The main reason for this large error is that the ionium was not pure but rather was only 25 percent by weight of a sample containing mostly thorium. Thus, the pro-rated thorium activity for each point had to be subtracted from the total activity in order to obtain numbers proportional to the ionium activity. Hence, any errors in the thorium curve were multiplied in the ionium curve.

It is also to be noted that we obtain a ratio for the thorium to uranium activity of approximately $\frac{1}{4}$, whereas Baldwin and Klaiber[2] observed a ratio of $\frac{1}{2}$. It appears that part of this discrepancy is due to the fact that Baldwin and Klaiber's fissionable material foils were all assumed to be completely thick compared with the fission fragment range; however, from the numbers that they quote it appears that their uranium sample was not completely thick. This difference might change their ratio to approximately 1 to 3, which would still leave a discrepancy between the two observed values.

The authors would like to express their appreciation to Messrs. R. D. England and A. N. Carson for their very considerable help in carrying out the above work.

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

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The Resonance Photo-Fission Cross Section for U^{238}*

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An attempt has been made to determine the shape of the U^{238} photo-fission cross section up to a gamma-ray energy of 22 Mev by an analysis of the excitation function obtained by varying the peak energy of the bremsstrahlung from a 22-Mev betatron. A resonance for the photo-fission process is indicated in the region of 15 Mev.

I. INTRODUCTION

The work of Baldwin and Klaiber[1] on photo-fission in heavy elements aroused considerable interest in the possibility of a resonance photo-fission cross section.[2] This work is an attempt to measure the shape of the U^{238} cross section up to 22 Mev by an analysis of the photo-fission excitation function obtained by varying the peak energy of the bremsstrahlung from a 22-Mev betatron.

II. EXPERIMENTAL METHOD

The arrangement used to observe the excitation function of U^{238} consisted essentially of a standard 22 Mev Allis Chalmers betatron to produce the x-ray spectrum and a fission chamber containing U^{238} to observe the number of fissions as a function of energy. The physical set-up of the experiment required that the x-ray beam from the betatron go through approximately $\frac{3}{8}$ in. of porcelain (the vacuum chamber wall), $\frac{3}{4}$ in. of wood, and 1.4 in. of aluminum before reaching the detecting system itself. In order to establish equilibrium between the primary gamma-rays and the secondary electrons a 4-in. thick layer of carbon was placed in the x-ray beam just in front of the ion chamber.

The detector was a flat plate ion chamber in which one surface was a thick uranium sample and the other a copper collecting plate. The uranium was in the form of a 5-mil thick disk 3 in. in diameter. The gap between the uranium and the collecting plate was $\frac{1}{4}$-in. The chamber was filled with argon at atmospheric pressure. In order to partially cancel the pulse due to the x-ray burst, a bucking chamber was placed behind the fission chamber in the x-ray beam. The bucking chamber was connected in such a manner that the output was of the opposite sign to that of the fission chamber. No fissionable material was in the bucking chamber. The output of the bucking chamber was then mixed with the output of the fission chamber and the result amplified and passed into a gating circuit which allowed only those pulses occurring within ± 5 μsec of the x-ray burst from the betatron to pass through. The output of the gating circuit was then fed into a discriminator and scaler where the pulses were counted. Two $\frac{1}{4}$-R-thimbles were placed in front of the fission chamber but enough to one side that the chamber was not shadowed by the R-thimbles. The betatron was then run at various energies and the number of fission counts per Roentgen unit of radiation was recorded. Since the ion chamber and R-thimbles were approximately 15 meters from the betatron the detectors received uniform intensity radiation, so that no correction for different angular spread of the beam at different energies was necessary

The energy calibration of the betatron was based upon a measurement of the observed threshold of the

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

[2] M. Goldhaber and E. Teller, Phys. Rev. 74, 1046 (1948).

TABLE I. Number of fissions per Roentgen unit observed as a function of the peak bremsstrahlung energy from the betatron.

X-ray energy (Mev)	Counts/R
8.75	42± 42
10.59	883± 32
12.4	1726± 75
14.3	3010± 37
16.1	4375± 69
17.1	4756±150
18.0	4918± 55
18.9	5443± 78
19.8	5434±148
20.8	5971±157
21.2	5663±182
21.7	5995±163

$N^{14}(\gamma,n)N^{13}$ reaction. The value of this threshold was calculated[3] to be 10.54 Mev.

III. RESULTS

The results of the measurement of the photo-fission excitation curve in U^{238} measured with a fission ion chamber are given in Table I. This lists the peak bremsstrahlung energy settings at which the betatron was run and the number of fissions per Roentgen unit observed at that energy where the number of fissions per Roentgen unit is the average of several runs. The errors quoted in Table I represent the probable error of the mean from the several runs at each point.

TABLE II. Data interpolated from Table I and used for the purposes of calculation.

X-ray energy (Mev)	Counts/R
7.5	0
8.5	0± 60
9.5	320± 60
10.5	790± 70
11.5	1280±100
12.5	1840±100
13.5	2420±100
14.5	3120±100
15.5	3880±100
16.5	4480±120
17.5	4900±150
18.5	5220±170
19.5	5480±200
20.5	5720±220
21.5	5920±220

For the purposes of calculation the data of Table I were interpolated to give the number of counts per Roentgen unit at 1-Mev intervals from $7\frac{1}{2}$- to $21\frac{1}{2}$-Mev peak bremsstrahlung energy. These numbers are shown in Table II. In order to determine the shape of the photo-fission cross section as a function of gamma-ray energy from these data it is necessary to know the relative number of quanta in each energy interval striking the uranium foil for each R recorded by the R-thimble. The initial x-ray spectrum emerging from the target was calculated[4,5] on the assumption of an effective target thickness of 1.5 Mev, using an equation derived by Schiff and Stehle.[6] That spectrum was then corrected for all absorbing materials between the target and the uranium foil. The response of the R-thimble was calculated assuming that it responded only to the secondary electrons coming out of the carbon which were in equilibrium with the primary gamma-rays. From these two calculations the number of gamma-rays per unit energy interval hitting the uranium per Roentgen unit was calculated. Using these numbers an attempt was made to derive the photo-fission cross-section shape from the observed excitation curve.

The equation for the excitation curve can be written as

$$\left(\frac{\text{counts}}{R}\right)_{E_m}=\frac{A\int_0^{E_m}\sigma(k)N(k,\,E_m)dk}{\int_0^{E_m}R(k)N(k,\,E_m)dk},$$

where $\sigma(k)$ is the cross section at energy k, $R(k)$ is the R-thimble response, and $N(k,E_m)dk$ is the number of photons in energy interval dk when the peak of the bremsstrahlung is E_m, and A is a constant having to do with the number of atoms of uranium in the counting system and the counting efficiency.

In principle, if one knows the photo-fission excitation curve exactly and the gamma-ray spectrum exactly, one can arrive at a unique solution for the photo-fission cross section as a function of energy. However, comparatively small errors in the excitation curve lead to very large errors in the deduced cross-section curve. Thus, a more sensible procedure seemed to be to assume various cross-section shapes and to try to fit these to the excitation curve. In practice this consisted of assuming a function for $\sigma(k)$, inserting the values in the above equation, performing the numerical integration with 1-Mev intervals, and arriving at a calculated excitation curve.

Although many shapes were assumed for the photo-fission cross section as a function of energy none would give an excitation function similar to that observed unless a maximum in the cross-section value were assumed in the neighborhood of 15 Mev.

A solution was attempted using the resonance formula

$$\sigma=A/[B+(E-E_0)^2].$$

It was found necessary, in order to make a proper fit to the observed excitation curve, to cut off the cross-section curve obtained from the above equation below 8 Mev and allow only a small value of the cross section at 8 Mev. The equation finally obtained which gave

[3] J. Mattauch, *Nuclear Physics Tables*, Interscience Publishers Inc. (1946).

[4] McElhinney, Hanson, Becker, Duffield, and Diven, Phys. Rev. **75**, 542 (1949).

[5] L. I. Schiff, Phys. Rev. **70**, 89 (1946).

[6] L. I. Schiff and P. Stehle, MDDC-43, unpublished.

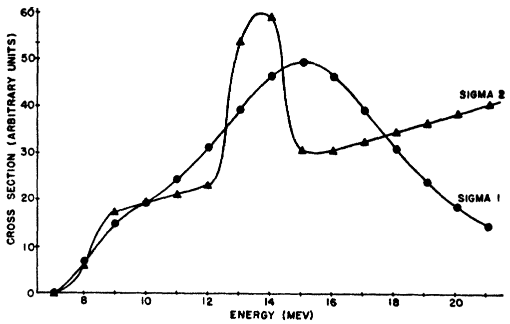

FIG. 1. Possible U^{238} photo-fission cross-section curves. $Sigma_1$ fits a resonance equation. (In the figure, 1 and 2 should be subscripts to sigma.)

an excitation curve that fell within the limits of error of Table II is

$$\sigma = 771.88/[15.625+(E-15)^2]$$

where E is the gamma-ray energy in Mev. The above equation does not imply that we know the cross-section shape to five significant figures. The numbers shown are simply those which will give a fit within the errors of the excitation curve. Attempts to fit the observed excitation curve using the above resonance formula are unsuccessful if the resonance peak is chosen more than $\frac{1}{2}$ Mev different from the 15 Mev assumed. A plot of this cross-section curve is shown in Fig. 1 and the exact values used are given in Table III listed under $Sigma_1$. $Sigma_2$, also listed in Table III and shown in Fig. 1, is another cross-section shape leading to an excitation curve that fits the observed data.

No correction has been applied to any of the data of this work for possible fission due to fast neutrons coming from the betatron. However, absorption and time-of-flight measurements have indicated that neutron-induced fission does not contribute appreciably above 8- or 9-Mev peak bremsstrahlung energy.

It should be emphasized that the experimental excitation curve arrived at in this work does not and cannot lead to unique photo-fission cross-section curves. However, the data should be sufficiently good to check on a theoretically derived cross-section shape.

A more complete description of this experiment giving the actual calculations of the bremsstrahlung spectrum incident on the U^{238} fission chamber, detailed calculations of the R-thimble response, and detailed calculations of the possible cross-section shapes, is given in the Los Alamos Report LADC-654.

TABLE III. Possible photo-fission cross-section shapes for U^{238}.

X-ray energy (Mev)	$Sigma_1$*	$Sigma_2$*
0 to 7	0	0
8	6.690	6.00
9	14.95	17.40
10	19.00	19.40
11	24.40	21.2
12	31.34	23.2
13	39.34	54.0
14	46.42	59.0
15	49.40	30.8
16	46.42	31.0
17	39.34	32.8
18	31.34	34.8
19	24.40	36.8
20	19.00	38.6
21	14.95	40.6

* Arbitrary units.

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