cross section. This is due to the rather reduced angular range of the statistical effects studied here.

We should like to conclude by again emphasizing that the scattering processes predicted by the models studied here could not represent but a qualitative description of these phenomena exhibited by liquid He_4 or liquid He_3, in the eventuality of an explicit effect of quantum statistics on neutron scattering. As mentioned briefly, the angular range in liquid He_4 where the statistical effects are prominent, if present, would be narrowed down by the broadening of the transmitted beam and the coherent beam. It would appear that the investigation of the scattering at some fixed intermediate angle as a function of the liquid temperature offers the most favorable way in which to look for the effect of statistics.[19]

[19] Dr. E. A. Long (University of Chicago) kindly informed the senior author (L.G.) of Dr. E. Fermi's independent suggestion of such experiments in 1948. He also briefly discussed this problem at the AEC Information meeting, Los Alamos, May 1949.

PHYSICAL REVIEW VOLUME 77, NUMBER 3 FEBRUARY 1, 1950

Experimental Photo-Fission Thresholds in $_{92}U^{235}$, $_{92}U^{238}$, $_{92}U^{233}$, $_{94}Pu^{239}$, and $_{90}Th^{232}$*

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(Received September 26, 1949)

An investigation of the photo-fission thresholds in $_{92}U^{235}$, $_{92}U^{238}$, $_{92}U^{233}$, $_{94}Pu^{239}$, and $_{90}Th^{232}$ with a 20-Mev betatron is reported. A method of alpha-self-cancellation is described which permits the detection of fissions and the determination of threshold energies in the two highly alpha-active samples of $_{92}U^{233}$ and $_{94}Pu^{239}$. An investigation of the photo-neutron threshold in nitrogen and the energy calculation from mass data provided a check of the absolute energy scale obtained from voltage measurements on the betatron.

INTRODUCTION

THE production of high energy x-rays of adjustable energy by a betatron makes possible the study of the photo-fission thresholds in uranium. Previous work with monokinetic energy gamma-rays[1] could only be concerned with predictions of these threshold energies. A Japanese paper,[1] for example, predicted the $_{92}U^{238}$ photo-fission threshold to be at 3.0 Mev. This was based on their measured gamma-ray cross sections in uranium of 2.2×10^{-27} cm^2 at 6.3 Mev and of 16.7×10^{-27} cm^2 at 17 Mev and an assumed functional variation of cross section with energy.

A more reliable prediction can be made theoretically by making use of the liquid drop model of Bohr and Wheeler.[2] Frankel and Metropolis[3] from calculations on the Eniac found the values given in Table I for classical fission thresholds, that is for energy differences between the initial spherical equilibrium shape of the drop and the saddle point shape. Changes in the constants used for the nuclear radius and the surface tension would change the relations of these values only very slightly.

The first attempt to determine experimentally a uranium photo-fission threshold was done by Baldwin and Koch[4] with a 20-Mev betatron. Their use of a sample of ordinary uranium powder and the catcher method for studying the activity in the fission fragments showed that the threshold was less than 8 Mev. Threshold assignment was not possible due to the lack of fission intensity at the lower energies. More recently a University of Illinois thesis[5] described the use of the betatron's x-rays in conjunction with a fission ionization chamber and a linear amplifier. The determination of the fission pulse yield as a function of betatron energies gave a threshold for $_{92}U^{238}$ at 5.8 Mev and for $_{90}Th^{232}$ at 6.25 Mev.

These experiments were continued using the 20-Mev betatron at the University of Illinois when separated samples of the uranium isotopes were made available by the Manhattan Project. It was hoped that a definite check of the relative values of the predicted photo-

TABLE I. Theoretical threshold energies.

Nucleus	Fission threshold energies (Mev)
U^{238}	7.0
U^{235}	6.1
U^{233}	5.7
Pu^{239}	4.9

* This work was done under the auspices of the Metallurgical Laboratory at the University of Illinois under contract W-7401-37-121 in 1944 and 1945. The report as here presented was submitted on January 30, 1947 and declassified on August 29, 1949.

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[1] Arakatu, Uemura, Sonoda, Shimizu, Kimura, and Muraoka, Proc. Phys. Math. Soc. Japan **23**, 440 (1941); Haxby, Shoupp, Stephens, and Wells, Phys. Rev. **59**, 57 (1941).

[2] N. Bohr and J. A. Wheeler, Phys. Rev. **56**, 426 (1939).

[3] S. Frankel and N. Metropolis, Phys. Rev. **72**, 914 (1947).

[4] G. C. Baldwin and H. W. Koch, Phys. Rev. **67**, 1 (1945).

[5] H. W. Koch, thesis, University of Illinois (1944).

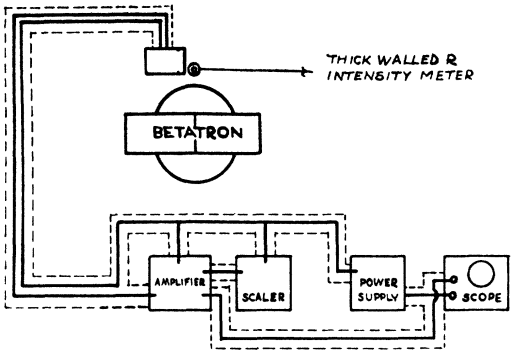

FIG. 1. Arrangement of apparatus.

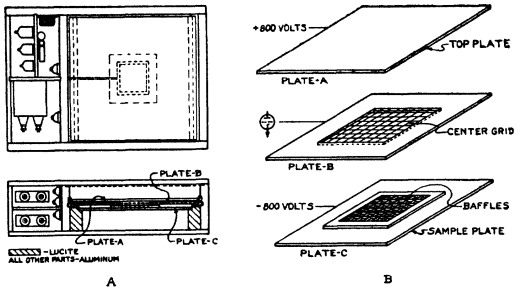

FIG. 2. Cancellation chamber. The alpha-particles from the sample of plate C are caused by proper collimation to traverse both chambers and to produce self-cancelling voltage pulses. Ideally, no alpha-particle voltage pulse is transmitted to the amplifier grid connected to plate B. On the other hand, the shorter range fission fragments produce voltage pulses across plates B and C and are registered by the linear amplifier-scaler counting circuits.

fission thresholds could be determined with the betatron.

The work has proceeded along two lines: the improvement in the particular detection techniques required for handling the various uranium isotopes and the improvement of the absolute calibration of the betatron's x-rays. A new chamber principle was employed to reduce the alpha-background by self-cancellation in samples whose alpha-activity was so high that it would have masked the fission pulses in an ordinary chamber.

The first check of the energy calibration of the betatron which was obtained from voltage measurements was made with the photo-neutron threshold in nitrogen. Mass data allowed an accurate calculation of the nitrogen (γ, n) threshold.

APPARATUS

Figure 1 shows the general experimental arrangement in front of the 20-Mev betatron. The chamber containing the sample was placed directly in the cone-shaped x-ray beam which proceeds from the betatron. The half-angle of this cone is approximately $\theta = 171/E$, where θ is in degrees and E in Mev. Because of the width of the beam at the photo-fission thresholds at 5 Mev, the chamber and the Victoreen R-meter were completely covered with roughly the same x-ray intensity when placed at a distance of 70 centimeters from the target. The x-ray intensity at 5 Mev was 1 R/min. at the chamber position.

The chamber with a built-in preamplifier was connected by means of a 50-foot shielded cable to a fast amplifier, a discriminator and a Higginbotham type of scaling circuit. The amplification of the amplifier was comparatively constant at roughly 105 up to a high frequency cut-off at 700 kilocycles per second.[6] The input time constant was 5 microseconds. Although low frequency pick-ups from sources such as the betatron power frequency of 180 cycle per second were entirely eliminated, a high frequency signal disturbance was observed due to the betatron electron injection pulse whose fundamental frequency was about 10^5 cycles per second. A grounded Faraday screen shield between the injection circuit and the chamber almost entirely eliminated this stray effect.

The preliminary work for the investigation was done

TABLE II. Summarized data for depleted uranium sample (Fig. 3).

Peak spectrum energy (Mev)	Total number of fission pulses	Total x-ray intensity R units	Total observation time (min.)	Fission counts per R	R.m.s.[a] deviation in counts/R
4.81	11	28.75	180	0.38	
4.88	9	36.70	210	0.25	
5.04	11	47.10	240	0.24	
5.20	78	54.05	255	1.44	
5.35	161	53.25	240	3.02	
5.51	390	66.40	270	5.87	
5.67	692	63.55	240	10.89	
5.84	1139	63.90	240	17.99	
6.00	1086	44.55	150	24.40	
6.16	1447	48.25	150	29.99	
6.33	1605	40.15	120	40.01	
6.49	2136	48.45	135	44.09	
6.66	2280	43.70	113	52.08	
6.82	2390	37.60	90	63.57	

[a] The data books containing the information for column 6 were not available at the time of this writing.

TABLE III. Summarized data for enriched uranium sample (Fig. 4).

Peak spectrum energy (Mev)	Total number of fission pulses	Total x-ray intensity R units	Total observation time (min.)	Fission counts per R	R.m.s.[a] deviation in counts/R
4.99	6	28.70	135	0.21	
5.07	5	36.67	178	0.13	
5.16	8	42.26	195	0.19	
5.25	8	39.93	180	0.20	
5.32	29	44.85	193	0.65	
5.41	49	42.60	190	1.15	
5.49	71	47.96	195	1.48	
5.64	134	45.98	180	2.92	
5.81	270	47.90	179	5.64	
5.98	353	45.45	160	7.74	
6.44	536	31.44	100	16.99	
6.93	1253	38.06	110	32.94	
7.43	1790	37.09	100	47.26	
8.48	3644	33.23	70	109.42	

[a] The data books containing the information for column 6 were not available at the time of this writing.

[6] Mr. T. Brill designed the amplifier circuits used in this work, and a great indebtedness is owed him for his suggestions.

with both a fast and a slow amplifier using an ordinary parallel plate ionization chamber. The fissionable material was coated on both inner sides of the chamber plates. Fission pulses as well as alpha-particle pulses could be detected by means of a linear amplifier and an oscilloscope when 1000 volts d.c. was applied to the chamber plates. The fission pulse height was at least 4 times the pulse heights due to alpha-particles obtained from an ordinary uranium sample. However, from a highly alpha-active source, many alpha-particles are emitted into the chamber simultaneously; thus they pile up and make fission pulses undetectable with the high alpha-background. Two of the isotopes used in our experiment, $_{94}Pu^{239}$ and $_{92}U^{233}$, have a high alpha-decay rate. In order to allow the use of ordinary surface densities of these two isotopes and thereby maintain a given sensitivity, a special chamber was developed which reduced the alpha-pulse heights by self-cancellation.

This chamber schematically shown in Fig. 2 consisted of three plates, *A*, *B*, and *C*, where *A* and *C* were run at positive and negative 800 volts respectively, while *B* was connected to the grid of the first amplifier stage. Air was used in the chamber at a pressure suitable for the given investigation. The samples to be irradiated were coated on the top of plate *C* facing into the bottom chamber volume. Plate *B* was a wire mesh grid. With the addition of a baffle placed over the sample on plate *C* (see Fig. 2) all those alphas whose paths formed too small an angle with the plates of the chamber were removed. The dimensions of the baffles were so determined that most alphas which did not ionize in both chambers and which, therefore, did not produce opposing voltage pulses for self-cancellation were eliminated.

The possibility of applying the chamber to photo-fission work is due to the fact that fission ranges in general are approximately one-half the alpha-ranges for any particular isotope. Thus alphas can be partially self-cancelled with a minimum in the reduction of the fission pulse size. Special care was taken to prevent the loss of any of the fission pulses, since the pulses of fission particles entering the chamber were initially reduced in height by the baffles. The baffles were directly over the sample and were $\frac{7}{32}''$ thick, while the chamber depth, which was adjusted to equal approximately the fission range, was $\frac{13}{32}''$. Therefore, since the baffles were at the same potential as the sample plate, the first $\frac{7}{32}''$ of the fission range was below the plane of the baffle surface and was lost. This represents about $\frac{1}{3}$ of the total fission ionization produced in the chamber.

The cancellation chamber was also effective in balancing out the background x-ray burst from the betatron which is $\frac{1}{2}$ microsecond wide. The x-ray pulses occurring in the two bucked chambers are canceled as are the alpha-pulses while the fission pulses in one chamber are registered.

Plates 13×13 inches in area were first used to give as large a practical chamber as possible. Alpha-particles could be detected in spite of this large capacity. However, because of definite limitations to the available sample supplies, a 3×3 inch center plate was used and the chamber volume was limited by Lucite walls. (See Fig. 2.) A desirable increase in the signal-to-noise ratio, a reduction in microphonics, and a standardization in sample data resulted from the use of the smaller chamber.

METHOD

The preparations required for taking data with the five fissionable isotopes available differed because of the high alpha background which was present in only two of the isotopes, $_{92}U^{233}$ and $_{94}Pu^{239}$. In the experiments with $_{92}U^{235}$, $_{92}U^{238}$, and $_{90}Th^{232}$, it was possible to

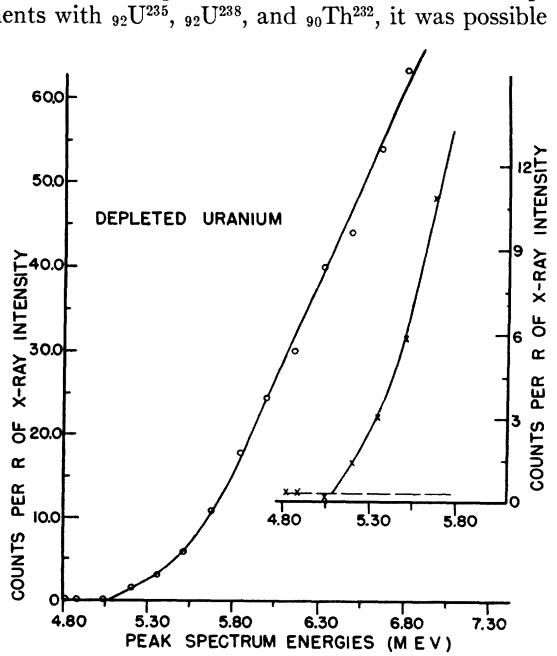

FIG. 3. $_{92}U^{238}$ experimental photo-fission threshold curve. The fission activities in terms of fission counts per *R* units of x-ray intensity are plotted as a function of the peak energy of the betatron x-ray spectrum. The background count level is shown by the dotted line.

disregard the alpha-cancellation technique and to replace the wire mesh grid of plate *B* in Fig. 2B by a solid plate. This permitted samples to be coated on both plates by forming the bottom chamber, i.e., plates *B* and *C*, and doubled the effective sample size, while still retaining the x-ray concellation.

The general arrangement as shown in Fig. 1 was to place the cancellation chamber containing the sample at a distance of approximately 75 centimeters from the betatron target and directly in the cone of x-rays issuing from the target. A Victoreen *R*-meter was placed in a 4 centimeter thick Bakelite container and was located close to the chamber in order to monitor the x-ray intensity. The procedure for taking data consisted in counting the number of fissions per roentgen

for each energy setting. The energy scale investigated was covered in successive steps resulting in sets of curves, which were averaged to give the completed data curves in Figs. 3–7.

No individual point was taken for more than a 30-minute period. Six or seven traversals of the energy scale were required to complete the data with a total x-ray intensity of approximately 40R at each energy setting. A given experimental arrangement was used for continuous running periods of three days or more, and a complete energy calibration was made for each three-day set of data.

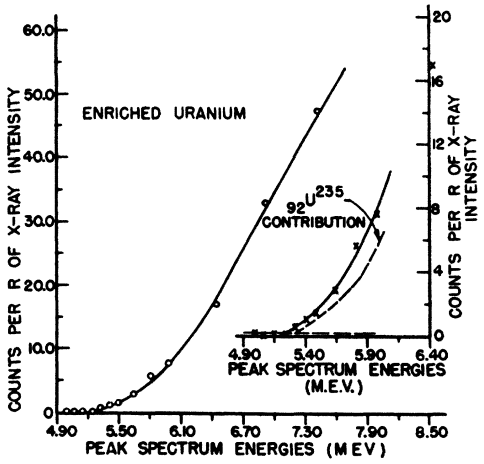

FIG. 4. $_{92}U^{235}$ experimental photo-fission threshold curve.

The only changes in procedure for the $_{94}Pu^{239}$ and $_{92}U^{233}$ concern the preparation of the chamber for alpha-cancellation. The general technique of observing fissions with these isotopes was facilitated by the use of a 100 milligram Ra-Be neutron source. By observing the ratio of fission pulse height to alpha-pulse height, it was possible to determine the optimum conditions for two of the variables—the chamber pressure and the amount of sample baffling. The best combination of chamber voltages and spacing, the only other variables, were determined from the tolerable degree of the residual alpha- and x-ray pulse heights after self-cancellation.

An air pressure of 30 centimeters of Hg was found to give the best fission height to alpha-noise ratio. Since the bottom chamber was 1.2 centimeters deep, these neutron data proved that much of the fission ionization was expended in the thickness of the sample and in the protective sample coatings.

Additional data taken with the neutron source showed the degree of baffling required by each sample. The $_{94}Pu^{239}$ sample required the most complete alpha-cancellation and hence the greatest reduction in the effective sample size. The transmission of the $_{94}Pu^{239}$ baffle was 0.006. This was determined by counting the number of fissions which occurred in the chamber with a $_{92}U^{235}$ sample exposed to neutrons. Runs were made with and without the sample baffle.

Similarly, neutron fission tests on $_{92}U^{233}$ showed that a smaller amount of baffling than required with $_{94}Pu^{239}$ could be used. The $_{92}U^{233}$ baffle produced a reduction in the effective sample weight to 1 percent of the actual weight.

A further decrease in the amount of baffling used on either sample gave an intolerable rise in the alpha-noise background. However, increased baffling produced little effect.

The x-ray cancellation data required that the distance between the top of the baffle and the center grid, as well as the top chamber distance, should be approximately similar and equal to 1.2 centimeters. With these interplate spacings, the baffles in the chamber and 30 centimeters of air pressure, tests were made on alpha-cancellation. Data on the alpha-background height were obtained by keeping the top chamber positive voltage fixed and varying the bottom chamber minus voltage. The cancelled alpha-noise height was then plotted as a function of the negative voltage and a minimum was observed. This minimum represented a reduction of 38 percent in the general alpha-level and was obtained with approximately 800 volts positive and negative on the two chambers. With a smoother control of the chamber spacings and, in general, a better chamber design, more complete alpha-cancellation should be possible.

RESULTS

The data in Tables II–VI were taken with each of the isotopes in turn. Emphasis was placed on an attempt to determine the relative values of the thresholds. Therefore, pairs of isotopes were run in quick succession with a given experimental set-up. This will be noted in the individual isotope discussions.

In the data tables are listed the number of fissions detected at each betatron energy setting normalized to a unit of x-ray intensity measured in R. These have been plotted in Figs. 3–7.

$_{92}U^{238}$ AND $_{92}U^{235}$

The $_{92}U^{238}$, or depleted sample, was depleted of $_{92}U^{235}$. It was coated on two plates[7] with a total area of 99 square centimeters.

The $_{92}U^{235}$, or enriched sample, was enriched in 235 with a 238/235 ratio of 1/4.95. Both the 238 and 235 samples had protective Zapon coating with a surface density of 0.1 mg/cm^2.

The data for $_{92}U^{238}$ and $_{92}U^{235}$ are given in Table II and III and are plotted in Figs. 3 and 4 as fission counts per R as a function of peak spectrum energies. Both sets of data were taken in succession with the same experimental set-up to assure a certainty in the relative energy values. On the plots are drawn the uncertainties

[7] The sample plates used in this experiment were coated by Mr. H. Hufford and Mr. D. C. Stewart of Dr. Cunningham's group at the Metallurgical Laboratory, University of Chicago. All the sample data were supplied by them.

in the experimental points. These uncertainties are the r.m.s. deviations listed in the last columns of Tables II–V. They were obtained from the actual spread in the experimental data obtained at each energy value. The statistical fluctuations were not calculated since the observed deviations should have included the statistical errors plus any other errors present. A dotted line has been drawn on the plots representing the natural background level, which was found experimentally. This background is due to counts produced by a coincidence of several alpha-pulses and also due to counts of the spontaneous fissions in the samples.

The thresholds as read from the curves in Figs. 3 and 4 are 5.08(±0.08) and 5.25(±0.10) for the depleted and enriched samples respectively. Note that the enriched sample threshold is well defined and does not show the presence of the $_{92}U^{238}$. This indicates some lack of definition. The estimated error represents the maximum possible reading error in the threshold and takes account of the uncertainties in the data for each energy value but does not include the errors in the energy scale. To the estimated reading errors must be added an r.m.s. error in the energy calibration.

Figure 4 shows a dotted curve obtained by subtracting 1/5.95 of the $_{92}U^{238}$ curve in Fig. 3 after a suitable correction for the difference in sample weights was made. The threshold obtained from the dotted curve is 5.31 Mev and this value is taken as the threshold for $_{92}U^{235}$.

Therefore, the threshold energies are:

$$E_t(_{92}U^{238}) = 5.08(\pm 0.15) \text{ Mev}$$
$$E_t(_{92}U^{235}) = 5.31(\pm 0.25) \text{ Mev}.$$

This shows that the $_{92}U^{235}$ threshold is 0.23 (±0.10) Mev higher than the $_{92}U^{238}$ value.

$_{94}Pu^{239}$

The $_{94}Pu^{239}$ sample was coated on an area of 58 square centimeters. The product was deposited in the form of $(NH_4)_2PuF_4$. A coating of Zapon protected the $_{94}Pu^{239}$ and had a density of 0.12 mg/cm^2.

The data for $_{94}Pu^{239}$ in Table IV are plotted in Fig. 5. A $_{92}U^{238}$ curve run in succession with the $_{94}Pu^{239}$ showed that the difference energy between the $_{94}Pu^{239}$ and $_{92}U^{238}$ thresholds is +0.23(±0.12) Mev. This fixed the $_{94}Pu^{239}$ threshold energy at 5.31(±0.27) Mev and determined the energy scale used in the plot of Fig. 5.

$_{92}U^{233}$

The $_{92}U^{233}$ sample was prepared in a like manner to the $_{94}Pu^{239}$. It was deposited as the ammonium fluoride. The protective Zapon coating had a surface density of 0.1 mg/cm^2.

Table V contains the $_{92}U^{233}$ photo-fission data. The plot of these values in Fig. 6 shows a threshold energy of 5.18(±0.27) Mev. The uncertainty in this energy was produced by the small number of experimental points and by the variable background. Time did not permit taking more complete data.

The difference energy found between the $_{92}U^{233}$ and a $_{92}U^{238}$ data curve taken in succession was +0.10(±0.12) Mev.

$_{90}Th^{232}$

The thorium sample was in the form of the oxide applied finely ground in an alcohol solution to the chamber plates. A thickness greater than the range of the fissions in the oxide was coated onto a total chamber area of 116 square centimeters.

The thorium data are listed in Table VI and plotted in Fig. 7. A set of $_{92}U^{238}$ data not shown, the $_{92}U^{233}$ data given above, and the thorium data were obtained in close succession. The threshold energy for $_{90}Th^{232}$ was found to be 5.40(±0.22) Mev. The $_{90}Th^{232}$ and $_{92}U^{238}$ threshold energy difference is +0.32(±0.07) Mev. This difference energy is to be compared with the value of +0.45 Mev obtained in 1944.[5]

A collection of the completed data of this photo-fission experiment, together with the thresholds predicted by Frankel and Metropolis[3] is shown in Table VII.

The errors associated with each difference energy of column 4 are the maximum limits to the errors in the experimental data and graphical plots. The errors assigned to the absolute energy values of column 2 are the sums of the errors in the $_{92}U^{238}$ calibration standard and of the errors in column 3. These errors again represent what are felt to be the maximum limits of the possible inaccuracies in the absolute photo-fission thresholds.

ENERGY CALIBRATION OF THE BETATRON

The spectrum of x-rays from the betatron is continuous up to a maximum energy determined by the accelerated electron energy at the time of the electron collisions with a target in the betatron. The calibration of this maximum spectrum energy as a function of betatron control panel settings permits the determina-

TABLE IV. Summarized data for $_{94}Pu^{239}$ (Fig. 5).

Peak spectrum energy (Mev)	Total number of fission pulses	Total x-ray intensity R units	Total observation time (min.)	Fission counts per R	R.m.s. deviation in counts/R
4.93	1	14.2	50	0.07	0.02
5.09	6	58.1	180	0.10	0.04
5.26	3	58.2	180	0.05	0.05
5.43	13	72.4	210	0.18	0.13
5.60	17	76.7	210	0.22	0.18
5.76	28	76.7	209	0.36	0.16
5.93	42	83.2	210	0.51	0.25
6.10	53	79.3	185	0.67	0.24
6.27	47	67.5	150	0.70	0.17
6.41	71	81.4	165	0.87	0.25
6.57	87	61.2	120	1.42	0.24
6.74	74	47.6	90	1.55	0.53
6.87	129	66.5	120	1.94	0.58
7.05	124	43.0	75	2.88	0.91
7.21	147	54.5	90	2.70	0.63

tion from excitation curves of threshold energies for gamma-processes.

The calibration has been accomplished by measuring directly the electron Hr values at the time of target collision and hence their kinetic energy by $T=3\times10^{-4}$ Hr-0.5 Mev. The magnetic field at the target position is measured by the difference voltage between two concentric coils which are placed accurately at radii 0.1 in. on either side of the target radius. The magnetic field, and from this the energy of the electrons, was determined as a function of betatron control panel settings.

The remaining portion of the calibration, aside from voltage measurements, concerns the selection of betatron energies, or the maximum spectrum energies. An energy selector originally designed by Dr. G. C. Baldwin was somewhat redesigned and completely rebuilt in order to increase the stability of an energy setting. The basis of the circuit is a trigger pair which fires at a predetermined input voltage. The electron collision with a target is timed by the output triggered pulse. Energy selections can be made in 100 kilovolt steps with a constancy accurate to at least ±20 kilovolts in the energy selector.

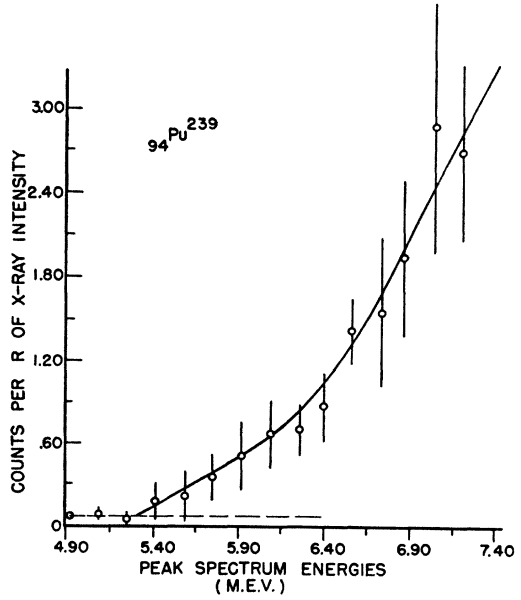

FIG. 5. $_{94}Pu^{239}$ experimental photo-fission threshold curve. The experimental r.m.s. deviations in the fission activities are plotted with each point.

An estimation of the maximum r.m.s. error to be expected in an energy value was made by considering the experimental r.m.s. deviations in each of the quantities appearing in the calibration. Errors other than that introduced by the difference voltage coils used for measuring the magnetic field lead to an estimated rms error of ±0.6 percent. This indicates the accuracy possible in the ability to reproduce energy setting; i.e., relative energy values should be accurate to ±0.6 percent.

TABLE V. Summarized data for $_{92}U^{233}$ sample (Fig. 6).

Peak spectrum energy (Mev)	Total number of fission pulses	Total x-ray intensity R units	Total observation time (min.)	Fission counts per R	R.m.s. deviation in counts/R
4.93	3	34.2	105	0.09	0.10
5.10	5	41.8	120	0.12	0.14
5.17	7	39.2	120	0.18	0.12
5.26	10	44.5	120	0.23	0.09
5.35	22	56.5	150	0.39	0.23
5.43	20	55.9	144	0.36	0.19
5.60	30	48.2	116	0.62	0.36
5.77	20	29.4	60	0.68	0.09
6.41	46	19.5	35	2.36	0.71

The absolute value of the energy readings are limited, however, by the skill with which the difference coils were machined and the care with which the measuring "coils" of silver paint were coated. The r.m.s. error here introduced to the absolute energy values will be less than 2 percent. Therefore, the total r.m.s. error in the absolute value of any energy setting has been estimated to be ±2.6 percent.

In a paper by Baldwin and Koch[4] it was suggested that the (γ, n) threshold in nitrogen could be used as a check on the betatron energy calibration obtained from voltage measurements. However, the positron intensities resulting from the photo-neutron processes were found at that time to be too small to give the desired accuracy.

Greater intensities by a factor of 17 were obtained in the present experiment. This was made possible by improved sample holders and positron counters, and by increased x-ray intensities at the sample position during irradiation.

The counter was a thin-walled aluminum counter. It was constructed at the Metallurgical Laboratory to have an aluminum cylindrical wall 0.011 centimeter

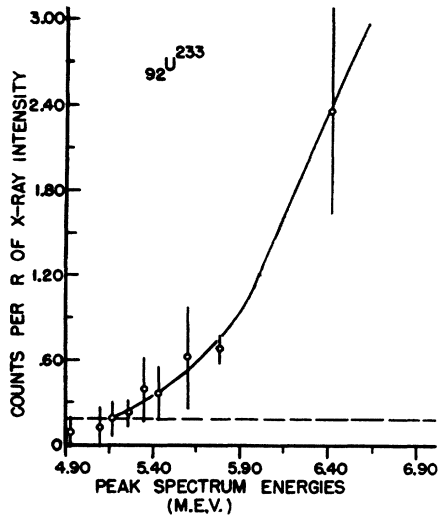

FIG. 6. $_{92}U^{233}$ experimental photo-fission threshold curve.

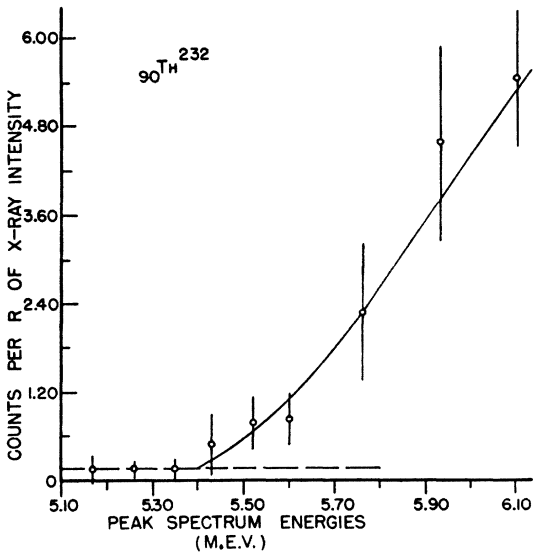

FIG. 7. $_{90}Th^{232}$ experimental photo-fission threshold curve.

thick, a 2.22-centimeter diameter, and a 12-centimeter length. A test with a 5-mg radium source proved the sensitive area to the 8 centimeters long.

The nitrogeneous material used was dicyandiamide ($C_2N_4H_4$). Approximately 60 grams of the powder filled the space between two concentric cylinders. The inner cylinder consisted of Cellophane, 0.025 centimeter thick, supported by Bakelite supports. The sample holder was 12 centimeters long and the annular section of $C_2N_4H_4$ was 0.72 centimeter thick. The material of which the sample holder was constructed was purposely made non-metallic so that it could be placed in the betatron alternating magnetic field and as close as 35 centimeters from the x-ray target. Three samples were prepared to allow alternate use, thus decreasing the possibility of residual activity.

TABLE VI. Summarized data for $_{90}Th^{232}$ sample (Fig. 7).

Peak spectrum energy (Mev)	Total number of fission pulses	Total x-ray intensity R units	Total observation time (min.)	Fission counts per R	R.m.s. deviation in counts/R
5.17	12	75.3	180	0.16	0.19
5.26	12	76.6	180	0.16	0.09
5.35	15	82.8	180	0.18	0.13
5.43	42	83.9	180	0.50	0.41
5.52	66	85.9	180	0.77	0.35
5.60	77	91.7	180	0.84	0.35
5.76	219	95.7	180	2.29	0.92
5.93	464	100.7	180	4.62	1.30
6.10	547	100.2	180	5.50	0.94

TABLE VII. Collection of data.

Sample	Photo-fission threshold (Mev)	Isotope threshold $-_{92}U^{238}$ threshold (difference energy) (Mev)	Theoretical[3] threshold energies (Mev)
$_{92}U^{238}$	5.08(±0.15)	0.00(±0.08)	7.0
$_{92}U^{235}$	5.31(±0.25)	+0.23(±0.10)	6.1
$_{94}Pu^{239}$	5.31(±0.27)	+0.23(±0.12)	4.9
$_{92}U^{233}$	5.18(±0.27)	+0.10(±0.12)	5.7
$_{90}Th^{232}$	5.40(±0.22)	+0.32(±0.07)	

The irradiation procedure was similar to that in the photo-neutron work.[4] A sample in its holder was irradiated in the x-ray beam for 10 minutes. Removal of the sample to a counter then followed, and the counting rates were studied. Data were obtained at successive betatron energies.

Figure 8 shows a decay curve of activity resulting from a 10-minute irradiation at a peak spectrum energy of 12.1 Mev. The half-life determined from Fig. 8 is 10.0(±0.3) minutes. This checks the half-life 9.93(±0.03) minutes found by Ward.[8] The decay curve shows no evidence of any other activity, which makes the comparatively low nitrogen threshold a satisfactory one for investigation.

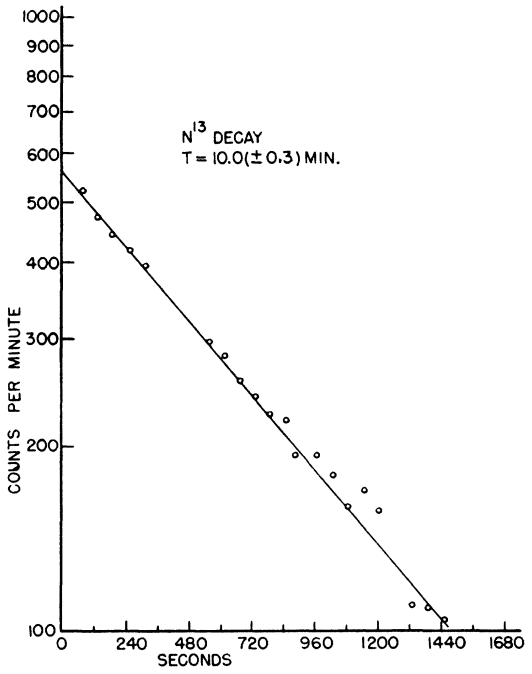

FIG. 8. Decay curve resulting from a 10-minute irradiation of a nitrogen sample at a peak betatron spectrum energy of 12.1 Mev.

In Fig. 9 is plotted the 10-minute counting totals corrected to an irradiation of 200R. The energy scale was calculated from voltage measurements. The threshold is seen to be 10.34(±0.25) Mev. The estimated error includes the graphical reading error added to the estimated r.m.s. error in the energy calibration.

For comparison, the (γ, n) threshold can be calculated from the following mass data:

$$M(_6C^{13}) = 13.00751 \pm 0.00010$$
$$M(_0n^1) = 1.00893 \pm 0.00003$$
$$2\ mc^2 = 0.00110$$
$$M(_7N^{14}) = 14.00751 \pm 0.00004$$
$$E_e{}^+ = 1.20 \pm 0.02\ \text{Mev}.$$

[8] A. G. Ward, Proc. Camb. Phil. Soc. **35**, 523 (1939).

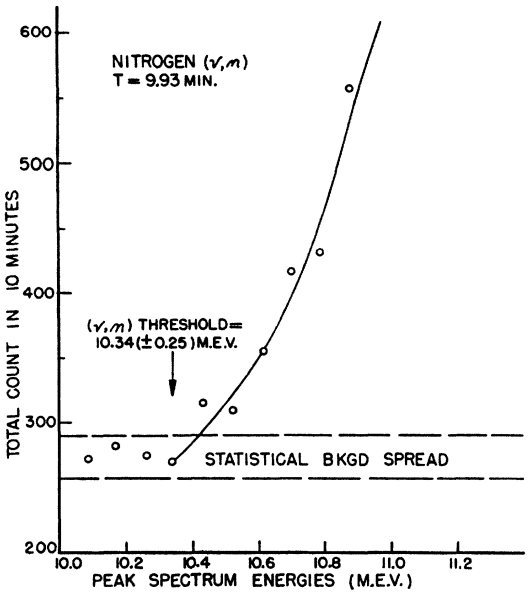

FIG. 9. $_7N^{14}(\gamma, n)$ threshold curve.

The expected photo-neutron threshold is 10.54(±0.06) Mev. Thus the voltage calibration method and the mass threshold calculation are in agreement within experimental error. The discrepancy of 1.9 percent which does exist is believed due to the error discussed above in the dimensions of the magnetic field measuring coils. It was thought justifiable to make this same percentage correction in the energy scale near the photo-fission threshold at 5 Mev. This procedure has been applied to all the energy values which have been reported in this paper.

The experimental thresholds determined are not in agreement with theory. From this investigation the photo-fission threshold values for $_{92}U^{238}$, $_{92}U^{235}$, $_{94}Pu^{239}$, and $_{92}U^{233}$ show a maximum difference or spread of 0.23 Mev, whereas the theory predicts a spread of 1.7 Mev. Also, the order of the experimental thresholds is not the same as the predicted order. Emphasis was placed on determining this order as accurately as was possible. For this reason, all the isotopes were referred to the $_{92}U^{238}$ threshold and were investigated in succession with $_{92}U^{238}$. The thresholds of $_{92}U^{235}$, $_{92}U^{238}$, and $_{90}Th^{232}$ were determined most accurately (see column 3 of Table VII). According to theory the $_{92}U^{238}$ threshold should be larger than the $_{92}U^{235}$ threshold by approximately 0.6 Mev. The experiment showed definitely that the order is reversed with the $_{92}U^{235}$ threshold the larger one by 0.23(±0.10) Mev. The orders of the experimental thresholds for $_{94}Pu^{239}$ and $_{92}U^{233}$ are also not in agreement with theory.

The fact that the thresholds are spread over such a small energy band raised the question of the influence of fissions induced by neutrons. The evidence found was not discussed because the data books containing specific data were not available at the time of this writing. However, general comments can be made. The number of fission counts at a particular betatron energy setting was determined as a function of different experimental conditions. The tests made were:

(1) Ionization chamber containing a fission sample was surrounded by 5 in. of paraffin.
(2) Same as (1) with $\frac{1}{32}$ in. of cadmium sheet interposed between chamber and paraffin.
(3) Ionization chamber was placed at the 0° and 15° positions with respect to the axis of the x-ray beam.

Neither the paraffin nor the paraffin plus cadmium appreciably changed the number of fissions counted. Also, the number of fissions was reduced in test number 3 by moving from the 0° position to the 15° position, but this fall-off can be explained by the decrease in the x-ray intensity at the 15° position. Because of these three tests it was concluded that the fissions counted in this experiment were principally produced by x-rays and not by neutrons.

ACKNOWLEDGMENT

The authors take pleasure in thanking Dr. Sidney Dancoff for his kind interest and invaluable assistance. They are also indebted to the members of the Chicago Metallurgical Laboratory for their cooperation.