium target, the threshold data from the 60-in. cyclotron show that for $r_0=1.43$ the fission cross section observed would equal the calculated reaction cross section. Taking this value of r_0 the total reaction cross section can be calculated in the region above the Coulomb barrier by an approximate formula given by Bethe and Konopinski[20]

$$\sigma_{\text{reaction}}=\pi\lambda\!\!\!^{-}{}^2P_0l_c{}^2,$$

where

$$l_c{}^2=g^2(x-1)+0.744g^{4/3}(2x-1)^{2/3}\quad\text{for}\quad x>1.$$

P_0 is the penertration probability of the Coulomb barrier and $\lambda\!\!\!^{-}$ is the projectile wave-length divided by 2π; x is the ratio of the energy to the effective barrier height, and g is a constant which depends on the nuclear radius. Since Bethe and Konopinski did not use a finite radius for the alpha-particle their r_0 should be 1.67 in order to correspond to Weisskopf's choice of 1.43. This value of r_0 gives the effective barrier height as 25.6 Mev, and a value of g of 23.0. The results of this calculation appear on the excitation function of thorium bombarded with alpha-particles (Fig. 9). It should be emphasized that the compound nucleus concept is not valid when the velocity of the projectile is much greater than the velocity of the nuclear particles (i.e., for $E_\alpha>$approx. 200 Mev).[21] This choice of r_0 gives the minimum possible competition with the fission process. With this choice of r_0 it is seen that the competition begins to become appreciable above 30 Mev and increases steadily with increasing alpha-particle energy. There is some chamical evidence obtained by James[16] that appreciable competition exists with the fission process for the bombardment of thorium by 37-Mev alpha-particles.

The author is especially grateful for the stimulating interest of Professor E. Segrè throughout this investigation and also wishes to thank Professor G. C. Wick and Professor V. Weisskopf for helpful discussions of the theoretical problems. Thanks are also due C. Wiegand and Dr. O. Chamberlain for many valuable suggestions. The cooperation of the personnel of the Crocker cyclotron and of the 184-in. cyclotron is gratefully acknowledged.

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[18] R. H. Goeckermann and I. Perlman, Phys. Rev. 73, 1127 (1948).

[19] P. R. O'Connor and G. T. Seaborg, Phys. Rev. 74, 1189 (1948).

[20] H. A. Bethe and E. J. Konopinski, Phys. Rev. 54, 130 (1938).

[21] R. Serber, Phys. Rev. 72, 1114 (1947).