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EXCITATION FUNCTION FOR PHOTONEUTRON PRODUCTION
FROM 80 TO 320 MEV

Lawrence Jones

(Thesis)

August 13, 1952

Berkeley, California

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EXCITATION FUNCTION FOR PHOTONEUTRON PRODUCTION
FROM 80 TO 320 MEV

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August 13, 1952

ABSTRACT

The excitation functions for neutron production by high energy quanta were investigated for eleven elements. By varying the maximum energy of the x-ray beam of the Berkeley synchrotron, photoneutron yields were obtained at eight maximum bremsstrahlung energies from 40 Mev to 320 Mev. The beam was monitored with the induced beta activities of copper foils at the various energies. Using a photon difference method, the yields were analyzed to give cross sections.

The cross sections increase with energy for all but the lightest elements from 100 Mev to 300 Mev. Correlations are observed between these results and results of other experiments which indicate that the cross sections for photonuclear interactions are at high energies about proportional to the atomic weight.

There is evidence that a compound nucleus may be formed in heavy elements by high energy quanta. An increase in the photon absorption cross section at energies below the meson threshold is evidence of a virtual meson type of interaction.

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August 13, 1952

I. INTRODUCTION

Relatively little is known about the cross section for photon absorption by nuclear material at energies above 30 Mev. In general any high energy nuclear interaction leads to the emission of neutrons, either as primary interaction products or as particles boiled out of a nucleus which was excited by a primary interaction. Therefore a study of the excitation function for photoneutron production may be interpreted in terms of photon absorption by the nucleus.

Eyges¹ first suggested an experiment of this type after noting a discrepancy between the neutron yields obtained from 320 Mev bremsstrahlung and the known (γ, n) cross section below 25 Mev. A preliminary experiment² showed that there were slow neutrons (of energy less than 20 Mev) produced by quanta of energy greater than 150 Mev. Later it was learned that Kerst³ had noted a similar neutron yield from high energy photons by comparing yields from 22 and 320 Mev bremsstrahlung.

High energy photonuclear reactions may be divided into three photon energy intervals. From the photoproton or photoneutron threshold energy to about 25 Mev all nuclei so far studied except deuterium (and hydrogen) show a resonance absorption^{1,4}. This region has been extensively studied using smaller betatrons and induced beta activities. However, little is known regarding the reaction from about 30 Mev to

the meson threshold at about 150 Mev. It has been proposed that the photon absorption falls off in that region as $1/E^{\frac{3}{2}}$ or some similar function as is predicted by the theory of the photoelectric disintegration of the deuteron⁵. Above the meson threshold photon absorption leading to meson production appears to be a rising function of energy up to 320 Mev⁶.

The experiment discussed here, together with a similar experiment at lower energies⁴, attempts to infer something about the nature of photon absorption in the energy region from 80 Mev to 320 Mev from the cross sections for photoneutron production.

II. EXPERIMENTAL PROCEDURE

A. Outline of Procedure

The total neutron yields from Be, C, Al, Fe, Cu, Mo, Ag, Sn, Ta, W, Pb, and U were obtained at eight maximum x-ray beam energies using the Berkeley synchrotron. Using a boron trifluoride proportional counter in a long counter geometry, yields were measured from bremsstrahlung spectra of maximum energies of from 40 to 320 Mev at 40 Mev intervals. In sections IIB and IIC the counter and experimental setup are described. In order to reduce neutron yields per unit of ionization (as indicated by the beam monitor ionization chamber) to units more adaptable to analysis, the amount of 9.9 minute half life positron activity induced in a copper foil per unit of ionization was determined at each energy. Then the neutron yields were expressed in terms of neutron yields per unit of copper activity. The monitoring is discussed in section IIF.

In section III, the method of analysis of the yield data is discussed, taking into account the continuous nature of the bremsstrahlung spectrum. This method consisted of correcting the yield from each maximum energy bremsstrahlung for the yields at each lower energy. The yield at the lowest energy was corrected using the cross sections obtained in a similar experiment⁴ from the photoneutron threshold through 70 Mev. Since the neutron yields from 40 Mev bremsstrahlung were obtained with rather poor statistics, it was decided to omit that point in the analysis and start with the 80 Mev yields, in view of the later comprehensive study at lower energies. The shapes of the bremsstrahlung spectra for the energies studied are determined as discussed in section IIIA.

B. Shielding and Geometry

The synchrotron beam was collimated by a 1-1/2 inch diameter tapered lead collimator 9.5 inches long in a 9.5 inch lead wall 60 inches from the platinum x-ray target in the synchrotron. A six inch lead wall with a larger tapered hole 3 inches behind the primary collimator further reduced scattered x-rays and electrons. Additional lead and paraffin shielding around the counter was found to be necessary to reduce the target-out background to a workable level. The overall configuration of the counter and shielding is presented in Figure 1.

The target materials were supported by clips on a brass platform. The targets of elements heavier than aluminum consisted of square metal slabs 2-1/2 x 2-1/2 inches to 3 x 3 inches and from one quarter inch thick to .040 inches thick. These slabs were oriented with their faces at 112° to the beam direction and at 22° to the axis of the long counter to minimize the effect of neutron scattering in the target. It was found in an earlier experiment⁷ that if the face of a heavy metal plate was parallel to the counter axis the neutron counting rate was reduced as much as 20 percent.

The aluminum, carbon, beryllium and water targets were all an inch or more thick, and therefore the neutron path through them to the counter was not much changed by orienting them perpendicular to the beam.

The water and heavy water target holders consisted of identical lucite cylinders 3 inches long and 2-1/2 inches inside diameter with one-eighth inch walls. One-sixteenth inch lucite was cemented to each end and two stainless steel filling screws were tapped into the walls of each.

The target specifications are listed in Tables I,A and I,B.

An earlier experiment at 320 Mev had shown that for all but the

lightest elements (carbon, beryllium and deuterium) the photoneutron yield was isotropic to within statistics, therefore no attempt was made to examine photoneutrons at other than 90° to the beam direction in this experiment. For the light elements the asymmetry seems to be, within statistics, the same at 320 Mev as at 22 Mev^{7,8}.

C. Neutron Detection

A boron triflouride proportional counter in the "long counter" geometry was used to count the photoneutrons. The reaction $B^{10} (n, \alpha) Li^7$ releases the α particle with a Q of 2.8 Mev. A gas-filled proportional counter filled with B^{10} enriched boron triflouride will give a large pulse from a captured neutron relative to pulses caused by fast electrons. This type counter is therefore ideally suited for detecting neutrons in the presence of the large γ -ray and electron flux surrounding the synchrotron. The "long counter" described by Hanson and McKibben⁹ consists of a cylinder of paraffin 8 inches in diameter with a cylindrical BF_3 -filled proportional counter along its axis. Fast neutrons of energies up to several Mev entering the cylinder parallel to its axis are moderated and may diffuse into the sensitive volume of the proportional counter at thermal energies, where they will be counted. The counter is almost uniformly sensitive to neutrons of energies from one hundred Kev to several Mev, depending on the length of the cylinder. According to Barschall, et al¹⁰, the counter counts 14 Mev and 18 Mev neutrons with 67 percent of its one Mev efficiency. The dimensions of the proportional counter used and of the paraffin cylinder surrounding it are shown in Figures 2 and 3. The counter is filled to 20 cm Hg with boron triflouride enriched to 95 percent B^{10} . The sensitivity⁹ of such a counter versus neutron energy is given in Figure 4.

In practice the neutron counter was not used with a parallel flux of neutrons (source at infinite distance). The target in the x-ray beam was placed only 7-1/2 inches from the end of the counter, so that the neutrons appeared in a diverging beam at the counter. This gives the counter relatively less sensitivity to high energy neutrons than that presented in Figure 4. As will be discussed later, however, it is believed that the majority of the neutrons boil off the nucleus with a Maxwellian distribution. Therefore there will be relatively little change in the overall neutron detection efficiency for different γ excitation energies. The long counter used has a detection efficiency of .7 percent for Ra-Be neutrons entering the 8 inch diameter face.

The BF_3 counter is condenser-coupled to a preamplifier by a simple RC filter. This filter prevents voltage fluctuations or pulses from the high voltage supply from being picked up in the signal lead. The preamplifier unit is a standard UCRL type 3T2393B modified for use with an external 1000 ohm delay line clipper. With this the signal pulses are allowed to rise to their full height in about 0.2 microseconds without appreciable differentiation. Using about 2 feet of delay cable (equivalent to .25 microseconds) shorted at one end the pulses were clipped to .5 microseconds. This was desirable for two reasons. If longer pulses were used, individual electron pulses in the counter would have time to add up to the height of a neutron pulse, and hence be counted as a neutron. Also two neutrons which entered the counter within a pulse-width time of each other would be counted as only one neutron. Although the electron "pile-up" and neutron "pile-up" introduce errors in the number of neutron counts of opposite sign, both are reduced by using as short a pulse length as is consistent with good proportionality.

A convenient feature of the "long counter" is the relatively long

diffusion time of neutrons in the paraffin before they are counted. A burst of neutrons released from the target simultaneously is counted with a distribution in time characteristic of an exponential decay, where the decay constant is about 200 microseconds. For this reason the x-ray beam pulse length may be as short as desired without increasing the probability of neutron "pile-up".

The output of the preamplifier was fed into a UCRL type 2T4404 linear amplifier operated at a voltage gain of 2500. The amplifier was fed into a UCRL type 3T8934 scaler biased to accept only pulses of 20 Volts or higher. The scaler was gated to accept counts only during a period extending from a few hundred microseconds before the beam pulse to 3000 microseconds after the beam pulse. This eliminated extraneous pulses introduced by the 100 KV synchrotron injector. The neutron background due to cosmic rays and sources other than the x-ray beam was completely negligible.

D. Collection of Data

The data were collected from three separate three day runs at the synchrotron and pains were taken to duplicate the experimental geometry each time. To insure reproducibility, before and after each run a 10 Mg. radium-beryllium neutron source was placed at the target position and counted for five minutes. The neutron counts from this source varied as much within one run as between successive runs, indicating that the equipment was relocated as accurately as the radium-beryllium source could be positioned. Since the beam was entirely within the neutron targets, the distance from the x-ray target to the neutron target was not critical. However, this distance was reproduced on successive runs to ± 0.5 inches. The beam at the neutron target position measured 2-5/16

inches in diameter.

Before each run a plateau of neutron counts versus voltage on the counter was obtained using the radium-beryllium neutron source. The plateau was three hundred volts wide from the voltage where all neutrons were counted to the voltage where electrons began to be counted. The counter was operated fifty volts above the lower voltage limit of the plateau.

To check on the reproducibility of the data, the neutron yield from the uranium target per Nunan (the unit of integrated beam) minus background was obtained several times during each run at 320 Mev. Again, the variation within a run was as large as between runs, so that the data from the separate runs were averaged together directly.

The neutron target-out background (due to neutrons produced in the synchrotron itself and in the collimator) varied from 50 percent of the carbon counts and 7 percent of the uranium counts at 320 Mev to 120 percent of the carbon counts and 20 percent of the uranium counts at 80 Mev.

The neutron counts were recorded on a scale of 128 scaler. From 3000 to 10,000 neutron counts were obtained for each point, and a minimum of 1000 counts for each background point. The yield from each element was taken three times at 320 Mev and 280 Mev, twice at 240 Mev and once at the lower energies. In addition, points which lay off a smooth yield curve, or for any other reason were in question, were repeated.

E. Determination of Synchrotron Energy

The Berkeley synchrotron magnet coil is connected in an LC resonant circuit with a condenser bank of about 818 microfarads capacity. The magnet itself has a calculated inductance of 30 millihenries, giving this circuit a nominal resonant frequency of 32.1 c.p.s. With the flux bars

removed, the resonant frequency was later determined (using an audio oscillator, an oscilloscope to determine resonance, and a scaler to calibrate the oscillator) to be 32.44 c.p.s. In operation, the flux bars are saturated when the magnetic field reaches 100 gauss, and at higher field strengths the inductance of the magnet is virtually the same as with the flux bars removed.

Since the peak magnetic field is 11,400 gauss and the magnet iron saturates at 14,000 gauss, the inductance of the magnet remains constant to within 1 percent¹¹ from the time the flux bars saturate to peak field. Therefore, the current through the magnet coils rises sinusoidally. By operating the magnet at a fixed peak current and turning off the R.F. accelerating voltage at a known time before peak field, the ratio of the energy of the beam to full energy may be simply determined:

$$E = E_0 \sin \left(\frac{7790-t}{7790} \right) \times 90^\circ \quad (1)$$

where E_0 is the energy of the beam at peak magnetic field, E is the energy of the beam brought out at t microseconds before peak field, and 7790 is the calculated rise time of the field in microseconds.

In this experiment, the above method was used for determining the bremsstrahlung energy for each run. The sweep of a Tektronic 512 oscilloscope was triggered at the beginning of the magnet pulse. On the sweep were displayed the signal from a photomultiplier in the x-ray beam, a sharp pulse indicating the time of peak field, and superimposed 100 and 1000 microsecond time markers. For a desired energy, E , the value of t was computed from (1), and the R.F. cutoff time was then adjusted so that the photomultiplier pip fell t microseconds (as determined by the time markers) before peak field. The nominal maximum energy, E_0 , of this synchrotron is 322 ± 6 Mev¹²; however, for purposes of convenience it has been taken as 320 Mev in this experiment.

The voltage across the condenser bank, and consequently the peak current, was seen to vary ± 1 percent. The time t could be determined only to ± 50 microseconds. Together these errors could give rise to an error of ± 1.5 percent at high energies and ± 2.5 percent at low energies in the beam energy determinations.

F. Calibration and Normalization

In order to reduce neutron yields per Nunan at different energies to units susceptible to analysis, the relative yields of the $\text{Cu}^{63} (\gamma, n) \text{Cu}^{62}$ reaction were obtained at each energy.

The $\text{Cu}^{63} (\gamma, n)$ reaction has been extensively studied by Sagane¹³, Almy and Diven¹⁴, and Johns¹⁵, et al. The reaction cross section has resonance shape, rising from a threshold at 10.9 Mev to a maximum at 17.5 Mev, and then falling to very low value above 24 Mev. Johns' curve is reproduced in Figure 5. By bombarding a standard size copper foil and then following the decay of its induced beta activity a given time in a standard geometry, the relative $\text{Cu}^{63} (\gamma, n) \text{Cu}^{62}$ yield per Nunan may be determined at each energy. Neutron yields per Nunan may then be re-expressed as neutron yields per unit of copper activity, Y , where

$$Y (E_0) = \frac{\text{neutron yield}}{\text{Cu}^{63} (\gamma, n) \text{ yield}} = \frac{\int_0^{E_0} \sigma_n (E) N (E_0 E) dE}{\int_0^{E_0} \sigma_{\text{Cu}^{63}}^{63} (E) N (E_0 E) dE} \quad (2)$$

In the above, σ_n is the cross section for neutron production, $\sigma_{\text{Cu}^{63}}^{63}$ is the $\text{Cu}^{63} (\gamma, n)$ cross section of Figure 5, and $N (E_0 E)$ is the number of quanta of energy E per unit energy in a bremsstrahlung of maximum energy E_0 .

The integral in the denominator was evaluated by plotting the product and integrating with a planimeter. Using the bremsstrahlung spectra

discussed in section IIIA, the ratio of these integrals for different E_0 from 40 to 320 was found to be the same as the ratio of 16.5 Mev quanta. * Therefore, in subsequent calculations of cross sections, bremsstrahlung areas are computed on the basis of normalization to 16.5 Mev, such that the values of $N(E_0, 16.5)$ are the same for all E_0 .

Experimentally, copper foils 3 x 3 x .016 inches were bombarded at each energy for 10 minutes at the target position. The beam integrator was read every minute during the bombardment. The foil was then rolled into a cylinder, taped together, and placed over a thin walled, cylindrical geiger counter (Victoreen Thyrode type 1B85) in a lead chamber. Every foil was rolled on the same rod so that each cylinder was the same diameter. Two minutes after the end of the bombardment, the scaler connected to the geiger counter was started and run for 10 minutes. A minimum of 20,000 geiger counts were obtained for each bombardment. The geiger counts were recorded every minute to insure that only the 9.9 minute half life of Cu^{62} activity was being seen. The 12.8 hour Cu^{64} activity was never apparent. Corrections were applied to the geiger data for geiger counter background, geiger counter dead time (determined experimentally with two radium γ sources), and for beam intensity variations during the bombardment.

The copper foil monitoring was done for each set of neutron data so that the neutron yield per copper yield could be obtained for each run independent of the others. This made values of Y independent of any changes in sensitivity of the beam monitor ionization chamber between runs.

$$* \text{ i.e. } \frac{N(E_1, 16.5)}{N(E_2, 16.5)} = \frac{\int_0^{E_1} \sigma(E) N(E_1, E) dE}{\int_0^{E_2} \sigma(E) N(E_2, E) dE}$$

Also, since both neutron counts per Nunan and copper foil activity per Nunan are more rapidly varying functions of energy than the ratio Y , calculating Y using the copper value obtained at the same time as the neutron counts reduces the effect of errors in energy setting.

The $\text{Cu}^{63} (\gamma, n)$ reaction was assumed to receive negligible contribution from quanta above 25 Mev following Sagane's results^{4,13}. In view of the $1/E$ nature of the bremsstrahlung, it seems doubtful that any higher energy $\text{Cu}^{63} (\gamma, n) \text{Cu}^{62}$ interaction would contribute appreciably to the total Cu^{62} yield. A possible source of error in this method of normalization is the $\text{Cu}^{65} (\gamma, 3n) \text{Cu}^{62}$ reaction, since the natural isotopic mixture of copper (30 percent Cu^{65} , 70 percent Cu^{63}) was used. Debs¹⁶, however, estimated the yield from this reaction to be less than 2 percent of the $\text{Cu}^{63} (\gamma, n)$ yield from a 300 Mev bremsstrahlung, and Strauch¹⁷ found that the yield of the $\text{Zn}^{66} (\gamma, 3n) \text{Zn}^{63}$ reaction was 3 percent of the yield of the $\text{Zn}^{64} (\gamma, n) \text{Zn}^{63}$ reaction from 320 Mev bremsstrahlung.

However, as a check of the validity of this normalization, the neutron yield from deuterium was obtained using the long counter and identical targets of water and heavy water. Since the neutron counter is not sensitive to high energy neutrons, and the $\text{D} (\gamma, n)$ cross section is known at low energies, this reaction also would serve to normalize the bremsstrahlung to the same number of low energy quanta. The peak of the $\text{D} (\gamma, n)$ cross section is at 4.4 Mev, and the normalizing energy * for the reaction is of that order. This energy lies below the normalizing

* The energy E_n for which

$$\frac{N(E_1, E_n)}{N(E_2, E_n)} = \frac{\int_0^{E_1} \sigma_D(\gamma, n)(E) N(E_1, E) dE}{\int_0^{E_2} \sigma_D(\gamma, n)(E) N(E_2, E) dE}$$

energy for the $\text{Cu}^{63} (\gamma, n) \text{Cu}^{62}$ reaction (16.5 Mev). From Figure 6 it may be seen that $N(80,5)$ is greater than $N(120,5)$. Therefore, it would be expected that Y for deuterium would be greater for low energy bremsstrahlung than for high. In Table IA it is seen that Y for deuterium is, within statistics, constant for all higher energies, and somewhat higher for 80 Mev. This, within experimental error, confirms the validity of the copper normalization.

As a further check, polystyrene foils were bombarded for 20 minutes and then counted in the geiger counter for 20 minutes at 320, 240, 160, 120, and 80 Mev. The $\text{C}^{12} (\gamma, n) \text{C}^{11}$ reaction has a 20 minute half life and exhibits a resonance peaked at about 22.5 Mev⁴. Although the statistics were poor here, again agreement with the copper normalization was found.

G. Errors

Errors in the values of Y were primarily due to counting statistics. In Table IA and IB the average probable error per point is listed for each element. This was determined from counting statistics at energies where only one run was taken, and from the expression

$$\text{probable error} = .845 \frac{\bar{d}}{\sqrt{n-1}}$$

where three runs were taken at one energy. Here $\bar{d}$ is the average of the differences between each run and the mean, and n is the number of runs. Probable errors were in general about twice as great at 80 Mev as at 320 Mev.

Limitations on the accuracy of the copper foil calibration were due to variations in foil thickness (less than 1/4 percent), errors in timing (less than .01 minute), and copper foil positioning. Since the foils

were wrapped into a cylinder of diameter about $1/8$ inch larger than the geiger tube, and were simply allowed to hang on the tube (oriented horizontally), the counting volume would intercept different solid angles from different sections of the foil. Since the intensity distribution of the beam on the foil is a function of energy (being almost uniform at low energies, and being concentrated toward the center at high energies) some systematic error could be introduced in this way. However, this error is estimated to be less than a percent over the energy range studied.

As the beam monitor ionization chamber was vented to the air, a change of room temperature of 10 degrees would produce a 3 percent change in the density of the air in the chamber, resulting in a 3 percent error in the number of ion pairs formed per unit of beam. This effect was not considered during the runs; however, a guarantee that it did not cause serious consequences is the reproducibility of the repeated points. Another source of error difficult to estimate was the occasional jitter of the synchrotron R.F. accelerating system, causing the beam to fall out as much as 2 or 3 thousand microseconds early. This could have accounted for some noticeably bad points (which were corrected by later runs), but was usually watched for and caught when it occurred.

Plateaus were taken of neutron counting rate from uranium per Nunan as a function of beam intensity in order to check the beam intensity were neutron pile-up or electron pile-up in the proportional counter became appreciable. Electron pile-up was observed on the monitoring oscilloscope when at 280 Mev the beam pulse was less than 4 microseconds wide and at maximum intensity, however, even at this extreme only a three percent increase in counting rate due to electron pile-up was observed.

Neutron pile-up (due to the scaler dead time) was observed at maximum beam intensity at 240 Mev. However, counting rates were always held to a value sufficiently low so that a maximum of 2 percent error (and usually much less) could have been introduced from this source at this energy.

Since both the neutron counter and geiger counter were operated on broad voltage plateaus, changes of counter voltage plateaus and changes of counter voltages or amplifier gains of less than 2-1/2 percent would have virtually no effect on the results.

Neutrons produced in the platinum x-ray target, in the synchrotron quartz and iron, and in the lead collimators might scatter from the neutron target into the counter. This effect is believed small with the possible exception of the lowest energy points of carbon and beryllium. The neutron yield observed goes as Z^2 approximately, while neutron scattering is proportional to $Z^{2/3}$ (the nuclear area). Also, the neutron background increases with decreasing beam energy (since the spread of the beam increases and more of it is intercepted by the collimator), and errors due to neutron scatter would also tend to increase. However, even the lightest elements showed decreasing neutron yield with decreasing energy. Agreement between the present results and those obtained with twice the collimation angle⁴ indicate error from this source is within statistics.

Another source of error in the absolute magnitude of the cross sections in beryllium and carbon is the angular assymetry of the photoneutrons. This would lead to measured values somewhat higher than reality.

It is worth noting that all major possible errors such as neutron pile-up, scattered neutrons, and contribution to the Cu^{62} activity by higher energy quanta would all tend to increase the slope of the yield curve, and consequently give rise to even higher cross sections for neutron production at high energies than herein reported.

III. DETERMINATION OF CROSS SECTIONS

A Bremsstrahlung

Fundamental to the interpretation of this experiment is a knowledge of the bremsstrahlung spectrum. Basically, the spectrum of x-rays produced by a beam of monoenergetic electrons striking an infinitely thin target integrated over all directions of the outgoing photons and electrons is given by the Bethe-Heitler formula¹⁸. This formula contains as parameters the target material and the energy of the incident electrons. Rossi and Griesen¹⁹ have plotted this expression for a family of initial energies for targets of lead and air taking into account the effect of screening. To obtain the curves of the Bethe-Heitler formula for the energies used here, the Rossi and Griesen curves for lead were read to three significant figures and graphically interpolated for the desired intermediate energies.

The Bethe-Heitler formula has been checked at high energies experimentally by Powell, et al¹², DeWire and Beach²⁰, Stokes²¹, and Emigh²². The Born approximation is used in the derivation of the Bethe-Heitler formula, and for 320 Mev electrons on platinum the conditions for its validity are not fulfilled. However, Davies and Bethe have recently made an exact calculation²³ of the bremsstrahlung cross section without the Born approximation. The result reduces to the Bethe-Heitler expression plus a constant term of magnitude of about 10 percent of the average Bethe-Heitler value. The resulting distortion of the assumed spectrum is consequently only one or two percent except close to the maximum energy.

Schiff²⁴ shows that for targets of finite width, multiple electron scattering in the target has the effect of averaging over all angles so that the Bethe-Heitler formula may be used even when only the beam in the

forward direction is considered.

Eyges²⁵ shows that for a target of thickness not small relative to a radiation length, the process of cascade showering modifies the spectrum. From expanding the shower equations and considering only first terms, he gives the following expression for the correct spectrum:

$$V\phi'(V) = V\phi(V) \left[1 - \frac{T}{2} \left\{ \sigma(E) - \ln(1-V) \right\} \right] \quad (3)$$

where $\phi(V)$ is the Bethe-Heitler spectrum, $\phi'(V)$ is the corrected spectrum, $V = \frac{E}{E_0}$ where E_0 is the energy of the incident electrons and E is the energy of the radiated quantum, T is the target thickness expressed in radiation lengths, and σ is the cross section of the target material per radiation length for absorption of quanta of energy E . In the case of the Berkeley synchrotron, the target is .020 inches of platinum, or .20 radiation lengths, therefore the thick target corrections are not negligible.

The log term of the expression represents re-radiation by an electron which has radiated once after it has traveled to a greater depth in the target, and the σ term represents the probability that a quantum will be reabsorbed before it escapes the target.

Williams²⁶ and Molière²⁷ have given somewhat different expressions for the multiple scattering of electrons. Schiff²⁴ and Lanzl and Hanson²⁸ have, using Williams and Molière expressions respectively, obtained the resulting angular distribution of bremsstrahlung from targets of finite thickness. Experimental results^{28,29} seem to support Molière's formula, although the two are not greatly different.

Multiple scattering of electrons in the target may modify Eyges' corrections. The radiation from a fast electron is predominately in the forward direction. If the x-ray beam is collimated so that the collimator

subtends a cone of central angle $\bar{\Phi}$ with its axis along the incident electron direction, the radiation from an electron traveling at an angle greater than $\bar{\Phi}$ will probably not pass through the collimator. Electrons entering the target will simultaneously radiate and scatter. An effective target thickness $\bar{t}$ may be found for a given collimator which represents the average depth an electron penetrates into the target before scattering out of the cone subtended by the collimator. Using the simplifying assumption that the radiation is entirely in the direction of motion of the electron, this effective target thickness is used to modify Ryges' expression for multiple scattering.

The quantity $\bar{t}$ is derived from the William's scattering expression, used instead of Molière's only for simplicity (the resulting $\bar{t}$ using the latter would not be significantly different). The normalized distribution of electrons per unit solid angle at depth t cm. in the target is given by

$$n(\theta)d\Omega = \frac{1}{2\pi\theta_0^2} e^{-\frac{\theta^2}{2\theta_0^2}} \quad (4)$$

where

$$\theta_0^2 = \left(\frac{9.2 Z e^2}{E} \right)^2 Nt = Ct \quad (5)$$

or

$$n(\theta)d\theta = \frac{\theta}{Ct} e^{-\frac{\theta^2}{2Ct}} \quad (6)$$

The number of electrons with directions θ of between zero and $\bar{\Phi}$ at depth t is then

$$N = \int_0^{\bar{\Phi}} n(\theta) d\theta = 1 - e^{-\frac{\bar{\Phi}^2}{2Ct}} \quad (7)$$

The fraction of electrons scattering out of the cone of angle $\bar{\Phi}$ at depth t per unit distance is then $\frac{dN}{dt}$ and $\int_0^T \frac{dN}{dt} dt$ is the average distance an electron travels before scattering out. To this number must be added the number of electrons which pass completely through the target without scattering out of $\bar{\Phi}$ weighted by T . Their number is simply $1 - e^{-\frac{\bar{\Phi}^2}{2CT}}$. The resulting average depth an electron penetrates before scattering out of the cone of central angle $\bar{\Phi}$ is then

$$\bar{t} = \int_0^T \frac{\bar{\Phi}^2}{2C} e^{-\frac{\bar{\Phi}^2}{2Ct}} \frac{dt}{t} + (1 - e^{-\frac{\bar{\Phi}^2}{2CT}}) T \quad (8)$$

The integral was graphically evaluated for the .020 inch target and the eight energies studied.

It is proper now to replace in (3) the $\frac{T}{2} [\ln(1-V)]$ by $\frac{\bar{t}}{2} \ln(1-V)$ and to replace $\frac{T}{2} \sigma(E)$ by $(T - \frac{\bar{t}}{2}) \sigma(E)$.

This modifies (3) to the following:

$$V \phi'(V) = V \phi(V) \left[1 - (T - \frac{\bar{t}}{2}) \sigma(E) + \frac{\bar{t}}{2} \ln(1-V) \right] \quad (9)$$

In applying this expression to the Berkeley synchrotron there is some question as to what value to use for T . Although the target is made from a .020 inch strip of platinum, it is possible that the electrons might only graze the edge of the target and hence only traverse a few mils. However the angular spread measurements of Rosengren²⁹ assuming a .020 inch target are consistent with the angular spread measurements of Ianzl and Hanson²⁸ using an externally deflected electron beam. Also the beam appears to be symmetric about its axis. This would not be the case if the electrons only grazed the target, some scattering into it and continuing to radiate and others scattering out of it. Therefore the thickness T in radiation lengths corresponding to .020 inches of platinum

was used in (9) to calculate the spectra actually used and plotted in Figure 6.

B. Calculation of Relative Cross Sections

The values of Y of Table IA and IB are plotted in Figures 7, 8, and 9 with smooth curves drawn through the points. For ease of comparison, values of Y are plotted normalized to unit yield at 320 Mev. Since the 40 Mev points are not used in the subsequent analysis, the yield curves are not extended to them.

In order to reduce these data to cross sections for neutron production, $\sigma(E)$, the cross section must be known for each target element for energies below 80 Mev. These were obtained from the work of K. M. Terwilliger⁴.

$$\text{The integrals } \int_0^{80} \sigma(E) N(E_0 E) dE \quad (10)$$

were evaluated for each element for values of E_0 of 80, 200, and 320 Mev, using $N(E_0 E)$ as the bremsstrahlung normalized to the same number of 16.5 Mev quanta. The values of the integral were then obtained for intermediate energies by graphical interpolation. Since tin was not among the elements studied at lower energies, no analysis of it was attempted in this experiment.

For any particular element, the relative average values of cross section may now be obtained for each 40 Mev interval knowing the integrals (10), the functions $N(E_0 E)$ (section IIIA), and the values of Y (from the intercepts of the smooth curves). The method is to work up from the lowest energy interval so that corrections to each successively higher energy increment may be made for the cross section at lower energies.

Let $\bar{Y}(E_1, E_2)$ represent the average yield due only to quanta of energies between E_1 and E_2 , and $\sigma(E_1, E_2)$ the average relative cross section

in that energy interval. Then

$$\bar{Y}(80,120) = [Y(120) - Y(80)] - Y(80) \left[\frac{\int_0^{80} \sigma(E)N(120,E)dE - \int_0^{80} \sigma(E)N(80,E)dE}{\int_0^{80} \sigma(E)N(80,E)dE} \right],$$

$$\bar{\sigma}(80,120) = \bar{Y}(80,120) / \int_{80}^{120} N(120,E)dE \quad (11)$$

Using this result,

$$\bar{Y}(120,160) = [Y(160) - Y(120)] - \bar{Y}(80,120) \left[\frac{\int_{80}^{120} N(160,E)dE - \int_{80}^{120} N(120,E)dE}{\int_{80}^{120} N(120,E)dE} \right]$$

$$- Y(80) \left[\frac{\int_0^{80} \sigma(E)N(160,E)dE - \int_0^{80} \sigma(E)N(120,E)dE}{\int_0^{80} \sigma(E)N(80,E)dE} \right],$$

$$\bar{\sigma}(120,160) = \bar{Y}(120,160) / \int_{120}^{160} N(160,E)dE \quad (12)$$

Similarly,

$$\bar{Y}(160,200) = [Y(200) - Y(160)] - \bar{Y}(120,160) \left[\frac{\int_{120}^{160} N(200,E)dE - \int_{120}^{160} N(160,E)dE}{\int_{120}^{160} N(160,E)dE} \right]$$

$$- \bar{Y}(80,120) \left[\frac{\int_{80}^{120} N(200,E)dE - \int_{80}^{120} N(160,E)dE}{\int_{80}^{120} N(120,E)dE} \right]$$

$$- \bar{Y}(80) \left[\frac{\int_0^{80} \sigma(E)N(200,E)dE - \int_0^{80} \sigma(E)N(160,E)dE}{\int_0^{80} \sigma(E)N(80,E)dE} \right],$$

$$\bar{\sigma}(160,200) = \bar{Y}(160,200) / \int_{160}^{200} N(200,E)dE \quad (13)$$

The procedure is repeated for each successively higher energy increment, with another correction term added each time. $\bar{Y}(280,320)$ has six correction terms subtracted from the yield increment.

The values $\bar{\sigma}(E_1, E_2)$ are assumed to represent $\sigma \frac{E_2 - E_1}{2} + E_1$.

Since σ is a slowly varying function of energy relative to the 40 Mev

energy intervals in this energy range, the above assumption is a close approximation to reality.

The method of obtaining a cross section curve is effectively a differentiation of the yield curve, modified due to bremsstrahlung overlapping. Therefore, the slope of the yield curve determines the magnitude of the cross section, its curvature determines the slope of the cross section, while the curvature of the cross section curve is related to the third derivative of the yield curve. Due to scatter of the data points a number of smooth yield curves could be equally well chosen to represent the true yield curve. However, most of these curves lead to incongruous results for the cross sections, such as cross sections alternating high and low for successive points. A broken line connecting the yield data points often leads to negative cross sections in some energy intervals. Therefore, in working out the curves a trial and error system was used, the smoothness of the resulting cross section curve being the criterion for correctness. It was noticed that the smooth cross section curve seemed to represent the average of the fluctuating cross section points resulting from the original trial yield curve.

To illustrate the above procedure for calculating cross sections, the numbers for the analysis of the silver data are presented in Table III. To facilitate analysis, the coefficients of the correction terms were previously computed and tabulated. These were used for all elements and are presented in Table II. Since the targets are not thin, the numbers of quanta were corrected for the absorption of quanta in the target. This factor is closely

$$\delta = e^{-\frac{\tau x}{2}}$$

where τ is the absorption coefficient of the target per radiation length, and x is the target thickness expressed in radiation lengths. Values of τ

were obtained from Heitler³⁰. The characteristics of the targets are given in Table IA and IB.

The least accurate portions of the yield curves are the ends, since one can not anticipate the slope of the yield curves through the extreme data points. The yield curves were adjusted at the low energy end so that the resulting cross section curves joined smoothly to Terwilliger's⁴ cross sections below 70 Mev.

From noting how much a smooth yield curve could be altered and still be consistent with the yield data and a smooth cross section curve, an estimate of the error in the yield curves could be obtained. For instance, a 2 percent change in the 320 Mev intercept of the yield curve, with the new curve drawn smoothly to the old 200 Mev intercept, resulted in a change in magnitude of the cross section at 320 Mev of 20 percent.

It is estimated that for yield data accurate to ± 2 percent, the cross section values at energies below 240 Mev are accurate to ± 15 percent, and at 300 Mev are accurate to ± 30 percent. On comparing the values of yield at 320 Mev obtained experimentally* with the values obtained by integrating the calculated cross sections times the bremsstrahlung from threshold to 320 Mev, excellent agreement was observed. The above error estimates then seem to represent conservative limits.

C. Reduction to Absolute Cross Sections

In an earlier experiment⁷ the total neutron yields from the same targets were obtained per mole/cm² per erg of 320 Mev bremsstrahlung. A similar neutron counter was used and calibrated for absolute neutron detection efficiency using a calibrated Ra-Be neutron source. The synchrotron beam energy was calibrated by W. Blocker³¹.

* Table I, also Reference 7.

These numbers represent

$$y \frac{\text{neutrons}}{\text{mole}} \frac{\text{erg}}{\text{cm}^2} \propto \frac{\int_0^{320} \sigma(E) N(320, E) dE}{\int_0^{320} E N(320, E) dE} \quad (14)$$

From a dimensional analysis, the relative cross sections from the present experiment may be determined in units of cm^2 per atom of target using this data. If y is expressed in units of neutrons / Mev per atom/ cm^2 , then the cross section for neutron production

$$\sigma(E_1, E_2) \text{cm}^2 = \left(\frac{\bar{Y}(E_1 E_2)}{\delta \int_{E_1}^{E_2} N(E_2, E) dE} \right) \left(\frac{\int_0^{320} E N(320, E) dE}{Y(320)} \right) y \quad (15)$$

$Y(320)$ is unity in the units of $\bar{Y}$, and $N(E_0, E)$ is in the same units in numerator and denominator. The integral in the numerator was evaluated using Figure 6 and a planimeter, and units were adjusted to give the value in Mev.

Since the values of y were not corrected for photon absorption in the target, the δ in the denominator is necessary for correct final values of .

By a similar dimensional analysis, the low energy cross sections of Terwilliger's⁴ were expressed in units of cm^2/atom , using for the normalization the 80 Mev yield point.

On comparing the ratios of the data from the previous⁷ experiment with the yields per mole/ cm^2 at 320 Mev of this experiment close agreement was observed. Since the statistics of the present experiment are superior, the average of the above ratios times the present yields were taken as corrected values for y .

The ratios of the 80 Mev experimental yields to those calculated from Terwilliger's experiment all varied less than 5 percent from 1.00.

Each value of y was further corrected by half of the error of this ratio, since Terwilliger's data is as valid as that herein presented. -

The cross section numbers are plotted as smooth curves for the elements studies in Figures 10, 11, and 12.

IV. RESULTS AND DISCUSSION

The results as presented in Figures 10, 11, and 12 show several interesting properties. The cross section in general increases with energy from below the meson threshold (about 150 Mev) through 300 Mev. The shapes of the curves show a general trend with increasing atomic weight, the ratio of the cross section at 300 Mev to the cross section at 100 Mev increasing with A. Beryllium, carbon, aluminum, and iron show cross sections decreasing or constant with energy at energies below 100 Mev. The absolute magnitude of the neutron production cross sections are very large for a photonuclear interaction (e.g., 10^{-24} cm^2 in uranium for 300 Mev photons). This fact, together with the energies of neutrons detected, immediately suggests that more than one neutron is produced from each high energy event. The cross sections at 300 Mev are proportional to A^2 , at 100 Mev proportional to $A^{1.6}$, and at 55 Mev proportional to $A^{1.4}$.

In an attempt to understand these features, previous high energy photonuclear investigations may be considered. Brueckner and Watson³², presenting a theoretical analysis of the experiments of Silverman and Stearns³³ and Steinberger and Bishop⁶, give the following values for total photomeson production from hydrogen:

Photon E (Mev)	200	250	300
$\sigma_{\pi^+ + \pi^0} (x 10^{-28} \text{ cm}^2)$	1.5	2.5	4.4

White³⁴ finds that the cross sections for π^+ meson production from deuterium are 75 percent of hydrogen cross sections, and the $\frac{\pi^+}{\pi^0}$ ratio is close to unity. Andre³⁵ finds the π^0 production cross section from deuterium twice that from hydrogen.

It seems plausible that the high energy photon interaction leading to neutron production observed in the present experiment could be

correlated to the same mesonic interactions responsible for stars, high energy protons, and real meson production.

In heavier nuclei, the exclusion principle lowers the average photomeson interaction cross section per nucleon. However, the closer packing of nuclear material and greater density of mesonic currents could increase the interaction, so that it is uncertain how well the above numbers represent photomeson cross sections per nucleon in heavy nuclei.

Mozley³⁶, Littauer and Walker³⁷, and Panofsky, et al⁶, find that photomeson production goes as $A^{\frac{2}{3}}$ for heavier nuclei, indicating production from the nuclear surface. This has generally been interpreted as due to the short mean free path of mesons within the nucleus.

Kikuchi³⁸ and Miller³⁹ have observed stars in photographic emulsions. The magnitude of the cross section for star production qualitatively agrees with the concept that photomesonic reactions occur in nuclei resulting in high energy protons. Undoubtedly neutrons are ejected from these stars with the observed protons. The cross section for star production is an increasing function of energy further suggesting a mesonic interaction.

Miller obtained the following cross sections for star production on carbon and silver:

Energy Interval	$\sigma_C (x 10^{-27} \text{ cm}^2)$	$\sigma_{Ag} (x 10^{-27} \text{ cm}^2)$
80-160 Mev	$.49 \pm .12$	$.94 \pm .16$
160-240 Mev	$1.7 \pm .4$	$3.6 \pm .5$
240-320 Mev	$1.4 \pm .6$	7.0 ± 1.2

Kikuchi's values are larger by a factor of 2.4, partly due to use of a more sensitive emulsion.

Wilson⁴⁰ and Huddleston⁴¹ suggest that the meson need not be

created physically and reabsorbed by the nucleus. Rather, the photon may interact with meson exchange currents or the meson field around the nucleons, where the photon energy may be absorbed by the nucleon directly. Due to the proximity of other nucleons, energy and momentum may be conserved, and a pair of highly energetic nucleons result from the interaction. These then either escape with high energy or make collisions within the nucleus, thus giving rise to a star. In a heavy element a true compound nucleus may be formed or left after the emission of one fast particle, resulting then in the boiling off of a number of nucleons of low energy.

The results of the high energy proton counting experiments are only expressed per equivalent quantum of beam, except for deuterium. Since most of the photoprotons are associated with stars, it is more convenient to use the star production data for discussion of photon absorption. The energy distribution of photoprotons from 320 Mev bremsstrahlung is proportional to $E^{-1.7}$ for energies less than half the maximum bremsstrahlung energy, and the yields are proportional to Z of the bombarded nucleus.

The cross sections of Figures 10, 11, and 12 may be represented as

$$\sigma(E) = \sigma_a(E) \int_0^E \gamma(E,e) P(e) de \quad (16)$$

where $\sigma(E)$ is the measured cross section, $\sigma_a(E)$ the photon absorption cross section, $\gamma(E,e)$ the fraction of the times that a nucleus excited to energy E will emit a neutron of energy e , and $P(e)$ the detection efficiency of the neutron counter relative to Ra-Be neutrons for neutrons of energy e .

$P(E)$ has been discussed in section 1.2. To arrive at $\sigma_a(E)$ and compare it with values discussed above, something must be known about $\gamma(E,e)$.

Byerly and Stevens⁴², and Almy and Dixon²⁴ have investigated the energy distribution of neutrons from copper bombarded by 22 Mev bremsstrahlung.

Their results show a Maxwellian distribution peaked at about 1 Mev with somewhat more neutrons of higher energies than predicted by the statistical model⁴³. These may be explained by a direct photoelectric interaction between the photon and a surface neutron. Kerst⁴⁴ has observed neutrons of energies greater than 50 Mev from 300 Mev bremsstrahlung, and has found them roughly equal in number to the protons of Levinthal and Silverman. These protons are less numerous by a factor of 10 or more than the neutrons observed in the present experiment from high energy quanta. A preliminary experiment by the author using a proportional counter telescope and a paraffin converter showed that less than 5 percent of the neutrons from 320 Mev bremsstrahlung on copper had energies greater than 5 Mev. Sugarman and Peters⁴⁵ and Debs⁴⁶ have found induced activities from high energy bremsstrahlung of 80 and 300 Mev respectively corresponding to photo-emission of at least 8 neutrons.

These experiments suggest that even photonuclear events of energy greater than 100 Mev result in a highly excited nucleus which boils off low energy neutrons according to the compound nucleus model. If this is correct, most of the neutrons coming from high energy interactions may be assumed to fall in the region of uniform sensitivity of the BF₃ long counter, and P(e) may be taken as unity. The quantity $\gamma(E, e)$ may then be integrated over all e. The resulting $\gamma(E)$ is the neutron multiplicity (the average number of neutrons produced for each photon of energy E absorbed.)

Assuming that the statistical model holds exactly, $\gamma(E)$ can be calculated for the heavy elements. Due to the height of the coulomb barrier, proton emission may be neglected within the present limits of error. Levinger and Bethe⁴⁶ express

$$\gamma(E) \approx E/E_n \quad (17)$$

where E_n represents the average energy spent in producing a neutron. The values of E_n are given for five elements as follows:

Element	Cu	I	Ta	Bi	U
E_n (Mev)	21	13	11	10	8

For instance, one would expect 150/10, or 15 neutrons from the absorption of a 150 Mev photon by a bismuth nucleus. The statistical model is probably not completely valid for energies above 100 Mev, since higher energy events can give rise to nucleons which carry off a large fraction of the total excitation energy before a compound nucleus is formed. However the above numbers should represent an upper limit to the neutron multiplicity and to the energy dependence of the multiplicity.

Recent Cornell experiments ⁴⁷ on the neutron production by meson absorption give an indication of the neutron multiplicity for 150 Mev excitation. Negative π mesons of 40 to 70 Mev energy were counted by a geiger counter telescope and absorbed in various targets. The resulting neutrons were counted by boron trifluoride counters in paraffin. The efficiency of the neutron counting system was determined using a Ra-Be neutron source. The results are presented below.

Element	Pb	Sn	Al	C
(E)	$9.8 \pm .5$	$6.3 \pm .5$	$2.1 \pm .2$	$1.6 \pm .2$

This multiplicity for lead is 30 percent lower than the multiplicity for bismuth guessed from the statistical model for the same excitation energy.

Taking the above results as the correct multiplicities, and assuming the value for tin represents what the value for silver would be, photon absorption cross sections at 150 Mev for four elements may be deduced.

Element	C	Al	Ag	Pb
$\sigma(150)$ Present Experiment ($\times 10^{-27}$ cm ²)	1.2	5.5	82	288
$\nu(150)$ Cornell data	1.6	2.1	6.3	9.8
$\sigma_a = \sigma/\nu$ ($\times 10^{-28}$ cm ²)	.75	2.6	13	29
σ_a / A ($\times 10^{-28}$ cm ²)	.62	.97	1.2	1.4

The value of σ_a for carbon is less than either Miller's or Kikuchi's values from stars. On the other hand σ_a for silver is larger than the values from star data. This may be due to the manner in which Miller analyzed his stars into carbon events and silver events. A simple explanation of the discrepancy in silver is that many of the star events might involve only one or no fast protons, the rest of the energy going into neutrons. Events of this type would not be included in the emulsion star data, but would contribute to neutron yields.

The values of σ_a/A indicate that the absorption cross section per nucleon for photons of about 150 Mev on nuclei is only a slowly varying function of the number of nucleons in the nucleus. It is worth noting that these values of σ_a/A are comparable to Brueckner and Watson's values for total photomeson production from hydrogen by 200 Mev photons. It is assumed that the mesons of the Cornell experiment were captured from atomic orbits and consequently gave to the absorbing nucleus an energy only equal to their rest mass.

The shapes of the cross sections curves as a function of energy show a greater slope for heavier elements. This may be interpreted as indicating that the heavier elements show a statistical model behavior at very high energies. In lighter elements the statistical model is less valid, although it is worth noting that even from carbon and beryllium slow neutrons are observed from 300 Mev quanta in numbers exceeding simply those expected from recoil nucleons from real meson production. In the extreme case of beryllium, the cross section for neutron production appears to decrease with energy above the meson threshold, although every indication is that photon absorption is increasing. Probably never more than two or three neutrons are ejected per interaction with a beryllium nucleus, as the probability for an intact alpha particle escaping is high.

With the neutron number constant, the neutron energies would be increasing with excitation energy, and their probability of being counted decreases. In fact it is possible that some of the neutrons seen from the beryllium target at 300 Mev may come from stars caused by absorption of negative mesons (produced in the beryllium) within the neutron counter.

The beryllium neutron production cross section is almost twice that of carbon below 100 Mev. The reason for this appears to be that the energy necessary to release two neutrons from beryllium (22.2 Mev) is about the same as that required to release one neutron from carbon (18.7 Mev).

It is of interest to speculate on the energy dependence of the photon absorption cross section in the vicinity of the meson threshold. The theory of Huddlestons and Lepore⁴¹ for photodisintegration of deuterium predicts an increase in photon absorption cross section below the meson threshold due to photon interaction with the exchange currents. By dividing the photoneutron production cross section by energy in heavy elements (assuming a neutron multiplicity proportional to E) a lower limit may be set on the slope of the photon absorption cross section curve. Values of this ratio are given in Table IV for Ta, W, Pb, and U. All show an increase in σ/E from 100 Mev to 150 Mev. The ratio increases less rapidly above the meson threshold than below, probably indicating a greater failure of σ/E to represent the real photon absorption which otherwise might be expected from (16) and (17). Even at 100 Mev the statistical model predicts the neutron multiplicity from uranium to be a less steep function of energy than $E^{1/48}$. Thus it seems fairly certain that photon absorption by heavy nuclei increases below the meson threshold as predicted by Huddlestons's theory, although a quantitative measure of this increase is difficult from the present data alone.

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TABLE IA
EXPERIMENTAL DATA

Element	D	Be	C	Al	Fe	Cu	Mo
Z	1	4	6	13	26	29	42
Target Thickness (inches) Normal to Beam	3.0	1.5	2.0	1.0	.271	.270	.136
Moles/cm ² x 10 ⁻²	-	76.6	66	26	9.7	9.6	3.71
Radiation Lengths	-	.08	.13	.42	.42	.51	.43
Y(320)	3.156	5.037	2.275	3.141	4.875	6.988	5.779
Y Normalized to 1.00 at 320 Mev							
320	.970*	1.00	1.00	1.00	1.00	1.00	1.00
280	1.005	.968	.923	.932	.919	.915	.934
240	1.030	.930	.880	.915	.908	.886	.898
200	1.000	.934	.817	.819	.826	.831	.843
160	.995	.885	.814	.792	.781	.817	.807
120	1.040	.839	.731	.722	.755	.747	.731
80	1.072	.764	.637	.608	.704	.637	.689
40	1.193	.695	.505	.525	.626	.573	.598
Average Probable Error %	2.8	1.5	2.0	1.0	1.8	1.9	1.6

* Normalized to 200 Mev

TABLE IB
EXPERIMENTAL DATA

Element	Ag	Sn	Ta	W	Pb	U
Z	47	50	73	74	82	92
Target Thickness (inches) Normal to Beam	.133	.131	.066	.065	.055	.067
Moles/cm ² x 10 ⁻²	3.24	4.08	1.56	1.72	.77	1.32
Radiation Lengths	.45	.33	.52	.61	.33	.7
Y (320)	6.009	4.748	7.007	7.977	3.854	13.05
Y Normalized to 1.00 at 320 Mev						
320	1.00	1.00	1.00	1.00	1.00	1.00
280	.931	.917	.901	.908	.904	.903
240	.899	.865	.892	.867	.860	.875
200	.830	.817	.774	.787	.765	.821
160	.809	.747	.741	.768	.726	.757
120	.760	.699	.700	.703	.663	.708
80	.644	.653	.644	.666	.577	.670
40	.598	.624	.548	.605	.528	.618
Average Probable Error %	1.7	2.3	1.0	2.1	2.1	1.4

TABLE IIA

CORRECTION TERM COEFFICIENTS

E_1	E_2	E_3	E_4	$\frac{\int_{E_1}^{E_2} N(E_4, E) dE - \int_{E_1}^{E_2} N(E_3, E) dE}{\int_{E_1}^{E_2} N(E_2, E) dE}$ $= \alpha(E_1, E_2, E_3, E_4)$
80	120	280	320	.030
		240	280	.032
		200	240	.048
		160	200	.045
		120	160	.125
120	160	280	300	.030
		240	280	.035
		200	240	.035
		160	200	.121
160	200	280	320	.028
		240	280	.005
		200	240	.149
200	240	280	320	.014
		240	280	.188
240	280	280	320	.193

TABLE IIB

BREMSSTRAHLUNG AREAS

E_1	E_2	$\int_{E_1}^{E_2} N(E_2, E) dE$ (Relative Units)
80	120	20.42
120	160	13.85
160	200	10.36
200	240	8.03
240	280	6.58
280	320	5.52

TABLE III
SAMPLE CALCULATION FOR SILVER

$E_{1,2}$	80	120	160	200	240	280	320
$Y(E)$	.670	.735	.793	.844	.893	.941	.991
$Y(E_2) - Y(E_1) = \Delta Y(E_1, E_2)$		.065	.058	.051	.049	.048	.050
$\frac{\int_0^{80} \sigma(E) N(E_2, E) dE - \int_0^{80} \sigma(E) N(E_1, E) dE}{\int_0^{80} \sigma(E) N(80, E) dE}$							
$= \beta(E_1, E_2)$		.020	.014	.011	.007	.006	.005
$Y(80) \times \beta(E_1, E_2)$		.013	.009	.007	.005	.004	.003
$\bar{Y}(E_3, E_4) \times (E_3, E_4, E_1, E_2)$							
$E_3 = 80 \quad E_4 = 120$			.006	.002	.002	.002	.002
$E_3 = 120 \quad E_4 = 160$				.005	.002	.002	.001
$E_3 = 160 \quad E_4 = 200$					.006	.000	.001
$E_3 = 200 \quad E_4 = 240$						.006	.001
$E_3 = 240 \quad E_4 = 280$							.007
$\bar{Y}(E_1, E_2)$		.052	.043	.037	.034	.034	.035
Target Absorption δ		.859	.855	.851	.848	.845	.843
$\delta \int_{E_1}^{E_2} N(E_2, E) dE$		17.56	11.84	8.81	6.81	5.56	4.66
$\bar{J}(E_1, E_2)$		2.96	3.63	4.20	5.00	6.11	7.51

TABLE IV

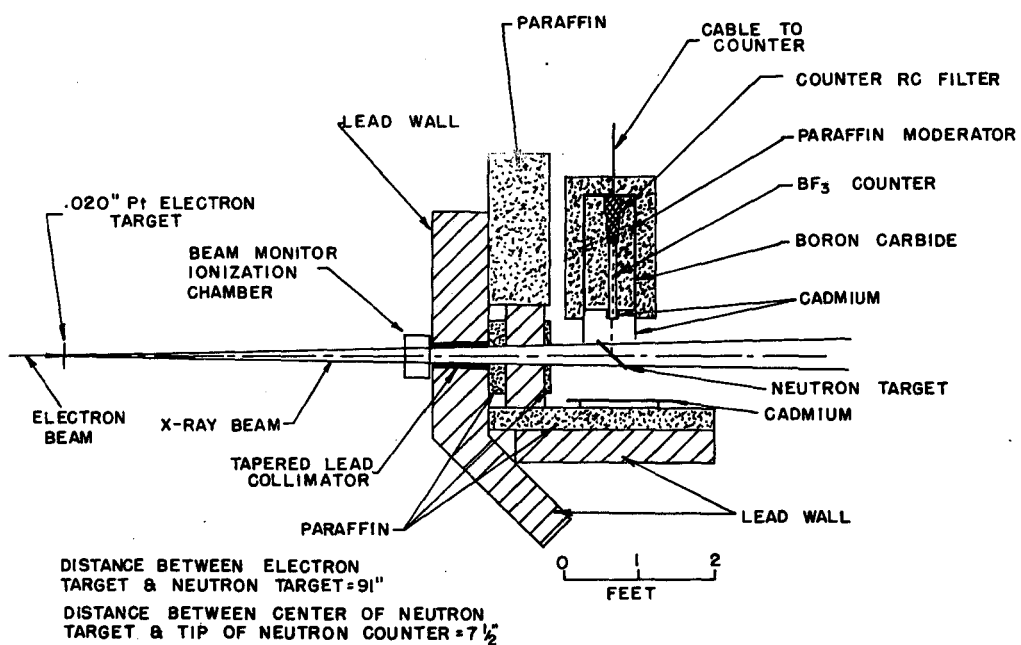
Ratios of Neutron Production Cross Sections to Energy for Heavy Elements

Photon Energy Mev	Ta σ ($\times 10^{-27}$ cm ²) σ/E		W σ ($\times 10^{-27}$ cm ²) σ/E		Pb σ ($\times 10^{-27}$ cm ²) σ/E		U σ ($\times 10^{-27}$ cm ²) σ/E	
60	84	1.40	90	1.50	76	1.27	130	2.07
80	115	1.44	110	1.38	115	1.44	190	2.38
100	150	1.50	130	1.30	166	1.66	255	2.55
120	187	1.56	155	1.29	217	1.81	320	2.66
140	223	1.59	190	1.36	264	1.89	395	2.82
160	260	1.63	230	1.44	308	1.93	480	3.00
180	295	1.64	270	1.50	350	1.95	565	3.14
200	332	1.66	320	1.60	395	1.99	560	3.25

FIGURE CAPTIONS

Figure

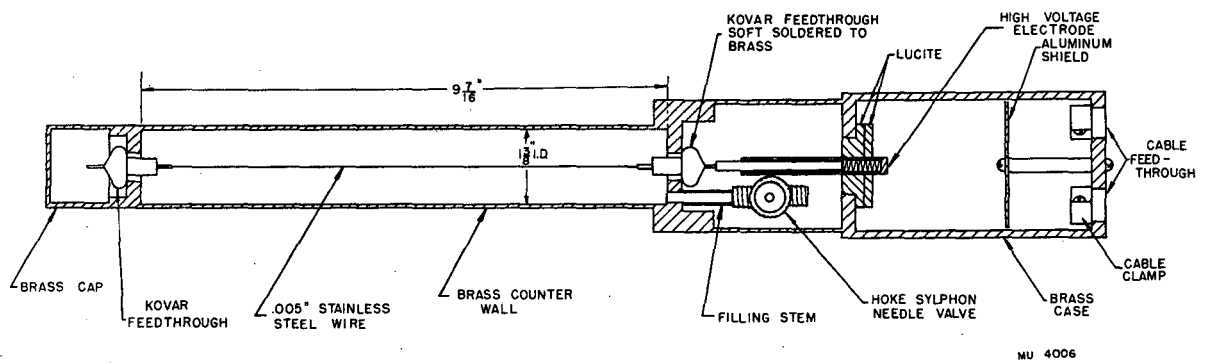
1. Horizontal section of the experimental layout in the plane of the synchrotron beam.
2. Scale drawing of the boron trifluoride proportional counter assembly.
3. Section and overall view of the long counter moderator and shielding assembly.
4. Relative energy sensitivity of the long counter to neutrons of various energies. The point taken with radium-beryllium neutrons is arbitrarily put at 5 Mev. This curve is taken from Rossi and Staub (Reference 9).
5. Excitation function for the reaction $\text{Cu}^{63} (\gamma, n) \text{Cu}^{62}$ taken from Reference 15.
6. Bremsstrahlung spectra for values of E_0 of 40, 80, 120, 160, 200, 240, 280, and 320 Mev. The values of $\text{EN} (E_0, E)$ are corrected as discussed in section IIIA and normalized to be equal at 16.5 Mev.
7. Total neutron yields from Be, C, and Al normalized to unit yield at 320 Mev.
8. Total neutron yields from Fe, Cu, Mo, and Ag normalized to unit yield at 320 Mev.
9. Total neutron yields from Ta, W, Pb, and U normalized to unit yield at 320 Mev.
10. Cross sections for total neutron production vs. photon energy for C, Be, and Al.
11. Cross sections for total neutron production vs. photon energy for Fe, Cu, Mo, and Ag.
12. Cross sections for total neutron production vs. photon energy for Ta, W, Pb, and U.



HORIZONTAL SECTION OF THE EXPERIMENTAL LAYOUT IN THE BEAM PLANE

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Figure 1



BF_3 PROPORTIONAL COUNTER ASSEMBLY

Figure 2

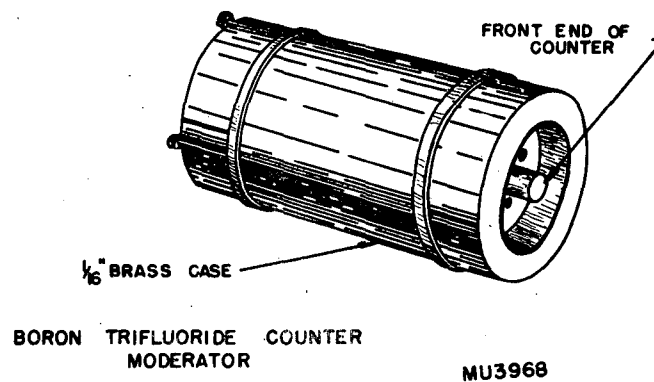
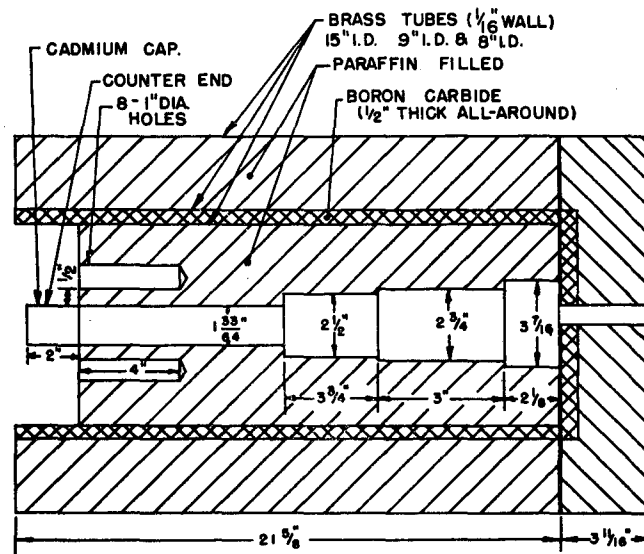


Figure 3

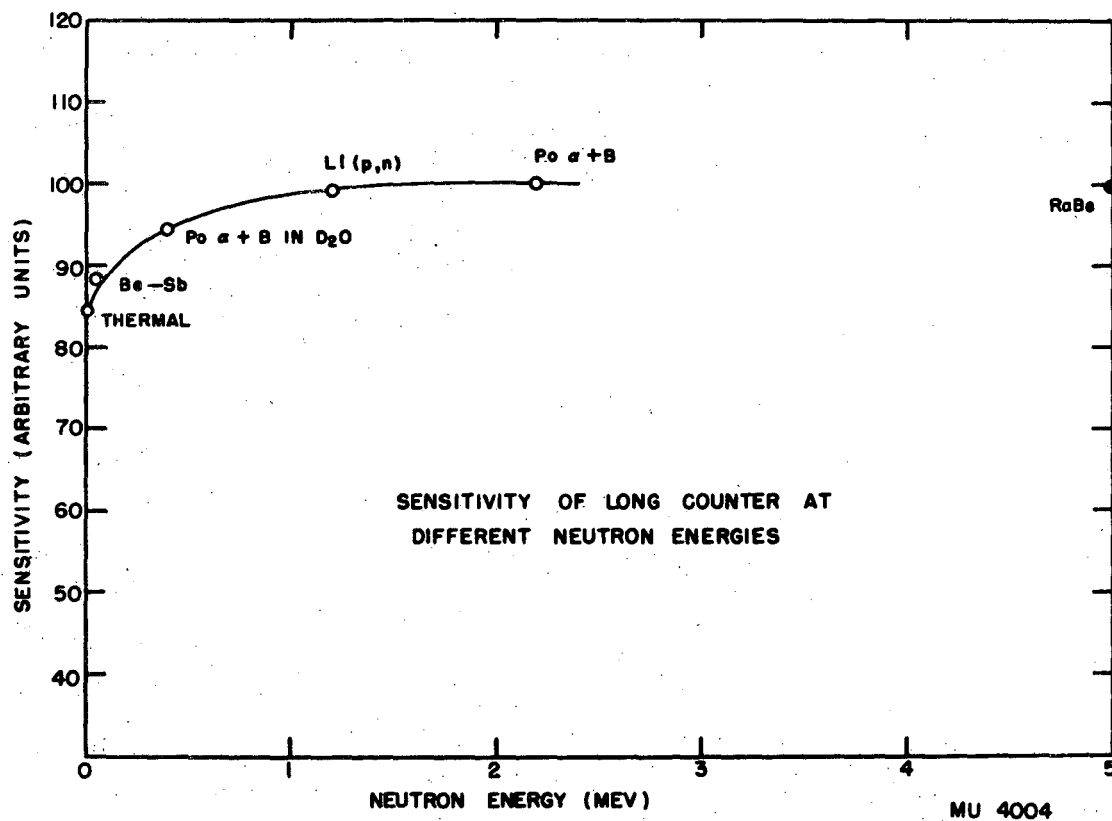


Figure 4

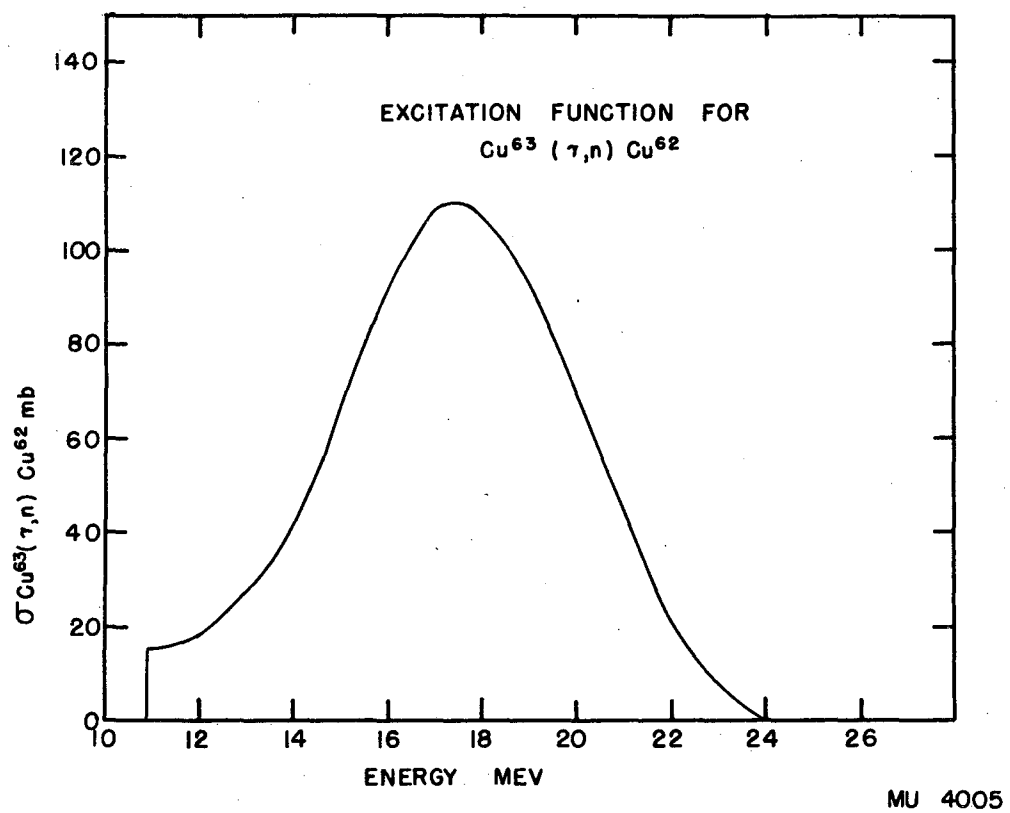


Figure 5

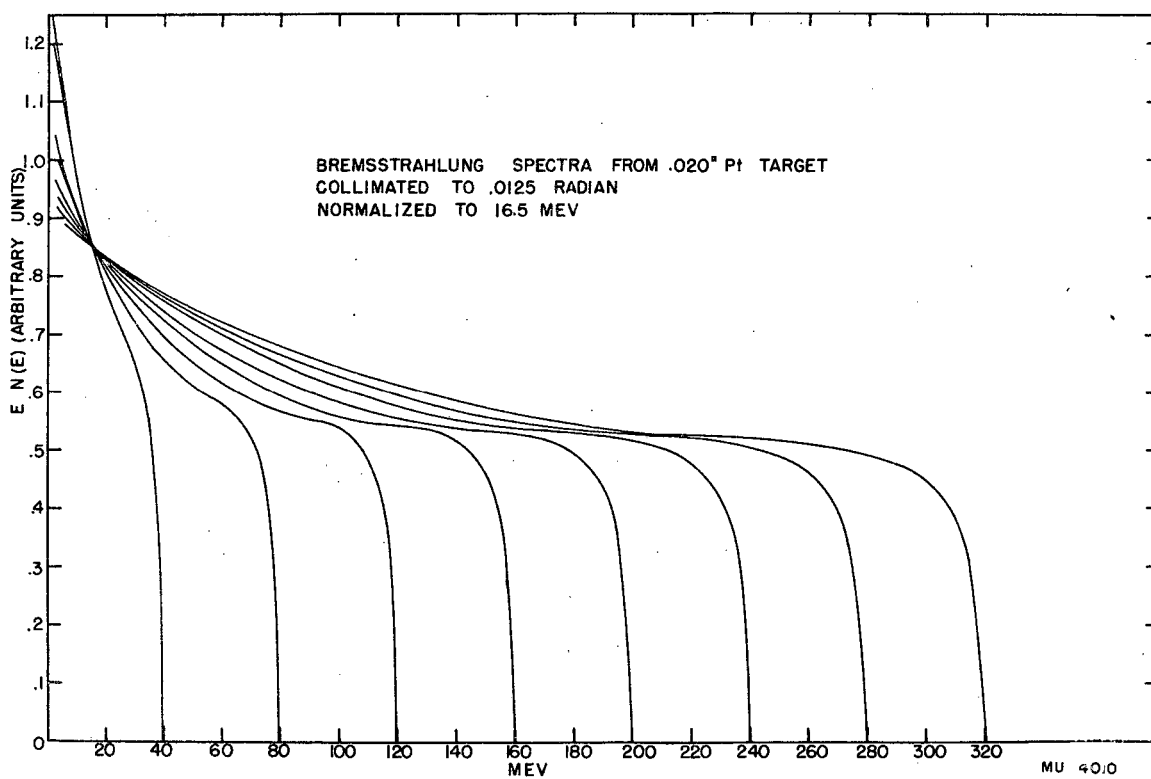


Figure 6

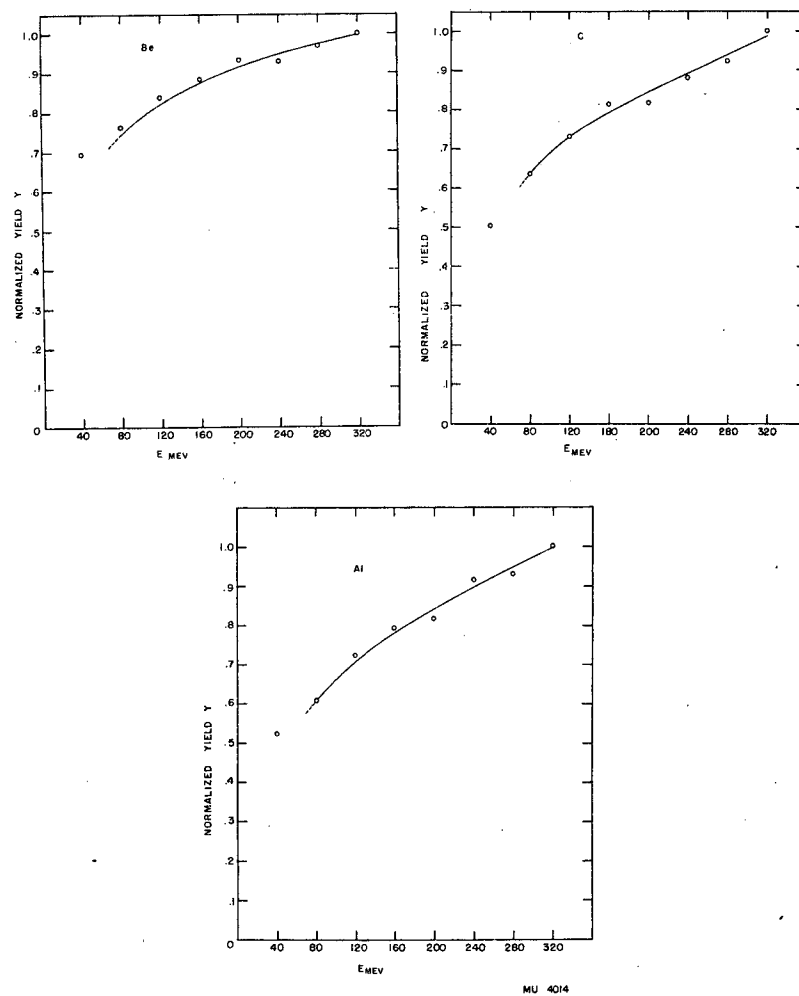


Figure 7

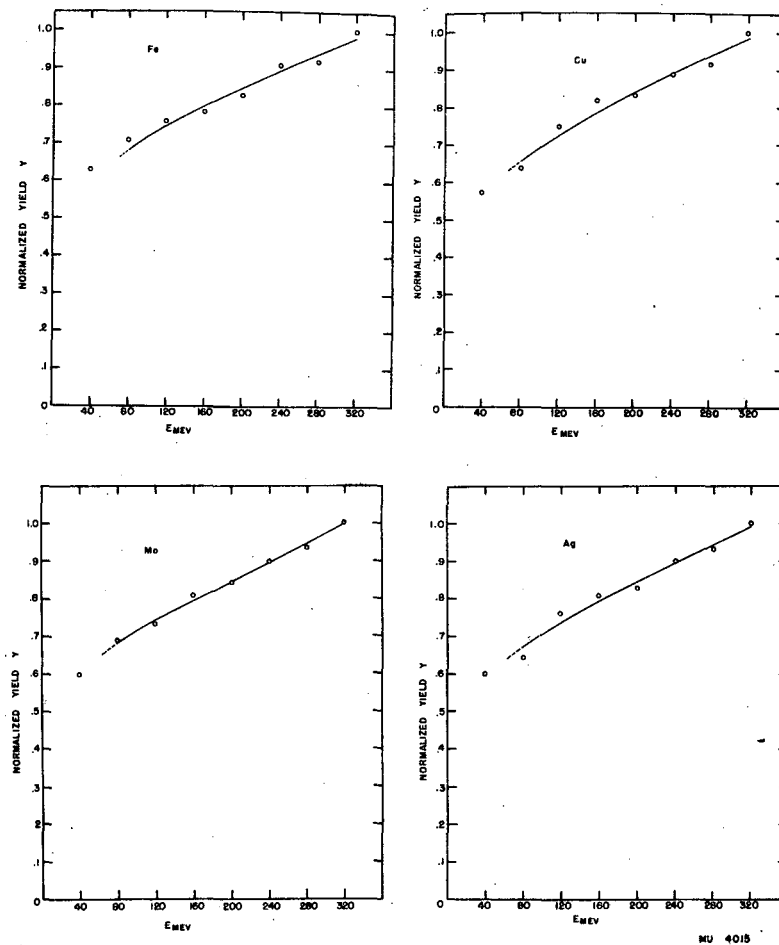


Figure 8

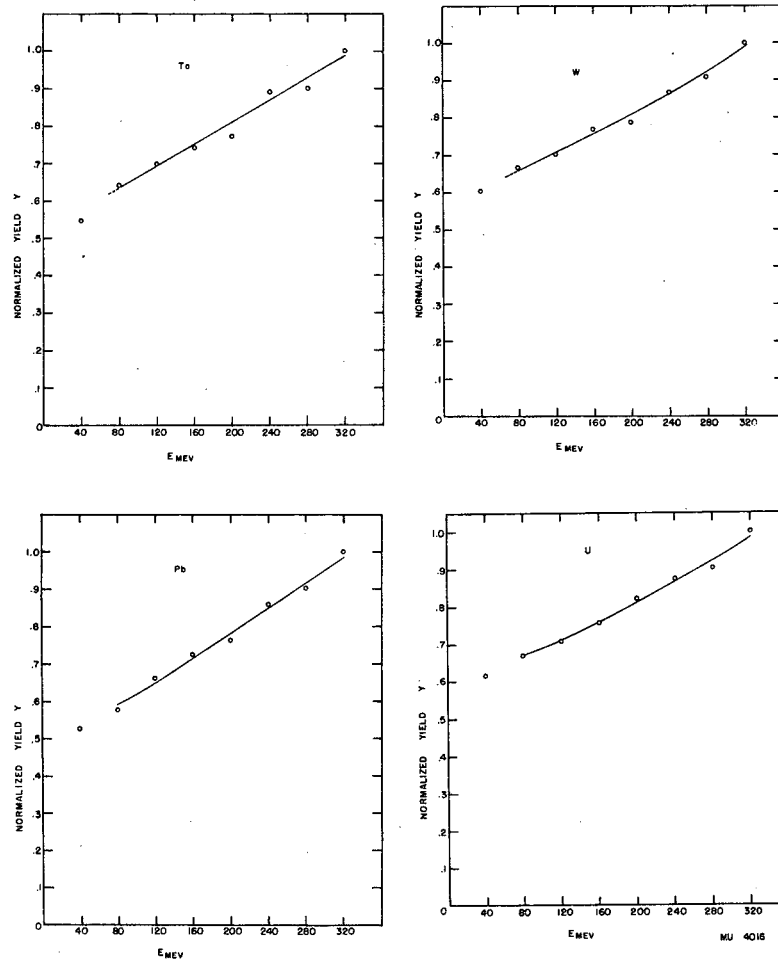


Figure 9

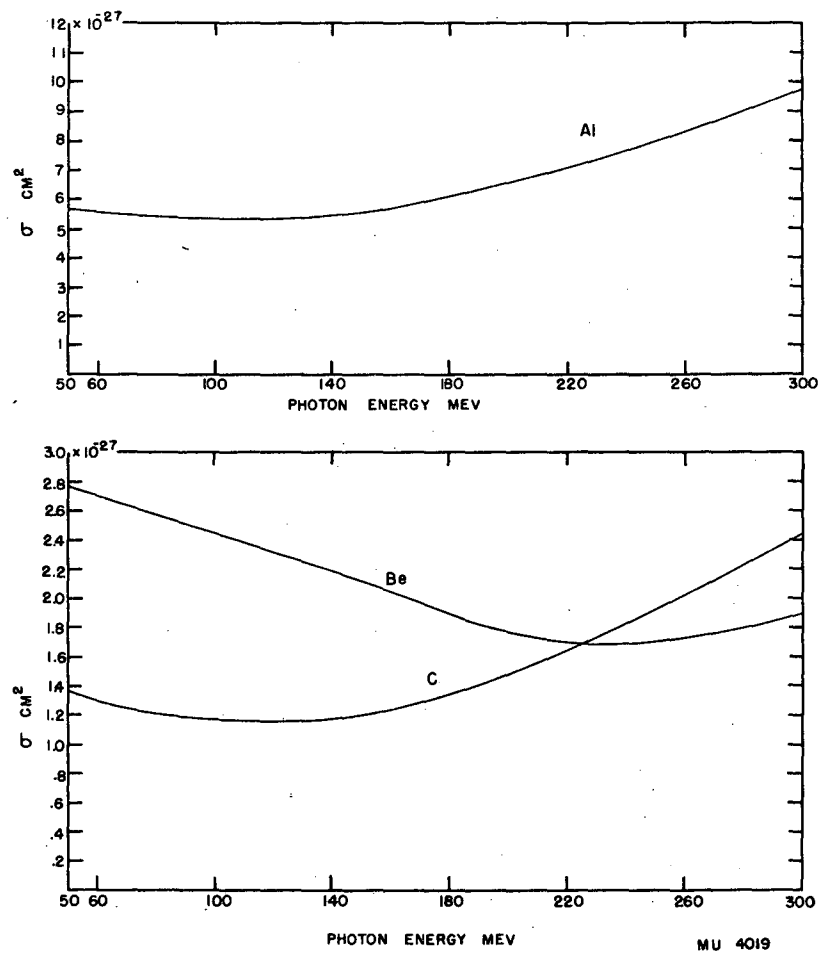
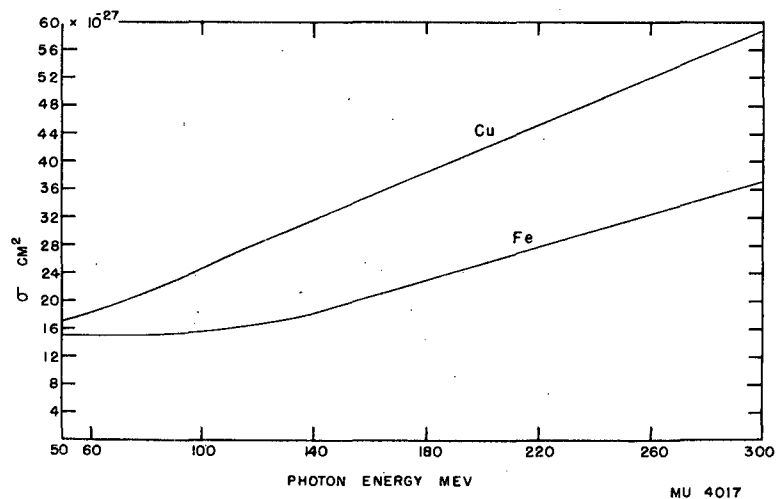
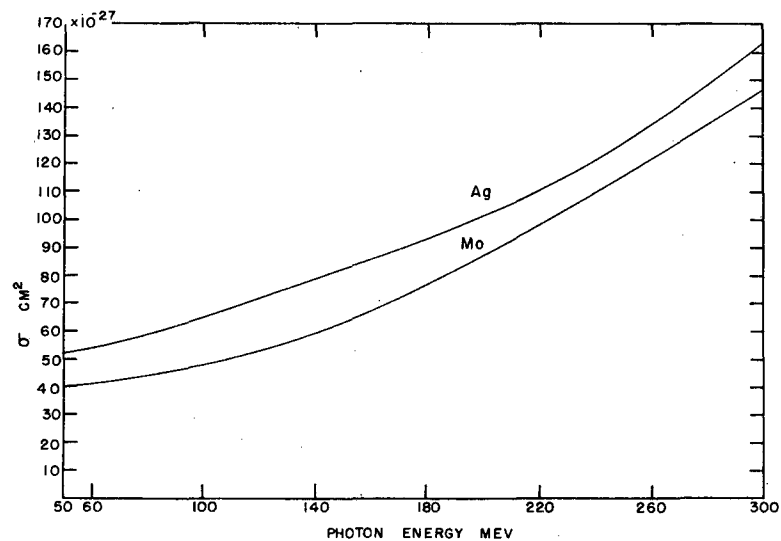


Figure 10



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Figure 11

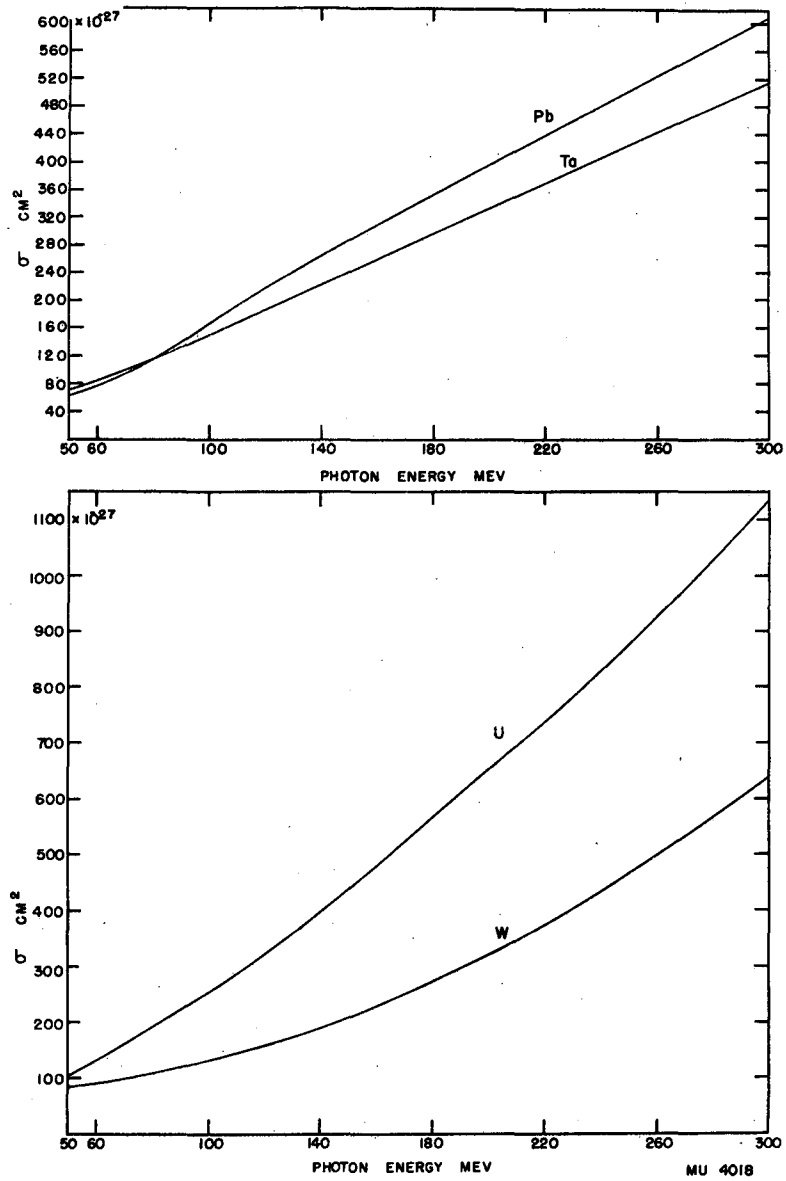


Figure 12