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FISSION EXCITATION FUNCTIONS FOR CHARGED PARTICLES

J. Jungerman

September 21, 1949

Berkeley, California

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FISSION EXCITATION FUNCTIONS FOR CHARGED PARTICLES

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I Introduction

The production of fission by means of bombardment with charged particles has been observed by various investigators.[1,2,3,4,5] All of the investigations have utilized the β-activity of the fission fragments as 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 β-activity of the fission fragments in order to obtain an absolute cross section scale. The assumption was made that the β-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 experiment 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 using a cancellation principle suggested by C. Wiegand*. This principle was used to measure fission excitation functions on the 60-inch Crocker cyclotron and the 184-inch Synchro-cyclotron.

II 60-inch Cyclotron Experiments

A. Apparatus

1. Beam Collimation and Energy Reducing Equipment. Fig. 1 shows a schematic

*It was later discovered that this method had been used by Baldwin and Klaiber[6] to measure fission pulses in an x-ray background.

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 1/4". 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 the figure. The arrangement was similar to that described by Kelly[8] except that a window of .001" 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/cm^2 to 30 mg/cm^2 and one slot had 339 mg/cm^2 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/cm^2 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/cm^2 of aluminum.

2. Fission Ionization Chamber and Beam Current Collecting Equipment. After leaving the wheels the beam passed through a .001" dural window, then through about 1 cm of air, and then entered the fission chamber through another .001 dural window. The beam encountered the fissionable material after passing through 3.4 cm of argon and another .001" 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 3/8" diameter. The mask was made of .002" brass and was therefore of a thickness which was greater than the range either of the fission fragments or of the alpha-particles emitted by the radioactive samples. Before striking the

sample the beam was further collimated by passing through a hole 5/16" in diameter in aluminum of .0625" thickness. The hole was accurately positioned with respect to the sample mask. It was thus assured that all the beam particles passing through the ionization chamber had actually traversed the fissionable substance.

The distance from the sample wheel to plate B was one half inch. 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 pre-amplifier. It was constructed of aluminum leaf (.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 the diagram. Since the pulse from the ionization in the chamber was determined by the collection of the electron, the cancellation action can be understood as follows: an electron falling in the potential gradient from A to B produces a small change in voltage of plate B. An electron falling from B to C produces a change in voltage of equal magnitude, but of opposite sign on plate B. If the distance AB is made equal to BC, then the ionization pulse produced by the charged particle beam from side AB will be cancelled by an equal and opposite pulse from side BC. The fission fragment, however, spends its kinetic energy producing ionization in side AB only and hence produces a relatively large unbalanced voltage on the pre-amplifier grid.

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 (600v) 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 .001" dural window. It then passed through 2 cm of air and entered a Faraday cup through a similar window. The vacuum in the cup was maintained by means of a connection

to the cyclotron vacuum by means of two feet of rubber hose of 3/8" inside diameter. Insulation for the Faraday cup was provided by a piece of polystyrene. 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 220 ev in order to escape being captured by the cup.

3. Electronics. A block diagram of the experimental arrangement is also shown in Figure 1. The pulses from the fission ionization chamber were pre-amplified before the signal was sent through the thirty 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 pre-amplifier 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.

The output of the amplifier was connected to a scale of 64 and mechanical register. Parallel outputs fed a pulse into a blocking oscillator which triggered the sweep of a Du Mont No. 248 oscilloscope while another pulse was simultaneously delivered to a delay line of two microseconds which terminated on the deflection plates of the oscilloscope. By means of this arrangement the form of the ionization pulse could be observed if a 5 microsecond sweep speed was used. The delay in the arrival of the pulse on the deflection plates provided time for the sweep to start. By this method one can also observe the form of the base line before the ionization pulse arrives at the deflection plates. The shape of a typical fission pulse can be obtained by observing the pulse form when fission is induced by slow neutrons. Amplifier RC was adjusted so that the pulse decayed to 1/e in 5 microseconds.

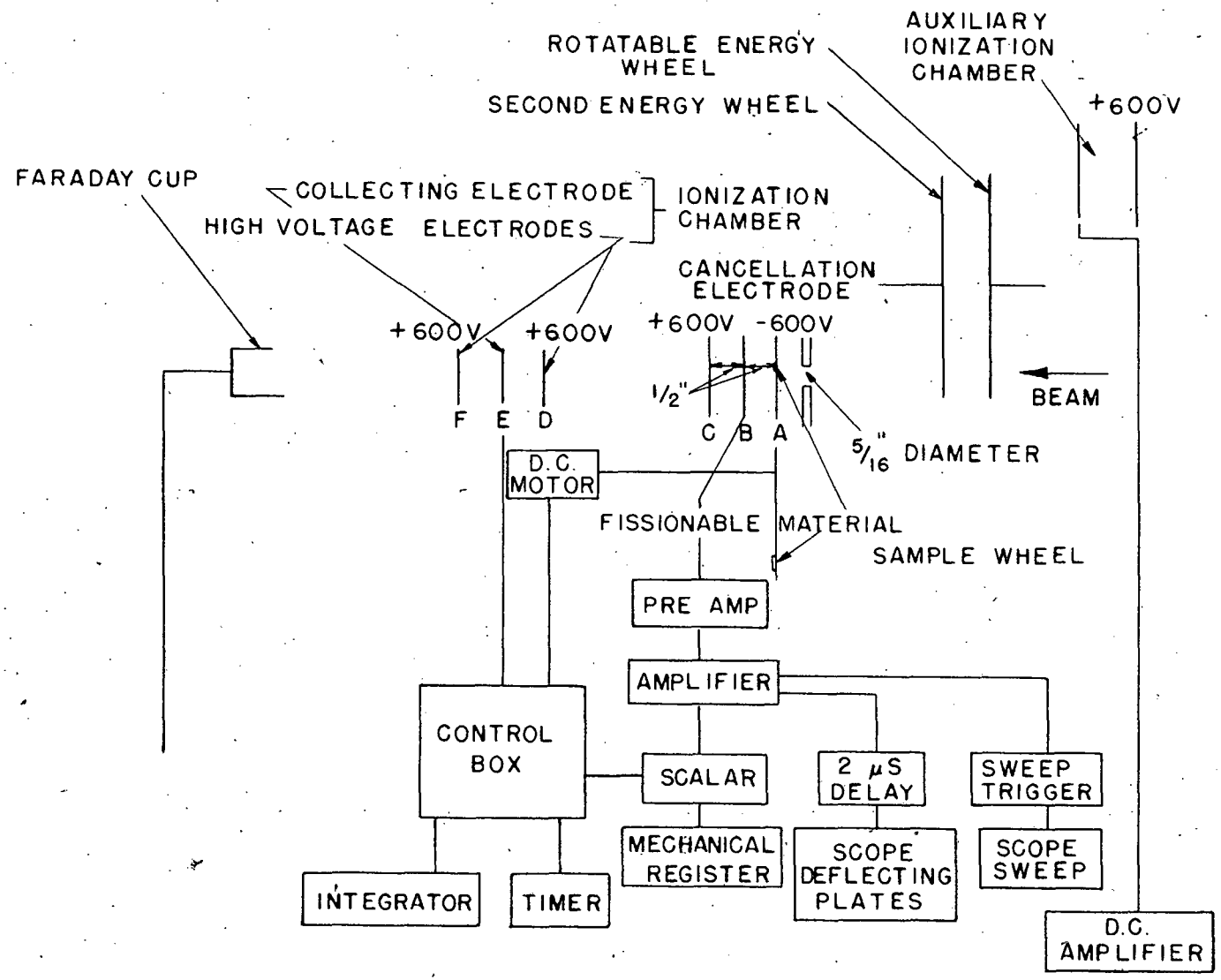

FIG. I
EXPERIMENTAL ARRANGEMENT

The pulses recorded as fissions in this experiment was 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.)

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 modification of a circuit of Vance[9] designed by C. Wiegand. The circuit is characterized by a high input resistance and therefore makes is possible to measure the voltage of the condenser without changing the value of the voltage. This was tested for the lowest capacity used in this experiment, that of the coaxial cables themselves (.001 microfarad), by charging the condenser to .7 volt and observing that the reading was unchanged after five minutes. The usual time for charging the condenser during the experiment was about two minutes. This instrument was calibrated using a Leeds and Northrup 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 microfarads was needed. Several of the usual oil-filled condensers were tried but none proved satisfactory. That is, the test described above showed that the condensers had enough dielectric absorption so that about one half of the charge originally stored in them would reappear during successive discharges. The condensers made by the John Fast Co. of Chicago did not show appreciable dielectric absorption or leakage by the above test. Their dielectric is made of polystyrene.

Since "fast" condensers of greater than .1 microfarad were not available, the range of the instrument was extended by using a potential dividing arrangement of capacitors. This had the consequence that the collecting electrode of the ionization chamber could reach as high as 100 volts on the least sensitive capacity selector position, while the integrator received only 1 volt. It might be suspected that such a high potential might have an effect on the current collected. This was proven not to be the case by collecting the current with a voltage of 100 volts and 1 volt with no detectable change in the amount of current obtained per unit beam current. (The beam current was monitored with the Faraday cup.) By this potential dividing arrangement equivalent capacities of 21.7, 2.00, and .205 microfarads could be selected. All capacity elements were measured with a General Radio 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. They were masked to 3/8" diameter circle in order to minimize the fission background due to neutrons generated by the cyclotron. The amount of fissionable material was determined by alpha counting. 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 (3 percent). In the case of U^{238} the specific activity was assumed to be known and equal to

750 counts per minute per milligram of uranium. Since the radioactive composition of the Th^{232} and U^{235} was unknown, the specific activity was determined experimentally. Two determinations of the specific activity were made for each substance. They agreed within two 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% 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. This started the charging of the capacity of the ionization chamber circuit, started the scalar operating, connected the ionization chamber circuit to the current integrator, and started the timing clock. When the integrator showed that the capacity had reached the appropriate potential, the master switch was returned to "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 versus the discriminator setting of the scalar 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. The beam ionization will always make some pulses due to the fact that the distance AB is not exactly equal to BC. Also nuclear reactions other than fission would cause a condition of unbalance if charged particles were emitted that did not pass through both of regions AB and BC. In order to minimize the number of spurious counts from the beam ionization, the operating point 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 (.001") 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

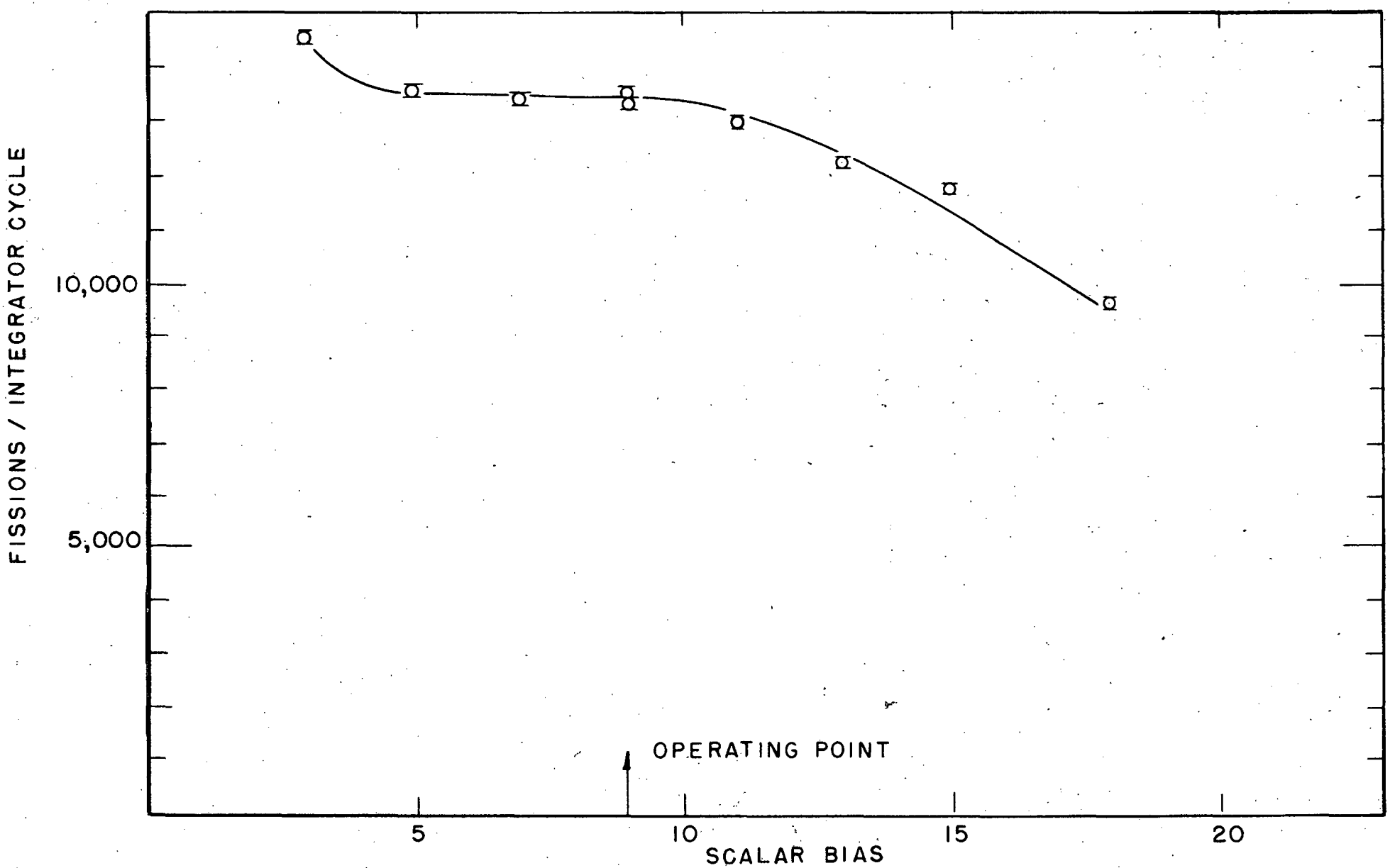

FIG. 2

FISSION PLATEAU, d BOMBARDMENT NO. I

1389-1

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 near the beam area as practicable. Since slow neutrons are very effective for producing fission in U^{235}, the entire fission ionization chamber was covered with 1/32" of cadmium. Even with these precautions the neutron effect was very sensitive to cyclotron conditions. 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. This gives an upper limit because some neutrons are formed in the aluminum in the slot as the beam is stopped there, whereas under conditions in which the beam passes through the slot the number formed there would be less. Some neutrons are always generated in the slot since it in general contains aluminum to lower the incident beam energy. The background was 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 Figure 1 was found useful for estimating the neutron background. It was merely a large (108 in^3) air filled chamber with 600v 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} amperes 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} ampere. A steady beam satisfying the conditions described above was in general more difficult to obtain in the case of alpha-particle bombardments. This difficulty with the alpha-particles was reflected in a neutron background which was comparable or greater than that formed by deuterons, although one might expect the opposite to be the case because of the small binding energy of the deuteron. The neutron background was especially important in the case of U^{235}. In this case, although it was only one percent at the full beam energy, it became the limiting factor at threshold energies.

The unsteadiness of the alpha particle beam was particularly troublesome at the energies near the fission threshold. In this region the fission counting rate is at a minimum and the energy loss by the beam in the fission chamber at a maximum. In order to get sufficient fissions in a reasonable time, it is then necessary to have the beam intensity as high as possible. Actually, it was necessary to lower the beam intensity from the high energy value to avoid spurious counts.

2. Measurement of the Average Energy Required to Form an Ion Pair. In each excitation function bombardment, data was 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 (F.C.) 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:

$$M = \frac{C_{I.C.} V_{I.C.} v}{C_{F.C.} V_{F.C.}} \qquad (1)$$

where v is the number of charges on the beam particle (v = 2 for alpha particles and v = 1 for deuterons) 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.

$$w = \Delta E/M \qquad (2)$$

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:

$$dE/dx = \frac{4\pi NzZe^4}{mv^2} \ln \frac{2mv^2}{I} \qquad (3)$$

This calculation was made by Aron et al.,[10] and they used the value 11.5 Z for I. This value was determined by Wilson[11] for protons of 4 Mev. If dE/dx is multiplied by the length of the ionization chamber (1.90 cm), ΔE is obtained. The value of dE/dx depends on the number of argon atoms per cm^3, N. This can be determined from the gas laws if the pressure and temperature of the gas is 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.

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, 4 and 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 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 2 counts for U^{238}, 0 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 1 count for U^{238}, 0 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 by as much as a factor five at

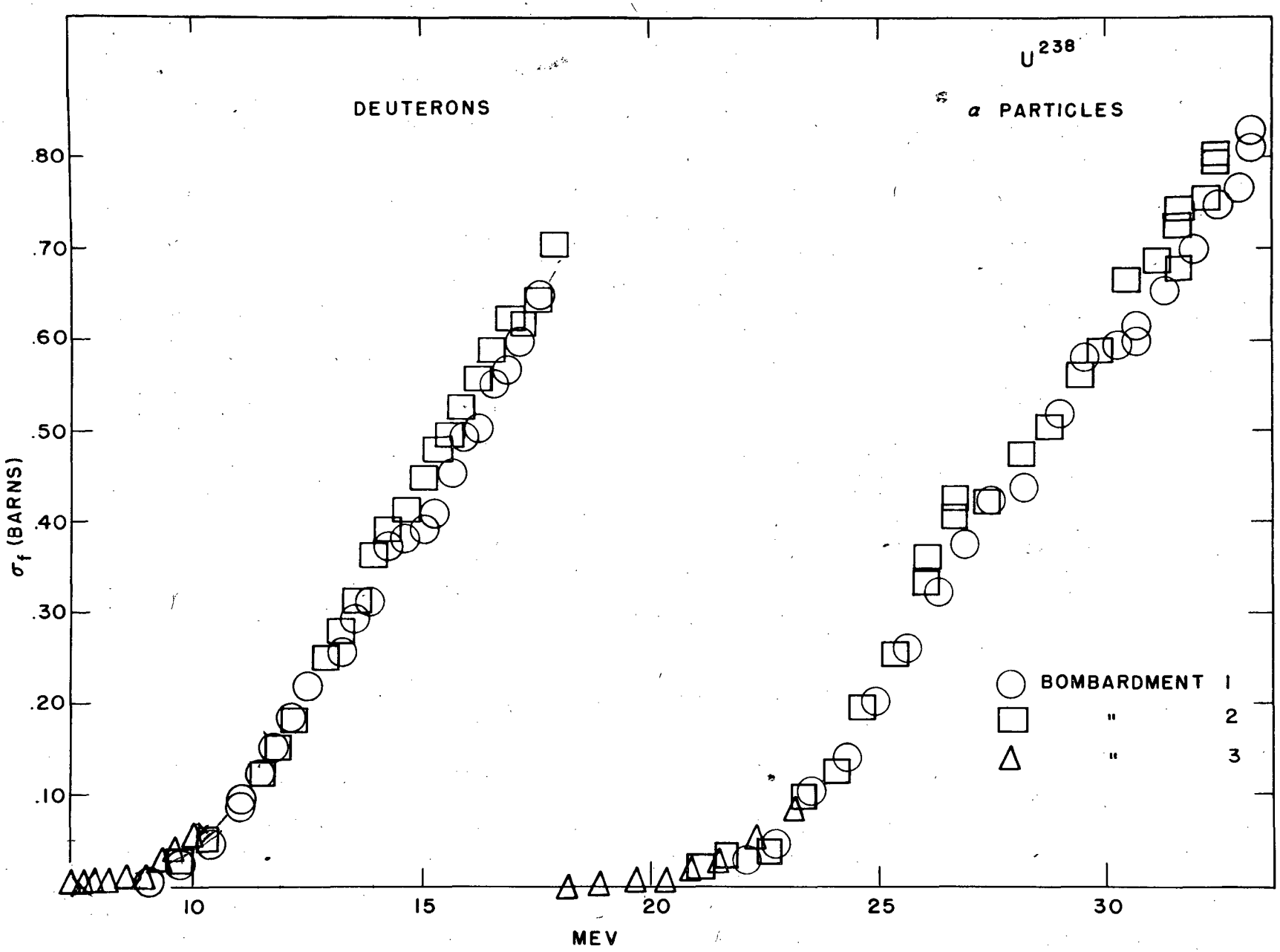
U238
DEUTERONS
α PARTICLES
σf (BARNS)
.80
.70
.60
.50
.40
.30
.20
.10
10
15
20
25
30
MEV
BOMBARDMENT 1
" 2
" 3

FIG. 3

OZ 616

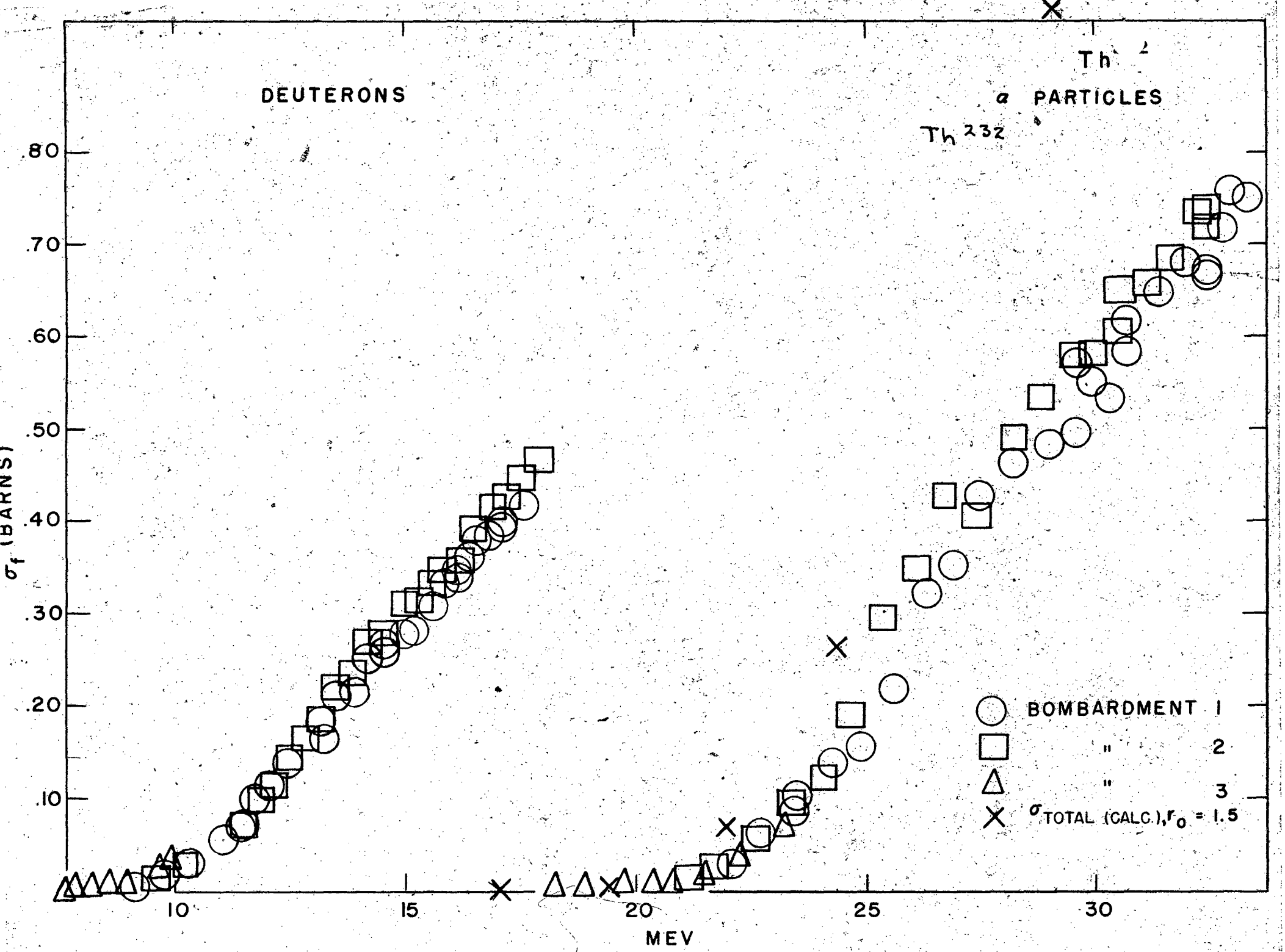
DEUTERONS
α PARTICLES
Th 232
.80
.70
.60
.50
.40
.30
.20
.10
σf (BARNS)
10
15
20
25
30
MEV
BOMBARDMENT 1
" 2
" 3
σTOTAL (CALC.), r0 = 1.5

FIG. 4

13680-4

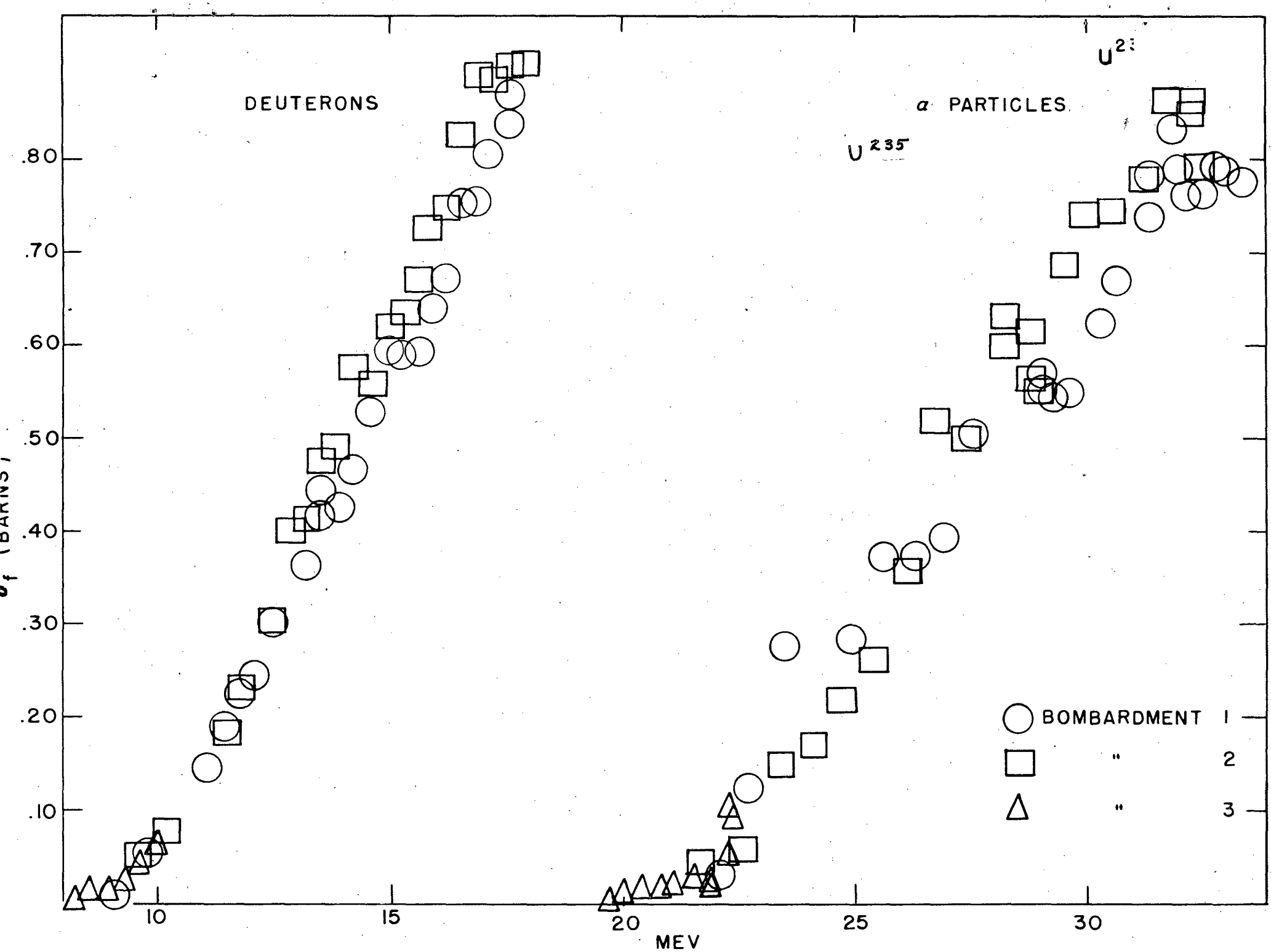
DEUTERONS
α PARTICLES
U 235
U 23
.80
.70
.60
.50
.40
.30
.20
.10
σf (BARNS)
10
15
20
25
30
MEV
BOMBARDMENT 1
" 2
" 3

FIG. 5

13678-1

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 four above the figures given.

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 fission count.

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* and Schmieder[13] reports 24.9

*quoted from Rossi and Staub, LA-1004R, Vol. I, Part II, p. 308

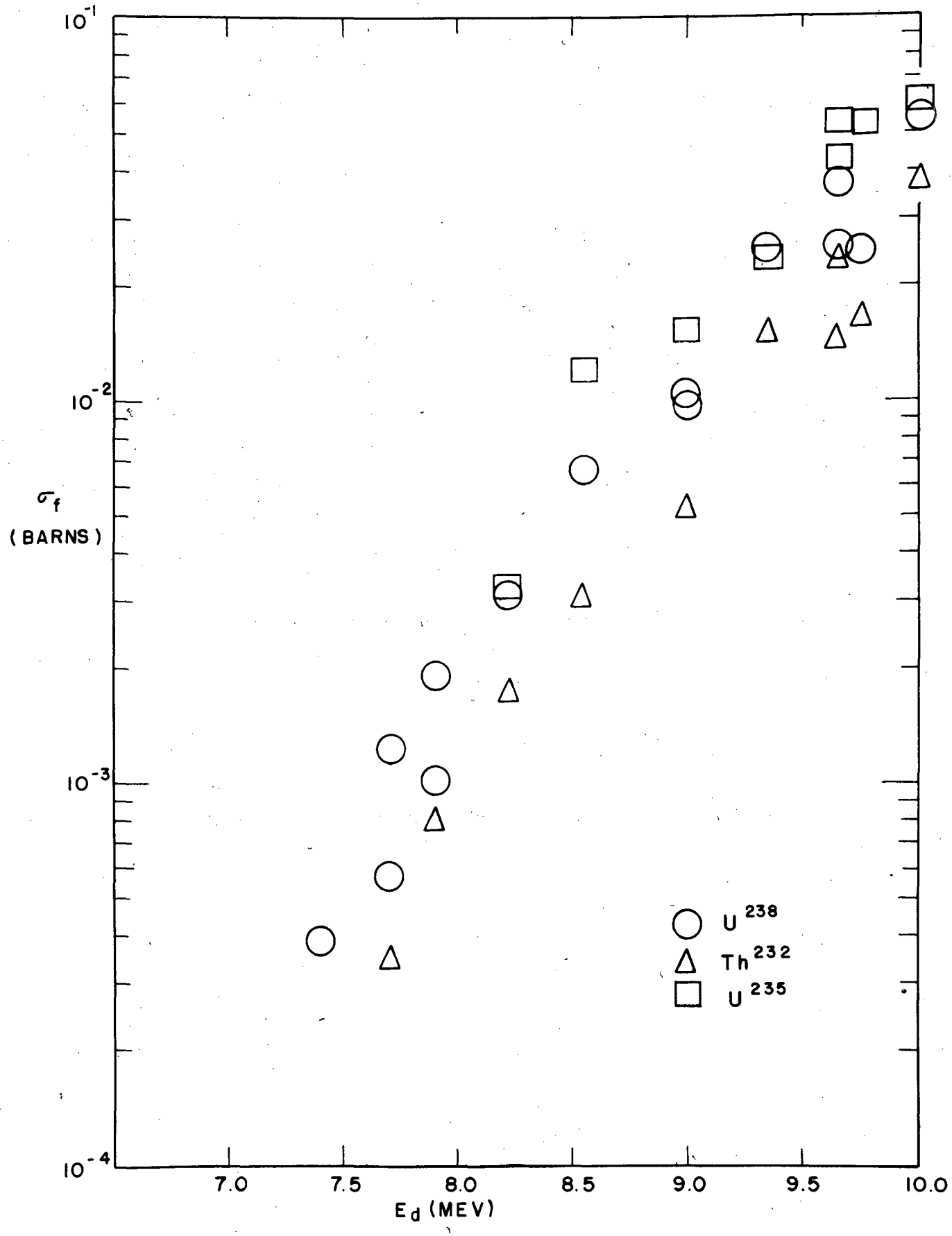
10^{-1}
10^{-2}
10^{-3}
10^{-4}
σ_f
(BARNS)
7.0
7.5
8.0
8.5
9.0
9.5
10.0
E_d (MEV)
U^{238}
Th^{232}
U^{235}

FIG. 6

OZ 615

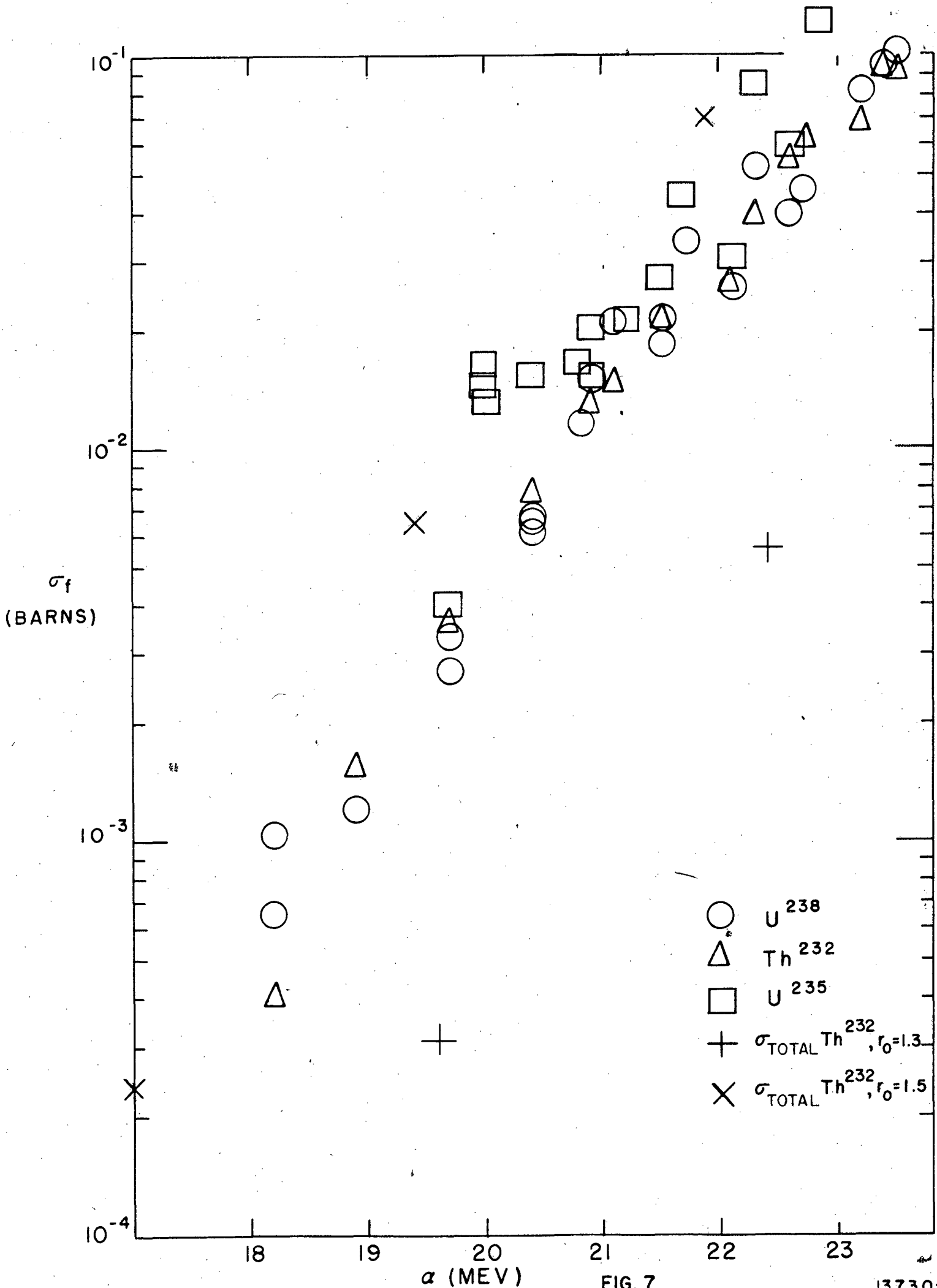
10^{-1}
10^{-2}
10^{-3}
10^{-4}
σ_f
(BARNS)
18
19
20
21
22
23
α (MEV)
U^{238}
Th^{232}
U^{235}
σ_{TOTAL} Th^{232}, r_0=1.3
σ_{TOTAL} Th^{232}, r_0=1.5

FIG. 7

13730-1

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.

TABLE I

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

3. Value of $Bi(\alpha,2n)At^{211}$ Cross Section. In order to have an independent check on the absolute value of the cross section, it was decided to measure the $Bi(\alpha,2n)At^{211}$ cross section with the equipment used in this experiment. The excitation function for this reaction has been extensively studied by Kelly and Segrè[7]. A bismuth foil of known thickness was kindly supplied by Kelly and it was placed as one of the targets on the sample wheel. The At^{211} formed by the alpha bombardment is an alpha emitter of 7.5 hour half life. An alpha count of the bismuth sample after a bombardment with a known number of alpha particles then furnished the cross section for formation of the At^{211}. At the beam energy used (32.4 Mev) At^{210} is also formed with about one half the cross section as that of At^{211}. Since it decays by K capture to Po^{210}, which has a 140 day alpha activity, it contributes a negligible activity if the sample is counted immediately after bombardment. The alpha count was made using the fission excitation function equipment; it was only necessary to increase the gain of the amplifier so that the scalar would be actuated. To provide a check on the

reliability of the apparatus as an alpha counter another of the target positions of the sample wheel was provided with a thin sample of U^{238} which had been carefully counted on the laboratory alpha counter. By selecting this target with the sample changer the condition of the apparatus could be checked at any time. The alpha activity was determined to about three percent. The value for the cross section obtained was 0.73 barns which is in agreement with the result given by Kelly and Segrè of 0.75 barns.

D. Discussion.

1. Comparison with β-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[15] has investigated the fission yield versus mass spectrum for fission induced in thorium by alpha-particles. He finds 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 considerably lower than the results of the present experiment. Part of the discrepancy may be found in 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 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 β-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[16] 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 $R = (r_o A^{1/3} + 1.48) \times 10^{-13}$, where A is the mass number of the target nucleus. Weisskopf gives points for $r_o = 1.3$ and $r_o = 1.5$. These points are plotted on the threshold excitation function for alpha particles.

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 $r_o = 1.5$ 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-inch Synchrocyclotron Experiment

A. Apparatus and Method

The fission chamber and samples used were the same as for the 60-inch cyclotron experiment. The sample areas were increased to 1/2 inch diameter and the beam was again collimated to 5/16 inch. 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 practical to have a collimator for each sample as in the 60-inch cyclotron experiment. The major collimation was done 12 inches 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 inches in diameter and 4-1/2 inches in length. This geometry is sufficient to trap the proton beam (340 Mev) according to the data of Petersen.* Secondary particles were trapped with a hollow two inch copper cylinder 1-1/8 inches in diameter and 1/8 inch thick, which was attached to the beam end of the large cylinder. Since the beam intensities were much smaller than the 60-inch 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 circuit. A small air-cooled oil diffusion pump maintained the Faraday cup at high vacuum (less than 5×10^{-4} mm Hg).

The external beam of the 184-inch 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 in the relatively continuous beam of the 60-inch 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 good 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 Figure 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 uncancelled 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

*V. Petersen, private communication

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-inch 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-inch cyclotron in the case of α-particle and deuteron bombardments. The straggling observed also is an indication of the homogeneity of the beam.

B. Results.

1. Excitation Functions. Figures 8 - 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-inch cyclotron experiment. The probable error of points that have zero cross section are computed on the assumption of one observed fission. The neutron fission background was about

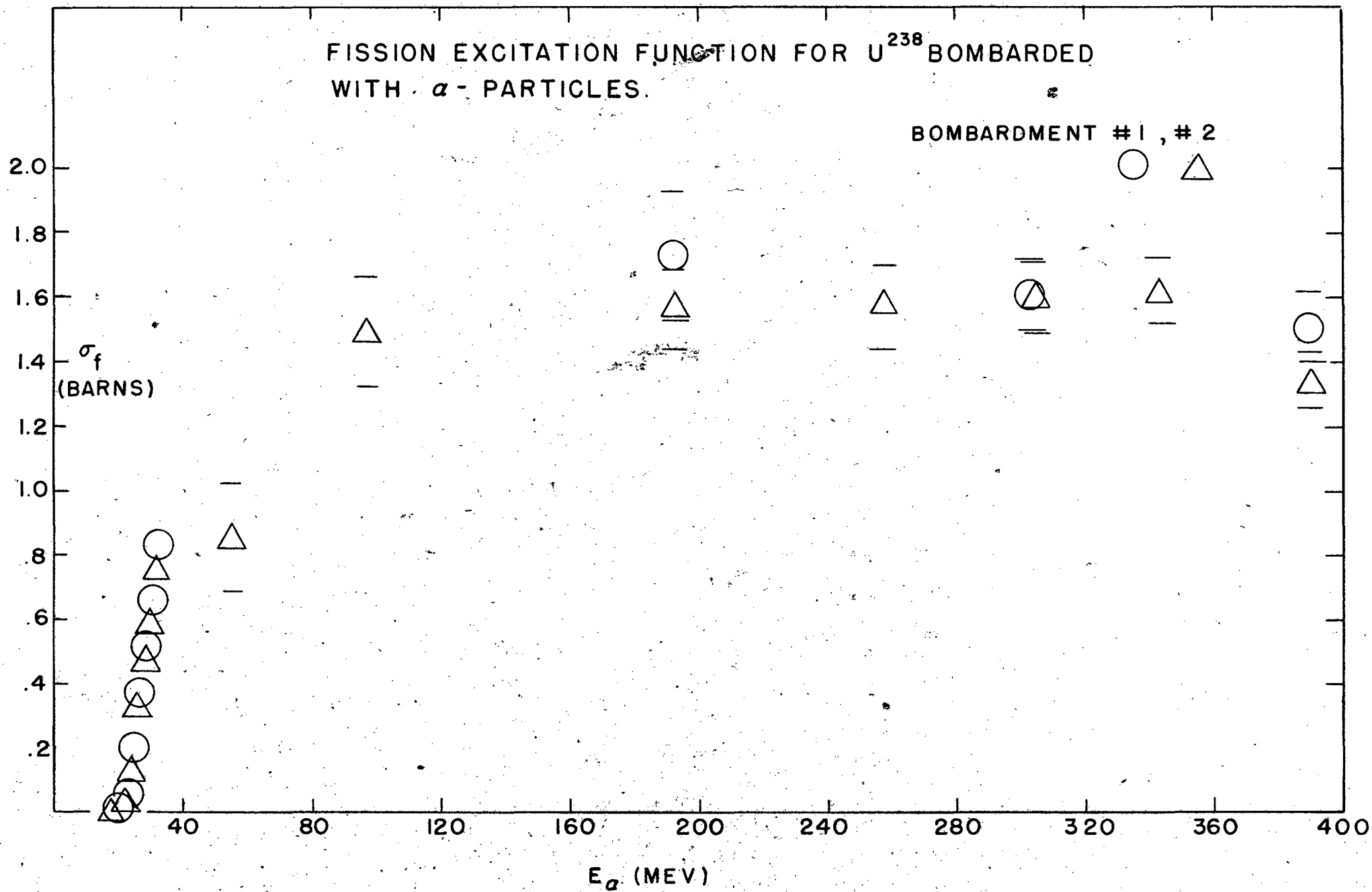
FISSION EXCITATION FUNCTION FOR U238 BOMBARDED WITH α - PARTICLES.
BOMBARDMENT #1 , #2
σf (BARNS)
2.0
1.8
1.6
1.4
1.2
1.0
.8
.6
.4
.2
40
80
120
160
200
240
280
320
360
400
Eα (MEV)

FIG. 8

13991-1

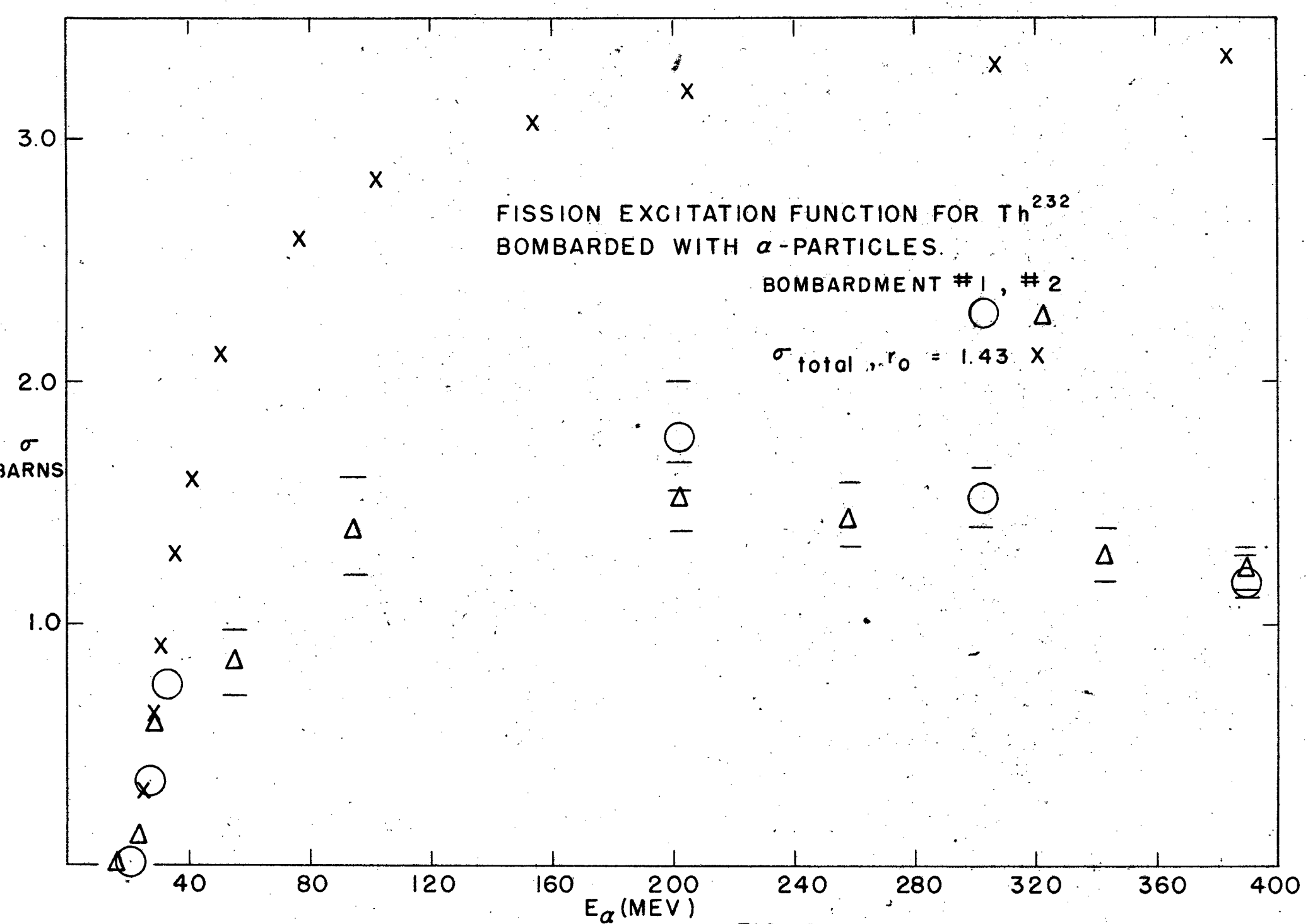
FISSION EXCITATION FUNCTION FOR Th^{232}
BOMBARDED WITH α-PARTICLES.
BOMBARDMENT #1, #2
σ_{total}, r_0 = 1.43 X
3.0
2.0
1.0
σ
BARNS
40
80
120
160
200
240
280
320
360
400
E_α (MEV)

FIG. 9

14076-1

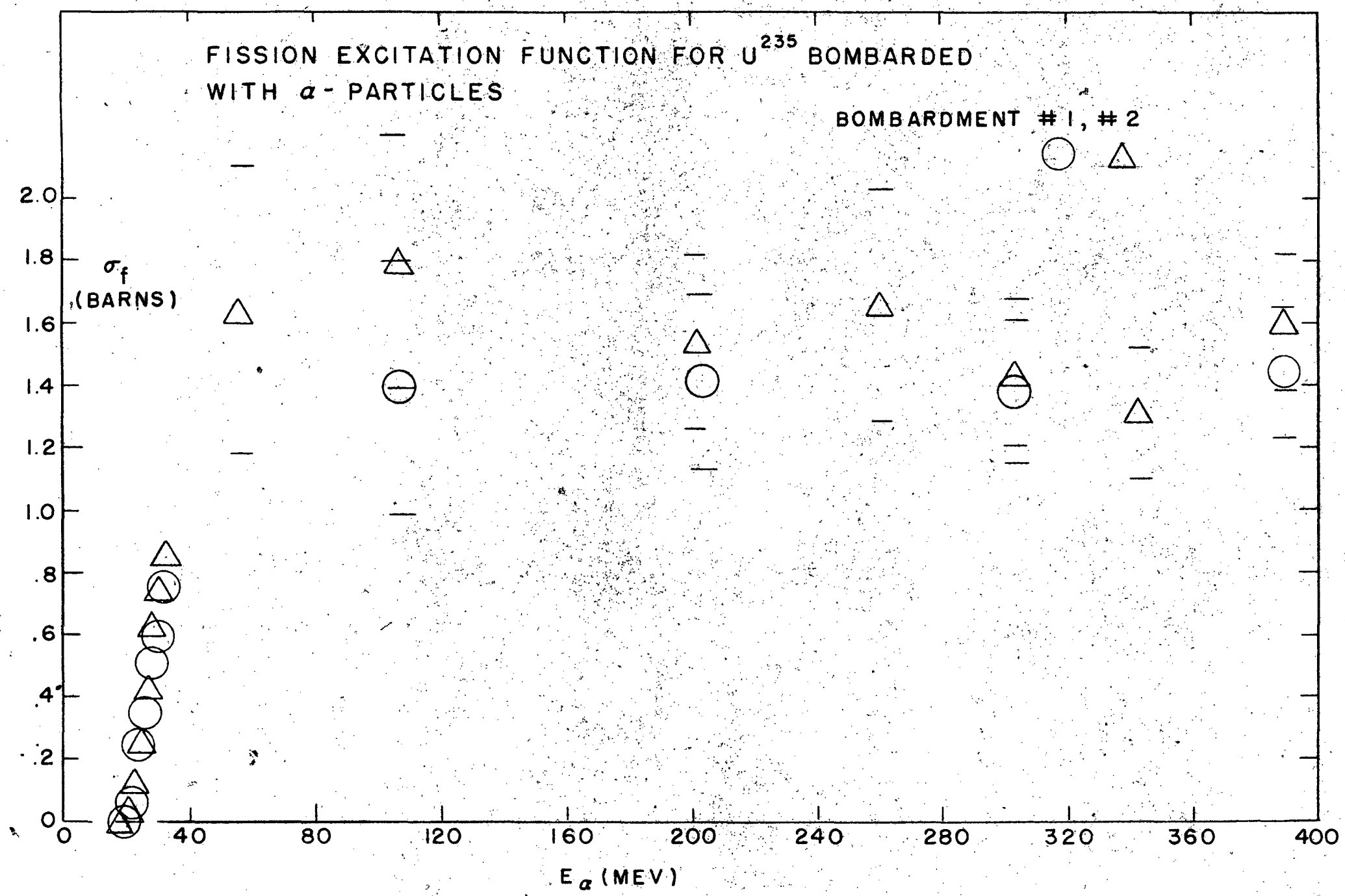

FIG. 10

14002-1

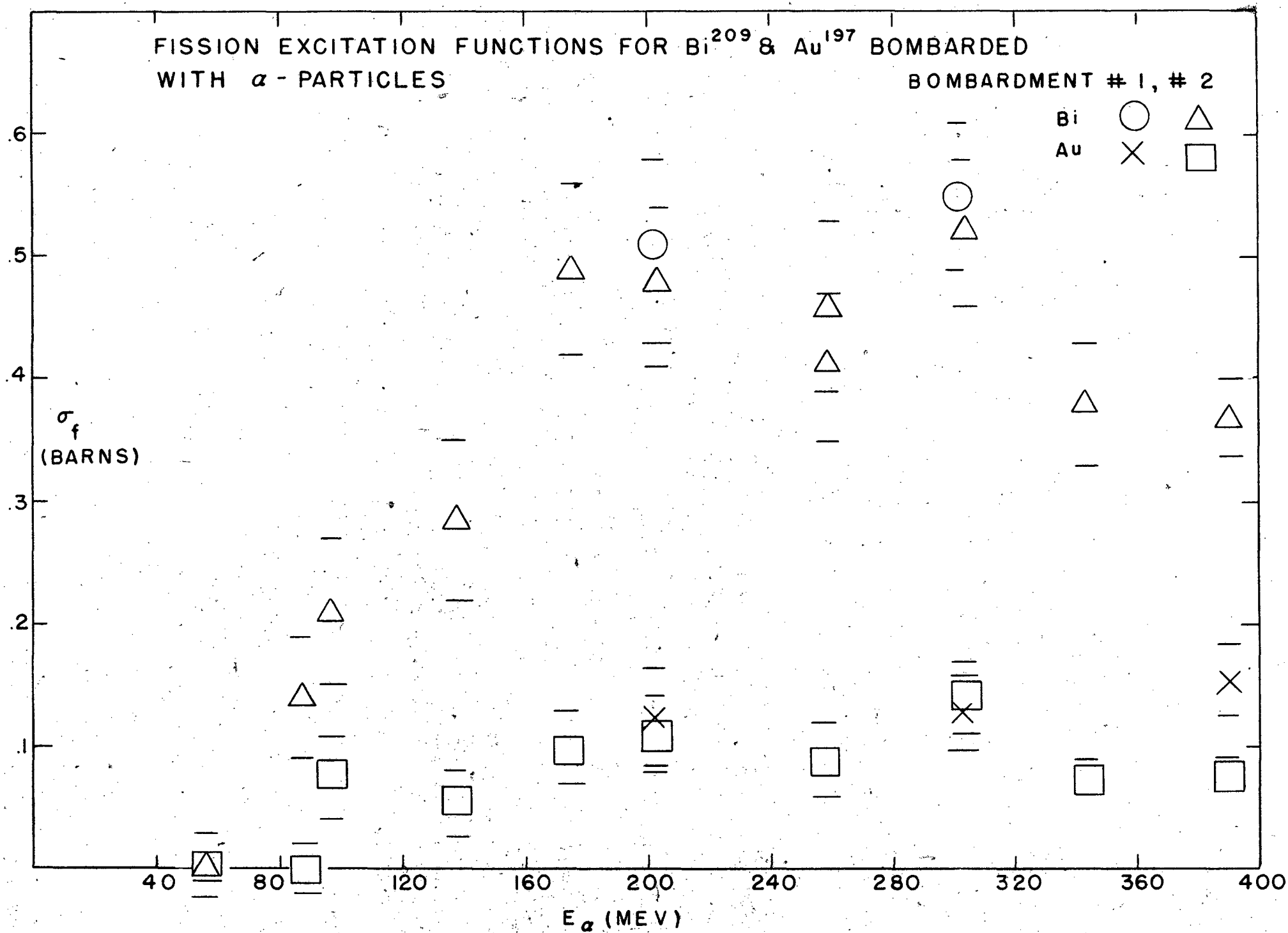

FIG. 11

13994-1

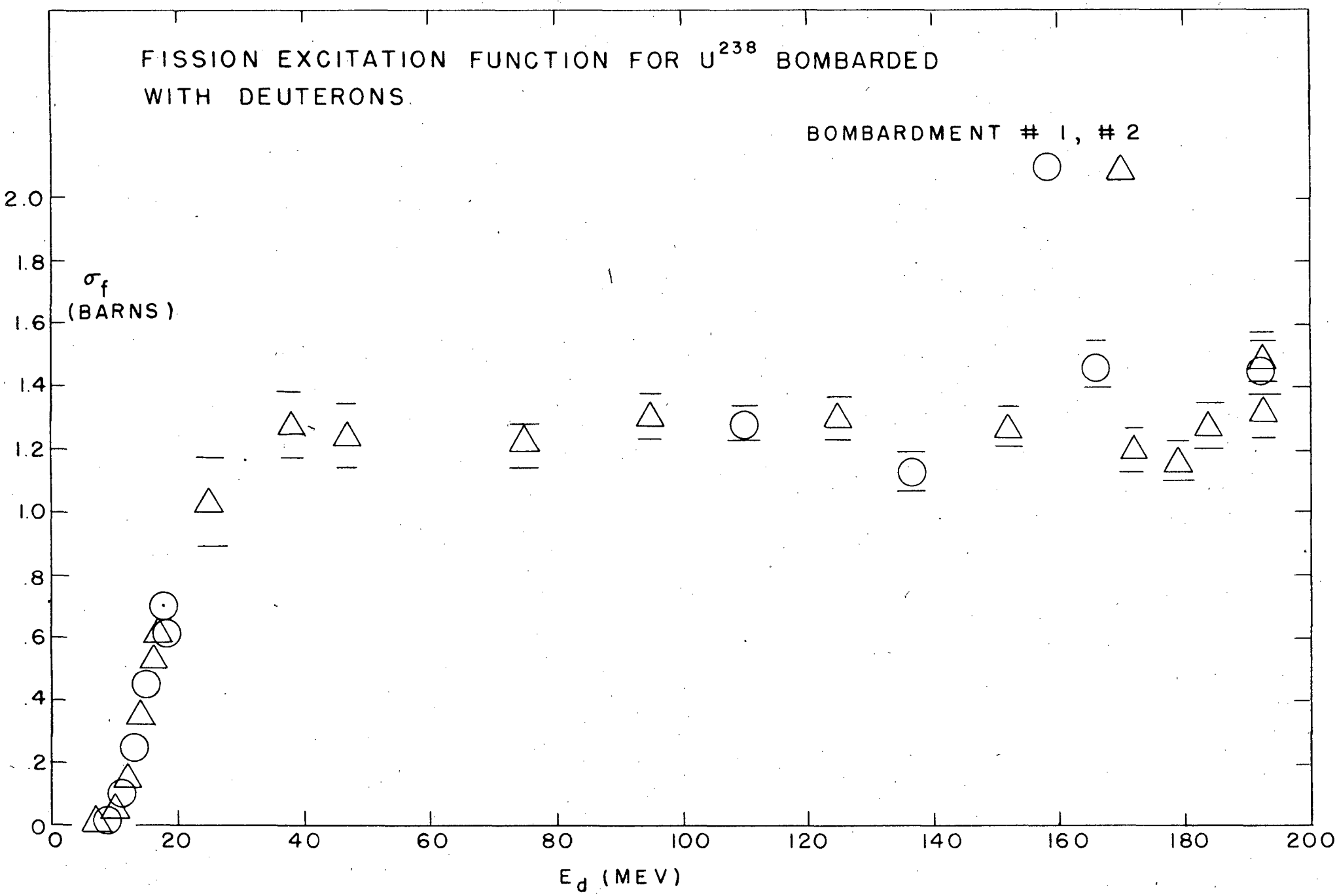
FISSION EXCITATION FUNCTION FOR U238 BOMBARDED WITH DEUTERONS
BOMBARDMENT # 1, # 2
σf (BARNS)
2.0
1.8
1.6
1.4
1.2
1.0
.8
.6
.4
.2
0
0
20
40
60
80
100
120
140
160
180
200
Ed (MEV)

FIG. 12

14001-

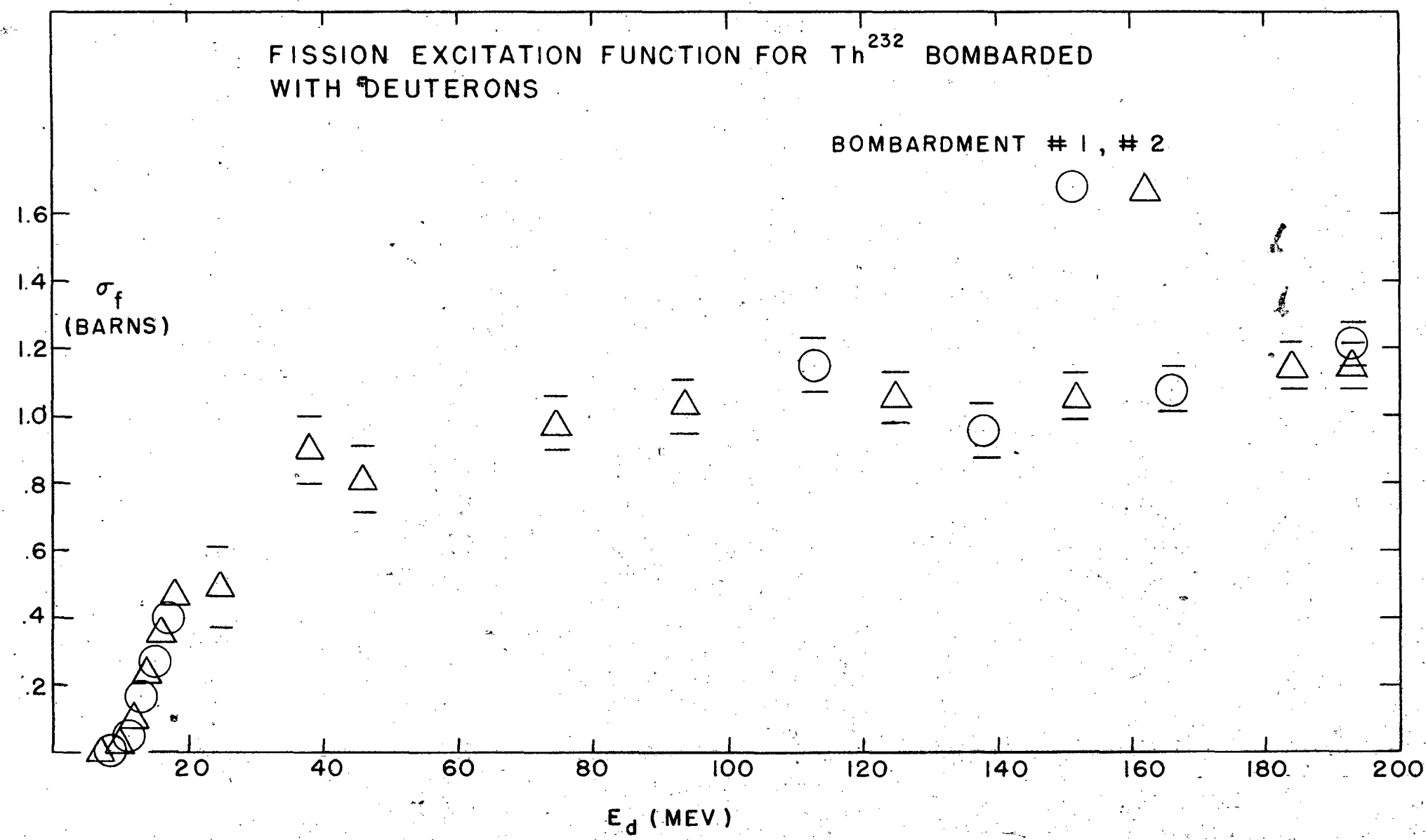
FISSION EXCITATION FUNCTION FOR Th232 BOMBARDED WITH DEUTERONS
BOMBARDMENT # 1, # 2
σf (BARNS)
1.6
1.4
1.2
1.0
.8
.6
.4
.2
20
40
60
80
100
120
140
160
180
200
Ed (MEV)

FIG. 13

13992

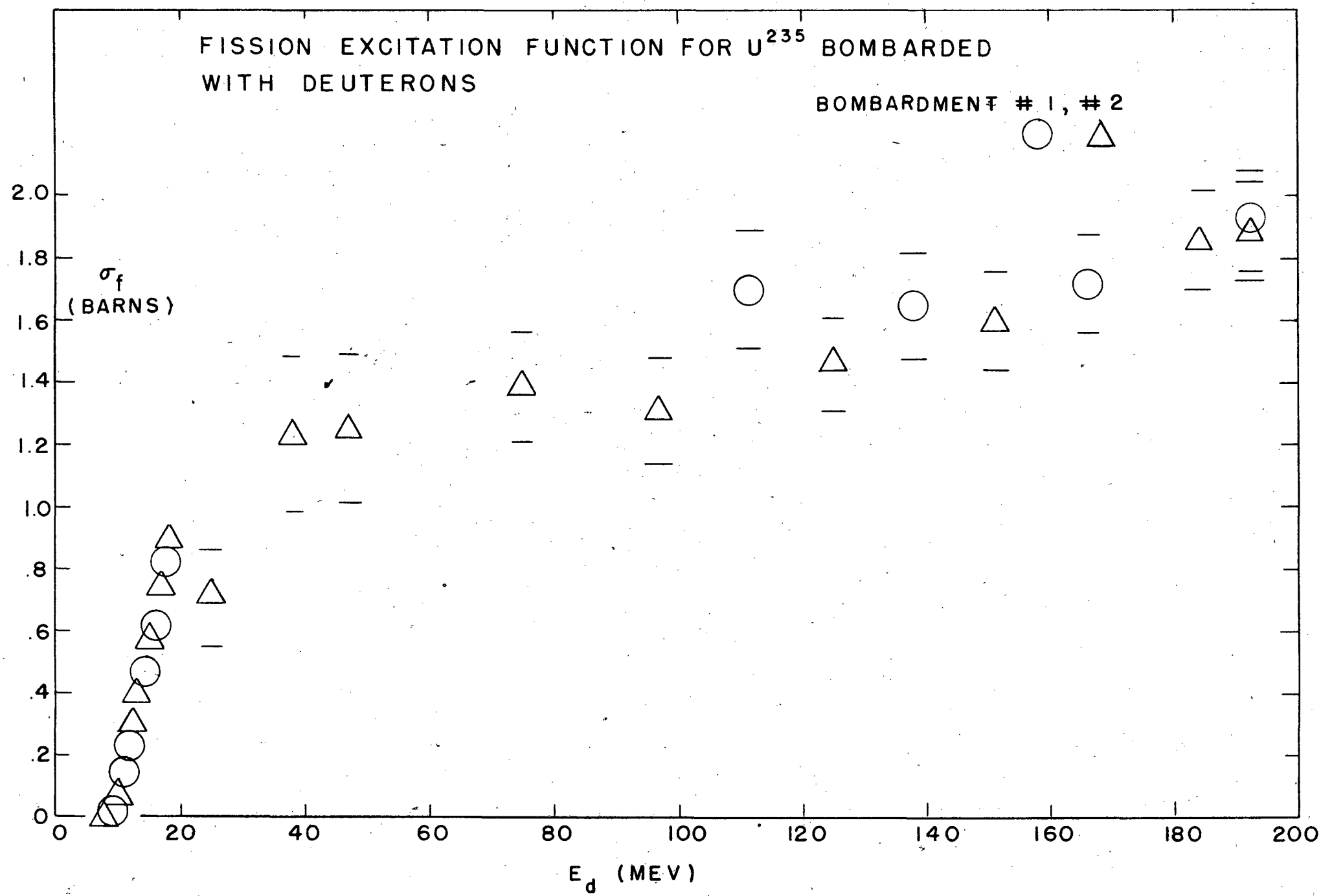
FISSION EXCITATION FUNCTION FOR U235 BOMBARDED WITH DEUTERONS
BOMBARDMENT # 1, # 2
σf (BARNS)
2.0
1.8
1.6
1.4
1.2
1.0
.8
.6
.4
.2
0
0
20
40
60
80
100
120
140
160
180
200
Ed (MEV)

FIG. 14

14000

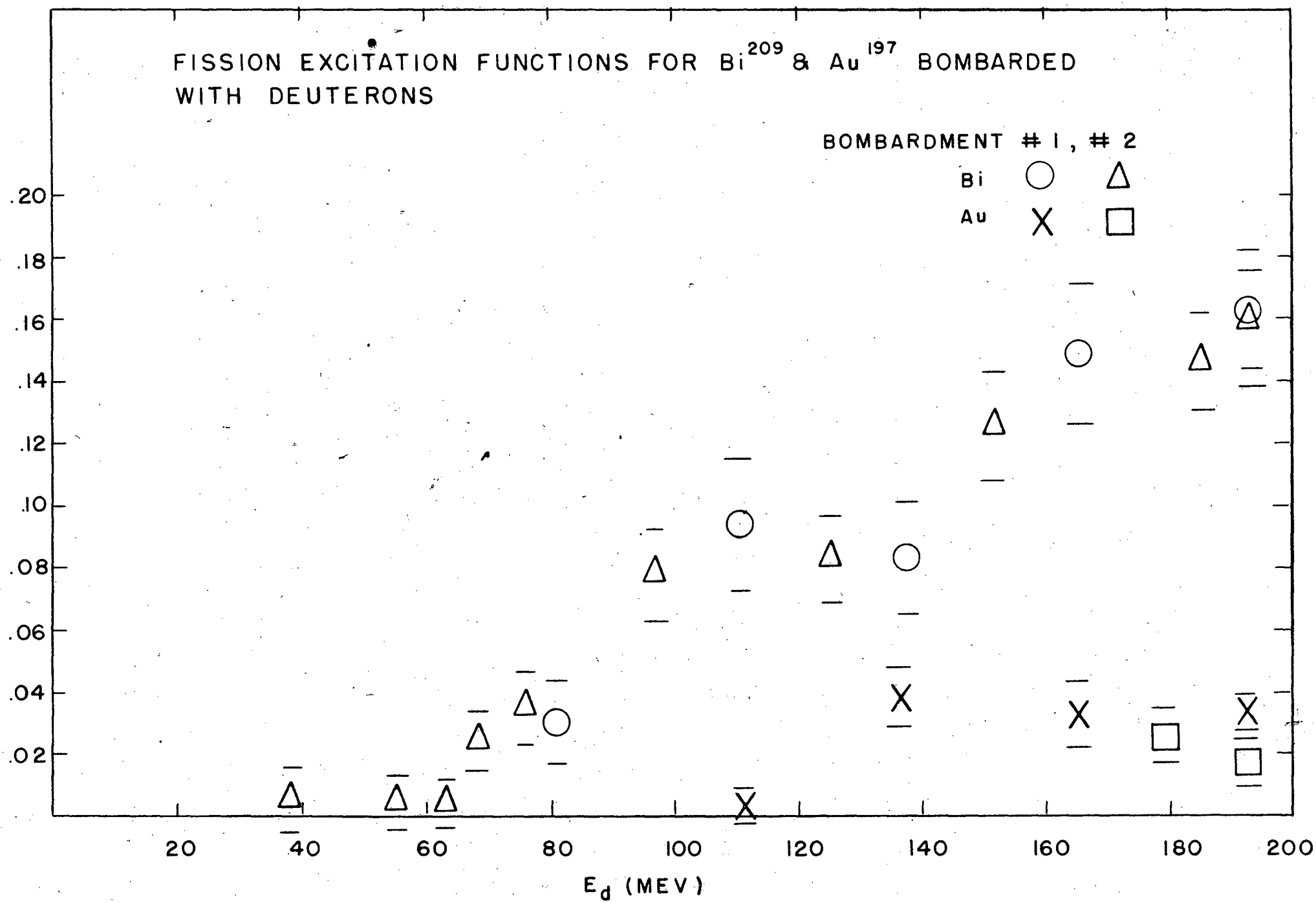

FIG. 15

13995-1

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. Only one bombardment has been made for energies below 200 Mev and so the results are given only for higher energies. 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 U^{238} and U^{235} checked within statistics with previous bombardments. The neutron fission background was about 2% 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 = 30 ev/ion pair. In the case of alpha particles, the measurements were more difficult due to the smaller beam strength, but verification was 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. It should be emphasized that the Faraday cup measurements were made with the same geometry as the fission excitation function experiment.

C. Discussion.

The fission cross section for full deuteron energy was investigated by Goeckermann and Perlman[17] using chemical techniques. They found a value

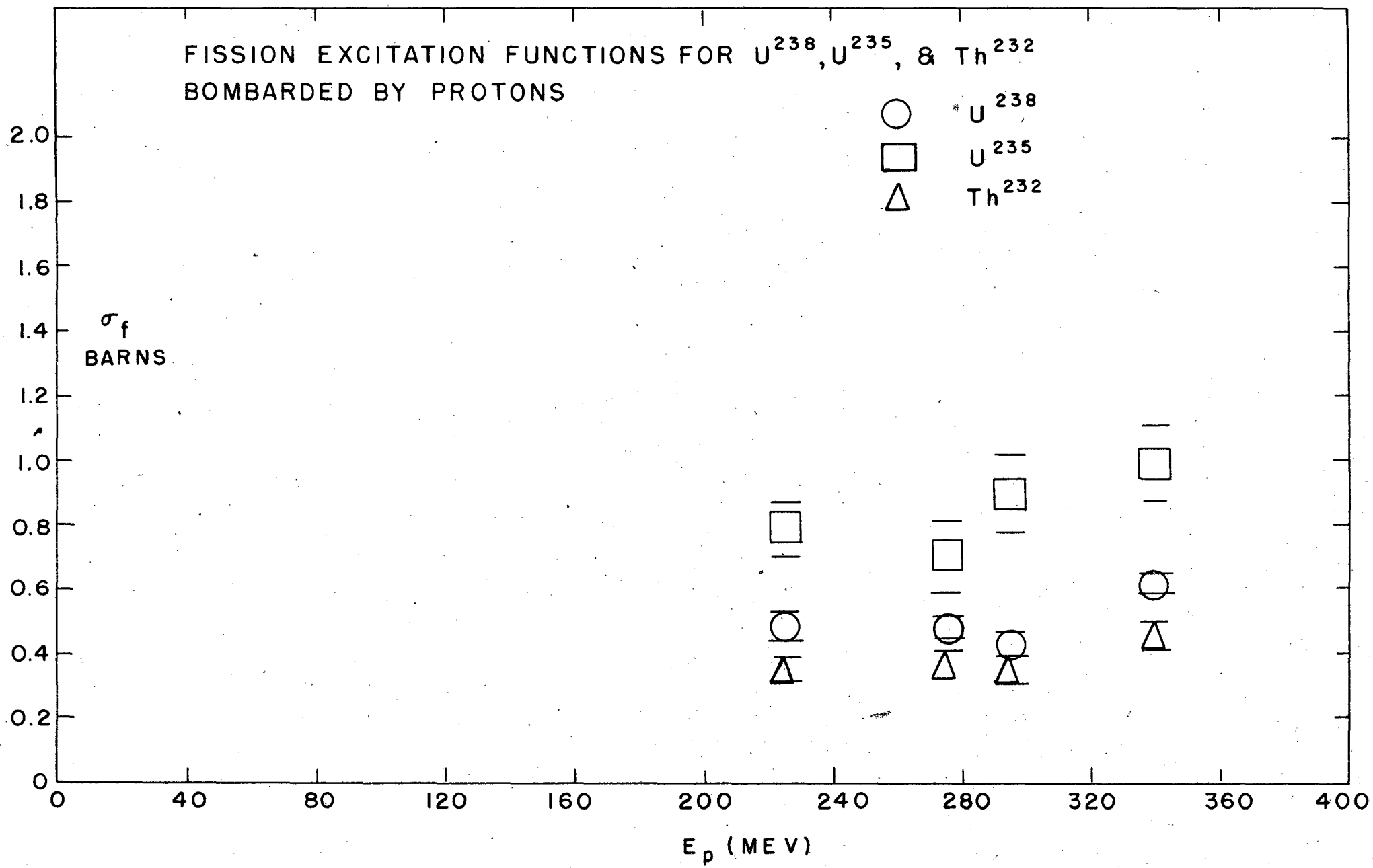

FIG. 16

14031-1

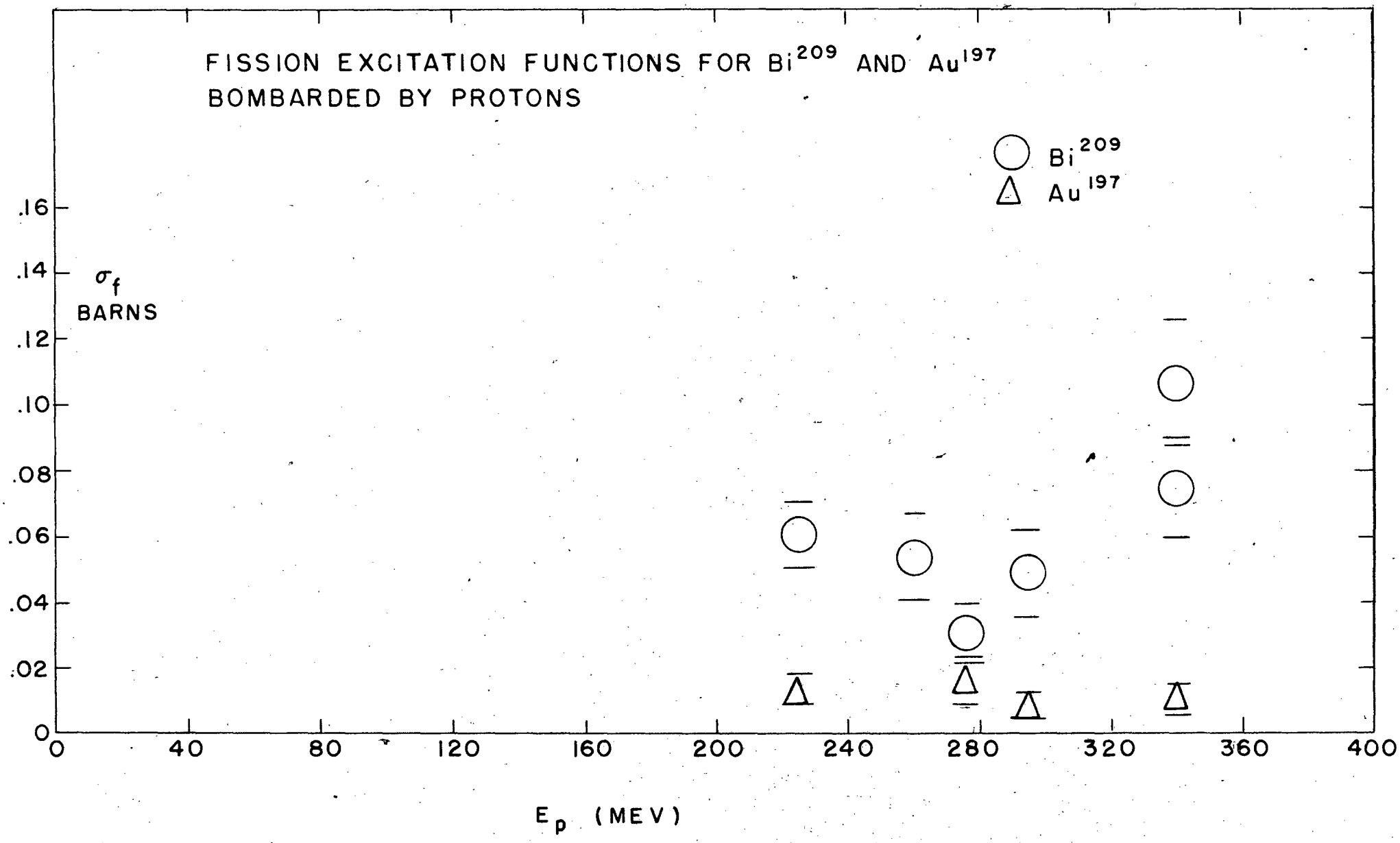

FIG. 17

14030-1

of 0.2 barns which is in agreement with the present experiment within the experimental errors. O'Connor and Seaborg[18] 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 2 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-inch cyclotron show that for $r_o = 1.43$ the fission cross section observed would equal the calculated reaction cross section. Taking this value of r_o the total reaction cross section can be calculated in the region above the Coulomb barrier by an approximate formula given by Bethe and Konopinski[19].

$$\sigma_{reaction} = \pi \lambda\!\!\!^{-2} \, Po \, \ell_c^{\,2}$$

where

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

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 do not use a finite radius for the alpha-particle their r_o should be 1.67 in order to correspond to Weisskopf's choice of 1.43. This r_o 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). This choice of r_o gives the minimum possible competition with the fission process. It is seen that the competition begins to become appreciable above 30 Mev and increases steadily with increasing alpha-particle energy. There is some chemical evidence obtained by James[15] 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 Prof. E. Segrè throughout this investigation and also wishes to thank Prof. G. C. Wick and Prof. V. Weisskopf for helpful discussions of the theoretical problems. Thanks are also due to C. Wiegand and Dr. O. Chamberlain for many valuable suggestions. The cooperation of the personnel of the Crocker cyclotron and of the 184-inch cyclotron is gratefully acknowledged.

The work was done under the auspices of the Atomic Energy Commission.

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